Robert C. Allen
Lectures and Readings

lecture 1: The long run history of poverty and living standards
Robert C. Allen, "Poverty Lines in History, Theory, and Current International Practice," Oxford University, Department of Economics, Working Paper 685, 2013.

Robert C. Allen, Jean-Pascal Bassino, Debin Ma, Christine Moll-Murata, and Jan Luiten van Zanden, "Wages, Prices, and Living Standards in China,1739-1925: in comparison with Europe, Japan, and India," *Economic History Review*, 2011, Vol. 64, pp. 8-38.

Robert C. Allen, *The British Industrial Revolution in Global Perspective*, Cambridge, Cambridge University Press, 2009, chapters 1-2.

lecture 2: globalization and economic growth in early modern Europe
Robert C. Allen, "Poverty and Progress in Early Modern Europe," *Economic History Review*, Vol. LVI, No. 3, August, 2003, pp. 403-443.

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Daron Acemoglu, Simon Johnson, and James Robinson, "The Rise of Europe: Atlantic Trade, Institutional Change and Economic Growth," *American Economic Review*, Vol. 95, 2005, pp. 546-79.

lecture 3: Explaining the Industrial Revolution
Robert C. Allen, *The British Industrial Revolution in Global Perspective*, Cambridge, Cambridge University Press, 2009, chapters 6-11.

Joel Mokyr (2005). "The Intellectual Origins of Modern Economic Growth" *Journal of Economic History* 65: 285-351.

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POVERTY LINES IN HISTORY, THEORY, AND CURRENT INTERNATIONAL PRACTICE

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Poverty Lines in History, Theory, and Current International Practice

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Measuring the standard of living has been a longstanding problem for economists and historians. A direct approach is to calculate the purchasing power of wages. The real wage is the ratio of the nominal wage to a measure of the price level. A common short cut is to use the price of grain as the measure of prices, in which case, the real wage becomes a 'grain wage' indicating the quantity of grain that can be purchased with a day's labour (Braudel and Spooner 1967, van Zanden 1999). An attraction of this procedure is that it provides an absolute measure of the standard of living. However, people consume more than grain, so it is preferable to measure the price level as a weighted average of the prices of the goods that workers consume. The weights should reflect consumer spending patterns. A limitation of this approach, as usually practised, is that the resulting real wage can only be interpreted as an index of relative income levels and has no absolute interpretation.

In Allen (2001, 2007) and Allen et al (2011), attempts were made to provided an absolute interpretation of real wages even when inflation is measured with an index of consumer goods prices. These studies examined mainly the wages of men employed in the building industry. The worker's annual earnings were computed by multiplying the daily wage by the number of days worked in a year (often taken to be 250). The earnings were divided by the annual cost of maintaining a family at a specified poverty line. The ratio of annual earnings to the cost of annual subsistence equalled the 'welfare ratio' of the family (Blackorby and Donaldson 1978). When the ratio equalled one, the worker earned just enough to keep his family at subsistence. Values greater than one equalled a surplus over subsistence, while values less than one equalled a deficit. The implications of a deficit depended on how 'subsistence' was defined.

The subsistence wage was a cornerstone of the classical economists (Ricardo, Malthus, Marx). They regarded English labourers as the bottom rung of the income hierarchy with incomes 'at subsistence' since they were the main beneficiaries of the Old Poor Law, which provided income supplements to keep labourer's consumption at subsistence–and no higher. The empirical counterparts to the classic theories were the surveys of budgets collected in David Davies' *The Case of Labourers in Husbandry* (1795) and Sir Frederick Eden's *The State of the Poor* (1797). Davies' and Eden's descriptions of spending are not problem free. They were often incomplete, but by combining details from several budgets a comprehensive view of family incomes and expenditure and can be assembled. The two prove to be in balance, and the quantities and prices of the main items consumed are known, so the budgets can be assessed for nutritional adequacy and so forth.

Table 1 shows the 'respectability basket' put together from Eden's work. The name identifies this was the standard of living to which a labourer in the south of England aspired. The table shows the consumption pattern for a man for one year.[1] The food items can be reasonably well determined from descriptions like Eden's and Davies'. When the basket is evaluated for other parts of the world, the contents are varied to reflect local food availability. Thus, olive oil and wine replace butter and beer in the Mediterranean, and price of the usual common meat or bean is used in each locality. The non-food items are harder to pin down, and the apparel component is represented by only a single item–linen or cotton cloth. This simplification was introduced since the cost of the budget must be calculated for many places

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[1]The particular representation in Table 1 is intended to be a medieval or early modern version of the budget in that it excludes the new goods (potatoes, sugar, tea) introduced from Asia and America. These exclusions were made so that the budget could be priced in the middle ages and in countries where these new goods were not consumed.

over centuries to measure real wages, and light cloth is the only item of dress whose price is consistently reported on this scale. Likewise, the rental cost of housing is represented by a 5% charge on the other items in the budget since the cost of housing cannot presently be measured for the times and places that interest historians.

Two features of the budget should be highlighted since they will be subjects of discussion in this paper. The first is the calorie content of the diet which works out to be 1940 kcalories per day. This appears to be a minimal standard and not atypical of the budgets in Eden and Davies. The second is the 'scaling factor' used to relate the family's subsistence cost to that of an adult male. On the assumption that a family consisted of a man, a woman, and two children, it was assumed that a family corresponded to three adult male equivalents, so the cost of the budget in Table 1 was multiplied by three to determine the annual subsistence cost of the family. There has been some discussion of the correctness of the value (Allen and Weisdorf 2011, Humphries 2012), and it is reassuring that detailed calculations by Floud et al. (2011, p. 46, 165-7) found that, indeed, the calorie requirement of the average person in England in the eighteenth and nineteenth centuries equalled 76% of the requirement of the average adult male, i.e. three adult males corresponded to four people in the overall population.

Figure 1 shows the welfare ratios for six cities in Eurasia when subsistence is calculated according to the respectability budget of Table 1. For labourers in London and Amsterdam, the results are in line with the views of the classical economists, for these workers earned only marginally more than subsistence. In the fifteenth century, workers in Florence and Vienna lived as well, but by the eighteenth century, their real wage had fallen to less than half of the respectability standard. Living standards were similarly low for wages in Delhi and Beijing.

What could the families do to make ends meet? Income could be increased if the man worked more or if the women and children earned money, but the chances of closing the gap were not good when the man earned less than half of the cost of the basket. In that case, spending economies would have to be made. These were possible because the respectability basket was, in fact, a high cost basket. Beer, meat, even bread were expensive sources of calories.

Costs could be cut by eliminating the expensive calories from the diet and by reducing the consumption of non-food items. Table 1 shows 'subsistence' baskets defined in this way. They are based on a diet in which most calories come from the cheapest available grain (oats in northwestern Europe, maize in the Americas and northern Italy, millet in northern India, sorghum in Beijing, and wheat flour today in many parts of the world), legumes are an important source of protein, butter or oil provides some fat, and meat or fish are rare luxuries. Diets along these lines, in fact, were common in many parts of the pre-industrial world.

For comparative purposes, a 'Northern' basket is also defined in Table 1. People in Northern Britain consumed an oat based diet in the eighteenth century (Dr. Johnson defined oats to be 'a grain, which in England is generally given to horses, but in Scotland supports the people.'), and that is an inspiration for the oat-based subsistence basket. However, many people in Northern Britain ate a more varied diet when they could afford it. Table 1 shows a stylized version. It is included since a diet based on coarse grain, potatoes, and milk is common in India and other poor places today.

Figure 2 shows the welfare ratios implied by the subsistence baskets. The geometry is similar to Figure 1, but the ratios are all higher since subsistence baskets cost less than respectability baskets. Workers in central and eastern Europe and in Asia ended up with subsistence ratios equal to about one in the eighteenth century. A man's earnings were just enough to keep the family at the level of income corresponding to the subsistence basket in Table 1. It is remarkable that the classical economists were wrong about the standard of living of the English labourer. His real income was, in fact, higher than that of workers in most of Eurasia. Indeed, in London in the eighteenth century labourers earned four times subsistence. English workers did not consume four times the oatmeal specified in Table 1; rather, they upgraded the quality of the food the consumed to the bread, beef, and beer of the respectability basket.

The welfare ratio using the respectability baskets was worked out in the 1990s, and since then great advances have been made in measuring food adequacy and poverty in developing countries. The United Nations Food and Agricultural Organization and the United States Department of Agriculture have established food security and insecurity lines and estimated the number of people in the world below them. The World Bank has established its $1 per day poverty line and undertaken poverty assessments for many countries. These indicate national poverty lines that reflect national conditions and do not necessarily equal the $1 per day standard.

The question explored in this paper is how these modern lines relate to the respectability and subsistence ratios. The indices are closely related. However, it is also discovered that the historical measures can be brought into closer alignment with the modern ones by raising the calories content of the basket from 1940 to 2100 and by increasing the scaling factor from three adult male equivalents per family to four. Given the assumptions about family size, this means the standard of 2100 calorie per day standard becomes the per capita norm rather than the norm per adult male equivalent. This change turns out to be warranted by activity levels in the past as well as by the aim of establishing consistency with modern measures. The first change increases the annual cost by about 5%, while the second increases it by one third

These themes will be developed by considering the food security lines and the poverty lines in turn.

<u>Food security lines</u>

Since 1996, the United Nations Food and Agricultural Organization (FAO) has published annually *The State of Food Insecurity in the World*. Since 1997, the US Department of Agriculture (USDA) has published a *Food Security Assessment* dealing with 70 developing countries. Both reports specify a per capita calorie consumption level that marks the division between security and insecurity. The USDA sets the frontier at approximately 2100 calories per day "depending on the region." (USDA 2010-20, p 1 n2) The FAO specifies country specific cut-offs that range from about 1750 calories per person per day to 1950 calories. The FAO figures are derived from a demographic model that relates calorie requirements to the population age distribution and physical activity levels. It is primarily differences in the former that account for the differences in calorie requirements.

Both reports specify higher calorie consumption than either the respectability or subsistence baskets. These set calorie consumption at 1940 calories per day, a figure seemingly at the upper end of the FAO range. There is an important difference, however, for the historical baskets apply this figure to an adult male rather than to the average person in the society. On the assumptions that a family had four members and equalled three adult male equivalents, the implied calorie consumption is 1455 calories per person per day (three quarters of 1940). As it happens, this corresponds to the average calorie intake of someone in the poorest decile of the Indian population (Suryanarayana 2009, p. 35). Setting the calorie intake at this level makes some sense in the case of the subsistence basket, which is intended to track to the minimal cost of survival. However, 1455 calories per person is arguably too low to provide the man with enough nutrition to do the labourer's job that generates the income in the numerator of the welfare ratio.

We can use the FAO's demographic model to set a more appropriate standard. The model requires the age structure of the males and females, and I have used values from the 1841 English census, which is the first to provide sufficient detail. The height of men and women at each age must also be specified. There is historical information about the heights of men, but the heights of women and children are less well established. As it happens, FAO (2008b, pp. 20-1) gives an example of its calculations, and the average height of men in that example is 166 centimetres, which was the average height of British men in 1841 (Floud et al. 1990, Cinnarella 2008). On the assumption that other heights were in proportion, I have applied the heights in the FAO example to England in 1841. One must also assume a Body Mass Index (BMI) for each age to compute weight from height. For adults, the FAO assumes the low value of 18.66 since the aim is to compute a minimum calorie requirement, and I follow their lead. Next, from these data, calorie requirements for basal metabolism for each age-sex group can be computed with equations developed by the World Health Organization and FAO.[2] Finally, total energy expenditure for each age-sex group is calculated by multiplying the calories required for basal metabolism by the physical activity level (PAL) of the group.

The physical activity level is computed by applying physical activity ratios (PAR) to an individual's annual time budget. The PAR is the ratio of energy expended in an activity to the energy required for basal metabolism in the same time period. The FAO (2001, pp. 36, 92-6) reports PAR's for a variety of domestic, agricultural, industrial, and recreational activities. These range from sleep (PAR = 1) to eating, chatting, or watching television (PAR = 1.4) to caring for children (PAR = 2.5) to planting maize (PAR = 4.1) to carrying wood (PAR = 6.6).

The PAL equals the fraction of the year spent sleeping multiplied by 1.0 plus the fraction spent watching television multiplied by 1.4 and so forth for all uses of time over the year. FAO (2001, p. 36) presents rough calculations for light, medium, and vigorous lifestyles. The corresponding PALs are 1.53, 1.76, and 2.25. (FAO, 36) No distinction is made in these examples between work days and non-work days, and length of the work day is shorter than the length of work days in the past or today in many less developed countries. Whether these features balance out is unclear.

Respectability and subsistence ratios have usually been calculated for building labourers and craftsmen. To determine the PAL for men doing these jobs, time budgets have been elaborated based on conditions in the past. The PAL for women is also need to compute the overall calorie requirement, so a corresponding time budget has been worked out for a

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[2]FAO (2008b, p. 18). The equation given for women age 18-29 is clearly erroneous. It should be noted that the equation given for women 18-29 is erroneous and was not used to compute the calorie requirements shown in the example on pp. 21 despite what it says there. From the example, I inferred the equation total energy expenditure = PAL *(451.5 + 15.688 * body mass in kilograms).

woman on the assumption that she was a spinner. The PAL for a woman who was mainly performing domestic tasks was similar.

The time budget for a building labourer is show in Table 2. Key parameters are taken from Voth (2000, pp. 118-33). In London in the mid-eighteenth century, people normally worked five days per week with Sunday and Monday being the days off. Consequently, it is assumed that the work year was 250 days, the number often adopted for welfare ratio calculations. The remaining 115 days were non-work days. Again, following Voth, I assume that people slept seven hours per night, and the work day was 11 hours. This is not as arduous as it appears since people spent 2.5 of the 11 hours eating breakfast, dinner, and tea. (Later in the evening, they ate a fourth meal during leisure time.)

Within this framework, I have allocated time among characteristic activities. Labourers were allotted several hours per day of strenuous activities like carrying wood and digging as well as the somewhat less strenuous tasks of cleaning, loading, and walking. Craftsmen were assumed to be carpenters and spent much of their time on the moderate activities of nailing and roofing, although some time was also spent sawing and carrying wood. Spinning was not a strenuous activity, since it was performed sitting down and did not involve heavy lifting. Indeed, spinning probably required no more energy than the daily routine of a women who earned no money. Both men and women were assumed to have devoted much of their leisure to non-strenuous activities like eating, drinking, playing cards, listening to sermons, etc. The most strenuous leisure activities were not overly energetic– personal care and cooking.

Tables 2-4 show the hours assumed to have been devoted to the various activities and the corresponding PARs. The implied annual PALs are similar to the FAO's calculated values. The PAL for the spinner (light work) is 1.74. The carpenter's PAL was 1.87 and the labourer's 2.16. Different assumptions would, of course, give different values, but the orders of magnitude are clear.

When the PAL values for the labourer and spinner are inserted in the demographic model based on English data for 1841, the average calorie requirement comes out at 2105 calories per person per year–almost precisely the USDA assumption[3]. (Had we used the carpenter's PAL instead of the labourer's, the calorie requirement would have been cut to 1990 per day.) The labourer himself is allocated 3160 calories per day averaged over non-working as well as working days. The spinner receives 2057 calories per day on average, and the children receive less. These calorie supplies are sufficient for their activities according to the FAO model.

In view of these results, it is reasonable to compute welfare ratios following the USDA model with a per capita calorie consumption of 2100. When the welfare ratios equal one, the budget is adequate for a labourer to earn the income to perform his job.

Raising the calorie content of the baskets to 2100 calories per person per day lowers welfare ratios everywhere but has no appreciable impact on relative rankings. Figure 3 shows the results. The patterns are the same as Figure 2, although the absolute values are smaller. Workers in northwestern Europe continued to earn several times subsistence throughout the period. The earnings of workers in central and southern Europe and Asia dropped below subsistence at the end of the eighteenth and beginning of the nineteenth centuries. These

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[3]The activity level of children must also be specified, and that has been set at 'strenuous.'

were, indeed, hard times. Either the labourers whose earnings are studied here were unmarried, so their wages did not have to support wives and children, or the other family members were put to work to bring family earnings up to subsistence.

World Bank Poverty Line

While one can, in principle, define a food security line with precision, the same is not true of a poverty line. The canonical poverty line is the World Bank's 'dollar a day' line, which is variously stated more precisely as $1 per day in 1985 prices, $1.08 in 1993 prices or $1.25 per day in 2005 prices. These values themselves are overly precise; indeed, the original analysis suggested a range of $.75 to $1.00 per day, which was later truncated to simply a 'dollar a day.'

The World Bank Poverty Line was not set by the Bank's defining a poverty budget along the lines of the respectability or subsistence baskets. Instead, the approach was statistical. Ravallion, Datt, and van de Walle (1991) examined the correlation between national poverty lines and GDP per capita for thirty-three countries ranging from the very poor to the very wealthy. They found that poverty lines increased with income, and, more surprisingly, clustered around $1.00 per day for the poorest countries. The 1990 *World Development Report* popularized this '$1 per day' poverty line, although in a nuanced fashion, for the report actually considered a range from 75¢ to $1 per day. "This range was chosen to span the poverty lines estimated in recent studies for a number of countries with low average incomes–Bangladesh, the Arab Republic of Egypt, India, Indonesia, Kenya, Morocco ,and Tanzania....The lower limit of the range coincides with a poverty line commonly used for India."[4] Ravallion, Chen, and Sangraula (2009) updated the analysis with a much larger sample and concluded that the $1 per day line had risen to $1.25 per day in 2005 due to inflation.

The World Bank Poverty Line has been highly controversial due to its method of construction. First, it is not clear what standard of comfort it represents since it was not set equal to the cost of a specified basket. Reddy and Pogge (2010), for instance, have argued that the World Bank should set an explicit standard adequate to meet basic needs. Ravallion (2010) has rejected a constant basket on the grounds that poor people vary their consumption in response to prices. One can overstate this, however. In the past, poor people were tightly constrained and ate mainly grain, legumes, and minimal quantities of animal protein and fat. Substitution consisted of choosing the cheapest kind of grain, the cheapest source of animal protein, and so forth. This sort of variation can be easily accommodated in the measurement of poverty, as has been done with the respectability and subsistence baskets.

Defining the poverty line as 'a dollar a day' has led to intractable disputes over price indices since comparing poverty levels across countries requires translating the dollar a day into local currencies. The World Bank procedure has been to use purchasing power parity (PPP) exchange rates for consumption. This is open to the objection that the set of prices indexed is broader than the range of goods purchased by the poor–and, hence, distorting.

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[4]World Bank (1990, p.27). Strangely, Chen and Ravallion (2001, p. 285 n.6) specify the countries as 'Bangaladesh, China, India, Indonesia, Nepal, Pakistan, Tanzania, Thailand, Tunisia, and Zambia.' The data points for Egypt, Kenya, and Morocco lie among these ten and apparently support the dollar a day standard in the original study.

Likewise, updating the line over time raises analogous problems since inflation rates differ between countries and national prices indices differ from those relevant to the poor, so the effects are not captured by the evolution of the PPP exchange rates. These problems could all be avoided by defining poverty explicitly in terms of a basket of goods (allowing for local adjustment in response to food availability) that could be priced anywhere at any time.

While the World Bank refuses to propose a basket of goods to define the international poverty line, the various national poverty lines that form the basis of the dollar a day line were themselves based on their own baskets (or, in a few cases, on a sense of what that basket might have been). This is clear in the 2005 revision where most of the data come from poverty assessments using an explicit budgeting procedure. It was also true for the original $1 a day line, although the procedures were less standardized. The upshot is that the World Bank Poverty Line depends on the poverty line baskets of the poor countries in the dollar a day group. By examining their baskets, we can see what the dollar a day line means, and how it relates to the historical poverty lines we have discussed.

The Ravallion, Datt, van de Walle, Chan (1991, p. 34) data set included fifteen countries with poverty lines less than or equal to $1/day. It would be desirable to find the poverty line baskets of all of these countries, but that is not possible. In a few cases, lines were chosen with only a vague reference to the consumption of the poor. In his study of Pakistan, Naseem (1973, p. 321) noted that a satisfactory poverty line "would require a considerably detailed investigation" into nutrition requirements, geographical variation, and the structure of prices. "In the absence of a detailed investigation for the precise estimation of the poverty line, we have chosen two arbitrary benchmarks for the rural areas of Pakistan" as well as two higher benchmarks for urban areas. These lines were set with an eye towards the incomes of the poor–Naseem alluded to the Indian poverty line– but without an explicit budget.

Many poverty lines are taken from World Bank staff reports written in the 1980s, and many of these are either unavailable or provide too few details to be useful. In his study of the Dominican Republic, Musgrove (1984, p. 115, cf. 1986, p. 356) reported that "there has not yet been a detailed calculation establishing a minimum adequate budget," however, he did estimate a poverty line "based on the total spending and food spending of households in the second decile of total income, with an upward adjustment to compensate for their estimated short fall in caloric intake." Unfortunately, the resulting basket was not reported. The poverty line for Nepal was a modification of a Nepalese Planning Commission line that stipulated an average consumption of 2250 calories per person per day and assumed that food amounted to only 65% of consumption expenditure–a very low value (World Bank 1989, Vol. II, pp. 176-7). Further details are unavailable. Likewise the poverty line for China is based on two different Chinese government poverty lines, neither of which is spelled out in detail, or on relative poverty lines equal to 35% and 50% of average income. In the absence of information about the prices people actually paid for food, "we use several different expenditure-based poverty lines, including the official poverty line, without attempting to assign nutritional equivalence." (Ahmad and Wand 191, p. 236)

We are in better shape with poverty lines defined by independent social scientists as they provide more details of their methods. The food baskets for studies of Egypt, Tanzania, and Kenya are shown in Table 5. The Egyptian basket was intended to reflect the actual consumption pattern of the median household in a random sample drawn from 18 villages in Egypt in 1977, although the food quantities were all reduced in the same proportion so that the diet gave the calorie content corresponding to norms at the time. (Radwan and Lee 1986, pp.. 17, 82-3). The Tanzanian diet contained only four foods and was intended to be 'deliberately austere.' (Jamal 2001, p. 38). The Kenyan diet with only maize and beans took simplification to the extreme. "Using only two staple commodities to compute a basic subsistence diet for small-holders in Kenya is bound to underestimate the cost of a realistic minimum diet, which would also contain small amounts of more palatable and expensive foodstuffs, such as meat, vegetables, dairy products, and sugar." (Crawford and Thorbecke 1980, p. 317). It will be no surprise that the costs of these diets vary enormously although they are all treated equivalently in inferring the dollar a day poverty line.

The measurement of deprivation and poverty has been studied in India since the late colonial period, and it remains contentious (Sukhatme 1961, Deaton and Kozel 2005). In 1962 the Indian Planning Commission chose the value of 20 rupees per month (in 1960/1 prices) as the minimum consumption level that should be a target of the fifth Five Year Plan. The Commission did not explain how it reached this figure, but a strong possibility, suggested by Rudra (2005, p. 373-6), is that it was based on the research of P.V. Sukhatme. He was a leading Indian statistician who investigated food issues, he was head of the statistics division of the FAO from 1952-70, and he lectured on "The food and Nutrition Situation in India" at the annual sessions of the Indian Society of Agricultural Statistics in the 1950s and 1960s (Sukhatme 1965, p. vi). He published various estimates of low cost diets that met nutritional objectives (eg. Sukhatme 1961, p. 498). In 1965, he published an influential assessment of India's food needs. His 'minimal level'diet, evaluated in 1960/1 prices, cost 15.63 rupees per month (Sukhatme 1965, pp. 120-1). Low income rural households at the time devoted approximately 79% of their spending to food (National Sample Survey 138, Table 1.6.0). Applying this percentage to the cost of Sukhatme's diet implies a total monthly expenditure of 19.8 rupees. This calculation would justify the Planning Commission's choice.

A weakness of this figure is that Sukhatme's diet contained more expensive foods than poor people consumed. Dandekar and Rath (1971, p. 7) observed that rural households with expenditures of 13 to 15 rupees per month in the NSS 1960/61 probably consumed about 2250 calories per person per day, which was adequate for the work they did. A more precise analysis of this group's spending shows that they consumed 2311 calories per day at a cost of 11.03 rupees for food and a total expenditure of 14.04 rupees per month. This was only 70% of the Planning Commission's 20 Rupee line, and it became the Indian point in the original World Bank Poverty Line data set (Ravallion, Datt, van de Walle, and Chan 1991, p. 34).

The Indian poverty line has been revised several times, most recently by the Tendulkar (2009) Commission. In the preceding generation, the established procedures for updating the poverty line to reflect inflation had generated a rural line that was no longer credible. Furthernore, despite a rise in real income as conventionally measured, per capita calorie consumption in rural India declined from 2266 calories per person in 1972/3 to 2047 in 2004/5 (Suryanarayana 2009, p. 35.) Apparently people were buying more expensive foods and more non-food items as their incomes rose. This behaviour calls into question the use of a calorie standard to set a poverty line. As a result, the Tendulkar (2009) Commission adopted the prevailing urban poverty line of 578.8 rupees per month as the national standard (as this one, unlike the rural one, had not been discredited) and worked out a new rural line from the differences in rural and urban prices. While explicitly renouncing a calorie basis for the poverty line, the line was none-the-less validated by showing that people at the line received adequate nutrition. A breakdown of expenditure for urban families on the line was provided (Tendulkar 2009,p. 32). These details indicate that the poverty line lay at about the average consumption pattern of the third and fourth declines of the urban population in the

2004/5 national sample survey, and from this information we can work out a budget that would generate the 2005 Indian poverty line. Table 6 shows Sukhatme's 1965 budget, the budget assumed by Dandekar and Rath (1971, p. 7) and built into the World Bank Poverty Line, and the budget implicit in the 2005 poverty line.

To establish the relationship between the 'dollar a day' line and the historical subsistence baskets, we can compare the baskets directly as well as their cost. They differ in three important ways. The first is the calories supplied per day. All other things equal, more calories implies a higher costs. The second is the range of foods. Generally, the more calories are derived from foods other than the basic carbohydrate, the more expensive is the diet. The third is the proportion of the spending devoted to food. More spent on non-food items raises costs. The historical baskets have somewhat lower than average calorie contents. The respectability and northern baskets contain more goods than the subsistence basket and look more like the Egyptian and Sukhatme baskets than the Kenyan and Tanzanian baskets. The subsistence basket has many similarities to the Kenyan and Tanzanian baskets, as well as the Dandekar-Rath basket for India. The non-food shares of the historical baskets are lower than those of most of the modern baskets.

The baskets can also be compared in terms of their cost. Table 7 shows estimates of the cost of historical subsistence baskets evaluated with prices from online shopping in the United States conducted mainly at the end of 2012. Most prices come from Safeway for delivery in San Francisco, and a few nonfood items come from other suppliers. The dollar a day line was recalibrated as $1.25 in 2005. If it is increased in line with the US consumer price index, it becomes $1.47 at the end of 2012. Comparison with Table 7 shows that the rice, maize, and wheat flour baskets bracket this figure with a mean of $1.58. Only the oatmeal basket at $2.47 per day looks out of line with the international poverty line. This provides some validation for the historical baskets in terms of World Bank practise.

The correspondence between the subsistence baskets and the $1 per day poverty line turns out to be looser when the subject is investigated over a longer time frame. Most of the relevant food and energy prices are available since 1980 in the US Bureau of Labor Statistics 'average retail food and energy prices' and the others can be inferred by extrapolating prices in Table 7. Figure 4 plots the cost of the various historical baskets valuing them with US prices. There was always a range in values with the wheat flour basket invariably the cheapest and the oatmeal basket the most expensive. In 1985 most baskets cost about $1 per day and in 2005 they bracketed $1.25 per day.

The modern poverty line baskets can be valued in US retail prices. Figure 5 shows the results for the Indian poverty lines. The Dandekar-Rath line lies between the cost of the maize and wheat flour subsistence baskets. The Sukhatme line, which is equivalent to the Indian Planning Commission 20 Rs line, and the 2005 line were both more expensive and greatly exceeded the 'dollar a day' standard as well as the other poverty lines.

The diversity in the value of different poverty lines is highlighted even more by Figure 6. The Egyptian line was extremely expensive and greatly exceeded the 'dollar a day' standard despite being in the original data set. Its exceptional cost is no surprise in view of its expensive foods and high non-food spending share. The Sukhatme-Planning Commission line and the 2005 line are the next most expensive. The various historical baskets and the Dandekar-Rath line, as well as the poverty lines for Kenya and Tanzania lie at the bottom.

The discrepancies among the poverty lines may reflect differences in the relative prices between countries. We can illustrate the problem with US and Indian prices in 2009 (Table 8). The prices received by farmers in the two countries were similar when converted at the market exchange rate of rupees to the dollars. Rice was the most expensive grain followed by wheat and then by maize and oats. In India, the ratios of the prices of processed consumer goods to the corresponding farm prices were small. Consumers paid only a 5% mark-up on rice, and wheat and maize flour cost 38% - 77% more per kilo. In the United States, on the other hand, the corresponding mark-ups were much greater, presumably reflecting higher wage rates, and the disconnect between retail and farm gate prices was enormous. Wheat flour sold at more than double the farm gate price of wheat, and rice at the retail level was almost five times as expensive as it was on the farm. Maize flour and oatmeal were marked up by factors of 17 and 24 over the farm gate prices of corn and oats. The effect of these mark-ups was to make maize and oats the most expensive products in US super markets whereas they were the cheapest products on the farm, and maize was one of the cheapest foods at any point along the food chain in India.

Did the differences in relative prices affect the rankings of the various baskets? Figures 7-9 value the baskets with Indian rural retail prices and then convert the results to US dollars using the World Bank's PPP exchange rates for private consumption. Figure 7 shows that the historical subsistence baskets based on wheat flour, rice, and maize all cost less than the 'dollar a day' standard (in contrast to Figure 4 where US retail prices were used). The significance of this is called into question, however, when the Indian poverty lines are expressed in US dollars. The Sukhatme-Planning Commission line is the highest but certainly on the low side of a 'dollar a day'. The Dandekar-Rath line is very low, indeed, being little different from the wheat historical basket. Figure 8 adds some of the other lines discussed. As in Figure 5, the Egyptian and Sukhatme-Planning Commission lines are the most expensive with the latter giving the best tracking of the 'dollar a day' standard. The 2005 Indian line was lower. Once again, the Dandekar-Rath line for India, the historical wheat subsistence basket and the poverty lines developed for Kenya and Tanzania cost less than a 'dollar a day' but were close to each other.

The question motivating these comparisons was the relationship between the historical baskets and modern poverty lines. The comparisons revealed a greater range in the value of modern poverty baskets than was anticipated. The comparisons depend in detail on the prices used to value the baskets, but the following were generally true: The respectability and northern baskets are on a par with the more expensive modern baskets like those of Egypt and those proposed by Sukhatme and in Tendulkar Commission for India. The subsistence basket has a cost like the baskets proposed for Tanzania or Kenya or the Dandekar-Rath poverty line for India.

An Inter-Temporal Price Issue

Table 7 raises a small mystery: For earlier periods in American history, a maize-based basket was used, and yet the wheat-based basket was clearly less expensive in 2011. Was the use of the maize basket in earlier years a mistake or had relative costs of the baskets changed? While the oat basket was never the cheapest in the Americas, its extremely high cost vis-à-vis wheat in 2011 raises the same question with respect to Northwestern Europe where an oat-based basket was used for historical calculations.

In fact, wheat emerged as the cheapest source of calories during or after the Industrial Revolution. Figure 10 shows the price paid per pound for oatmeal and wheat flour by Greenwich Hospital from 1748 to 1902. Before Waterloo, oats were always cheaper by a substantial margin, and this had been the relationship since the middle ages. From about

1815 to the 1870s, Greenwich Hospital paid similar prices for wheat flour and oat meal. From the 1880s onward, wheat flour was substantially cheaper and remains so. The fall in the price of wheat was a consequence of the global market in wheat that emerged in the nineteenth century and the immense exports originating from Australia, Russia, Argentina, and North America.

Maize remained the cheaper source of calories in the Americas later than oats in Europe. Figure 11 shows the retail price of wheat flour and corn meal in Boston from 1785 to 1930. Before the 1890s, corn meal was always cheaper. From 1890 to 1925, the prices were similar. After 1925, wheat dropped below maize. Its unfortunate that the Bureau of Labor Statistics stopped publishing Boston prices in 1930, so we cannot track the evolution since then. Certainly today, wheat flour is much cheaper than maize flour.

It was always clear that different subsistence baskets should be used in different parts of the world since the cheapest grain was different in different places. The implication of Figure 11 is that baskets are not constant over time. They should also be changed from time to time to reflect changes in relative food prices

Conclusion

This paper has explored the interface between historical real wage indices and modern food security and poverty lines in an effort to connect our understanding of the past to the present. Connection requires consistently defined indicators. In this case, the main issue is the deflator used to adjust income differences for differences in the prices of consumer goods.

Analysis of the logic and practice of food security lines suggests that we can improve the historical measures by raising the calorie content of the food basket to 2100 calories and interpreting the basket to apply to each person rather than to an adult male equivalent. These changes would bring the baskets into alignment with modern food security lines, as well as the nutritional assumptions underlying many poverty lines. Furthermore, explicit calculations indicate that this calorie standard is consistent with the energy requirements of people living in earlier times.

Analysis of the World Bank poverty line indicates that a subsistence basket based on 2100 calories per person is consistent with the 'dollar a day' line under many assumptions. The analysis does highlight many of the unsatisfactory features of the World Bank Poverty Line, however, that result from its method of construction. Perhaps the World Bank can learn a lesson from historians and settle on an explicit definition of poverty that can be applied across space and over time. Historical research indicates that this is practical. The benefits in terms of transparency and intelligibility would be large.

Table 1

Historical Baskets

		Respectability	Subsistence	Northern
bread	kg	182		
grain	kg		170	121
beans/peas	kg	34	20	
potatoes	kg			163
meat	kg	26	5	5
butter	kg	5.2	3	5
cheese	kg	5.2		3
eggs	kg	52		
milk	litres			220
beer	litres	182		120
sugar	kg			1.4755
tea	kg			1.4755
soap	kg	2.6	1.3	1.3
cloth	metres	5	3	3
candles	kg	2.6	1.3	1.3
lamp oil	litres	2.6	1.3	1.3
fuel	Mill BTU	5	2	2
calories/day		2103	2099	2101
food share				86%

note:
Grain- This diet assumes the grain was oats. Different quantities are used for other grains, eg maize (182), rice (187), millet (184), wheat flour (195).
subsistence-
Northern-65 kg of barley plus 56 kg of oatmeal

Table 2

Labourer’s Annual Time Budget

			days at work			days not at work	
labourer (male)							
	PAR		hours	PAR*hours		hours	PAR*hour
rest hours							
sleep	1		7	7		7	7
personal	2.3		1	2.3		1	2.3
eating	1.4		1	1.4		4	5.6
drinking	1.4		2	2.8		3	4.2
chores	2.3		2	4.6		2	4.6
misc	1.5		0	0		7	10.5
work hours							
digging (a	5.6		1.5	8.4		0	0
loading (m	3.2		2	6.4		0	0
cleaning e	4		2	8		0	0
carry woo	6.6		2	13.2		0	0
walking	2.3		1	2.3		0	0
eating	1.4		2.5	3.5		0	0
total hours =			24	59.9		24	34.2
work hrs/day =			11	2.495833			1.425
days/year =				250			115
				623.9583			163.875
PAL =				2.158447			

Table 3

Carpenter's Annual Time Budget

			days at work			days not at work	
carpenter							
	PAR		hours	PAR*hours		hours	PAR*hour:
not at work							
sleep	1		7	7		7	7
personal	2.3		1	2.3		1	2.3
eating	1.4		1	1.4		4	5.6
drinking	1.4		2	2.8		3	4.2
chores	2.3		2	4.6		2	4.6
misc	1.5		0	0		7	10.5
work							
nailing	3		4.5	13.5		0	0
roofing	2.9		2	5.8		0	0
sawing	6.7		0.5	3.35		0	0
carry wooc	6.6		0.5	3.3		0	0
walking	2.3		1	2.3		0	0
eating	1.4		2.5	3.5		0	0
			24	49.85		24	34.2
work hrs/day =			11	2.077083			1.425
				250			115
				519.2708			163.875
PAL =				1.871632			

Table 4

Spinner’s Annual Time Budget

			days at work			days not at work	
spinner (female)							
	PAR		hours	PAR*hours		hours	PAR*hour:
rest hours							
sleep	1		7	7		7	7
personal	2.3		1	2.3		1	2.3
eating	1.4		1	1.4		4	5.6
leisure	1.4		1	1.4		3	4.2
cooking	2.1		2	4.2		2	4.2
houseworl	2.8		1	2.8		7	19.6
work hours							
spinning	2.2		7.5	16.5		0	0
loading (m	3.2		0	0		0	0
cleaning e	4		0	0		0	0
carry wood	6.6		0	0		0	0
walking	2.3		1	2.3		0	0
eating	1.4		2.5	3.5		0	0
total hours =			24	41.4		24	42.9
work hrs/day =			11	1.725			1.7875
days/year =			2750	250			115
				431.25			205.5625
PAL =				1.744692			

Table 5

Some Modern Baskets underlying
the World Bank Poverty Line
(Kilograms per person per year)

	Egypt	Tanzania	Kenya
wheat	34.2		
maize	33.6	188.2	136.9
millet	1.1		
flour	44.7		
rice	22.7		
macaroni	54.2		
beans/pulses	20.9	37.6	58.7
meat	5.5		
poultry/fish	3.6		
eggs	3.4		
oil/fat/butter	7.8	5.4	
milk	3.4		
cheese	8.2		
potatoes	12.1		
onions	8.0		
tomatoes	13.7		
other veg/fruit	6.6		
sugar	14.8	11.47	
Kcal/day	2114	2200	1715
food share	60%	75%	75%

sources:
Egypt-Radwan and Lee (1986, p. 83)for food consumption per adult equivalent, p. 84 for ratio of food to total, and p. 86 for ratio of people to adult equivalents. The quantity of beans and pulses were increased in proportion to the calories derived from the consumption of cooked beans and falafel, the quantities of which are not reported.
Tanzania-Jamal (2001, p. 38). This appears to be a published version of the source cited by Ravallion, Datt, van de Walle, and Chan (1991).
Kenya-Crawford and Thorbecke (1980, p. 316) for diet per adult equivalent and p. 318 and 319n16 for the ratio of people to adult equivalents.

Table 6

Indian Poverty Line Budgets

	Sukhatme	Dendekar-Rath	Tendulkar (implicit)
grain	147.10	204.67	122.52
starchy roots	16.79		
legumes/pulses	37.96	20.09	9.80
milk	73.37	14.60	29.07
oil	6.57	2.33	7.32
meat etc	2.56	1.54	7.92
fish & eggs	6.94		
sugar	18.25	6.69	8.1
salt & spices			2.96
fruit & veg	50.01		61.64
other food		2.38	17.04
intoxicants			1.78
clothing		7.91	
fuel & light		1.52	
miscellaneous		[1.3 R.]	
Kcal/day		2311	1960
food share		79%	56%

Note: all food is kilograms/person/year. Clothing is metres of cloth, fuel & lighting is in millions of BTUs (derived from implicit consumption of kerosene). The 1.3 Rupees shown as ‘miscellaneous’ is the spending on miscellaneous items in NSS 138, Table 1.6.0 for 13–15 Rs. per person per month.

Table 7

The Cost of Subsistence Budgets in USA in 2011

Barebones subsistence at 30 jan 2011				Prices of Delivery to area code 94115, San Francisco, CA.							
www.safewway.com											
		oat	rice	maize	wheatflour	prices		oat	rice	maize	wheatflour
						$/unit					
wheat flour	kg				195	$1.10					$214.13
oat porridge	kg	170				$3.69		$626.91			
rice	kg		185			$1.96			$362.25		
Flour corn	kg			182		$2.43				$442.87	
red kidney beans	kg	20	20	20	20	$4.28		$85.56	$85.56	$85.56	$85.56
meat-beef roasting	kg	5	5	5	5	$7.70		$38.49	$38.49	$38.49	$38.49
butter, unsalted	kg	3				$9.68		$29.04	$0.00	$0.00	$0.00
vegetable oil	l		3	3	3	$2.46		$0.00	$7.38	$7.38	$7.38
soap	kg	1.3	1.3	1.3	1.3	$5.48		$7.12	$7.12	$7.12	$7.12
candles	kg	1.3	1.3	1.3	1.3	$3.27		$4.25	$4.25	$4.25	$4.25
oil (lighting) (veg o	l	1.3	1.3	1.3	1.3	$4.64		$6.03	$6.03	$6.03	$6.03
cotton cloth	sq m	3	3	3	3	$4.66		$13.99	$13.99	$13.99	$13.99
coal	mill BTUs	2	2	2	2	$23.21		$46.41	$46.41	$46.41	$46.41
charcoal	mill BTUs					$242.33		$0.00	$0.00	$0.00	$0.00
No 2 home heating	mill BTUs					$25.50					
total								$857.81	$571.48	$652.11	$423.37
rent allowance @5%								$42.89	$28.57	$32.61	$21.17
total per person ($)								$900.70	$600.06	$684.71	$444.54
cost per day ($)								$2.47	$1.64	$1.88	$1.22

Table 8

Indian and USA prices, 2009

United States prices $/kg				
		farm		retail
		$/kg		$/kg
wheat		$0.25		$0.51
rice		$0.37		$1.76
maize		$0.16		$2.73
oats		$0.14		$3.35
Indian prices				
	farm	farm	retail	retail
	Rups/kg	$/kg	Rups/kg	$/kg
wheat	12	$0.25	16.54	0.341698
rice	18.2	$0.38	19.21	0.396858
maize	9	$0.19	15.92	0.32889

Figure 1

Respectability Ratios

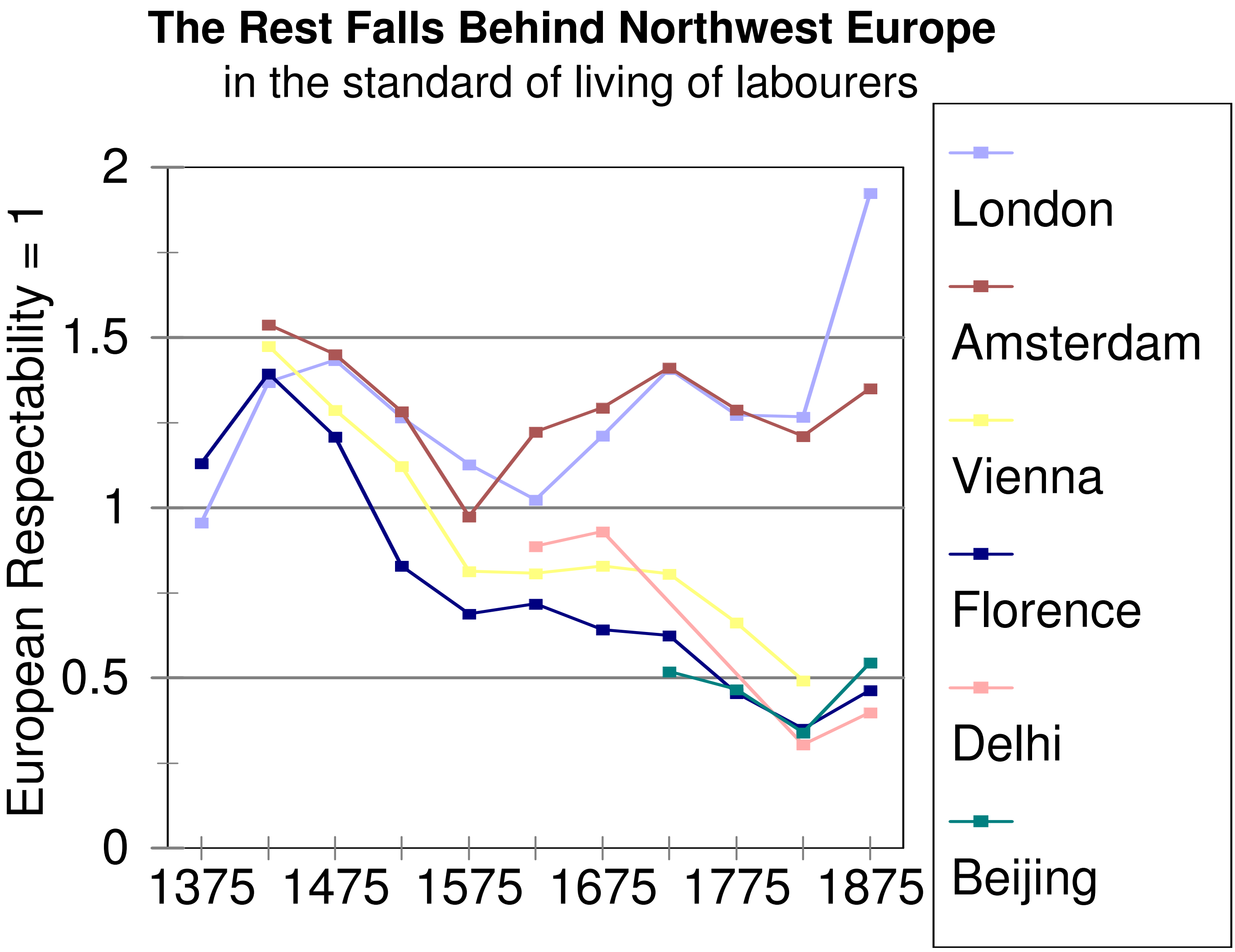


Figure 2

Subsistence Ratios

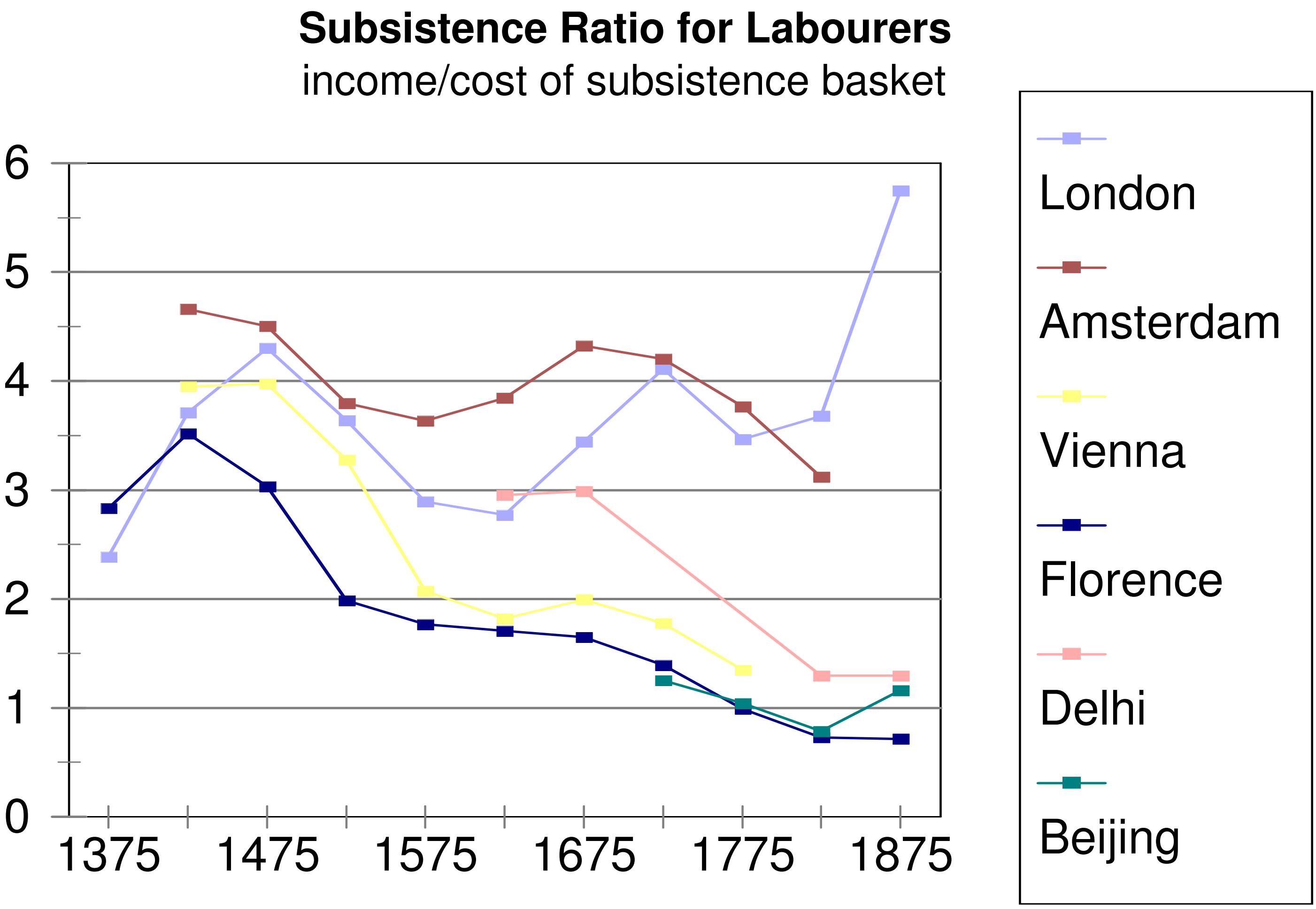


Figure 3

Subsistence Ratio (new basis)

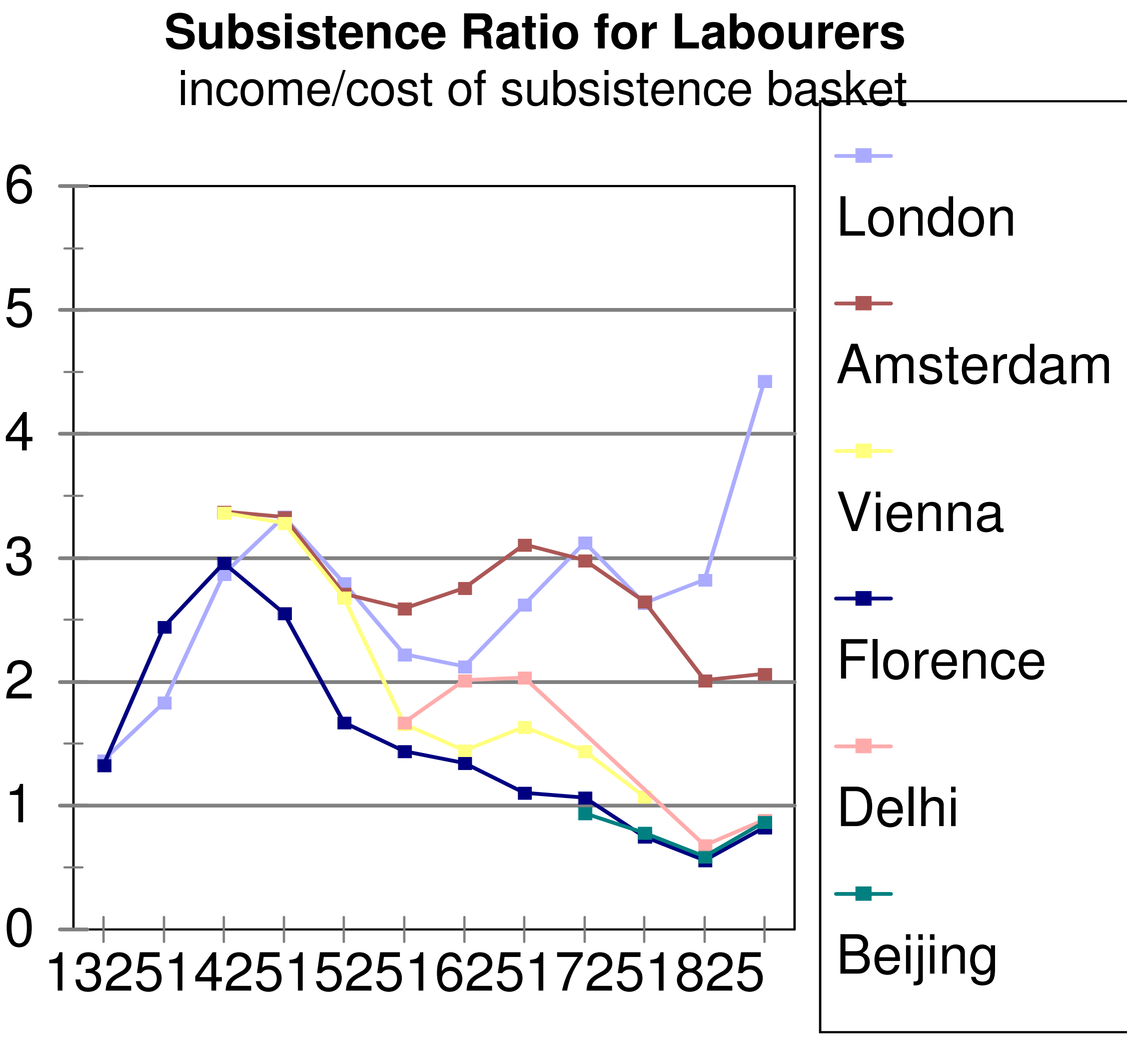


Figure 4

Historical Subsistence Baskets valued in US retail prices

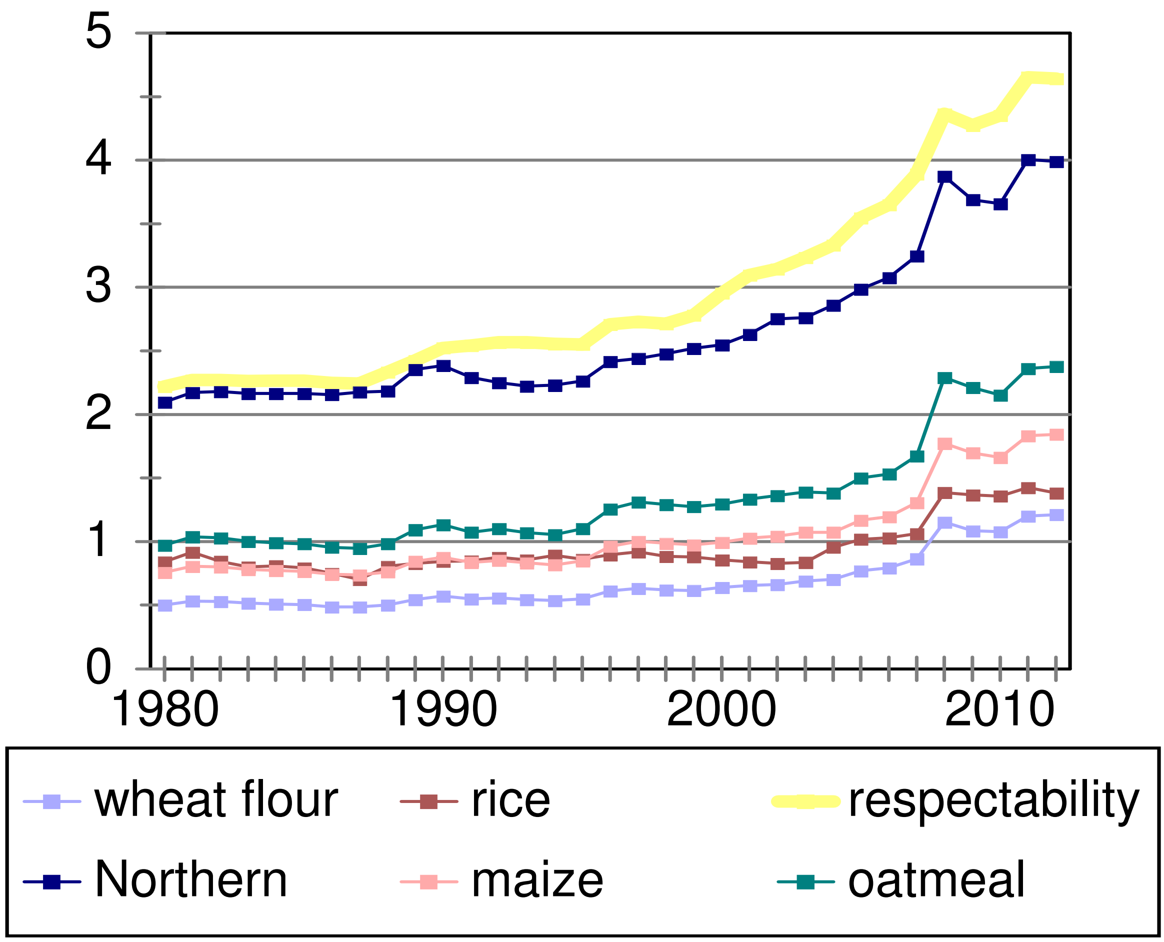


Figure 5

Indian Poverty Budgets valued in US retail prices

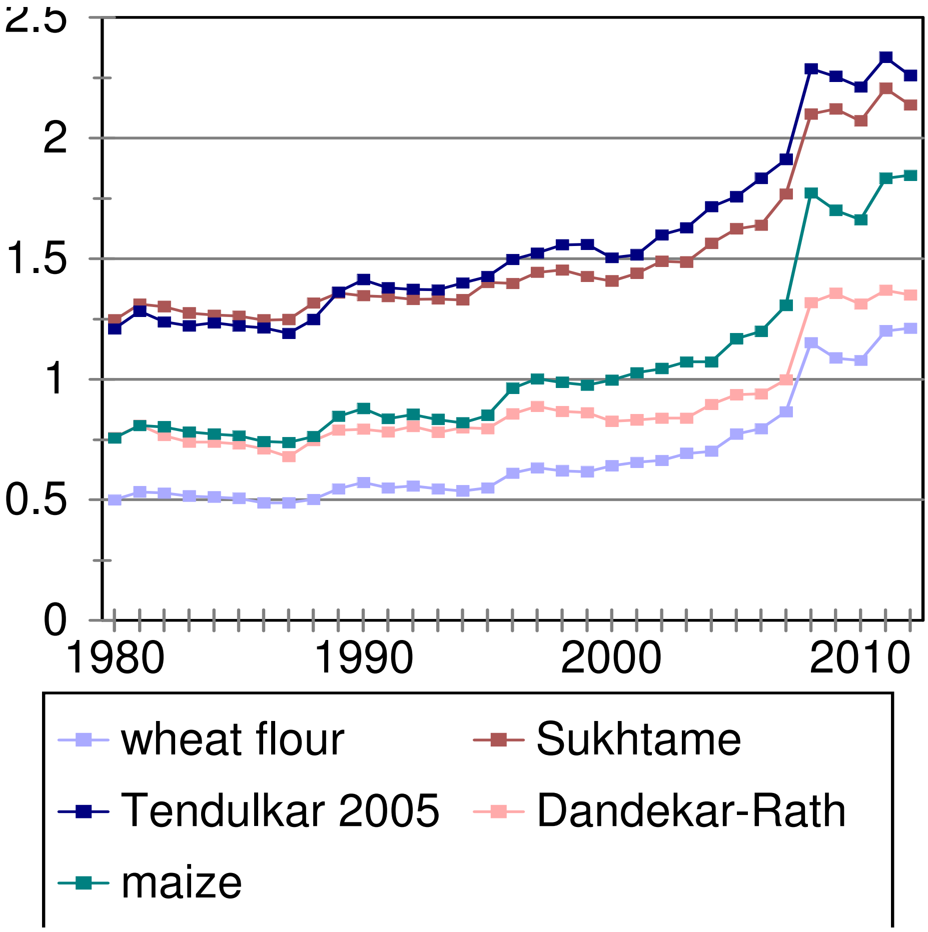


Figure 6

Modern Poverty Budgets valued in US Retail Prices

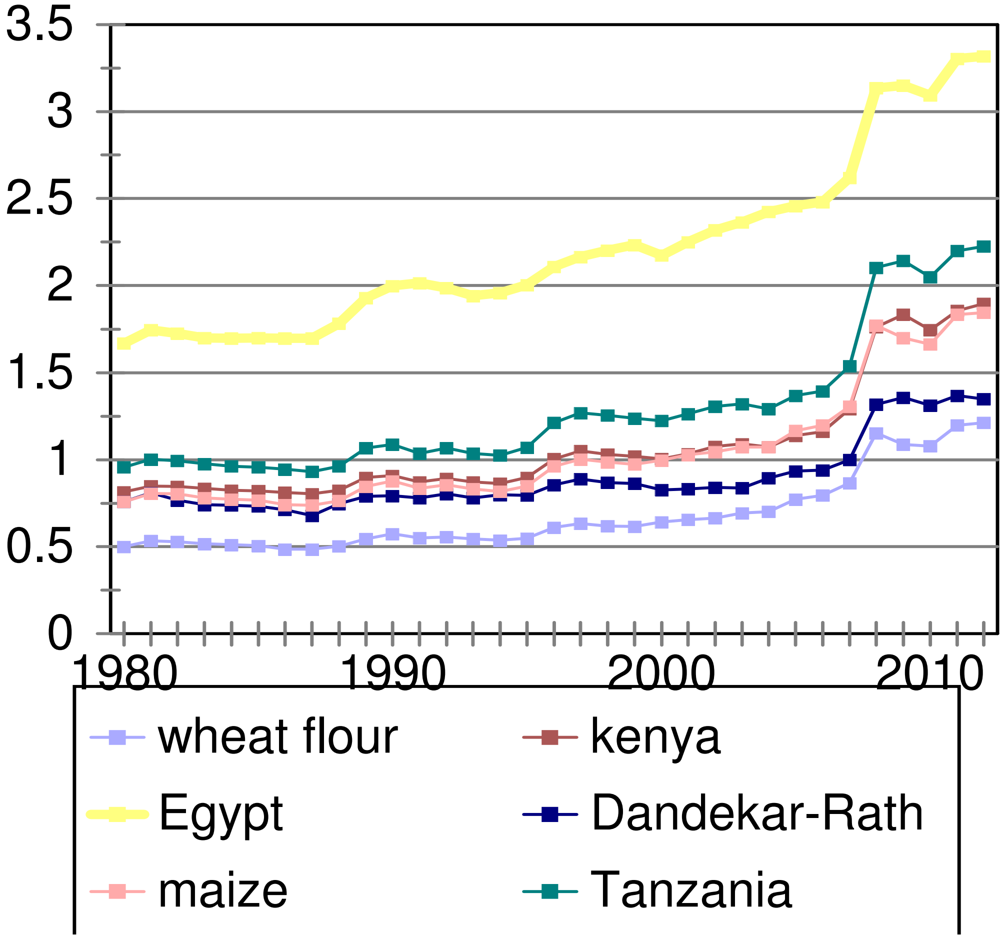


Figure 7

Historical Subsistence Baskets Valued in Rural Indian Prices

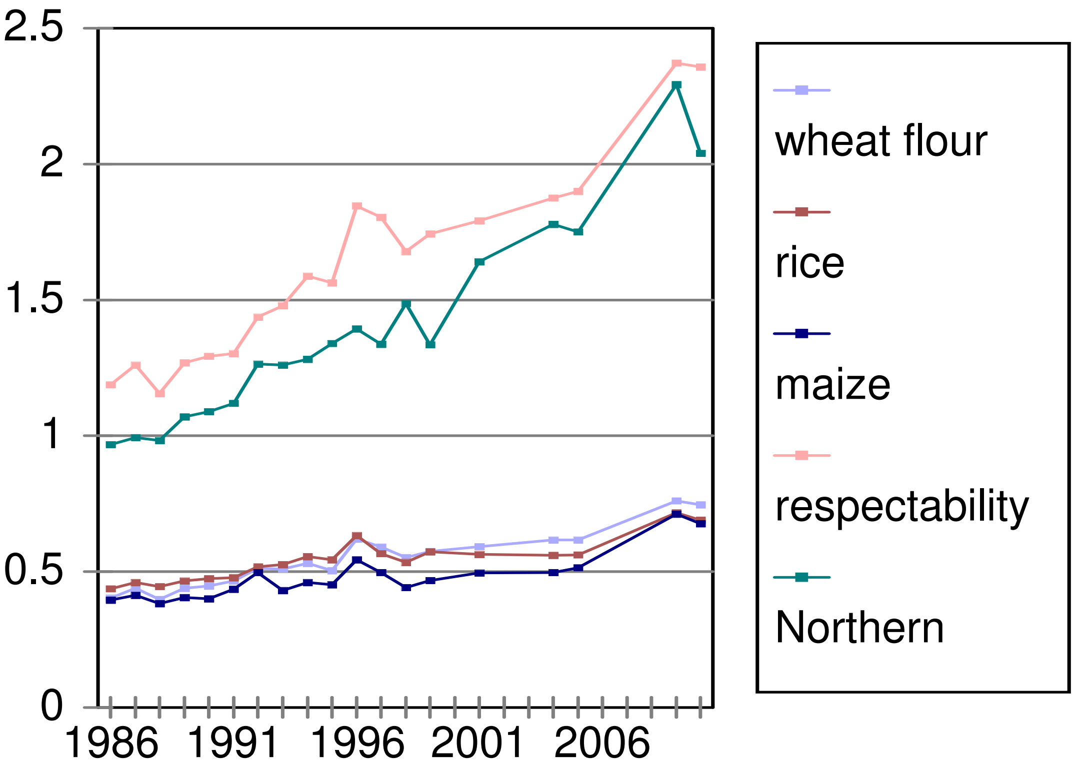


Figure 8

Indian Poverty Budgets value in Rural Indian Prices

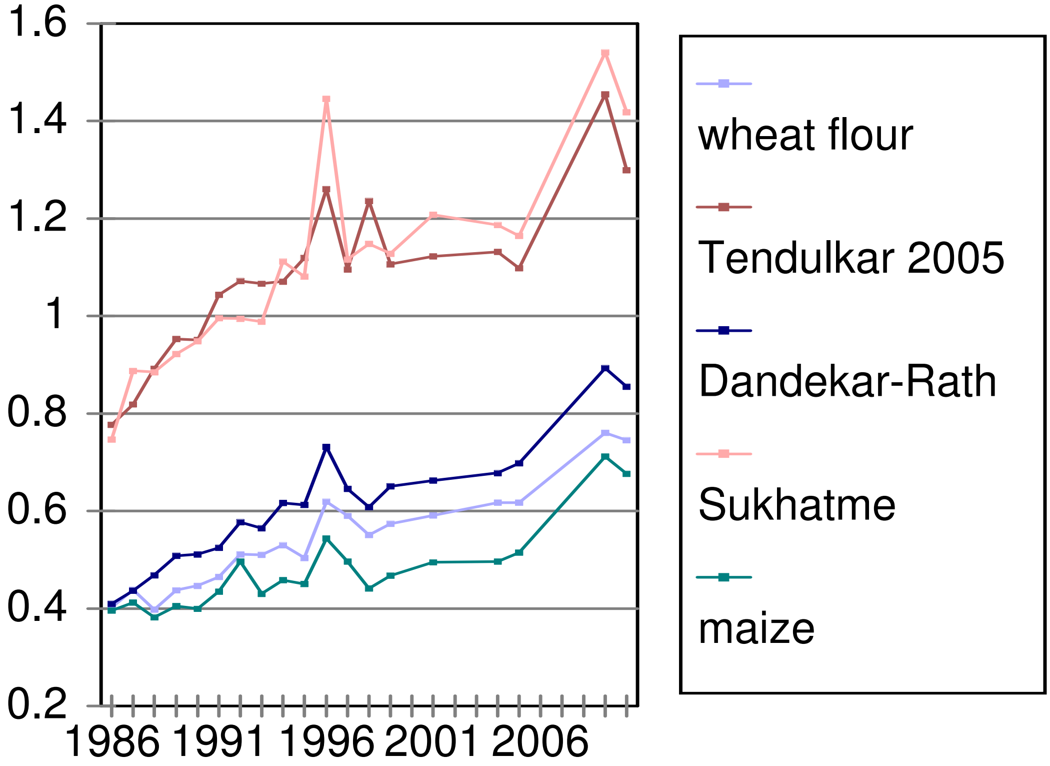


Figure 9

Modern Poverty Budgets valued in Rural Indian Prices

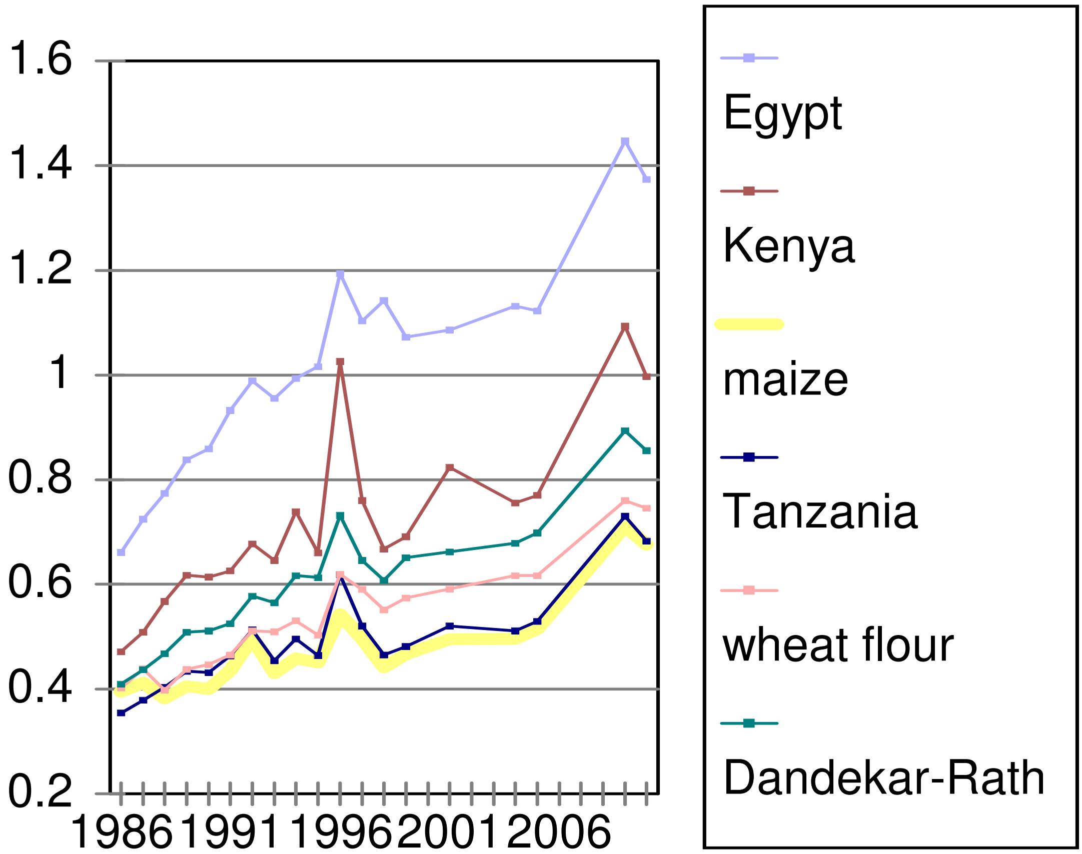


Figure 10

Price Paid by Greenwich Hospital for Wheat Flour and Oatmeal

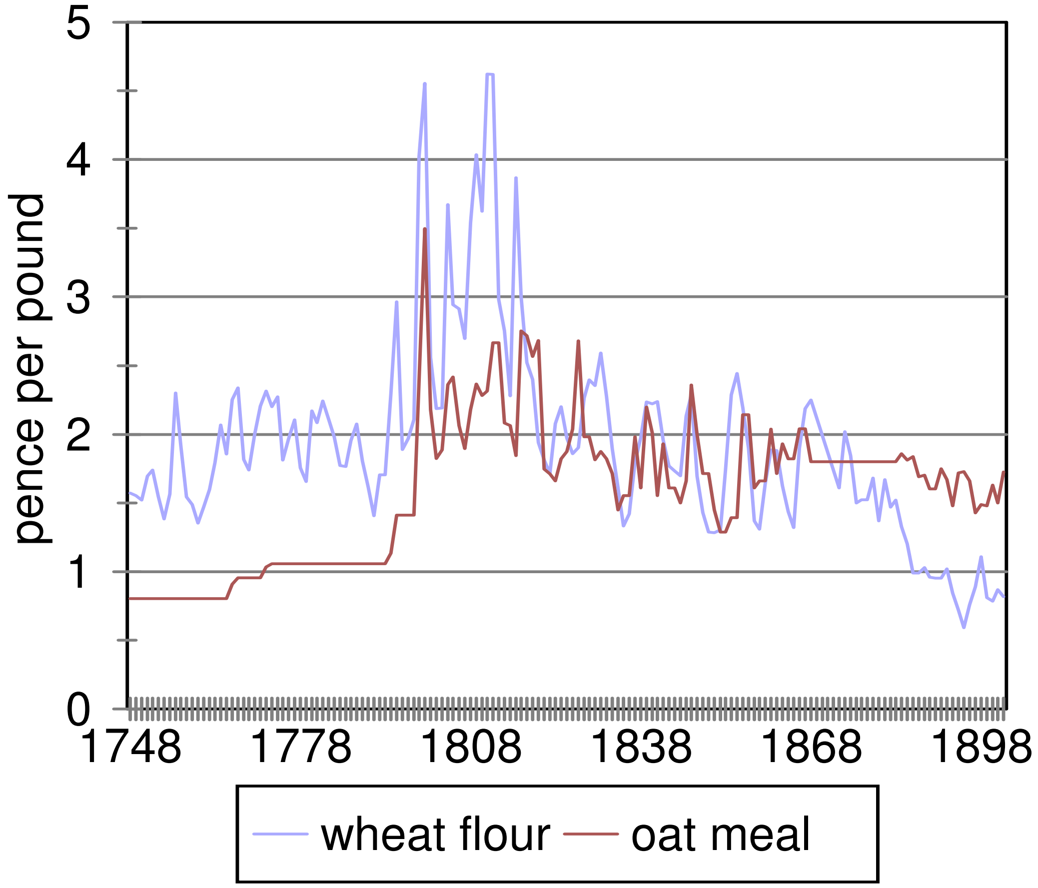
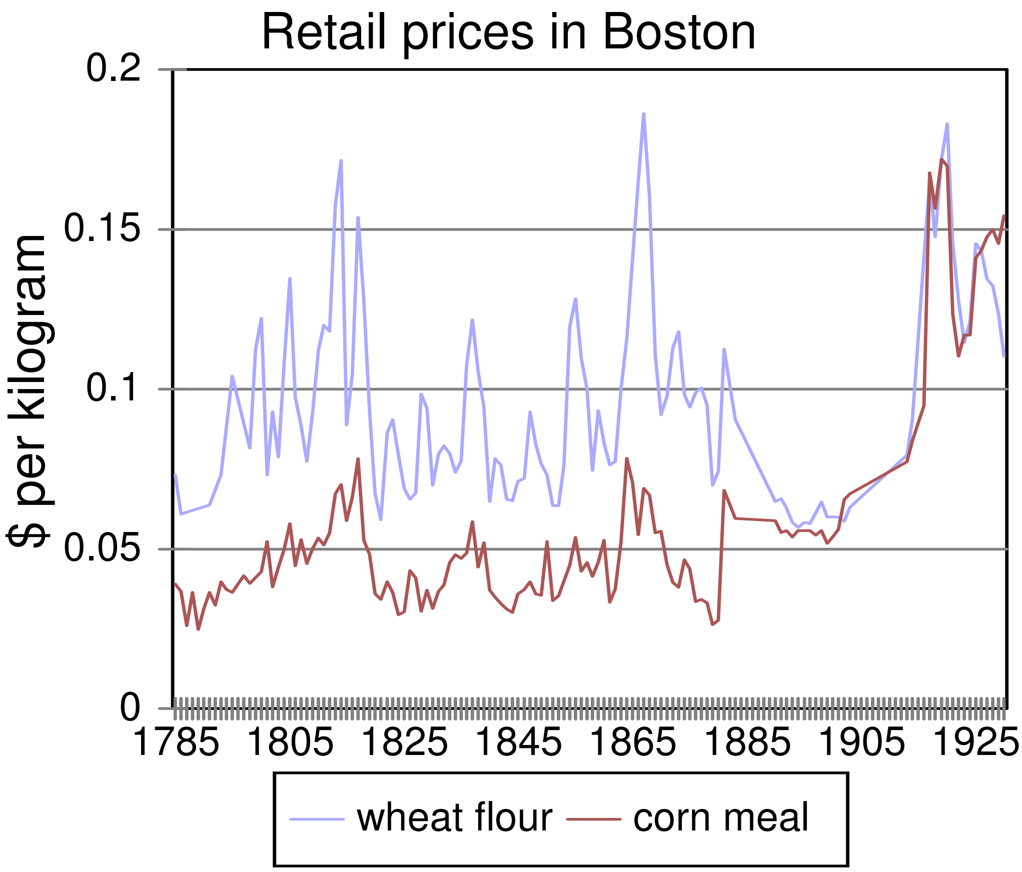


Figure 11

Retail Price in Boston for Wheat Flour and Corn (Maize) Meal



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Wages, prices, and living standards in China, 1738–1925: in comparison with Europe, Japan, and India[1]

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This article develops data on the history of wages and prices in Beijing, Canton, and Suzhou/Shanghai in China from the eighteenth century to the twentieth, and compares them with leading cities in Europe, Japan, and India in terms of nominal wages, the cost of living, and the standard of living. In the eighteenth century, the real income of building workers in Asia was similar to that of workers in the backward parts of Europe but far behind that in the leading economies in north-western Europe. Real wages stagnated in China in the eighteenth and early nineteenth centuries and rose slowly in the late nineteenth and early twentieth, with little cumulative change for 200 years. The income disparities of the early twentieth century were due to long-run stagnation in China combined with industrialization in Japan and Europe.

> 'The difference between the money price of labour in China and Europe is still greater than that between the money price of subsistence; because the real recompence of labour is higher in Europe than in China'.
>
> Adam Smith, *Wealth of nations*[2]

The comparative standard of living of Asians and Europeans on the eve of the industrial revolution has become a controversial issue in economic history. The classical economists and many modern scholars have claimed that European living standards exceeded those in Asia long before the industrial revolution. Recently, this consensus has been questioned by revisionists, who have suggested that Asian living standards were on a par with those of Europe in the eighteenth

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[2] Smith, *Wealth of nations*, p. 189.

century and who have disputed the demographic and agrarian assumptions that underpin the traditional view.[3] The revisionists have not convinced everyone, however.[4]

One thing is clear about this debate, and that is the fragility of the evidence that has been brought to the issue. Most of the comparative studies relied on indirect comparisons based on scattered output, consumption, or demographic data. The few that attempted comparisons of direct income were largely based on scattered information about wages and prices in Asia.[5] Our knowledge of real incomes in Europe is broad and deep because since the mid-nineteenth century scholars have been compiling databases of wages and prices for European cities from the late middle ages into the nineteenth century when official statistics begin.

This article, by assembling and constructing systematic data on wages and prices from Imperial ministry records, merchant account books, and local gazetteers, is an attempt to fill that gap for China in the eighteenth and nineteenth centuries. These wage series, deflated by appropriate cost of living indices using reconstructed consumption baskets, are then compared to the Japanese, Indian, and European evidence to assess the relative levels of wage earners' real income at the two ends of Eurasia. The comparisons paint a less optimistic picture of Asian performance than the revisionists suggest.

Taking the hypothesis of Adam Smith at the head of this article as a point of departure, the present study compares the 'money price' of labour in China and Europe. For this purpose, wage rates are expressed in grams of silver earned per day in the two regions. Unminted silver measured in taels (one tael equalled 37 grams)[6] was a universal medium of exchange in China in this period. The terms on which silver coins exchanged defined the market exchange rate of European and Asian moneys. Next, the 'money price of subsistence' is compared. This is a more complicated problem since the subsistence foods were different in China and Europe. Fortunately, the different methods adopted to tackle this problem turn out to imply similar relative price levels. Once they are measured, the differences between European and Chinese money wages and costs of subsistence and the implications of those differences for the 'real recompence of labour' can be perceived.

The rest of the article is divided into six sections with a conclusion. The first two sections review a variety of Chinese wage data to establish the history of nominal wages from the eighteenth to the twentieth centuries. The focus is set on the histories of Canton, Beijing, and the nearby cities of Suzhou and Shanghai in the Yangzi Delta, because more information is available for these cities, and because they are comparable to the large cities in Europe and Japan for which we have similar information. In section III, nominal wages in China and Europe are compared to see if Smith was correct about the 'money price of labour'. Section IV

[3] For instance, Pomeranz, *Great divergence*; Parthasarathi, 'Rethinking wages'; Wong, *China transformed*; Lee and Wang, *One quarter of humanity*; Li, *Agricultural development*; Allen, 'Agricultural productivity'; idem (2004) 'Mr Lockyer meets the index number problem: the standard of living in Canton and London in 1704' [WWW document]. URL http://www.economics.ox.ac.uk/Members/robert.allen/Papers/Lockyer.pdf [accessed on 10 June 2009]; idem, 'Real wages in Europe and Asia'; Allen, Bengtsson, and Dribe, eds., *Living standards in the past*.

[4] For instance, Broadberry and Gupta, 'Early modern great divergence'; Allen, 'India in the great divergence'.

[5] Pomeranz, *Great divergence*; Lee and Wang, *One quarter of humanity*.

[6] The present study applies this average value; variation for the four most important varieties ranged between 36.54 and 37.58 grams. See Peng, *Zhongguo huobi shi*, p. 669, nn. 4–7.

turns to the 'price of subsistence' and develops consumer price indices to compare the cost of living across Eurasia. In section V, the authors compare Smithian price indices to Fisher Ideal Indices for broader consumer bundles and show that they yield similar results in a comparison of London and Beijing. In section VI, the real wage income in Canton, Beijing, and Suzhou/Shanghai from the mid-eighteenth century to the 1920s is estimated. Smith's belief about the 'real recompence of labour' is tested by comparing real wage income in these Chinese cities to their counterparts in other countries. For Japan, Chinese urban incomes are compared to a composite picture of Kyoto and Edo (modern Tokyo) in the eighteenth and early nineteenth centuries, and Tokyo for the late nineteenth and early twentieth centuries, based on Bassino and Ma's study 'Japanese unskilled wages'. Real wages in China are compared to those in India using the results in Allen's 'India in the great divergence'. The perspective on Asian performance is broadened by contrasting living standards there with those in London, Amsterdam, Leipzig, and Milan, as worked out by Allen in 'Great divergence'. The study concludes with a discussion of the significance of its findings for Adam Smith and the great divergence debate.

I

Before comparing living standards, the level and trend of nominal wages in China must be established. Since most European wages are recorded for urban labourers in the building industry, the present study concentrates on unskilled male workers in three large Chinese cities. No single source covers the whole period from the eighteenth century to the twentieth, so the wage history of China must be pieced together by combining disparate information.[7]

For Beijing, some wages for labourers on eighteenth-century government building projects are known, and wages for similar workers from the 1860s to the 1920s can be found. For Canton, wage data of unskilled port labour hired by European trading companies in the eighteenth century are available. For Suzhou, the daily earnings of men engaged as calenderers pressing cloth in the textile industry can be estimated. This series can be linked to the wages of spinners in cotton textile mills in Shanghai in the twentieth century. Indeed, a more complete picture of labour incomes in the Yangzi Delta can be developed by also assessing the earnings of male farm labourers, rural women spinning and weaving cotton cloth, and peasant households as a whole. By matching eighteenth-century wages for specific unskilled occupations in China with corresponding wages for the early twentieth century, the long-term history of Chinese wages can be reconstructed for comparison with European wages.

This wage survey begins with three sets of wage data for the eighteenth century that are reasonably continuous and well defined. The first set is the piece wage rates of the cotton calenderers inscribed on steles for crafts and commerce in Suzhou, the largest industrial and trading city in the Yangzi Delta during the eighteenth and nineteenth centuries. The case of cotton calenderers and their wage disputes has been the subject of numerous studies.[8] The calenderers' job was 'to

[7] For a survey of existing studies on wages and prices, see Kishimoto, *Shindai chūgoku*, pp. 11–46.

[8] Quan, 'Qingdai Suzhou de chuaibuye'; Terada, 'Sōshū tampogyō'; Santangelo, 'Urban society'; Xu, ed., *Jiangnan tubu shi*.

soften and polish cotton cloth after it had been pressed and rubbed'.[9] The inscribed data give us the guild-negotiated piece wage rates for the years of 1670, 1693, 1701, 1715, 1730, 1772, and 1795. As these are piece wages quoted in silver taels, there are no ambiguities about copper–silver exchange rates or additional food allowances. The major issue is the conversion of piece rates into daily wages, for which Xu's study on the early twentieth century was used, as explained in appendix I A. Overall, the daily wages thus derived come to 0.09944 and 0.1144 silver taels in 1730 and 1772 respectively.

In the eighteenth century, the calenderers were mostly migrants to Suzhou from the impoverished provinces of northern Jiangsu and Anhui. They 'had to be strong men, considering the especially tiring nature of their job: using their arms as levers on wooden supports while balancing, they had to rock a huge forked stone with a ground base onto cotton cloth wrapped around a wooden roller which rotated in a groove in the base of the stone'.[10] Calenderers were only a little above unskilled building labourers but probably below a fully skilled worker in the pay scale.

Our second source for private sector wages is the archives of the Dutch East Indies Company (VOC). Many VOC ships docked at Canton, which was the city where Europeans were allowed to trade with China in the eighteenth century. The VOC hired many Chinese workers to repair ships and move cargo. A recent study by van Dyke offers a detailed description of the workings of the provisioning system in Canton. From the VOC archives, 63 wage quotations spanning the eighteenth century can be obtained.[11] The wages fluctuated, but they clustered between 0.08 and 0.1 taels per day with no additional food allowances.

The third set of wage data comes from diverse sources. We begin with two government regulations. The first is the *Wuliao jiazhi zeli* (*Regulations and precedents on the prices of materials*) of 1769, which is a very detailed and systematic government report on the prices of building materials and the wages paid at construction projects, and an attempt to set these prices and wages for the future. According to the editorial introduction, it contained information about 1,557 administrative units described in a compilation of 220 chapters. The original compilation has not been preserved, but the editions for 15 provinces covering 945 districts are extant. Most of them contain the daily wages of unskilled and skilled craftsmen for each district; a few are more detailed and present wages for occupations such as master sawyers, carpenters, stonemasons, paint-makers and painters, tailors, plasterers, canopy makers, paperhangers, and cleaners (in Zhili). Occasionally additional food provisions and their monetary value are recorded, so that the total wage value can be calculated. Where no food provisions are mentioned, probably no food allowance was given, as these wage regulations were supposed to cover the entire labour cost of these public building projects.[12]

[9] Santangelo, 'Urban society', p. 109.

[10] Ibid., p. 109.

[11] See van Dyke, *Canton trade*, and Jörg, *Porcelain*, pp. 21–73, for the details of the organization of the VOC in Canton. We specifically used the files in the National Archives of the Netherlands, The Hague, Archives VOC, nos. 4373, 4376, 4378, 4381, 4382, 4386, 4388, 4390, 4392, 4395–4401, 4403, 4405, 4408, 4409.

[12] The introductory memorial to these regulations by the compiler Chen Hongmou, 'Wuliao jiazhi zonglue' ['General remarks on the prices of materials'], states that market prices and wages were investigated in the regions, and that the prices and wages quoted in these volumes were near to market prices at low market activity; see *Wuliao jiazhi zeli*, ch. 1, fol. 4b, available as WWW document, URL [http://www.uni-tuebingen.de/uni/ans/project/shp/zeli/zonglue.htm] [accessed on 10 Jan. 2010]. The provincial editions for Zhili, Henan, Shandong,

Table 1. *Nominal wages of workers in public construction, 1769–95, and in arms manufacture, 1813 (in taels per day)*

	Construction (unskilled)	*Construction (skilled)*	N =	*Arms manufacture (unskilled)*	*Population (millions in 1787)*
Manchuria and the north-western frontier					
Heilongjiang	0.100	0.191	2/6 (unskilled/skilled)		
Jilin	0.095	0.160	6		1.0***
Shengjing	0.057	0.100	13		
Xinjiang	0.097	0.110	3		0.5
North					
Rehe*	0.066	0.120	7		
Beijing*	0.077	0.141	24		
Tianjin/Baoding*	0.071	0.112	34		23.0****
Residual Zhili*	0.054	0.081	82	0.060****	
Gansu	0.044	0.054	48		15.2
Shanxi	0.054	0.073	85	0.040	13.2
Shaanxi	0.044	0.050	74	0.040	8.4
Shandong	0.045	0.061	50	0.040	22.6
Middle					
Henan	0.037	0.039	106	0.040	21.0
Jiangsu**	0.040	0.051	63	0.040	31.4
Zhejiang**	0.040	0.060	63	0.040	21.7
Hunan	0.039	0.050	10	0.040	16.2
Hubei				0.040	
Jiangxi				0.030	
Guizhou				0.040	
Sichuan	0.048	0.062	47	0.040	8.6
Yunnan	0.048	0.068	84	0.030	3.5
South					
Fujian (including Taiwan)	0.030	0.050	9	0.040	12.0
Guangdong	0.040	0.050	89	0.040	16.0
Guangxi				0.040	
Average (unweighted)	0.053	0.081			
Average (weighted by N)	0.047	0.065	901/905 (unskilled/skilled)		
Average (weighted by population)	0.044	0.060			214.5

Notes: *Part of the province of Zhili; **Yangzi Delta; ***whole of Manchuria; ****whole of Zhili. N: number of districts for which data are available.
Sources: For wages, see app. I; for population data: Wang, *Land taxation*, p. 87.

A virtue of the *Wuliao jiazhi zeli* is its comprehensive regional coverage of Chinese wages. For each province we calculated the unweighted average of the wage norms for labourers in all districts. Table 1 presents the results of these calculations for 21 regions. Zhili is divided into a number of sub-regions because of the large wage differences within this province. The total population of these

Shanxi, Shaanxi, Gansu, Jiangsu, Zhejiang, Guangdong, and Yunnan all carry the same introductory memorial dated 1769. Other editions have no preface, such as those for Hunan, which is a fragment, and 'Manchuria' (Shengjing/Jilin/Heilongjiang). The 1791 Sichuan and the 1795 Rehe editions are later compilations. No special edition was ever compiled for Xinjiang, but a few Xinjiang data are mentioned in the Gansu, Sichuan, and Rehe editions. Digitized datasets for the provinces Gansu, Zhili, Yunnan, Hunan, and Shanxi are available online in the 'Databases on materials, wages, and transport costs in public construction in the Qianlong era' [http://www.uni-tuebingen.de/sinologie/project/shp/databases.html]. See also Song and Moll-Murata, 'Notes', pp. 93–9.

regions in 1776 was about 214.5 million, or 73 per cent of the total population of China of about 293 million.[13]

The pattern that emerges from the *Wuliao jiazhi zeli* is that daily wages in parts of Manchuria (Heilongjiang and Jilin), the home territory of the ruling Manchu Dynasty, and the sparsely populated north-western frontier of Xinjiang, stand out as the highest, followed by areas in and near the capital city of Beijing. Average daily wages in the rest of China seem to have been fairly uniform, with the coastal Fujian province fetching the lowest, 0.030 taels for unskilled labourers.

A second government source is the so-called *Gongbu junqi zeli* (*Regulations and precedents on weapons and military equipment by the Ministry of Public Works*) of 1813, which contains more government wage regulations on an empire-wide scale. The *Gongbu junqi zeli* contains wages for master artisans and unskilled labour that produced military equipment. This dataset includes information for skilled and unskilled labourers.[14] This source shows again that, with the exception of Zhili where Beijing is situated, the norm for average daily wages of unskilled labourers in most provinces in 1813 was about 0.04 taels, very close to that in the 1769 regulations.

Extreme caution should be exercised in the interpretation of these government data. The *Wuliao jiazhi zeli* wage data collected at the county level often show identical wages across a vast number of counties within one province, with little distinction between the more and less urbanized ones. This poses the question whether these data reflect actual market conditions or rather government policies, which tended to favour the capital region as well as Manchuria, the home territory of the Qing rulers.[15]

To tackle the question of how accurately these government regulated wages approximate wages in the private sector of the economy, we place these wage series against a broader dataset of 264 scattered wage quotations from many sources and for different parts of China. The problem with these disparate wages from the private sector is a lack of the kind of detailed information available for the Suzhou calenderers and Canton VOC labourers. Also, there is a general lack of comparability due to the multiplicity of labour contracts, payment systems, and currency units. Employment contracts could last for a day, a month, or a year, and careful attention must be given to the number of days worked in a month or a year to reduce the payment information to a consistent daily rate. There are many cases for which food allowances were given in addition to cash payments. Possibly the most difficult issue of all is the quotation of wages in different currency units (copper coins, silver taels) with exchange values that were both highly localized and fluctuating over time. Studies not taking full cognizance of these problems can be very misleading.[16]

[13] Wang, *Land taxation*, p. 87.

[14] See You, 'Lun junqi zeli', p. 314. Wages of skilled craftsmen were 0.020 or 0.010 taels higher than those of unskilled labourers.

[15] The Qing government restricted the migration of Han Chinese to the land and resource rich, but labour-scarce region of Manchuria until the mid-nineteenth century.

[16] Vogel, 'Chinese central monetary policy', contains the most comprehensive collection of market exchange rates for various provinces in China for the seventeenth to nineteenth centuries, but these exchange rates do not apply to the case of the co-circulation of multiple versions of silver and copper cash within the same locality, an issue pointed out in Kuroda's recent study, 'Copper coins'. For a case of neglecting these complicated currency problems in the study of nominal and grain wages, see Chao, *Man and land*, pp. 218–20.

The most important official source for private wages consulted in the present study is the records of the imperial Ministry of Justice, which summarized judicial cases dealing with wage payment. A sample of 188 manufacturing and handicraft wages was obtained from Peng's compilation on craft history, which is based on judicial records from *c.* 1740 to 1820.[17] They are contained in the archival documents of the Ministry of Justice, *Qingdai xingbu chao'an* (*Copies of archival materials from the Qing Ministry of Justice*).[18] This represents a widespread sample which includes scattered wage data for different occupations, in different regions, using different means of payment (silver taels or copper coins), covering different time periods (per day, month, or year), and spread over a long period. The Ministry of Justice records also contain samples of agricultural wages. These are available in the work of Wei and Wu.[19]

The resulting large, if disparate, sample of wages covers many provinces, industries, and types of employment in eighteenth-century China. To extract basic patterns from this information, a wage function was estimated using all of the collected wages, including the VOC and government regulation wages. All wages were converted to daily wages in silver taels by means of Vogel's regional dataset of silver–copper conversion ratios.[20]

The following independent variables were defined: (1) regions: Manchuria, Zhili, the north (Shanxi, Shaanxi, Gansu, Shandong), the Yangzi Delta (Jiangsu and Zhejiang), the 'middle', and the south (see table 1 for the exact specification of the regions; Canton is also distinguished separately); (2) branches (agriculture, coal mining, the iron industry, construction, textiles, and other industries); (3) a time-trend with 1700 as the base year; (4) skill (a dummy for skilled labour was used; unskilled labourers were all agricultural workers, the unskilled labourers in construction and the 'helpers' in other industries); (5) regulation (data drawn from the two government documents *Wuliao jiazhi zeli* (1769) and *Gongbu junqi zeli* (1813) were identified by a dummy for 'regulation'). We also include a few additional government regulation data from *Suzhou zizhao ju zhi* (1686) and *Da Qing huidian shili* (for 1723 and 1736).[21]

The total number of observations was 327, relatively equally spread over the different regions and branches. There are only four observations for the late seventeenth century. Most observations cluster between the 1740s and the 1810s; no observations after 1820 were included.

[17] Peng, *Zhongguo jindai shougongye*, vol. 1, pp. 396–414.

[18] Ibid., vol. 1, p. 397, n. 2.

[19] Wei, 'Ming-Qing'; Wu, 'Qing'.

[20] Vogel, 'Chinese central monetary policy'. Another problem was how to convert monthly and annual wages into daily wages; a few observations of both daily and monthly or annual wages suggests conversion factors of about 15 (days/month) and 60 (days/year). The next step was to use these conversion factors and estimate dummies for monthly and annual wages in the wage regression. The dummies became close to zero when somewhat different conversion factors were used, namely 13 and 90. We used these conversion factors in the estimation of wage levels in the wage regressions shown in tab. 1; therefore, the dummies for monthly and annual wages have not been included.

[21] Wage data from *Suzhou zizhao ju zhi* (*Treatise on the Suzhou weaving offices*) for 1686, included in Peng, *Zhongguo jindai shougongye*, vol. 1, pp. 90–2, were also consulted, as well as wage data from *Da Qing huidian shili*, ch. 952, fos. 4b–5a, pp. 16,640–1. The complete wage dataset used in this study can be found at http://www.iisg.nl/hpw/data.php#china; it presents an overview of the different datasets, their compilers (Christine Moll-Murata, Debin Ma, and Paul van Dyke), and the linked Excel files.

Table 2. *Wage regressions for eighteenth-century China, standardized on the daily wage of an unskilled construction labourer in the Yangzi Delta in 1769 (in taels)*

	Coefficient	T-*value*
Constant	0.0456	4.00
Trend	−0.0000351	−0.348
Manchuria	0.0902	6.73
Zhili (including Beijing)	0.0441	4.36
North	0.0132	1.397
Middle	−0.0022	−0.026
South	−0.000593	−0.056
Canton	0.0379	3.55
Skilled	0.0295	4.79
Regulated	−0.0171	−2.21
Iron industry	0.0092	1.12
Coal mining	−0.0093	−0.83
Agriculture	−0.0072	−0.744
Textiles	0.0403	3.22
Other	−0.0147	−1.93
R^2	0.408	
F (14,312)	15.34*	
N	327	

Note: *Significant at the 1% level.

Table 2 presents the results of the wage regression. All independent variables except the time trend are dummies for regions, branches, and so on; the standard for comparison is the market wage of a construction labourer in the Yangzi Delta in 1700. The constant in the equation is his wage, which is estimated as 0.0456 taels. The regional pattern mirrors the results from the analysis of the *Wuliao jiazhi zeli*: wages in Manchuria and Zhili were (much) higher than in the rest of the country, whereas the differences between the Yangzi Delta and the rest of the rice region were very small. Most industry dummies were insignificant. Finally, the dummy for skill premium is significant; its level in regression is 63 per cent of the wage of an unskilled labourer in the Yangzi Delta.

To get a perspective on our wage regression, we plotted in figure 1 the wage rates of Suzhou and Canton against the predicted wages from our regression. Figure 1 shows that the baseline predicted wages, set as the constant plus the time trend in the wage regression (the rate equivalent to that of an unskilled labourer in the Yangzi Delta), is about half the level of Suzhou and Canton wages. While VOC and calenderers' wages were rising gently, wages in China in general were declining slowly, as indicated by the wage equation. This difference in trend is not significant for our purpose. Figure 1 also plots the predicted wages of Beijing which uses the dummy coefficients for Zhili from the wage regression.

These results make sense: large cities in Europe, the counterparts of Canton, Suzhou, and Beijing, had higher wages than small towns and rural districts in part because the cost of living was higher in the large cities and also because they had to recruit population from the countryside. This conjecture is in agreement with Pomeranz's description of the earnings of a Yangzi Delta farm worker employed by the year in the mid-eighteenth century. Pomeranz reckoned that the cash component of these earnings was two to five taels, and that the food allowance over a full

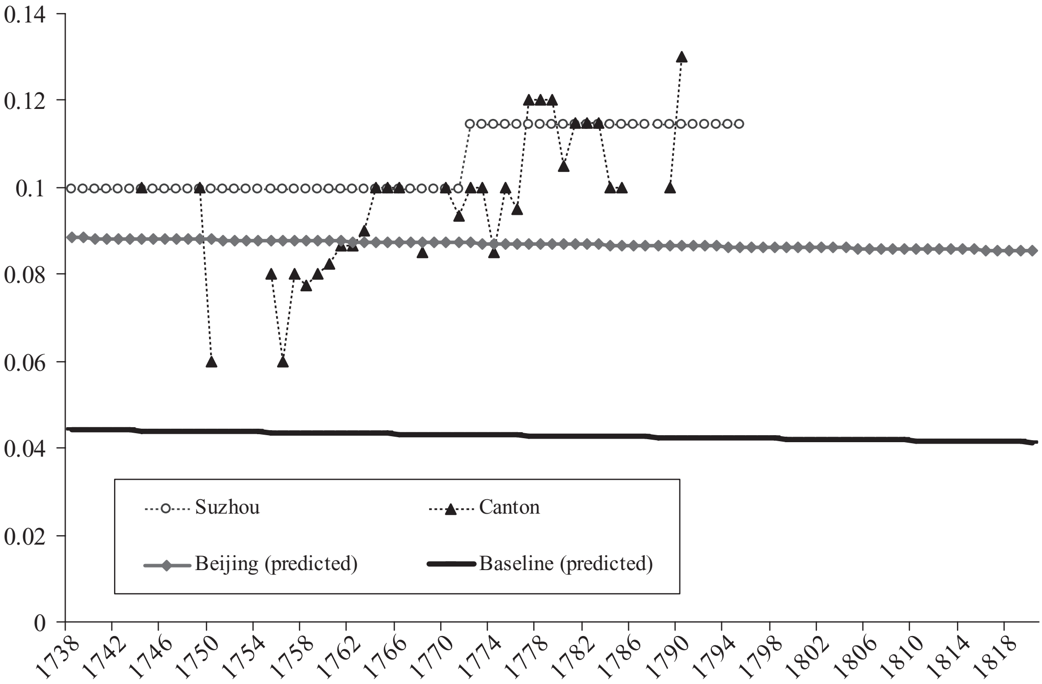

Figure 1. *Nominal wages in Beijing, Suzhou, and Canton (in silver taels)*
Source: See section I.

year was perhaps five *shi* of rice worth 8.4 taels, so the total earnings over the year were 10.4 to 13.4 taels. Dividing by 360 implies daily earnings of 0.035 to 0.045 taels per day, very close to the baseline wage level from our regression result.[22]

As the wage regression contains some wage data that might include additional food allowances, we have experimented with alternative regressions by adding 0.024 taels—roughly the cost of one kilogram of rice in Canton or millet in Beijing in the middle of the eighteenth century—to the daily earnings of those workers earning less than six taels per year (0.5 taels per month). The alternative regression leads to changes of little significance to the coefficients of most significance for this study.

The level of our baseline wage in figure 1 matches the empire-wide averages in the *Wuliao jiazhi zeli* and *Gongbu junqi zeli* in the official regulation data. This leads us to

[22] Pomeranz, *Great divergence*, pp. 319–20. The average of agricultural wages on daily contracts collected in our sample was 0.045 taels. Wages on daily contract were likely to be higher, as usually day labourers were more often employed during the planting and harvest seasons. It is unclear whether additional food was provided. A national level survey conducted by Chen in the 1930s, *Gesheng nonggong*, reveals the existence of both types of payment arrangements for daily wages, either with or without food payment, the latter being higher. However, in cases where there was food payment, the portion amounted to about 33 per cent of the total cash wage, much less than for the eighteenth- and nineteenth-century agricultural wages on annual contracts (Chen, *Gesheng nonggong*, p. 9). Li, *Agricultural development*, p. 94, also seems to indicate that seventeenth-century nominal wage levels may not be far apart from those of the eighteenth to nineteenth centuries. He discusses wage levels in agriculture and silk production in the Yangzi Delta, and estimates the average wage in rice cultivation at 0.06 taels per day, adding 'the official standard was 0.04 taels a day which is a bit low compared to the wages in some farms in Huzhou, Zhejiang province'.

believe that the government regulation wages may have been set as a wage floor for the market wages, which the government used for the purpose of cost-accounting. Both these sources also reveal higher wage levels for the capital region than the national average, which may be a reflection of possible governmental discrimination. If carefully interpreted, the regulated wage is more useful as a benchmark for a national wage floor than as an indication of regional wage patterns. For the subsequent analysis, the wage level for Beijing and Canton was set in 1700, based on the predicted values in the regression of 0.0897 and 0.0835 taels respectively, equal to the constant coefficients plus dummy coefficients for Zhili and Canton respectively. For Suzhou, 0.09 taels for 1700 were used, very close to the 0.0968 taels for the calenderers' wages. The national trend level was used for all these three series in the international comparison. Clearly, we view our wage series as more reliable in indicating long-term trends than short-term fluctuations.

Somewhat contrary to the claims that Lower Yangzi had the highest living standards, our dataset collected at this stage do not reveal a higher nominal wage for unskilled laborers in that region. While the implications of possible regional wage difference will be discussed later (in particular, see footnote 54), the rest of this study focuses on cross-national comparison of average wage income for unskilled labourers between China and Europe. On the assumption that these wages are complete payments for unskilled labourers in the three major urban centres, they most likely represent the upper bound estimates of our larger dataset. Thus, if the average level turns out to be lower than our nominal wages, then actual Chinese living standards would be even lower.

II

Jumping forward in time, the best available information on wages in Beijing, Canton, and Shanghai is for the early twentieth century. Our wage series for Beijing is anchored in the work of Sidney Gamble (1890–1968). Gamble was an American sociologist who lived in China in the 1920s and 1930s. He conducted a survey of workers in Beijing in 1921. This provided the weights for a consumer price index for Chinese capital for 1900–24, and that index, in turn, was used in a study of real wages for the period. Gamble and his associates also recorded wage series for unskilled construction workers in Beijing for the period 1862–1925 using the records of the Beijing guilds for construction workers. This is our source for unskilled wages in the capital.[23]

Gamble carried out another important study based on the account books of a fuel store in the rural area of Beijing. The information runs from 1807 to 1902 and is possibly the only consistent wage series for nineteenth-century China. The nineteenth-century wage payments were recorded in copper cash and were broken around the mid-nineteenth century due to the monetary debasement in the period of the Taiping Rebellion. Gamble does provide vital information on copper–silver rates in that area from which we derive a silver-based wage series for 1807–1902,

[23] This series is composed of two parts. The first part is the 1870–1900 copper cash wages (inclusive of food money) in Gamble, 'Daily wages', p. 66, which we converted to silver wages using copper–silver rates from Peng (*Zhongguo huobi shi*, p. 548). The second series is the 1900–24 series by Meng and Gamble, 'Wages, prices, and the standard of living', p. 100.

as shown in appendix I B. The level of the wage rates seems very low and is difficult to interpret in its own right, as Gamble indicated that workers received unrecorded food allowances.[24] We apply the trend (not the levels) of these silver wages to fill in the 1820–62 gap for the light it throws on the Taiping Rebellion and its aftermath.

Information on Cantonese wages is less comprehensive than that for Beijing. As noted above, estimates of wages in the eighteenth century have been derived mainly from VOC records and summarized in the wage regression. For the early twentieth century, the simple average of six series of union-regulated shows wage rates for unskilled labourers in the construction sector from 1912 to 1927 is used.[25] For the nineteenth century, various plausible wage data exist, but were not included in the analysis as they were incomplete and scattered.

Similarly, no systematic wage series for Suzhou in the nineteenth century was available. From the middle of the nineteenth century, Shanghai was emerging as China's predominant trading and industrial city under the treaty port system imposed by western imperialism. Setting out from wage notations for female cotton spinners in Shanghai between 1910 and 1934, we have calculated the wage levels of male unskilled labourers based on a wage survey of the 1930s.[26]

III

Adam Smith thought that the 'money price of labour' was higher in Europe than in China. To test that, Chinese and European wages must be compared. Building on our earlier studies of European daily wage rates earned by labourers in the building industry,[27] we have been careful to exclude wage quotations where the earnings included food or other payment in kind that could not be valued and added to the money wage. As with China, we have converted the European wages to grams of silver per day by using the market price (in units of account) at which silver coins of known weight and fineness could be purchased.

Figures 2 and 3 show the daily wage rates of unskilled workers in London, Amsterdam, Leipzig, Milan, Beijing, and Kyoto/Tokyo from the eighteenth century to the twentieth. Figure 2 shows the series from 1738 to 1870. For this period, Adam Smith was half right. Wages were, indeed, highest in London and lowest in Beijing, but the other series show that the world was more complex than Smith thought. The silver wage in Milan or Leipzig was not appreciably higher than the wage in Beijing, Canton, or Suzhou throughout the eighteenth century.[28] The statistics of other European and Chinese cities show that this similarity was general.

[24] Gamble, 'Daily wages', p. 41.

[25] Department of Peasantry and Labour, *Reports of statistics*, vol. 3, 'Wage tables in the construction sector'. Our wage series is the simple average of five types of unskilled labourers in the construction sector.

[26] We make use of the series by Rawski, *Economic growth*, p. 301, and the Bureau of Social Affairs, *Cost of living index*, pp. iii–iv. According to Yang, 'Shanghai gongren shenghuo', p. 250, female workers in 1927–8 were paid about 80% of the level of male workers.

[27] van Zanden, 'Wages and the standards of living'; Allen, 'Great divergence'.

[28] As indicated earlier in section I and in fig. 1, the silver wages we used for Beijing, Canton, and Suzhou/Shanghai are broadly equal. For reasons of easy visibility, we only plot the silver wage for the Beijing series on figs. 2 and 3. Complete price and wage series for figs. 2–6 can be downloaded from the websites at http://www.iisg.nl/hpw/data.php and http://gpih.ucdavis.edu/Datafilelist.htm.

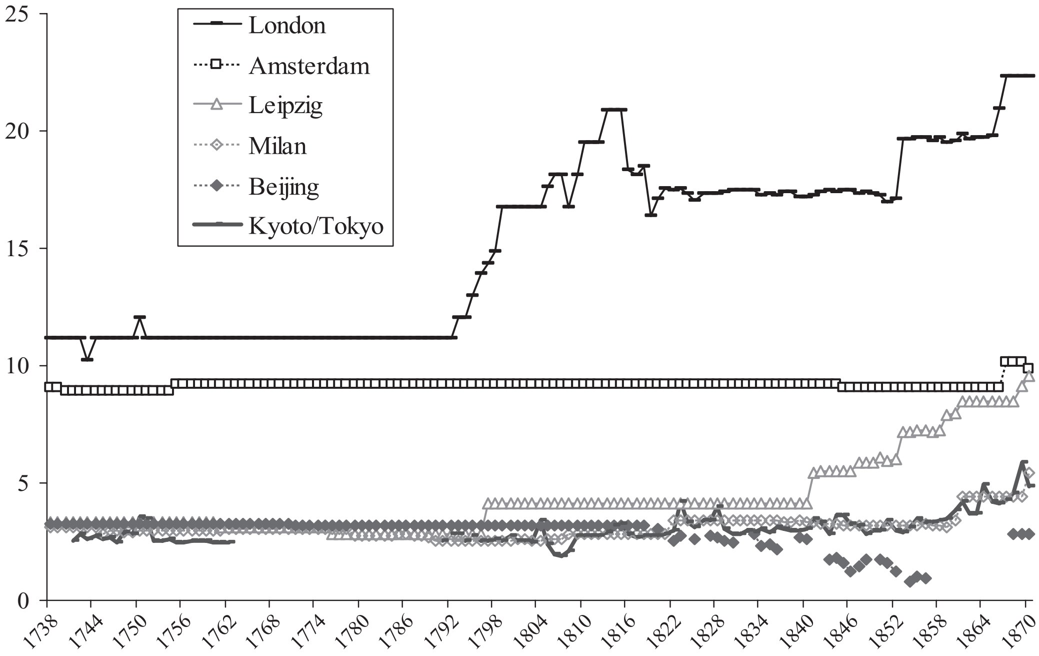

Figure 2. *Daily wages in grams of silver, 1738–1870*

Sources: For wages in Kyoto/Tokyo, see Bassino and Ma, 'Japanese unskilled wages'; for the rest, see section III, n. 31.

Amsterdam occupies a peculiar position in figure 2. Nominal wages there were remarkably constant for a century and a half. At the outset the Amsterdam wage was similar to the London wage. The same was true of Antwerp. Indeed, the Low Countries and the London region stand out from the rest of Europe for their high wages in the seventeenth and eighteenth centuries. These high wages were probably due to the active involvement of these regions in intercontinental commerce. However, this pattern changed as the nineteenth century advanced. The industrial revolution raised British wages above Dutch levels. Indeed, the early industrialization of Germany is seen in figure 2 as a rise in the Leipzig wage.

These developments intensified after 1870, as shown in figure 3. British wages continued to increase. By the First World War, German wages had caught up with the British level, and Dutch wages closed the gap as well. Italian wages were also growing, but the increase was muted compared to the industrial core of Europe. Outside Europe, Japanese wages before 1870 stayed largely flat, in keeping with the low Italian level. After 1890, Japanese wages, spurred by the industrialization drive in the Meiji era, began to rise, but continued to stay substantially below the rising trend of early twentieth-century European wages.

Chinese wages, in contrast, changed little over the entire period. There was some increase in the silver wage after 1870, but figure 3 emphasizes that the gain was of little importance from a global perspective. By the First World War, nominal wages in China were very much lower than wages in Europe generally.

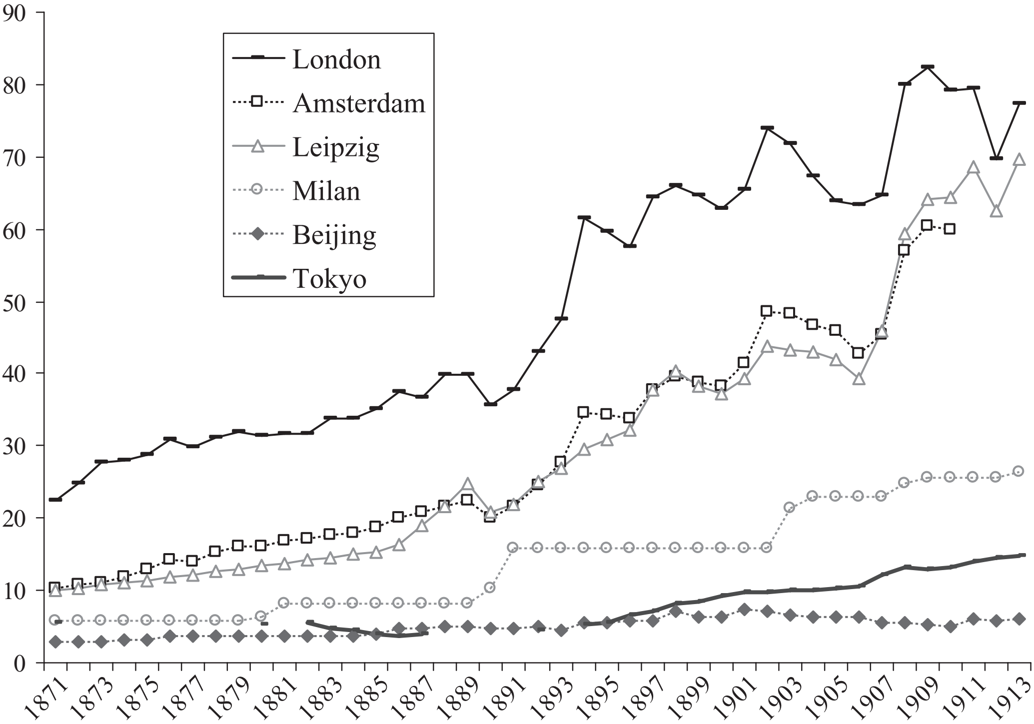

Figure 3. *Daily wages in grams of silver, 1870–1914*

Sources: For wages in Kyoto, see Bassino and Ma, 'Japanese unskilled wages', pp. 231–3; for the rest, see section III, n. 31.

Taken at face value, Adam Smith's generalization about Chinese and European wages was more accurate at the time of the First World War than when he penned it in 1776.

IV

What of Adam Smith's second generalization? He remarked that 'the difference between the price of subsistence in China and in Europe is very great'.[29] This generalization can be tested by computing price indices. We have tried many formulae and sets of weights, and the reassuring result is that our conclusions about relative real wages do not depend in any important way on the choice of price index.

The index number problem is a difficult one, since diet and lifestyle were radically different in different parts of Eurasia. How precisely does the real income of an English worker who consumed beef, bread, and beer compare to that of a Chinese labourer who ate rice and fish?

The approach considered in this section takes Adam Smith's comment as its point of departure. His generalization about price levels is expressed in terms of the 'price of subsistence'. We operationalize that by defining consumption baskets that represent the 'bare bones' minimum for survival (see tables 3–4). The baskets

[29] Smith, *Wealth of nations*, p. 189.

Table 3. *Subsistence lifestyle: baskets of goods in China*

	Suzhou/Canton			*Beijing*		
		Nutrients/day			*Nutrients/day*	
	Quantity per person per year	*Calories*	*Grams of protein*	*Quantity per person per annum*	*Calories*	*Grams of protein*
Rice	171 kg	1,677	47			
Sorghum				179 kg	1,667	55
Polenta						
Beans/peas	20 kg	187	14	20 kg	187	14
Meat/fish	3 kg	8	2	3 kg	21	2
Butter						
Oil	3 kg	67	0	3 kg	67	0
Soap	1.3 kg			1.3 kg		
Cotton	3 m			3 m		
Candles	1.3 kg			1.3 kg		
Lamp oil	1.3 kg			1.3 kg		
Fuel	3 M BTU			3 M BTU		
Total		1939	63		1,942	71

Note: For conversion of calories and proteins, see tab. A2. M: metres. M BTU: million BTU.
Sources: As explained in section IV.

Table 4. *Subsistence incomes: baskets of goods in Europe*

	Northern Europe			*Milan*		
		Nutrients/day			*Nutrients/day*	
	Quantity per person per year	*Calories*	*Grams of protein*	*Quantity per person per annum*	*Calories*	*Grams of protein*
Oats	155 kg	1,657	72			
Sorghum						
Polenta				165 kg	1,655	43
Beans/peas	20 kg	187	14	20 kg	187	14
Meat/fish	5 kg	34	3	5 kg	34	3
Butter	3 kg	60	0	3 kg	60	0
Oil						
Soap	1.3 kg			1.3 kg		
Cotton	3 m			3 m		
Candles	1.3 kg			1.3 kg		
Lamp oil	1.3 kg			1.3 kg		
Fuel	3 M BTU			3 M BTU		
Total		1,938	89		1,936	60

Notes: M: metres. M BTU: million BTU.
Sources: As explained in section IV.

provide 1,940 calories per day mainly from the cheapest available carbohydrate. In Shanghai, Canton, Japan, and Bengal that was rice; in Beijing it was sorghum; in Milan it was polenta; and in north-western Europe it was oats. The diet includes some beans and small quantities of meat or fish and butter or oil. Their quantities were suggested by Japanese consumption surveys of the 1920s and by the Chinese rural consumption survey in the 1930s carried out by the National Agricultural

Research Bureau (NARB).[30] Despite relying on the cheapest carbohydrates, these baskets provide at least the recommended daily intake of protein, although the amount varies from basket to basket. Polenta (closely followed by rice) is the least nutritious source of calories in this regard. Non-food items include some cloth and fuel. The magnitudes of the non-food items were also suggested by the Japanese and Chinese consumption surveys of the interwar period. It would have been hard for a person to survive on less than the cost of one of these baskets.

Having specified the consumption 'baskets' in tables 3–4, time series of the prices of the items shown are necessary, so that the cost of the baskets can be calculated across the eighteenth, nineteenth, and twentieth centuries. For Europe, the prices described in Allen's 'Great divergence' can be applied.[31] New databases were compiled for the Chinese cities under observation. For Beijing, we extended Gamble's retail prices for 1900–24 back to 1738.[32] Food prices were extended using wholesale agricultural prices for Zhili province compiled by Li.[33] The implicit assumption in these extrapolations was that the ratio of retail to wholesale prices remained constant. The details and the procedures for cloth and fuel are explained in appendix II. For Shanghai and Canton, twentieth-century retail prices were extracted from official sources.[34] For the eighteenth century, Wang's Yangzi Delta rice price series was used for Suzhou and Chen's series for Guangdong.[35] These are probably wholesale rather than retail prices. No allowance was made for retail mark-ups—a procedure which is again biased against our conclusions, for if rice prices in China were higher then living standards would have been even lower. The prices of other foods and fuel were taken from the costs incurred by European trading companies in provisioning their ships in Canton. These prices have been compared to the estimated prices for Beijing, and the agreement is close. For most of the eighteenth century, competition was intense in supplying these ships.[36]

The cost of the basket is Adam Smith's 'money price of subsistence', and its history is plotted in figure 4 for leading cities in China and Europe in the eighteenth and nineteenth centuries. The findings would have surprised Smith, for it contradicts his claim that China had cheaper subsistence than Europe. The silver cost of a 'bare bones' basket in Beijing or Suzhou was in the middle of the European range. A corollary is that the silver prices of grains, which dominate the cost of these indices, were similar across Eurasia. Another casualty of figure 4 is

[30] Department of Crop Reporting, Division of Agricultural Economics, The National Agricultural Research Bureau (NARB), China, Crop reports, vol. 5, issues 7 and 8; Rōdō undō shiryō iinkai, *Nihon rōdō*, p. 568. Alternative baskets constructed on the basis of these surveys can also be found in our earlier working paper, R. C. Allen, J.-P. Bassino, D. Ma, C. Moll-Murata, and J. L. van Zanden, 'Wages, prices, and living standards in China, Japan, and Europe, 1738–1925', Global Price and Income History Group working paper no. 1 (2005) [WWW document]. URL [http://gpih.ucdavis.edu/Papers.htm#1].

[31] The data are available on-line at http://www.nuffield.ox.ac.uk.

[32] Meng and Gamble, 'Wages'.

[33] Li, 'Integration'.

[34] The Canton data are based on *Reports of statistics* compiled by the Department of Peasantry and Labour, Kwangtung Government, China, in 1928; it covers the period 1912 to 1927. The Shanghai price is from Bureau of Social Affairs, *Cost of living index*, pp. 35–44.

[35] Wang, 'Secular trend', pp. 40–7; Chen, *Sichang jizhi*, pp. 147–9.

[36] See van Dyke, *Canton trade*.

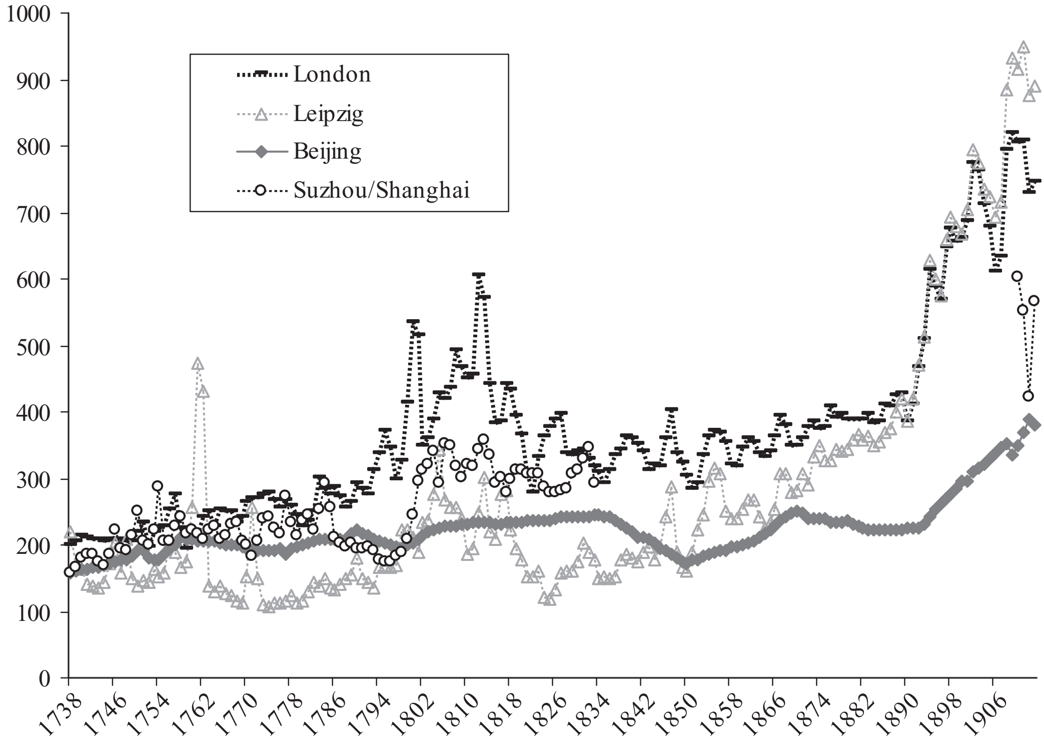

Figure 4. *Costs of the baskets in grams of silver per person per annum*
Source: As described in section IV.

Smith's generalization that 'rice in China is much cheaper than wheat is anywhere in Europe'.[37]

Another feature of figure 4 is worth highlighting. The figure shows very little difference between the two consumer price indices for both Beijing and Suzhou/Shanghai (or Canton, not shown in the figure) for the eighteenth century. These two cities represent the two agrarian halves of China—the northern small grain region and the southern rice region. However, from the beginning of the eighteenth century, rice prices began a secular rise over those of sorghum, which led to a somewhat more expensive basket for the unskilled labourers in the south than in the north. While the implication of this finding needs further research, this difference matters little for our purpose of international comparison. Overall, as seen in figure 4, price gaps between Europe and China really opened up from about the mid-nineteenth century.

V

Before considering the implications of the cost of the baskets for comparative living standards, the results of indexing prices in other ways can be briefly summarized.

[37] Smith, *Wealth of nations*, p. 189.

In modern theory, the index number problem unfolds thus. Suppose an individual or family receives a particular income and faces particular prices. The income and prices determine the maximum level of utility (highest indifference curve) that the individual can reach. Now suppose that prices change. What proportional change in income would allow the individual to reach the original indifference curve in the new price situation? The price index is supposed to answer that question. Comparing the actual change in income to the index shows whether consumer welfare has risen or fallen.

There are no insuperable difficulties in applying the theory to real income changes over time in either Europe or Asia, provided full information about wages, consumer prices, and spending patterns is available. Yet how can living standards between Europe and Asia be compared? The pattern of goods—particularly foods—consumed in the two regions was radically different. The standard theory of consumer welfare assumes that all the goods are available in both regions and that there is a 'representative agent' who would voluntarily choose to consume rice, fish, and sake when confronted with Asian prices and bread, beef, and beer when confronted with English prices. In fact, all goods were not available everywhere, and, moreover, it is unlikely that there were people flexible enough to shift their consumption voluntarily between the European and the Asian patterns in response to the difference in prices. This is the reason why we approached the problem in terms of Adam Smith's 'cost of subsistence'. By building on the results of these calculations, the outcome of a more orthodox approach can be approximated. During the comparative process, the associated data problems come sharply into focus. We concentrate on a comparison of Beijing and London because the Beijing diet was based on small grains that were more comparable than rice to English grains.

We first approach the question from the point of view of a Beijing resident and ask how much it would have cost to live the 'bare bones' Beijing lifestyle in London. This is the pertinent question, for the typical labourer could not afford to buy anything more. The difficulty is that we cannot cost out the Beijing basket in London, for sorghum was not sold in London. However, oats were the counterpart of sorghum in Britain—it was the least costly, most inferior grain—and if we take oats and sorghum to be equivalent, we realize that we have already answered the question by comparing the cost of the 'bare bones' baskets.

We can also ask how much the London lifestyle would have cost in Beijing. That lifestyle is represented by the 'respectable' consumption basket in table 5, which summarizes spending in north-western Europe.[38] The diet is late medieval in inspiration, in that it does not contain new commodities like sugar and potatoes introduced into Europe after the voyages of discovery.

The basket in table 5 contains important items for which we lack prices in China. Bread is the most important, and we have estimated what bread would have sold for, had it been produced commercially, from Allen's 'bread equation'.[39] This is a statistical relationship between bread prices, wheat prices, and wage rates prevailing in many cities in Europe. Since we have time series of wages and wheat prices for Zhili province, which includes Beijing, the price at which bread would

[38] Allen, 'Great divergence', pp. 420–1.
[39] Ibid., p. 418.

Table 5. *Comparison of different basket costs around 1750*

	'Bare bones' basket		*'Respectable' basket*		*London prices (in grams of silver)*	*Beijing prices (in grams of silver)*
	Europe	*North China*	*Europe*	*North China*		
Oats/sorghum	155 kg	179 kg			0.76	0.48
Bread			182 kg	182 kg	1.28	0.95
Beans			40 kg	40 kg	0.5	0.84
Meat/fish	5 kg	3 kg	26 kg	31 kg	3.19	2.04
Cheese			5.2 kg		2.07	
Eggs			52 pieces	52 pieces	0.37	0.074
Butter	3 kg		5.2 kg		6.45	
Beer/rice wine			182 l	49 l	0.39	1.98
Oil/cooking		3 kg		5.2 kg		4
Soap	1.3 kg	1.3 kg	2.6 kg	2.6 kg	6.36	1.65
Linen/cotton	3 m	3 m	5 m	5 m	4.87	6.14
Candles	1.3 kg	1.3 kg	2.6 kg	2.6 kg	5.4	3.3
Lamp oil	1.3 kg	1.3 kg	2.6 kg	2.6 kg	2.8	3.3
Fuel	3 M BTU	3 M BTU	5 M BTU	5 M BTU	5.59	11.2
Total basket cost (grams of silver)	213	182.6	558.6	499.3		
Europe/Beijing ratio	'Bare bones' basket 1.17		'Respectable' basket 1.12		Geometric average 1.14	

Notes: M: metres. M BTU: million BTU.
Sources: See sections IV and V, and app. II.

have been supplied had it been produced in the European manner can be calculated. Likewise, the price of beer is unknown. For it, we substituted the quantity of rice wine (*sake*) that contained the same quantity of alcohol.[40] We estimated the price of rice wine using the Japanese relationship between the retail price of sake and the wholesale price of rice. In this way we proxied the missing prices needed to cost out a European basket in Beijing.

The European and Beijing baskets define Paasche and Laspeyres price indices. The final step in comparing the cost of living in London and Beijing is to compute the geometric average of the two, which is a Fisher Ideal Price index. This is a 'superlative' price index, which corresponds to a generalized Leontief expenditure function.[41] That representation of consumer preferences has the property that indifference curves are tangent to prices at both consumption patterns. In other words, the representative consumer whose behaviour is summarized by the price index would shift from an English to a Chinese spending pattern as prices shifted from the London to the Chinese configuration. Using this index number imposes the assumptions of modern theory on the reality of eighteenth-century behaviour—certainly a debatable procedure.

How does the Fisher Ideal Price index compare to the 'bare bones' indices? In fact, they are very similar. The relative cost of the European basket in London and Beijing was always close to the relative cost of the 'bare bones' baskets, which are equal to ratios of 1.12 and 1.17 respectively in table 5. Hence, their geometric average is also similar. Consequently, a superlative index number, in this case, gives

[40] 182 litres of beer at 4.5% alcohol contain as much alcohol as 41 litres of sake at 20%.

[41] Diewert, 'Exact and superlative index numbers'. The use of alternative consumption baskets for Canton and Japan based on comparable calories and protein contents also confirm the findings here; see Allen et al., 'Wages, prices, and living standards' (see above, n. 30).

the same result as a comparison of Smith's 'cost of subsistence'. Since the latter has so many intuitive interpretations, we use it as the axis of our discussion in the confidence that it is not misleading us when the index number problem is considered from other perspectives.

VI

The purchasing power of wages is usually measured by the ratio of the wage to the consumer price index. Our procedure elaborates that approach. In constructing the consumer price index, a notional budget was specified that represented the least costly way to survive (tables 3 and 4, however, do not include housing costs, so we increase them now by 5 per cent, which is a minimal allowance for rent). The budget was an annual budget for an adult male. If the man supported a family, the expenditures would have been higher, so that the cost of the budget (augmented by 5 per cent for rent) was multiplied by three to represent the annual budget of a family. This increase is roughly in line with the calorie norms for a man, a woman, and two young children.[42] On the income side, our income measure is the annual earnings that a worker could have gained if he worked full time for a year. We assume that one year's work consisted of 250 days—roughly full-time work allowing for holidays, illness, and slack periods. The earnings from full-time work provide a useful benchmark for comparing Europe and Asia and for defining the economic strategies of families. The ratio of estimated full-time earnings to the annual cost of the family budget is a real wage index.

Our real wage index has a particular interpretation since it answers a specific question, namely, whether a man working full time could support a family at the 'bare bones' level of consumption. Real wage indices of this sort are called 'welfare ratios'. When the welfare ratio equalled one, an unskilled labourer working full time could earn just enough to support his family at subsistence level. Higher values indicate some surplus, while values below one mean either that the family size had to be reduced or work effort had to be increased since there was little scope for reducing expenditure.

Figures 5 and 6 show welfare ratios for unskilled male workers from 1738 to 1923 in the European cities we discussed and the Chinese cities. Several features stand out. Firstly, as shown in figure 6, the Yangzi Delta is reputed to have had the most advanced economy of any Chinese province, but the real wage there was not noticeably higher than the real wage in Beijing or Canton, as we will see. Secondly, the Chinese cities were in a tie for last place with the Italian cities, which had the lowest standard of living in Europe, so an optimistic assessment of China's performance is difficult. Thirdly, the existing information about Beijing wages in the nineteenth century indicates that the real wage continued to slide until the Taiping Rebellion in mid-century, when it reached a life-threateningly low level. After authority was restored, living standards improved slowly into the early twentieth century. Fourthly, the most striking feature of figures 5 and 6 is the great lead in living standards enjoyed by workers in the rapidly growing parts of western Europe. The standard of living of workers in London was always much higher than

[42] Precisely, two children aged 1–3 and 4–6 respectively. For a discussion of food requirements for a notional family of four, see Allen, 'Great divergence', p. 426.

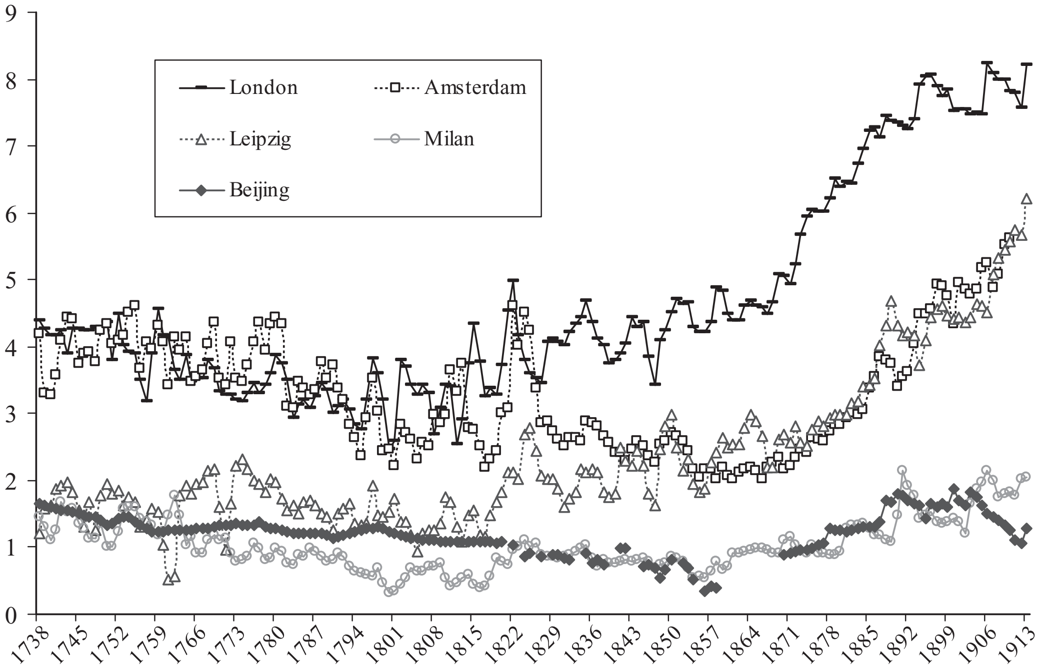

Figure 5. *Welfare ratios*
Source: As described in section VI.

that of workers in Beijing or the Yangzi Delta. After the middle of the nineteenth century, London living standards began an upward trajectory and increased their lead over China. While workers in Amsterdam in the eighteenth century also lived better than their counterparts in Beijing, the Dutch economy faltered in the early nineteenth century.[43] By mid-century, however, growth resumed and real wages were climbing to new heights. At the same time, the rapid growth of the German economy was translating into rising real wages for workers in Leipzig. By the First World War, the standard of living of workers in the industrial core of western Europe had greatly increased over their counterparts in Beijing and Suzhou. The standard of living in China remained low and on a par with the regions of Europe untouched by the industrial revolution. Fifthly, the workers in north-western Europe with welfare ratios of four or more did not eat four times as much oatmeal as their 'bare bones' diet presupposes. Instead, they ate higher-quality food—beef, beer, and bread—that was a more expensive source of calories. In addition, they bought a wide range of non-food items. In the eighteenth century, these included the Asian imports and novel manufactures that comprised the 'consumer revolution' of that era. By the same token, workers in north-western Europe could afford the basket of goods shown in table 5, while workers in Asia could not, and had to subsist on the 'bare bones' baskets. After all, in regions of settled agriculture, the

[43] van Zanden and van Riel, *Strictures*, pp. 121–30, pp. 188–91.

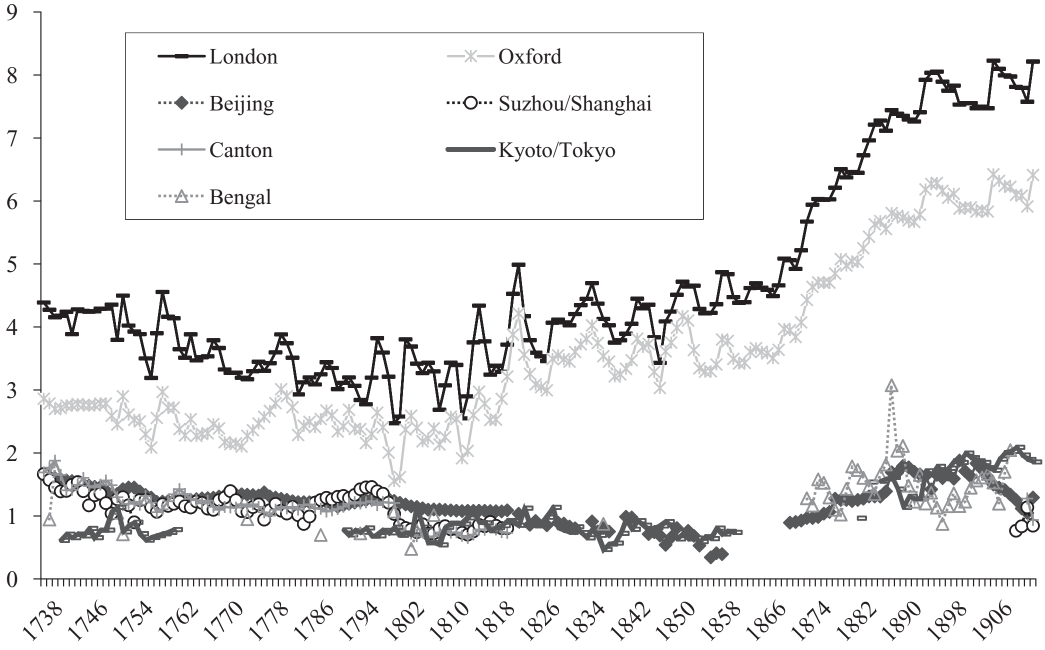

Figure 6. *Welfare ratios in Asia*

Sources: For Bengal welfare ratio, see Allen, 'India in the great divergence'. Kyoto/Tokyo welfare ratio is based on Bassino and Ma, 'Japanese unskilled wages'. As the 'Japan B' consumption basket constructed in Bassino and Ma article is roughly equivalent to the 'bare bones basket', we use real wages deflated by the cost of the 'Japan B' basket.

least expensive way to get calories is to boil the cheapest grain into a gruel or porridge. In northern Britain, the poorest people ate oat porridge; in the Yangzi Delta, they ate wheat gruel.[44]

Figure 6 tests the generality of these conclusions by including all of the Asian welfare ratios for comparison. There was variation in experience, but that variety does not qualify the conclusion that Asian living standards were at the low end of the European range. The history of living standards in Japan, India, and Canton was very similar to that of Beijing or Suzhou. Real wages in Istanbul, as shown by Özmucur and Pamuk, were at a level as low as China's, so it may have characterized much of the non-industrializing world in the eighteenth century.[45] There is evidence of rising living standards across Asia after 1870, but the gains were not enough to catch up to the standard of mid-eighteenth-century London or Amsterdam, let alone the much higher standard of living enjoyed by workers in those cities in the early twentieth century.

Figure 6 broadens our comparison by inserting the welfare ratio of Oxford, with the view that London may be exceptional in terms of real wages among English towns. Indeed, real wages in Oxford were always lower than in London, although the gap narrowed from the late eighteenth century.[46] Nonetheless, at a welfare ratio between 2.5 and 3.0 during the eighteenth century, Oxford still seemed far more

[44] Li, *Agricultural development*, p. 207, n. 25.
[45] Özmucur and Pamuk, 'Real wages'.
[46] For welfare ratios in Oxford and other towns in England, see Allen, 'Great divergence', pp. 415–16.

prosperous than Beijing. London (the capital and a major port) and other big cities were chosen because they are comparable to Beijing (the capital) and Canton (a major port), which are likely to be at the top of the wage scale in their country or region. Oxford, meanwhile, ranked much lower on the urban hierarchies compared with the cities in our study. Thus, the inclusion of Oxford as a robustness check assured us that our finding is not driven by the relative position of London.

A more important question is how representative wages are of labour incomes in China in general. Our knowledge of labour market conditions and the extent of regional migration seem to substantiate the view that wage rates may serve as a reasonable proxy for the average earnings of a particular socio-economic group as well as the marginal productivity of labour in the economy as a whole. The existence of a vibrant and active labour market, particularly for short-term or day labour, in early modern China (and Japan) is well documented, although the precise proportion remains elusive.[47] For the early twentieth century, which shared much of the institutional and economic continuities of the eighteenth and nineteenth centuries, large-scale household surveys reveal, for example, that between 30 and 50 per cent of rural households in the 1930s Wuxi county in the Yangzi Delta region hired day labourers during peak season, whereas the long-term labour market was extremely thin. Furthermore, those households whose main income derived from farm labour fetched an average income 20 per cent below the mean per capita income of all the Wuxi households. This income distance of 20 per cent from the mean shows that agricultural day labourers were at the lower end—but not a marginal fringe—of the income ladder.[48]

Secondly, at least for the commercialized regions near the major urban centres, evidence of a relatively high degree of integration of labour markets between urban and rural areas can be perceived. As noted earlier, most calenderers in Suzhou were migrant workers from the relatively impoverished rural Northern Jiangsu. Similarly for the Beijing wage series, Gamble's detailed study reminds us of the close linkage between urban and rural wages in the nineteenth century. Indeed, if labour market and regional labour migration in eighteenth-century China were as flexible as claimed by the revisionists, there is all the more reason to believe that the wage rates for unskilled labourers we measure are representative of labour earnings for a substantial part of the population at the relatively low end of income distribution.[49]

Our notional wage income can be directly compared with the labour income data cited by Pomeranz and Li when they in fact argue the reverse case, namely, that labouring people in the Yangzi Delta had a high standard of living. Pomeranz,

[47] The literature on the prevalence of labour employment and contracts in Ming and Qing China is voluminous. Examples of this literature can be seen in Pomeranz, *Great divergence*, pp. 81–2, and Huang, *Peasant family*, pp. 58–62. Wei, 'Ming-Qing', documents in detail the improved legal status of labourers towards the eighteenth century.

[48] For information on the labour market in north China and the Yangzi Delta, see Huang, *Peasant family*, p. 110. The Wuxi survey summary can be found in Kung, Lee, and Bai, 'Human capital', tabs. 1 and 2. For a nationwide survey of the labour market in the 1930s, see Chen, *Gesheng nonggong*. Similar labour market and income distribution can also be found in Tokugawa Japan. Bassino, Ma, and Saito, 'Level of real wages', calculate that the welfare ratios of the wage earnings of farm labourers were roughly equivalent to those of tenant cultivators who, in turn, were about 20% below those of the median class.

[49] For linkage between urban and rural wages, see Gamble, 'Daily wages', p. 67. See Pomeranz, *Great divergence*, ch. 2, for an argument on the flexibility of product and factor markets and labour migration in early modern China.

for instance, estimates that a male agricultural labourer employed full time over the course of a year would have realized about 12 taels. Using average prices for 1745–54, the 'bare bones' cost of maintaining a family was 22.59 taels, so the labourer was only earning 53 per cent of subsistence; in other words, the welfare ratio was 0.53. He could barely support himself, let alone a wife and children. A woman spinning and weaving cotton for 200 days per annum, which Li and Pomeranz both reckon was about the maximum possible, could earn 14.61 taels, a bit more than a man.[50] Again, this was less than the cost of maintaining a family. Husband and wife together, however, would have earned 26.61 taels, which was 1.18 times the cost of maintaining a family. A family could survive on that, so long as nothing went wrong, but the standard of living was far behind that in London or Amsterdam where the labourers earned four times the cost of a 'bare bones' standard of living in the middle of the eighteenth century.

So far, this comparison has focused on the wage income of unskilled labourers. However, the wage regression and the twentieth-century wages summarized by Gamble for Beijing all indicate that the ratio of skilled to unskilled wages was about the same in China as in north-western Europe. While future research is needed, this evidence suggests that our conclusions about comparative living standards could still hold true if the comparison were broadened to include all kinds of wage earners.[51]

VII

Our investigation of Asian and European wages and prices shows that the situation differed somewhat from Adam Smith's impressions. Money wages were in accord with his view: in China, they were certainly lower than wages in the advanced parts of western Europe in the eighteenth century and similar to those in the lagging parts of Europe. By the twentieth century, however, wages in all parts of Europe were higher than in China. Contrary to Smith, the cost of living was similar in China and in Europe in the eighteenth century.

The upshot of the wage and price comparisons is that living standards were low in China. In the eighteenth century, advanced cities like London and Amsterdam had a higher standard of living than Suzhou, Beijing, or Canton. The standard of living in the Chinese cities we have studied was on a par with the lagging parts of Europe, the Ottoman Empire, India, and Japan. By the twentieth century, enough progress had occurred in even the backward parts of Europe that their standards of living were beginning to creep above those in China. Wages seemed to have slipped in China in the eighteenth century. Still, most of the difference between Europe and China in 1913 was due to European advance rather than Chinese decline.

In spite of the above, a major surprise is our finding that unskilled labourers in major cities of China and Japan—poor as they were—had roughly the same standard of living as their counterparts in central and southern Europe for the

[50] Li, *Agricultural development*, pp. 149, 152. Pomeranz, *Great divergence*, pp. 318–19, offers two calculations pointing to slightly lower earnings. Li's calculation assumes women received 0.19 shi per bolt of cloth; Pomeranz's is slightly higher. They do not use precisely the same prices. We use average values for 1745–54.

[51] J. L. van Zanden, 'The skill premium and the "great divergence" ', paper presented at the conference 'Towards a global history of prices and wages' (Utrecht, 19–21 Aug. 2004) [WWW document]. URL http://www.iisg.nl/hpw/papers/vanzanden.pdf [accessed on 10 June 2009].

greater part of the eighteenth century. This calls into question the fundamental tenet of the large 'rise of the west' literature that sees western Europe—as a whole—surpassing the rest of the world in the early modern era. Our article suggests that it was only England and the Low Countries that pulled ahead of the rest. The rest, in this context, includes not only Asia but also much of Europe.[52]

In this regard, Adam Smith neglected regional variation and thereby overgeneralized the comparison of Europe and China. But our findings also dispute the revisionists' claim that the advanced parts of China, such as the Yangzi Delta, were on a par with England on the eve of the industrial revolution, for we find real wages for unskilled labourers in the Yangzi Delta to have been no higher than those in Beijing or Canton. Clearly, our database on China could be greatly improved and we do not claim to have given the final answer to this question. Nevertheless, any newly discovered data would have to be very different from what is currently available in order to convince us that pre-industrial Chinese living standards were similar to those in the leading regions of Europe.[53] In this regard, Adam Smith's pessimism looks closer to the truth than the revisionists' optimism. Of course, establishing the existence of an income gap between north-western Europe and China in the early modern era only takes us halfway towards the resolution of the great divergence debate. The search for a causal explanation of the great divergence still looms large as a future research agenda.

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[52] For a coverage of welfare ratios of unskilled workers across 16 major urban centres of continental Europe in the early modern period, see Allen, 'Great divergence'.

[53] For the discussion of higher living standards in the Yangzi Delta, see Pomeranz, *Great divergence*, and Li, *Agricultural development.* Huang's comparative regional study, *Peasant family*, also makes a strong case that the Yangzi Delta overall had higher productivity levels and income than north China. Our findings of roughly comparable nominal and real wage levels in the three major Chinese urban centres do not necessarily preclude the possibility that broader measures of per capita income and living standards could still be higher in the Yangzi Delta. A recent study by Ma, 'Economic growth', shows that the per capita income of the two provinces in the Yangzi Delta in the 1930s were 55% higher than the Chinese national average. There is good reason to believe the regional income gap in China in the 1930s would have been larger than in the eighteenth century. While future empirical research is needed to construct a comprehensive regional wage profile for eighteenth- and nineteenth-century China, the magnitude of regional variation within China as discussed in these other studies pales in comparison with the gaps in average real wages in urban centres between China and England.

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APPENDIX I: NOTES ON THE SOURCES FOR CHINESE WAGES, 1686–1902

A. Cotton calenderers' wages

In the seventeenth to nineteenth centuries, most calenderers in Suzhou were migrant workers from impoverished regions in Northern Jiangsu or Anhui. They usually worked under a contract system, renting capital and place of work from cotton cloth merchants. Although forbidden by the government to form their own guilds, they often went on strike for higher wages, hence the documentation of these negotiated wage rates in the stele records.

Information on the daily productivity quoted in Xu's study can be applied for converting the piece rates into daily wages. According to Xu, a calenderer could press one bolt of cloth in about 40 minutes.[54] In a day of about 11 working hours, he could press about 12 bolts of cloth. For conversion, we use 11 bolts of cloth pressed per day to adjust it roughly to a 10-hour working day. However, the calenderers would have to hand in 20 per cent as payment for rental and other expenses. Deducting the 20 per cent from the final wage, we converted the piece wage of 0.0113 taels (in 1730) and 0.013 taels (in 1772 and 1795) per bolt of cloth into 0.0994 and 0.1144 taels per day respectively. The daily productivity data in Xu's study are based on suburban Shanghai in the early twentieth century, but Xu explicitly states that both technology and organization then had changed little from the early modern period.[55]

B. Gamble's nineteenth-century wage series

The wage series in Gamble's 'Daily wages', which spans almost the entire nineteenth century, was derived from detailed account books of a fuel store in rural Beijing. Gamble presented three series of average wages for the months of May to August, April to September, and January to December respectively.[56] His careful study reveals the highly seasonal nature of the annual wage patterns which corresponds with the agricultural harvest season. We chose the annual average wage series (January to December), which is the lowest of the three, as it includes the rates for the slack winter period. This wage series in copper cash is shown in the first column of appendix table 1 below.

The original wage series are all quoted in copper cash. Since Gamble was mainly interested in constructing wage indices, he presented nominal and copper wage indices in table 6 of his article without explicitly giving the copper–silver conversion rates.[57] Moreover, due to a major debasement around 1860 and a corresponding change of monetary account in the fuel store account books, Gamble broke his silver and copper wage indices at 1860, setting 1845 as a base 100 for the pre- and post-1860 periods respectively. Thus, it is possible to derive the index—not the actual rate—of copper–silver exchange from his copper and silver wage indices.

Gamble did mention the actual silver–copper conversion rates in numbers of *tiao* (strings of copper cash) per silver tael for selected years of 1807, 1827, 1862, 1884, and so on.[58] Our procedure for arriving at a consistent series of copper–silver exchange rates for the nineteenth century is to combine these benchmark rates with the derived copper–silver exchange indices.

However, interpreting the value of one *tiao*, which usually contained 1,000 copper coins but could vary by region, is a major hurdle. Gamble remarked that one *tiao* in rural Beijing was equal to 500 copper cash before 1860 and 100 copper cash after 1860.[59] In other words, the copper cash before 1860 circulated in that locality was only half of the value of the official cash. This seems to be corroborated by Yan et al.'s study of prices and exchange rates.[60] They derived the exchange rate series (1807–50) from the account books of a merchant store located in Daliu zhen of Ningjin County in Hebei province, about 300 kilometres from Beijing. In a footnote to their exchange rate table, the authors pointed out that the value of two copper cash was counted as one.[61] A comparison of their copper–silver exchange series and our implicit Gamble series shows that their trends are nearly identical.

[54] Xu, ed., *Jiangnan tubu shi*, p. 378.
[55] Ibid., p. 375.
[56] Gamble, 'Daily wages, p. 61.
[57] Ibid., p. 60.
[58] Ibid., pp. 44, 69.
[59] Ibid., p. 44.
[60] Yan et al., eds., *Zhongguo jindai jingjishi*, p. 428.
[61] Ibid., tab. 31, p. 38.

Despite their footnote, Yan et al. derived their copper–silver series based on the standard rate of one *tiao* being equal to 1,000 cash. Our copper–silver exchange rate series in the second column is similarly derived, with the standard of one *tiao* equal to 1,000 cash. In order to derive the accurate wage rate in silver tael, the third column of table A1 is the silver wage converted from the first two volumes further divided by two. The wage rate thus derived seems extraordinarily low. However, as indicated by Gamble, workers were also given additional food.[62] As shown in section II, we use only the trend (not the level) for this study.

Table A1. *Gamble's rural Beijing wage series in copper cash and silver taels, 1807–1902*

Year	*Copper wages in cash (wen)*	*Copper cash per silver tael*	*Silver wages in taels (= col.1/(col.2x2)*	Year	*Copper wages in cash (wen)*	*Copper cash per silver tael*	*Silver wages in taels (= col. 1/(col. 2x2)*
1807	81	979	0.041	1860	255		
1808	83	1,020	0.041	1865	265	5,180	0.026
1812	81	1,078	0.038	1870	287	5,576	0.026
1813	80	1,067	0.037	1871	333	5,892	0.028
1816	87	1,129	0.039	1872	355	6,170	0.029
1817	80	1,123	0.036	1873	382	6,383	0.03
1818	89	1,106	0.04	1874	388	6,611	0.029
1819	87	1,183	0.037	1875	389	6,681	0.029
1820	95	1,159	0.041	1876	370	7,446	0.025
1822	99	1,203	0.041	1877	368	8,325	0.022
1824	83	1,208	0.034	1878	348	8,314	0.021
1825	88	1,192	0.037	1879	375	8,342	0.022
1827	88	1,265	0.035	1880	410	8,510	0.024
1829	95	1,294	0.037	1881	401	8,341	0.024
1830	96	1,329	0.036	1883	387	7,154	0.027
1831	92	1,346	0.034	1884	356	6,722	0.026
1832	89	1,347	0.033	1885	395	7,573	0.026
1835	94	1,251	0.038	1886	402	6,950	0.029
1836	85	1,378	0.031	1887	395	7,024	0.028
1837	96	1,488	0.032	1888	361	7,883	0.023
1838	91	1,553	0.029	1889	421	7,314	0.029
1841	98	1,382	0.035	1890	393	7,254	0.027
1842	100	1,439	0.035	1891	390	7,627	0.026
1845	86	1,823	0.024	1892	372	7,651	0.024
1846	96	2,010	0.024	1893	410	7,212	0.028
1847	87	2,013	0.022	1894	443	6,722	0.033
1848	68	2,049	0.017	1896	448	6,501	0.034
1849	80	2,046	0.02	1900	422	5,312	0.04
1850	94	1,997	0.024	1901	462	5,758	0.04
1852	93	2,018	0.023	1902	470	6,079	0.039
1853	93	2,205	0.021				
1854	90	2,723	0.017				
1856	110	4,970	0.011				
1857	105	3,935	0.013				
1858	130	4,970	0.013				

[62] Gamble, 'Daily wages', p. 41.

APPENDIX II: NOTES ON THE SOURCES FOR CHINESE PRICES

Our series of prices for Beijing begins with Meng and Gamble's study of wages and prices in Beijing between 1900 and 1924.[63] For that period they collected the retail prices of most elements of the basket detailed in table 4. We abstracted the following series: wheat flour, *lao mi* (old, blackened rice), bean flour, millet, corn flour, pork, sweet oil, peanut oil, foreign cloth, and coal balls. 'Sweet oil' was treated as 'edible oil' in our scheme and 'peanut oil' as 'lamp oil'. Coal balls were two-thirds coal dust and one-third earth, and the price was converted to an energy basis by rating one kilogram of coal balls at two-thirds of the energy content of coal, which was itself rated at 27,533 BTU per kilogram.

To estimate the price of soybeans for 1900–8, we increased the wholesale price per kilogram of black beans by 50 per cent to allow for trade mark-ups and quality differences. The wholesale price was derived from Li, 'Grain prices'.[64] For 1909 onwards, when the Li series ends, the 1908 price was extrapolated on the basis of Meng and Gamble's price series for bean flour.[65]

Since no information on the price of candles was available, we assumed their price per kilogram to be the same as that of one litre of lamp oil. Based on European precedents, we estimated the price of soap at half of the price of lamp oil.

The next problem was to extend these series back to the pre-industrial period. It should be noted that in several important respects Meng and Gamble's data were ideal: they were retail prices of goods that consumers actually bought. In contrast, many historical price series are wholesale prices of intermediate goods. For instance, Meng and Gamble recorded the price of wheat flour in a shop, while historians must usually make do with the price of unprocessed wheat in wholesale markets.

Taking advantage of these ideal features of Meng and Gamble's data, we applied Li's study of wholesale grain prices in Zhili province, which includes Beijing. From the graphs in her paper, we could read off the prices of wheat, millet, and sorghum from 1738 to 1908, as well as the relative price of black beans to wheat. These are five-year moving averages, so annual fluctuations are suppressed, but that is of little consequence for the present study.[66] On the basis of these series, the retail prices of wheat flour, millet, corn flour, bean flour, and soybeans were extrapolated back to 1738. The resulting extrapolated series are linked using the average of 1901–4 as the base period. This procedure assumes that the ratio of the retail price of the consumer good to the wholesale price of the unprocessed good remained constant.

The retail prices of other products were extrapolated back to 1738 as follows: for meat, edible oil, lamp oil, and candles, the price of wheat flour was applied, based on the benchmark period of 1901–4 for meat (the average price of pork and mutton), and 1902 for the rest. For corn flour, the price of sorghum based on the 1901–4 benchmark was used, and for rice (*lao mi*, old or blackened rice), the price of rice in the Yangzi Delta, based on the 1901–4 benchmark.[67]

[63] Meng and Gamble, 'Wages, prices, and the standard of living', pp. 28, 38–9, 51, 59.
[64] Li, 'Grain prices', pp. 69–100.
[65] Meng and Gamble, *Prices*, p. 28.
[66] Professor L. M. Li kindly supplied us with some of the underlying series for her paper, 'Integration'.
[67] Wang, 'Secular trends', pp. 40–7.

Two things can be said in favour of these extrapolations. First, most of the long-term agricultural time series inflate at the same rate, so the values projected back into the eighteenth century do not depend critically on which price series is used for the extrapolation. Second, the extrapolations can be checked by comparing the values we obtain in the eighteenth century for prices listed in the VOC records for Canton. Since the extrapolated prices are similar to prices paid then, this gives us some confidence in the procedure.

The price series of cotton cloth is based on several sources. First, the Beijing retail price of foreign cloth was projected back to 1871 using Feuerwerker's series of the price of cotton cloth imported into China.[68] Imported cloth was measured in pieces which were usually 40 yards long by one yard wide (360 square feet). Meng and Gamble's price was the price per 100 feet. We interpret that to mean 100 linear feet from a bolt of cloth, which we assume was three feet wide—a typical width. On those assumptions, the retail price per square foot of foreign cloth in Beijing was about 50 per cent more than the price at which it was landed. This is not an unreasonable mark-up.

In his detailed discussion of eighteenth-century cloth prices and weaving incomes, Pomeranz estimated the price of cloth in a low price scenario at 0.5 taels per bolt.[69] On this assumption, 300 square feet of cloth were worth 4.59 taels, and we interpret this as the eighteenth-century counterpart to Meng and Gamble's price for a 100-foot length of a piece of cloth three feet wide. Following Pomeranz, we assume that cloth prices remained constant over the eighteenth century.[70]

For the years between 1800 and 1870, we were guided by the history of cloth prices in Indonesia. A series of the price paid for cotton cloth in Java from 1815 to 1871 shows that from 1815 to 1824, the price was 4.89 grams of silver per square metre, which compares to a Chinese price of 5.12 grams per square metre for the eighteenth century. This correspondence is reassuring since cotton cloth was traded across Asia, so we would not expect extreme differences in its price. Starting in the 1830s, the price in Java dropped fairly quickly to a value of about 2.5 grams of silver per square metre and stayed at that level until 1871.[71] That low price is similar to the value of cloth imported into China—2.36 grams of silver per square metre in 1871. On the assumption that cloth prices in China followed the same temporal pattern as those in Java, the eighteenth-century price derived from Pomeranz was continued to 1830, and then interpolated linearly between 1830 and 1871.

The price of energy was also combined from diverse sources. For 1739–69, we used the data implied by charcoal prices in Zhili province in the 1769 *Wuliao jiazhi zeli*, and for 1816, the price implied by the price of coal in Beijing given by Timkovski.[72] From 1900 onwards, the cost of energy was based on the price of coal balls. One of the striking features of this scattered information is that it gives a fairly constant price for energy. In view of that constancy, the values for the missing years were interpolated.

[68] Feuerwerker, 'Handicraft', p. 344.

[69] Pomeranz, *Great divergence*, p. 319, decided that a cloth of 16 *chi* in length cost 0.4 taels. According to Li, *Agricultural development*, p. xvii, a bolt of 20 *chi* had 3.63 square yards. Hence, the price of cloth was 0.5 taels per bolt.

[70] Pomeranz, *Great divergence*, p. 323.

[71] See Korthals Altes, 'Prices', for cloth prices in Java.

[72] Timkovski, *Voyage*, p. 200.

Since no Chinese alcohol prices were available, the present study used the Japanese data, which show that one litre of sake equalled 1.31 kg of rice.[73] This ratio is applied to Beijing and Canton, assuming that the technology for processing rice wine was similar in China and Japan.

Table A2. *Caloric and protein contents*

	Unit (metric)	*Calories per unit*	*Grams of protein per unit*
Bread	kg	2,450	100
Beans/peas (Europe)	litre	1,125	71
Beans (Asia)	kg	3,383	213
Meat	kg	2,500	200
Butter	kg	7,268	7
Cheese	kg	3,750	214
Eggs	pieces	79	6.25
Beer	litre	426	3
Soy beans	kg	4,460	365
Rice	kg	3,620	75
Wheat flour	kg	3,390	137
Barley	kg	3,450	105
Millet	kg	3,780	110
Buckwheat	kg	3,430	133
Corn flour	kg	3,610	69
Fresh fish	kg	1,301	192
Edible oil	litre	8,840	1
Alcohol (20°)	litre	1,340	5

Sources: The caloric and protein content are based on Allen, 'Great divergence', p. 421, for bread, beans/peas consumed in Europe (fresh with pods, measured in litres), meat, butter, cheese, eggs, and beer. For other items, we relied on US Department of Agriculture (USDA) National Nutrient Database for Standard Reference [http://www.nal.usda.gov/fnic/foodcomp/search/] [accessed 11 Jan. 2010].

[73] On the basis of sake and glutinous rice price data in Osaka in the period in 1824–54 reported in Bunko, ed., *Kinsei Nihon*, tab. 8, pp. 113–17.

The Rise of Europe: Atlantic Trade, Institutional Change, and Economic Growth

By Daron Acemoglu, Simon Johnson, and James Robinson*

The rise of Western Europe after 1500 is due largely to growth in countries with access to the Atlantic Ocean and with substantial trade with the New World, Africa, and Asia via the Atlantic. This trade and the associated colonialism affected Europe not only directly, but also indirectly by inducing institutional change. Where "initial" political institutions (those established before 1500) placed significant checks on the monarchy, the growth of Atlantic trade strengthened merchant groups by constraining the power of the monarchy, and helped merchants obtain changes in institutions to protect property rights. These changes were central to subsequent economic growth. (*JEL* F10, N13, O10, P10)

The world we live in was shaped by the rapid economic growth that took place in nineteenth-century Western Europe. The origins of this growth and the associated Industrial Revolution are generally considered to lie in the economic, political, and social development of Western Europe over the preceding centuries. In fact, between 1500 and 1800, Western Europe experienced a historically unprecedented period of sustained growth, perhaps the "First Great Divergence" (i.e., the first major sustained divergence in income per capita across different regions of the world), making this area substantially richer than Asia and Eastern Europe. There is little agreement, however, on why this growth took place in Western Europe and why it started in the sixteenth century.

This paper establishes the patterns of economic growth in Western Europe during this era, develops a hypothesis on the origins of the rise of (Western) Europe and provides historical and econometric evidence supporting some of the implications of this hypothesis.

We document that the differential growth of Western Europe during the sixteenth, seventeenth, eighteenth, and early nineteenth centuries is almost entirely accounted for by the growth of nations with access to the Atlantic Ocean, and of *Atlantic traders*. Throughout the paper, the term Atlantic trader refers to Britain, France, the Netherlands, Portugal, and Spain, the nations most directly involved in trade and colonialism in the New World and Asia. *Atlantic trade,* in turn, means trade with the New World, as well as trade with Asia via the Atlantic, and includes colonialism- and slavery-related activities.[1] The differential growth of Atlantic traders suggests a close link between Atlantic trade and the First Great Divergence. In fact, it appears that the rise of Europe between 1500 and 1850 is largely the rise of Atlantic

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[1] Atlantic trade opportunities became available only during the late fifteenth century, thanks to the discovery of the New World and the passage to Asia around the Cape of Good Hope. These discoveries resulted from a series of innovations in ship technology, primarily pioneered by the Portuguese, that changed the rigging and hull design of ships and developed knowledge of oceanic navigation.

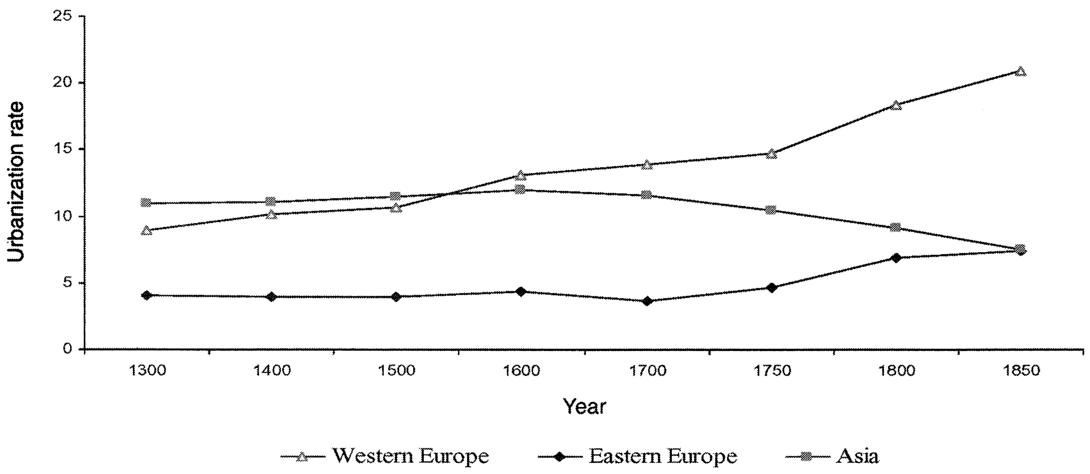

FIGURE 1A. WESTERN EUROPE, EASTERN EUROPE, AND ASIA: URBANIZATION RATES, WEIGHTED BY POPULATION, 1300–1850

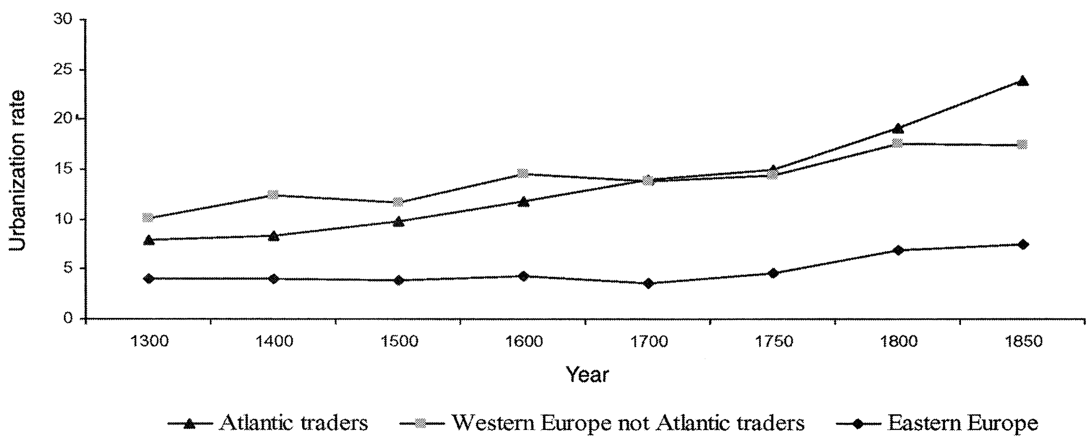

FIGURE 1B. ATLANTIC TRADERS, WEST EUROPEAN COUNTRIES NOT ATLANTIC TRADERS, AND EASTERN EUROPE: URBANIZATION RATES, WEIGHTED BY POPULATION, 1300–1850

Europe, and is quite different in nature from the European growth that took place before 1500.

Not all societies with access to the Atlantic show the same pattern of growth, however. The data suggest an important *interaction* between medieval political institutions and access to the Atlantic: the more rapid economic growth took place in societies with relatively nonabsolutist initial institutions, most notably in Britain and the Netherlands. In contrast, countries where the monarchy was highly absolutist, such as Spain and Portugal, experienced only limited growth in the subsequent centuries, while areas lacking easy access to the Atlantic, even such nonabsolutist states as Venice and Genoa, did not experience any direct or indirect benefits from Atlantic trade.

Figures 1 and 2 illustrate the central thesis of this paper. Figure 1, panel A, shows that urbanization in Western Europe grew significantly faster than in Eastern Europe after 1500.[2] Figure 1, panel B, shows that these

[2] For the purposes of this paper, Western Europe is taken to be all the countries west of the Elbe, i.e., Austria,

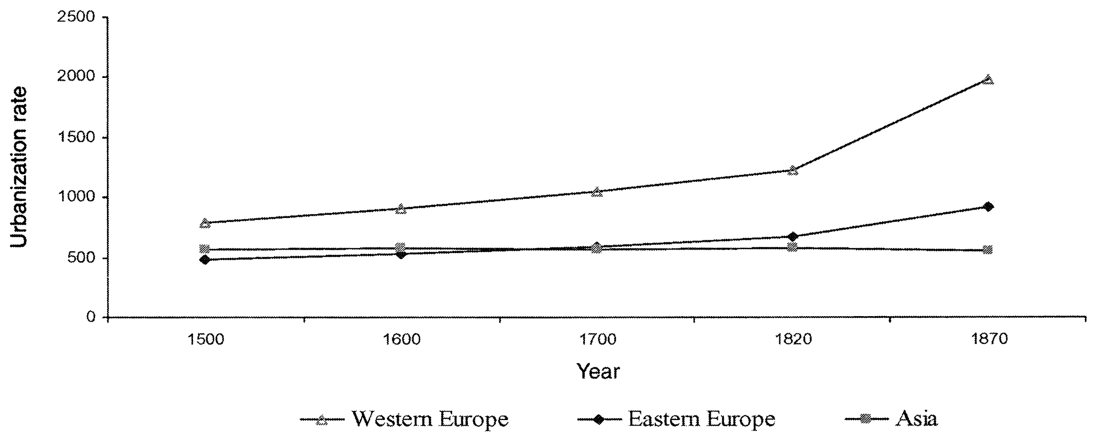

FIGURE 2A. WESTERN EUROPE, EASTERN EUROPE, AND ASIA: GDP PER CAPITA, WEIGHTED BY POPULATION, 1500–1870

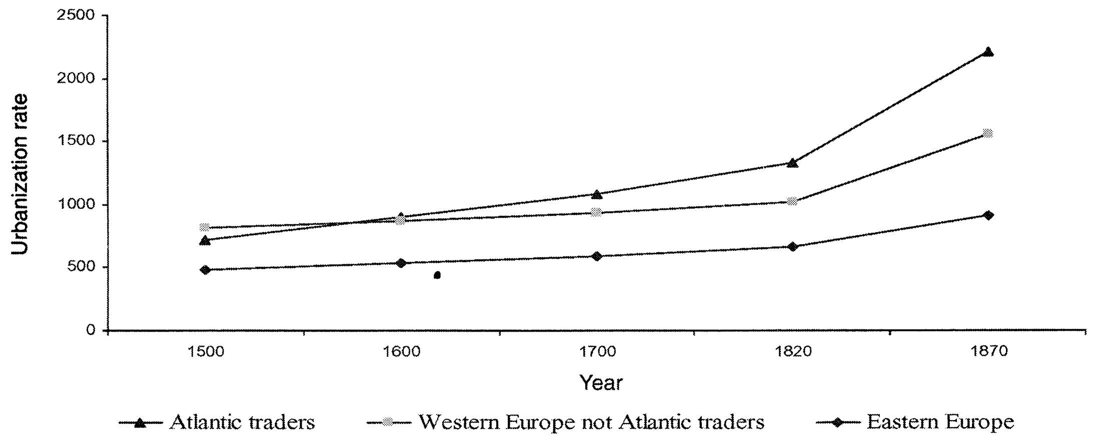

FIGURE 2B. ATLANTIC TRADERS, WEST EUROPEAN COUNTRIES NOT ATLANTIC TRADERS, AND EASTERN EUROPE: GDP PER CAPITA, WEIGHTED BY POPULATION, 1500–1870

differential trends are due in large part to the growth of Atlantic traders. The rest of Western Europe had a relatively high average urbanization rate of 10 percent in 1300 (and 11.4 percent in 1500), but grew at approximately the same rate as Eastern Europe from 1500 to 1850, by a factor of less than 2, to reach 17 percent by 1850. In contrast, Atlantic traders started with a lower average urbanization rate of 8 percent in 1300 (and only 10.1 percent in 1500), which almost tripled in the subsequent 550 years to reach 24.5 percent in 1850, overtaking average urbanization in the non-Atlantic parts of Western Europe between 1600 and 1700 (see Table 1). Panels A and B in Figure 2 show the same pattern, using Angus Maddison's (2001) estimates of GDP per capita. While GDP per capita rose by a factor of almost two among Atlantic traders between 1500 and 1820, in the rest of Western Europe it grew at approximately the same rate as in Eastern Europe, just under 30 percent.

The patterns depicted in Figures 1 and 2 do

Belgium, Britain, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, and Switzerland. Eastern Europe is all European countries to the east of the Elbe, including Russia and excluding Turkey. See Section I A for details on urbanization and GDP data. All averages are weighted by population, using numbers from Colin McEvedy and Richard Jones (1978).

TABLE 1—DESCRIPTIVE STATISTICS

	Whole sample, unweighted	Whole sample, weighted	Atlantic Western Europe	Non-Atlantic Western Europe	Eastern Europe	Asia
			Weighted by population			
Urbanization in 1300	6.6	9.9	8.0	10.0	4.1	11.0
	(5.2)	(3.2)	(2.8)	(6.1)	(3.3)	(0.7)
Urbanization in 1400	7.6	10.3	8.5	12.1	3.9	11.1
	(9.5)	(3.6)	(2.4)	(10.0)	(1.5)	(0.5)
Urbanization in 1500	8.3	10.6	10.1	11.4	4.0	11.5
	(7.6)	(3.4)	(5.3)	(6.8)	(1.8)	(0.7)
Urbanization in 1600	9.6	11.7	13.6	14.0	4.4	12.0
	(7.6)	(4.0)	(7.6)	(8.8)	(2.7)	(0.7)
Urbanization in 1700	10.7	11.2	14.5	13.1	3.7	11.6
	(8.5)	(4.1)	(6.8)	(8.1)	(2.2)	(0.7)
Urbanization in 1800	14.1	10.3	19.8	16.9	7.0	8.9
	(9.1)	(4.9)	(7.9)	(7.5)	(3.3)	(1.4)
GDP per capita in 1500	627.54	608.3	721.46	850.73	506.94	575.0
	(159.3)	(118.0)	(31.1)	(217.1)	(78.2)	(35.4)
GDP per capita in 1600	740.73	630.5	916.31	908.22	578.29	576.8
	(225.6)	(144.2)	(149.3)	(167.3)	(112.3)	(35.3)
GDP per capita in 1700	862.12	622.2	1079.21	980.82	636.0	574.2
	(348.4)	(208.1)	(321.4)	(128.2)	(136.1)	(35.3)
GDP per capita in 1820	988.00	691.7	1321.95	1095.40	719.5	575.5
	(373.6)	(264.5)	(348.7)	(125.3)	(174.9)	(45.7)
Constraint on executive in 1500	1.67	1.73	1.75	1.99	1.46	
	(0.76)	(0.79)	(0.56)	(0.99)	(0.79)	
Constraint on executive in 1600	1.67	1.53	1.62	1.54	1.45	
	(1.01)	(0.84)	(1.24)	(0.59)	(0.79)	
Constraint on executive in 1700	1.83	1.52	1.83	1.41	1.30	
	(1.31)	(1.17)	(1.76)	(0.94)	(0.76)	
Constraint on executive in 1800	2.25	2.18	4.00	1.90	1.00	
	(1.82)	(1.83)	(1.79)	(1.78)	(0.00)	
Atlantic coastline-to-area	0.0057	0.0014	0.0118	0.0026	0.00	0.00
	(0.0117)	(0.0065)	(0.0181)	(0.0052)		

Notes: First column is unweighted means; other columns are mean values weighted by total population in year indicated, from McEvedy and Jones (1978). Standard deviation is in parentheses. There are 24 European countries in these data. Atlantic Western Europe is England, France, the Netherlands, Portugal, and Spain. Non-Atlantic Western Europe is Austria, Belgium, Denmark, Finland, Germany, Ireland, Italy, Norway, Sweden, and Switzerland. Eastern Europe is Albania, Bulgaria, the Czech Republic, Greece, Hungary, Poland, Romania, Russia, and Serbia. Asia is India and China. Urbanization for Europe is percentage of population living in towns with population of at least 5,000 at some time between 800 and 1800, from Paul Bairoch et al. (1988) for Europe; comparable data for Asia are from Bairoch (1998). GDP per capita is from Maddison (2001). Constraint on executive is on a scale of 1 to 7, where a higher score indicates more constraints; this is coded using the Polity IV methodology, as explained in the text. We have not coded constraint on the executive for Asia. Atlantic coast-to-area includes those parts of Germany, Denmark, and Norway that are on the North Sea. For more detailed definitions and sources, see Appendix, Table 1.

not simply reflect the tendency of more successful nations to engage in Atlantic trade. There is no differential growth of Atlantic traders before the opening of Atlantic sea routes, and below we show similar results using an exogenous measure of *access to the Atlantic*—ratio of Atlantic coastline to land area—instead of the distinction between Atlantic traders and nontraders. Nor do the results reflect some post-1500 advantage of coastal nations: Atlantic ports grew much faster than other European cities, while Mediterranean ports grew at similar rates to inland cities.

This evidence weighs against the most popular theories for the rise of Europe, which emphasize the continuity between pre-1500 and post-1500 growth and the importance of certain distinctive European characteristics, such as culture, religion, geography, and features of the

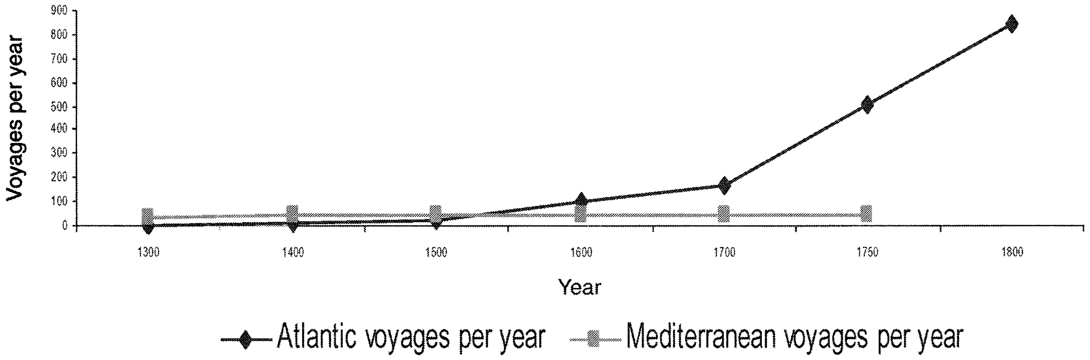

FIGURE 3. VOLUME OF ATLANTIC AND MEDITERRANEAN TRADE (VOYAGE EQUIVALENTS PER YEAR), 1300–1800

European state system.[3] Instead, it is consistent with theories that emphasize the importance of profits made in Atlantic trade, colonialism, and slavery.[4] Nevertheless, other evidence suggests that overseas trade and the associated profits were not large enough to be *directly* responsible for the process of growth in Europe. Stanley L. Engerman (1972) and Patrick K. O'Brien (1982) demonstrate that the contribution of profits from slavery and trade with the rest of the world to European capital accumulation was modest. O'Brien (1982, p. 2) writes that trans-oceanic trade "... could in no way be classified as decisive for economic growth of Western Europe." Although recent work by Joseph E. Inikori (2002) estimates larger trade flows than those of O'Brien, his estimates are not large enough to suggest that European growth was driven solely by the direct impact of Atlantic trade on profits or resources.

We advance the hypothesis that West European growth during this period resulted, in part, from the indirect effects of international trade on institutional development. Although there were some improvements in *economic institutions* in the late medieval and early modern period, rapid economic development did not begin until the emergence of *political institutions* providing secure property rights to a broader segment of society and allowing free entry into profitable businesses (Douglass C. North and Robert P. Thomas, 1973; North and Barry R. Weingast, 1989). The critical political institutions were those that constrained the power of the monarchy and allied groups.[5] Checks on royal power and prerogatives emerged only when groups that favored them, that is commercial interests outside the royal circle, became sufficiently powerful politically. From 1500, and especially from 1600, onward, in countries with nonabsolutist initial institutions and easy access to the Atlantic, the rise in Atlantic trade enriched and strengthened commercial interests outside the royal circle and enabled them to demand and obtain the institutional changes necessary for economic growth. Although profits from Atlantic trade were small relative to GDP, they were still substantial, and much larger than previous trading profits. For example, Figure 3 shows that by the end of the seventeenth century, the volume of Atlantic trade was much larger than that of long-distance Mediterranean trade (see the Appendix for the construction of these series). The recipients of these profits became very rich by the standards of seventeenth- and eighteenth-century Europe, and typically politically and socially very powerful.

These changes did not take place in countries with highly absolutist institutions such as Spain,

[3] See, e.g., Max Weber (1905), Eric Jones (1981), John A. Hall (1985), and David S. Landes (1998).

[4] E.g., Eric E. Williams (1944), Andre Gunder Frank (1978), and Immanuel M. Wallerstein (1974–1980).

[5] It is important to note that these new political institutions neither protected the rights of all citizens nor were democratic. They can best be characterized as oligarchic, since they increased the political power of wealthy merchants, and at least in the British case, of the gentry and nascent industrial interests. Nevertheless, they constituted a distinct improvement over the previous set of institutions, which placed many fewer checks on the power of the monarchy.

Portugal, and to a large extent France, where the crown was able to closely control the expansion of trade. Consequently, in these countries, it was the monarchy and groups allied with it that were the main beneficiaries of the early profits from Atlantic trade and plunder, and groups favoring changes in political institutions did not become powerful enough to induce them. Our hypothesis, therefore, predicts an important interaction between initial institutions and Atlantic trade, which is the pattern we find in the data.

The major premise presented in this paper is consistent with the emphasis of a number of historians, including, among others, Ralph Davis (1973a), Jan de Vries (1984), Paul Bairoch (1988), Fernand Braudel (1992), and de Vries and Ad van der Woude (1997). Although this historical literature emphasizes the differential growth of Atlantic ports and Atlantic nations, to the best of our knowledge, there are no other studies documenting the quantitative importance of Atlantic traders and Atlantic ports, or showing that the differential growth of Western Europe is accounted for largely by the growth of Atlantic traders.

On the theoretical side, our hypothesis builds on the notion that institutional change, even when socially beneficial, will be resisted by social groups that stand to lose economic rents or political power. Consequently, the process of institutional change involves significant conflict between different groups—in the European context, between the monarchy and its allies, versus commercial interests outside the royal circle.[6] Our historical account can also be viewed as a marriage between the Marxist thesis linking the rise of the bourgeoisie and the development of the world economy (e.g., among others, Williams, 1944; Frank, 1978; and Wallerstein, 1974–1980) and the neoclassical emphasis on the development of political institutions and secure property rights in Western Europe (e.g., North and Thomas, 1973; Eric L. Jones, 1981; North, 1981; J. Bradford De Long and Andrei Shleifer, 1993). Distinct from these approaches, however, we offer an explanation, based on the interaction between Atlantic trade and medieval political institutions, of why strong private property rights emerged in Western Europe, especially in Britain and the Netherlands, starting in the sixteenth century. Although some scholars have noted the important role of overseas merchants in particular instances of political change during this period (most notably Robert Brenner, 2003, and Steven Pincus, 2002, in the British case), we are not aware of a theory along the lines developed in this paper.

The paper is organized as follows. Section I documents the key premise of the paper, and shows that the pattern seen in Figures 1 and 2 is robust. Section II develops our hypothesis for the rise of Europe and the role played by Atlantic trade in this process, and provides historical evidence supporting our interpretation. Sections III and IV provide evidence on some implications of our hypothesis (Section III shows that the evolution of European institutions is closely linked to Atlantic trade, and Section IV documents an important interaction between initial institutions and Atlantic trade in European economic growth). Section V concludes. The Appendix summarizes the construction of the variables used in the empirical analysis, and further detail can be found in Acemoglu et al. (2002b).

I. Atlantic Trade and the Rise of Europe

A. *Data*

We use three data series to measure economic development. First, we construct estimates of urbanization based on the urban population numbers of Bairoch et al. (1988). This is a comprehensive dataset with information on all 2,200 European cities that had, at some time between 800 and 1800, 5,000 or more inhabitants.[7] We use these data as our measure of urban population and divide by the population

[6] See, for example, North (1981), Mancur Olson (1982), Per Krusell and Jose-Victor Rios-Rull (1996), Stephen Parente and Edward C. Prescott (1999), Acemoglu and Robinson (2000, 2002), and Raghuram G. Rajan and Luigi Zingales (2003). Ronald Rogowski (1989) is particularly notable in this context, since he also emphasizes how trade affects political coalitions via its impact on factor prices, although he does not focus on how trade might induce institutional change by strengthening commercial interests.

[7] These data begin in 800, and there are estimates for every 100 years until 1700, then for every 50 years through 1850. Bairoch et al. (1988) emphasize, however, that estimates before 1300 are rough and less reliable (and they skip the year 1100 due to lack of information). These data were used previously by De Long and Shleifer (1993).

estimates of McEvedy and Jones (1978) to calculate urbanization (percentage of the population living in cities with more than 5,000 inhabitants). We also use estimates of urbanization rates for Asia from the quantitative and qualitative assessments of Bairoch (1988). Bairoch (1988, ch. 1) and de Vries (1976, p. 164) argue that only areas with high agricultural productivity and a developed transportation network could support large urban populations. In addition, in Acemoglu et al. (2002a) we presented evidence that both in the time series and the cross section there is a close association between urbanization and income per capita before, as well as after, industrialization. We therefore take urbanization as a proxy for GDP per capita.

Second, we use estimates of GDP per capita from Maddison (2001). These estimates start in 1500 and are available for 1600, 1700, 1820, and then more frequently. Note that these estimates are no more than educated guesses, especially before 1820. We therefore think of these GDP data as a check on our results using urbanization data.

Third, we use the European city–level data from Bairoch et al. (1988) to investigate which urban centers were driving demographic and economic growth, and also to contrast the growth of Atlantic ports to other ports and to inland cities.

Table 1 gives the estimates of urbanization and income per capita at various dates. The first column is for the whole sample and is unweighted. The second column is weighted by population in the corresponding year, giving a better sense of the aggregate changes. The remaining columns give weighted means for Atlantic traders (Britain, France, the Netherlands, Portugal, and Spain), for West European countries that were not Atlantic traders (Austria, Belgium, Denmark, Finland, Germany, Ireland, Italy, Norway, Sweden, and Switzerland), for East European countries, and for the Asian countries in our sample.[8] These numbers confirm the patterns shown in Figures 1 and 2. In the regression analysis, we will report both weighted and unweighted results. The bottom third of the table also shows the evolution of our measure of institutions, constraint on the executive, which we will be described in greater detail and used in Section III.

[8] We take current countries as the unit of observation. Although these do not always correspond to the independent polities of the time, this discrepancy should not bias our empirical inference. For example, if we had data on each Italian city-state, their average would show the same pattern as our single Italy observation (presuming that our data for the aggregate of Italy are accurate), but because of the larger number of observations, the standard errors would be smaller. The analysis of city-level growth in Section I B is informative on differential growth across historical political boundaries.

B. *Economic Growth in Europe*

Figures 1A and 1B show the evolution of urbanization rates in Western and Eastern Europe, and contrast the behavior of Atlantic traders versus non-Atlantic traders. We first look at Atlantic traders, since the main beneficiaries from the Atlantic should be those countries that engaged in Atlantic trade and colonialism. However, whether or not a country is an Atlantic trader is clearly endogenous, i.e., it is the outcome of some political or economic process. For this reason, we also present results using a measure of access to the Atlantic, which is a country-level geographic characteristic.

We can test the idea that West European growth after 1500 was due primarily to growth in countries involved in Atlantic trade or with a high potential for Atlantic trade by estimating the following regression equation:

$$(1)\quad u_{jt} = d_t + \delta_j + \sum_{t \geq 1600} \alpha_t \cdot WE_j \cdot d_t + \sum_{t \geq 1500} \beta_t \cdot PAT_j \cdot d_t + X'_{jt} \cdot \gamma + \varepsilon_{jt}$$

where u_{jt} is urbanization in country j at time t, WE_j is a dummy indicating whether the country is in Western Europe, the d_t's denote year effects, the δ_j's denote country effects, X_{jt} is a vector of other covariates, and ε_{jt} is a disturbance term. In addition, PAT_j, our measure of the potential for Atlantic trade, is a dummy for Atlantic trader (Britain, France, the Netherlands, Portugal, and Spain) or alternatively the Atlantic coastline-to-area ratio (in both cases, a time-invariant characteristic of the country). The β_t's, the coefficients on the potential for

TABLE 2—ATLANTIC TRADE AND URBANIZATION
Dependent variable is country-level urbanization

	Panel, 1300–1850 (1)	Panel, 1000–1850 (2)	Panel, 1300–1850 (3)	Panel, 1000–1850 (4)	Panel, 1300–1850, unweighted (5)	Panel, 1300–1850, with Asia (6)	Panel, 1300–1850, without Britain (7)	Panel, 1300–1850 (8)	Panel, 1000–1850 (9)	Panel, 1300–1850, unweighted (10)
			Potential for Atlantic trade is measured by:							
			Atlantic trader dummy					Atlantic coastline-to-area		
			Panel A: Flexible specification							
p-value for Western Europe × year dummies, 1600–1850	[0.00]	[0.00]	[0.45]	[0.09]	[0.80]	[0.00]	[0.12]	[0.09]	[0.01]	[0.78]
Potential for Atlantic trade × 1500			0.016	0.0086	0.055	0.014	0.018	0.50	0.38	0.75
			(0.021)	(0.019)	(0.026)	(0.022)	(0.016)	(0.68)	(0.65)	(0.87)
Potential for Atlantic trade × 1600			0.006	−0.004	0.0495	0.0054	0.0085	0.21	0.03	0.94
			(0.023)	(0.021)	(0.028)	(0.028)	(0.018)	(0.68)	(0.64)	(0.94)
Potential for Atlantic trade × 1700			0.032	0.022	0.071	0.032	0.024	1.81	1.64	2.01
			(0.021)	(0.019)	(0.028)	(0.026)	(0.016)	(0.63)	(0.58)	(0.94)
Potential for Atlantic trade × 1750			0.032	0.022	0.073	0.032	0.023	2.16	1.99	2.60
			(0.021)	(0.018)	(0.028)	(0.025)	(0.015)	(0.62)	(0.57)	(0.94)
Potential for Atlantic trade × 1800			0.048	0.038	0.110	0.047	0.028	3.30	3.12	3.76
			(0.019)	(0.017)	(0.028)	(0.023)	(0.015)	(0.57)	(0.51)	(0.94)
Potential for Atlantic trade × 1850			0.085	0.076	0.115	0.084	0.043	5.05	4.88	4.67
			(0.018)	(0.016)	(0.028)	(0.022)	(0.014)	(0.51)	(0.44)	(0.94)
R-squared	0.87	0.85	0.89	0.87	0.82	0.84	0.93	0.94	0.92	0.83
Number of observations	192	240	192	240	192	208	184	192	240	192
			Panel B: Structured specification							
p-value for Western Europe × year dummies, 1600–1850	[0.00]	[0.00]	[0.35]	[0.06]	[0.83]	[0.00]	[0.11]	[0.16]	[0.02]	[0.81]
Potential for Atlantic trade × volume of Atlantic trade			0.011	0.0083	0.016	0.011	0.005	0.75	0.65	0.62
			(0.0024)	(0.0020)	(0.0034)	(0.0029)	(0.0018)	(0.07)	(0.06)	(0.11)
R-squared	0.87	0.85	0.88	0.86	0.81	0.84	0.92	0.92	0.90	0.82
Number of observations	192	240	192	240	192	208	184	192	240	192

Notes: Standard errors are in parentheses. Panel regressions with full set of country and year dummies; regressions are weighted unless otherwise stated. Weighted regressions use total population in each year as weights, from McEvedy and Jones (1978). Dependent variable is level of urbanization (percentage of population living in towns that had at least 5,000 population at some point between 800 and 1800) in each country in each year. Urbanization in Europe is from Bairoch et al. (1988), and urbanization in Asia is from Bairoch (1998). We report results with two different measures of potential for Atlantic trade: a dummy for whether a country was an Atlantic trader (one for Britain, the Netherlands, France, Spain, and Portugal; zero for all others) in columns 3, 4, 5, 6, and 7; and the ratio of Atlantic coastline to area for the Atlantic trader countries plus Belgium, Denmark, Germany, Ireland, and Norway (columns 8, 9, and 10). Column 6 includes the available data on Asia (just for India and China) and column 7 drops the data for Britain. Volume of Atlantic Trade is the log average number of voyages per year. For more detailed data definitions and sources see Appendix, Table 1.

Atlantic trade and the post-1500 time dummies, are the main parameters of interest. Since our focus is on the rise of Western Europe as a whole, our basic regressions are weighted by population in each year, but we also report unweighted regressions for completeness.

Columns 1 and 2 of Table 2 include only the interaction terms between the Western Europe dummy and dates from 1600, $\Sigma_{t\geq 1600}\ \alpha_t \cdot WE_j \cdot d_t$, which capture the differential growth of West European countries relative to Eastern Europe. The top row reports the p-value from the F-test of the joint significance of these interactions. Column 1 includes data only for 1300–1850, while column 2 extends the sample back to 1000. Consistent with Figure 1A, both specifications show significantly faster growth in Western Europe than in Eastern Europe. For example, the point estimates (not shown in the table to save space) indicate that in the specification of column 1, West European urbanization grew by 6.9 percentage points relative to East European urbanization between 1500 and 1850.

Column 3 allows differential growth for countries engaged in Atlantic trade, by including the term $\Sigma_{t\geq 1500}\ \beta_t \cdot PAT_j \cdot d_t$. We include 1500 as a "specification check" on the timing of the effects. We start with PAT_j as a dummy for Atlantic trader. Significant positive estimates of β_t's imply that Atlantic traders grew starting in the period between 1500 and 1600. The estimates confirm the pattern seen in Figure 1B and show large effects from the interaction between the Atlantic trader dummy and dates after 1600. These effects become statistically significant after 1750; in columns 8–10, the effects are statistically significant starting in 1700. For example, the estimate for 1850, $\beta_{1850} = 0.085$, implies that urbanization among Atlantic traders grew by approximately 8.5 percentage points more than in other Western and Eastern European nations. Notice also that the estimate of β_{1500} in this column, which measures the differential growth of Atlantic traders between 1300–1400 and 1500, is insignificant and small. This is reassuring; since Atlantic trade was very limited before 1500, this finding shows that there is no differential growth for Atlantic traders *before* Atlantic trade actually became important.[9]

Consistent with the patterns shown in Figure 1B, the inclusion of the Atlantic trade interactions explains almost the entire differential growth of West European nations relative to Eastern Europe. The $\Sigma_{t\geq 1600} \alpha_t \cdot WE_j \cdot d_t$ terms are no longer statistically significant, and the point estimates (not shown in the table) imply that West European urbanization grew only by 2.9 percentage points relative to Eastern Europe between 1300–1500 and 1850, as opposed to 6.9 percentage points in column 1.

Columns 4 and 5 show that the results are similar for the 1000–1850 period and when observations are not weighted by population.[10] Column 6 includes Asian countries. This has little effect on the estimates of the differential growth of Atlantic traders, but now West European countries are growing faster relative to the control group, which includes Asian countries (see Figure 1A). Finally, column 7 excludes Britain from the sample and shows that the results do not simply reflect British growth. The estimates in column 7 are about half the size of those in the other columns, but they show the same pattern.

An important concern with the results reported so far is endogeneity. Being an Atlantic trader is an ex post outcome, and perhaps only countries with high growth potential—or those that were going to grow anyway—engaged in substantial Atlantic trade and colonial activity. Belgium, Ireland, Denmark, Germany, and Norway also had access to the Atlantic, either directly or via the North Sea, but they did not take a major part in long-distance oceanic trade. In columns 8, 9, and 10, we use a geographic measure of potential access to the Atlantic, Atlantic coastline-to-area ratio, as our time-invariant PAT_j variable, which gives positive Atlantic trade potential to all these countries.[11] This measure allows Atlantic trade to play a more important role in the growth of countries with more Atlantic coastline relative to their land area.[12]

[9] Although the analysis above does not count Denmark and Sweden as Atlantic traders, Sweden had a small colony on the Delaware river 1637–1681 and Denmark controlled several small Caribbean islands (now the U.S. Virgin Islands). To check the robustness of our results, we also experimented with a more inclusive definition of Atlantic trader that includes Denmark and Sweden, with results very similar to those reported in column 3. The p-value for Western Europe × year interactions increases to [0.51], while the pattern of coefficients on potential for Atlantic trade × year dummies is largely unchanged; the interactions before 1700 are insignificant, then 0.035 (s.e. = 0.022) in 1700, 0.035 (s.e. = 0.021) in 1750, 0.046 (s.e. = 0.02) in 1800, and 0.08 (s.e. = 0.02) in 1850.

[10] In column 4, the interaction between the West European dummy and the post-1500 dates is significant at the 10-percent level, which reflects the lower level of East European urbanization in the base period, which is now 1000–1400.

[11] Information on the length of coastline and the land area of particular countries is taken from Integrated Coastline Management (http://icm.noaa.gov/country/ICM-pro.html), which reports a standardized measure. We use only Atlantic coastline, i.e., omitting coastlines in the Mediterranean, the Baltic, and the Arctic. Details are provided in the Appendix of Acemoglu et al. (2002b). It is important to exclude the Baltic coastlines of Denmark and Germany from our measure, since significant Baltic trade predated the rise of Atlantic trade, and economic growth driven by Baltic trade could be an alternative explanation for the patterns we observe. In any case, our results are generally robust to including the Baltic or the Arctic coastlines. For example, we obtain very similar results to those reported in Tables 2 and 3 when we include the west coastline of Sweden, or when we include the entire Norwegian coastline on the Arctic and the entire German coastline on the Baltic. Our results are also generally similar when we include all the coastline of Sweden, Germany, Norway, and the entire Baltic coastline of Denmark, but the size of the coastline-to-area times year interactions are smaller than in our baseline, and Western Europe times year interactions become significant.

[12] Alternatively, we could use the Atlantic coastline-to-area measure as an instrument for the Atlantic trader dummy. The results we report can be thought of as the reduced form for this IV strategy (a univariate regression of the Atlantic trader dummy on the coastline-to-area measure

The results using the coastline-to-area measure for PAT_j are similar to those using the Atlantic trader dummy. Most notably, the differential growth related to the Atlantic, now captured by interactions with the Atlantic coastline-to-area ratio, is still strong; the point estimates for the β's are significant starting in 1700 and quantitatively large. For example, the coefficient $\beta_{1850} = 5.05$ indicates approximately 6.5 percentage points more urbanization growth in the Netherlands than in Italy between 1300–1400 and 1850 (the Atlantic coastline-to-area ratio for the Netherlands is 0.013 and for Italy it is 0). This explains over half of the differential 12-percentage-point actual urbanization growth between Italy and the Netherlands between these two dates. Other specifications using the Atlantic coastline-to-area measure in columns 9 and 10 give similar results.

Equation (1) allows for an arbitrary pattern of differential growth in Atlantic traders. Instead, we might expect the differential growth of Atlantic traders to be related to the volume of Atlantic trade. For this reason, in panel B we report results from estimating a structured model of the form

$$(2) \qquad u_{jt} = d_t + \delta_j + \sum_{t \geq 1600} \alpha_t \cdot WE_j \cdot d_t + \beta \cdot PAT_j \cdot \ln AT_t + X'_{jt} \cdot \gamma + \varepsilon_{jt}$$

where AT_t denotes our estimate of the aggregate volume of Atlantic trade, shown in Figure 3. The construction of this variable is explained briefly in the Appendix, and further details and robustness results can be found in Acemoglu et al. (2002b).

Note that the model in equation (2) is more restrictive than that in (1), since we are forcing the pattern of β_t's in (1) to be the same as that of $\ln AT_t$. In all columns, the estimate of β, the coefficient on the interaction term between the log volume of Atlantic trade and potential for Atlantic trade at the country level, is highly significant, while the interaction terms between Western Europe and dates from 1600 onward are again insignificant. Notably, the R^2 of this more restrictive regression is close to the R^2 of the flexible specifications reported in panel A. These results suggest that the significant interaction between potential for Atlantic trade and dates after 1600 is due to the importance of Atlantic trade, not some other parallel process.

Table 3, which has the same structure as Table 2, provides regression evidence using log GDP per capita as the dependent variable. Maddison (2001) reports estimates of GDP per capita for 1500, 1600, 1700, 1820, and 1870. We take 1500 as the base year, and add interactions between our measure of potential for Atlantic trade, PAT_j, and the dates from 1600 on to capture the importance of Atlantic trade for the country (so we can no longer test for preexisting trends using the interaction between PAT_j and 1500). Output numbers for 1870 are already heavily influenced by differential industrialization experiences of various countries, so our baseline specification stops in 1820. For completeness, we also report regressions that extend the sample to 1870.

Parallel to our results in Table 2, West European countries grow faster after 1500, although this pattern is somewhat less pronounced, especially when we limit the sample to 1500–1820. The interactions between the Atlantic trader dummy and the dates after 1600 are typically significant starting either in 1600 or 1700, and quantitatively large. For example, the estimate of $\beta_{1820} = 0.27$ in column 3 indicates that Atlantic traders grew, on average, 31 percent ($\approx$0.27 log points) more than non-Atlantic trader West European nations between 1500 and 1820. Columns 4 to 7 report similar results to those in Table 2. The pattern is the same when the sample is extended to 1870, with unweighted regressions, when Britain is excluded from the sample, and when Asian countries are included. Columns 8 to 10 report similar results using the Atlantic coastline-to-area measure.

Panel B of Table 3 reports structured models similar to (2) where we include the interaction term, $PAT_j \cdot \ln AT_t$ instead of the full set of post-1500 interactions between PAT_j and time

in our sample has an R^2 of 0.30). Nevertheless, we prefer the specification in the text, since it is plausible that, even conditional on being an Atlantic trader, a country with greater Atlantic coastline will trade and grow more than another with less coastline, making such an IV procedure invalid. In fact, a comparison of columns 3–7 with columns 8–10 shows that the fit of the models with the Atlantic coastline-to-area ratio is marginally better than those with the Atlantic trader dummy, because the former measure gives greater potential for trade to Britain and the Netherlands, which have relatively high coastline-to-area ratios.

TABLE 3—ATLANTIC TRADE AND GDP PER CAPITA
Dependent variable is country-level log GDP per capita

	Panel, 1500–1820	Panel, 1500–1870	Panel, 1500–1820	Panel, 1500–1870	Panel, 1500–1820, unweighted	Panel, 1500–1820, with Asia	Panel, 1500–1820, without Britain	Panel, 1500–1820	Panel, 1500–1870	Panel, 1500–1820, unweighted
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
			Potential for Atlantic trade is measured by:							
			Atlantic trader dummy					Atlantic coastline-to-area		
			Panel A: Flexible specification							
p-value for Western Europe × year dummies, 1600–1820 or –1870	[0.44]	[0.05]	[0.92]	[0.23]	[0.17]	[0.01]	[0.89]	[0.97]	[0.58]	[0.31]
Potential for Atlantic trade × 1600			0.14	0.15	0.16	0.14	0.13	4.43	4.46	3.42
			(0.07)	(0.11)	(0.07)	(0.13)	(0.07)	(2.42)	(3.61)	(2.21)
Potential for Atlantic trade × 1700			0.18	0.19	0.21	0.18	0.14	8.84	8.80	6.32
			(0.07)	(0.10)	(0.07)	(0.12)	(0.06)	(2.27)	(3.40)	(2.21)
Potential for Atlantic trade × 1820			0.27	0.27	0.18	0.27	0.20	12.03	11.89	8.06
			(0.06)	(0.10)	(0.07)	(0.11)	(0.06)	(2.10)	(3.14)	(2.21)
Potential for Atlantic trade × 1870				0.22					15.84	
				(0.09)					(2.93)	
R-squared	0.94	0.94	0.96	0.95	0.96	0.92	0.96	0.96	0.96	0.96
Number of observations	96	120	96	120	96	104	92	96	120	96
			Panel B: Structured specification							
p-value for Western Europe × year dummies, 1600–1820 or –1870	[0.44]	[0.05]	[0.92]	[0.48]	[0.14]	[0.01]	[0.88]	[0.99]	[0.54]	[0.23]
Potential for Atlantic trade × volume of Atlantic trade			0.069	0.040	0.047	0.069	0.051	3.21	3.18	2.22
			(0.016)	(0.017)	(0.018)	(0.028)	(0.015)	(0.53)	(0.50)	(0.58)
R-squared	0.94	0.94	0.96	0.95	0.96	0.92	0.96	0.96	0.96	0.96
Number of observations	96	120	96	120	96	104	92	96	120	96

Notes: Standard errors are in parentheses. Panel regressions with full set of country and year dummies; regressions are weighted unless otherwise stated. Weighted regressions use total population in each year as weights, from McEvedy and Jones (1978). Dependent variable is log GDP per capita, from Maddison (2001). We report results with two different measures of potential for Atlantic trade: a dummy for whether a country was an Atlantic trader (one for Britain, the Netherlands, France, Spain, and Portugal; zero for all others) in columns 3, 4, 5, 6, and 7; and the ratio of Atlantic coastline to area for the Atlantic trader countries plus Belgium, Denmark, Germany, Ireland, and Norway (columns 8, 9, and 10). Column 6 includes the available data on Asia (just for India and China) and column 7 drops the data for Britain. Volume of Atlantic trade is the log average number of voyages per year. For more detailed data definitions and sources, see Appendix, Table 1.

dummies. This more structured specification again shows that the differential growth of Western Europe from 1600 is closely linked to the extension of Atlantic trader.

Overall both Table 2 and Table 3 show an important role for Atlantic trade in West European growth. When the effect of Atlantic trade is not taken into account, the estimates of α_t's are significant, positive, and large: Western Europe is growing faster than Eastern Europe and Asia. Once Atlantic trade interactions are included, α_t's are typically no longer significant, while the effect of Atlantic trade is very strong. Furthermore, the estimates show no evidence of differential growth by Atlantic traders before the age of Atlantic trade.

C. *Other Determinants of Economic Performance*

To check the robustness of our results, Table 4 adds a number of covariates to our basic regressions. The overall patterns are not affected. To save space, Table 4 reports only the structured specifications of equation (2).

Weber (1905) and Landes (1998) argue that religion is an important determinant of economic and social development. To assess the importance of religion, we allow Protestant countries to grow at rates different from non-Protestant countries by interacting a dummy for being a majority Protestant country in 1600 with year dummies starting in 1600.[13] The p-values from the joint significance test reported in columns 1 of panels A and C show that when the dependent variable is the urbanization rate, these interactions are either insignificant or only marginally significant. In contrast, when the dependent variable is log GDP per capita and

[13] See the Appendix for the construction of the variables used in this subsection.

TABLE 4—ROBUSTNESS CHECKS

	Panel, 1300–1850, controlling for religion	Panel, 1300 to 1850, controlling for wars	Panel, 1300 to 1850, controlling for Roman heritage	Panel, 1300 to 1850, controlling for latitude	Panel, 1500–1820, controlling for religion	Panel, 1500 to 1820, controlling for wars	Panel, 1500 to 1820, controlling for Roman heritage	Panel, 1500 to 1820, controlling for latitude
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Using Atlantic trader dummy measure of potential for Atlantic trade							
	Panel A: Dependent variable is level of urbanization				Panel B: Dependent variable is log GDP per capita			
p-value for Western Europe × year dummies, 1600–1850	[0.67]	[0.42]	[0.49]	[0.09]	[0.24]	[0.91]	[0.15]	[0.85]
Atlantic trader dummy × volume of Atlantic trade	0.013	0.011	0.011	0.011	0.089	0.070	0.125	0.078
	(0.002)	(0.003)	(0.003)	(0.002)	(0.013)	(0.017)	(0.017)	(0.015)
p-value for Protestant × year	[0.07]				[0.00]			
Wars per year in preceding century		−0.0006				0.075		
		(0.008)				(0.029)		
p-value for Roman heritage × year			[0.89]				[0.00]	
p-value for latitude × year				[0.11]				[0.00]
R-squared	0.89	0.89	0.89	0.89	0.97	0.95	0.97	0.97
Number of observations	192	176	192	192	96	88	96	96
	Using Atlantic coastline-to-area measure of potential for Atlantic trade							
	Panel C: Dependent variable is level of urbanization				Panel D: Dependent variable is log GDP per capita			
p-value for Western Europe × year dummies, 1600–1850	[0.19]	[0.23]	[0.39]	[0.09]	[0.99]	[0.98]	[0.71]	[0.81]
Coastline-to-area × volume of Atlantic trade	0.79	0.76	0.75	0.78	2.78	3.33	3.32	2.96
	(0.08)	(0.08)	(0.07)	(0.07)	(0.54)	(0.56)	(0.54)	(0.56)
p-value for Protestant × year	[0.51]				[0.05]			
Wars per year in preceding century		0.0082				0.033		
		(0.007)				(0.026)		
p-value for Roman heritage × year			[0.77]				[0.32]	
p-value for latitude × year				[0.52]				[0.38]
R-squared	0.93	0.93	0.92	0.93	0.97	0.96	0.97	0.97
Number of observations	192	176	192	192	96	88	96	96

Notes: Standard errors are in parentheses. Weighted panel regressions with full set of country and year dummies. Weights are total population of country in each year from McEvedy and Jones (1978). Dependent variable in panels A and C is level of urbanization (percent of population living in towns with more than 5,000 population). Urbanization in Europe is from Bairoch et al. (1988). Dependent variable in panels B and D is log GDP per capita, from Maddison (2001). Panels A and B use the Atlantic trader dummy as the measure of potential for Atlantic trade (one for Britain, France, Spain, Portugal, and the Netherlands; zero for all others). Panels C and D use the ratio of Atlantic coastline to area. Volume of Atlantic Trade is the log average number of voyages per year. Protestant is a dummy for whether country was majority Protestant in 1600. Protestant × year is the Protestant dummy interacted with year dummies for 1600 and after. Wars per year are in preceding century through 1700, 1700–1750 for 1750, 1750–1800 for 1800, and 1800–1850 for 1850. Roman heritage is dummy for whether country was in the Roman Empire; this is interacted with year dummies for 1600 and after. Latitude is distance from the equator for capital city of this country today; this is interacted with year dummies for 1600 and after. For more detailed data definitions and sources, see Appendix, Table 1.

we use the Atlantic trader dummy for our potential Atlantic trade measure (panel B), there is a significant effect from these religion times year interactions. Nevertheless, this has little impact on the pattern of differential growth between Western and Eastern Europe, or between Atlantic and non-Atlantic traders. Moreover, the quantitative effects of Protestantism on economic growth are smaller than those of Atlantic trade.[14]

Many social scientists view war-making as an important factor in the process of state building and subsequent economic development (e.g., Otto Hintze, 1975; Paul Kennedy, 1987; Charles Tilly, 1990). Incidence of wars might also proxy for the importance of interstate competition, which many historians, including Jones (1981) and Hall (1985), have emphasized. To assess the importance of wars, in columns 2 and 6 we include a variable which is the average number of years at war during the previous period (a century or

[14] The point estimates (not reported) imply that Protestant countries experienced 4.5 percentage points greater urbanization growth between 1500 and 1850, and 30 percent more GDP growth between 1500 and 1820. The corresponding numbers for Atlantic traders in the flexible specifications, including the Protestant dummy interacted with dates from 1600, are 8.4 percentage points more urbanization and 41 percent more GDP growth.

half-century). We find that this variable itself is insignificant in the urbanization regressions and has no effect on the patterns documented so far.[15]

A popular view sees the roots of European growth in the Roman Empire (e.g., Perry Anderson, 1974; Jones, 1981; Landes, 1998), and perhaps in the culture of Ancient Greece. To investigate whether Roman heritage is important for the rise of Europe, we created a dummy that indicates whether a country was part of the Roman Empire. We then interacted this variable with dates from 1600 onward to see whether there is differential growth depending on the extent of Roman heritage (columns 3 and 7). These interactions are typically insignificant and do not affect the patterns reported in the previous tables. The only exception is when we use log GDP per capita as the dependent variable and the Atlantic trader dummy for PAT_j. But in this case, the results indicate that countries with Roman heritage grew more rapidly between 1400 and 1600, and significantly more slowly thereafter.

Finally, in columns 4 and 8 we add interactions between distance from the equator (the absolute value of the latitude of the nation's capital) and dates from 1600 to see whether the move of economic activity away from Southern toward Northern Europe can explain the rise of Atlantic nations. Once again the addition of these variables does not affect the importance of Atlantic trade, and the latitude interactions are typically insignificant (except in panel B, where the point estimates have the wrong sign).

D. *Urban Expansion and Atlantic Ports*

We next turn to an analysis of data on the population of individual cities compiled by Bairoch et al. (1988). Figure 4A shows that the urban expansion of Western Europe was driven by cities that were Atlantic ports. Table 5 confirms this pattern with regression analysis. It estimates models similar to (1), with the log of city-level urban population as the dependent variable. The key right-hand side variable is the interaction between a dummy indicating whether the city is an Atlantic port (or in our alternative specification, whether it is a potential Atlantic port), denoted by AP_i, and dummies from 1500.[16] The sample for all regressions in Table 5 is the balanced panel of cities for which we have observations in each date.[17]

In column 1, AP_i is a dummy for Atlantic port, and observations are weighted by current population in each year. The interactions between the Atlantic port dummy and dates after 1600, the $AP_i \cdot d_t$ terms, are statistically and economically significant and positive. For example, the coefficient of 0.79 implies that Atlantic ports grew approximately 120 percent ($\approx$0.79 log points) relative to other cities between 1300–1400 and 1800. Notably, there appears to be no differential growth of Atlantic ports before 1600, once again supporting the notion that the growth of these ports is related to the emergence of trading and colonial opportunities via the Atlantic. In the bottom panel, we report results from a structured specification similar to equation (2). Once again, the coefficient on the interaction term between the volume of Atlantic trade and the

[15] As an alternative exercise more favorable to the war hypothesis, we also controlled for the average number of years at war that ended in victory during the previous 50 or 100 years. To the extent that rich nations are more likely to succeed in war, the coefficient on this variable will be biased upward. The inclusion of this variable has remarkably little effect on our estimates of the interaction between access to the Atlantic (or Atlantic trader) and the post-1500 years (or the volume of Atlantic trade), and this war variable itself is insignificant when the dependent variable is the urbanization rate and marginally significant with log GDP per capita.

[16] See the Appendix of Acemoglu et al. (2002b) for the list of Atlantic ports in our panel. In Figures 4 and 5, we use the definition of actual Atlantic port. In the regression analysis, we also report results with a dummy for potential Atlantic port. The distinction between Atlantic port and potential Atlantic port parallels our use of Atlantic trader dummy and the coastline-to-area measure of potential for Atlantic trade in Tables 2, 3, and 4.

[17] The focus on a balanced panel of cities avoids problems of composition bias, which would result from the fact that cities enter the dataset only once they exceed a certain threshold (typically 5,000 people). For example, if an area is growing rapidly, the population of the smaller cities in this area will also grow and exceed the relevant threshold, but the addition of cities with population around 5,000 may reduce the average population of the cities in this area. Nevertheless, in practice this bias does not seem to be important, and in Acemoglu et al. (2002b) we report similar results using a larger, unbalanced panel of cities.

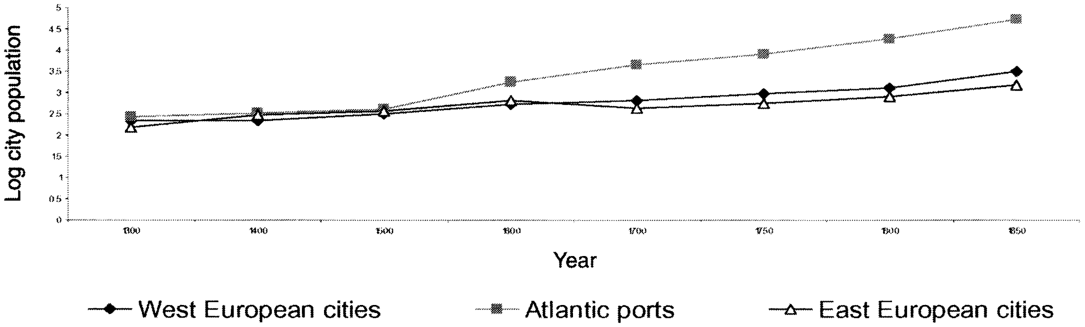

FIGURE 4A. AVERAGE OF LOG CITY POPULATION IN ATLANTIC PORTS, WEST EUROPEAN CITIES THAT ARE NOT ATLANTIC PORTS, AND EASTERN EUROPE (BALANCED PANEL), 1300–1850

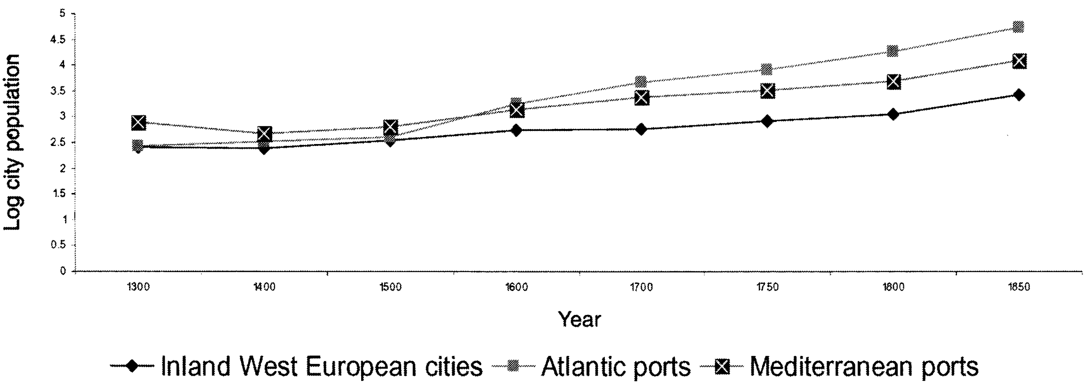

FIGURE 4B. AVERAGE OF LOG CITY POPULATION IN ATLANTIC PORTS, MEDITERRANEAN PORTS, AND WEST EUROPEAN CITIES THAT ARE NOT PORTS (BALANCED PANEL), 1300–1850

Atlantic port dummy is highly significant, and the R^2 of this more restrictive regression is almost the same as the regression reported in the top panel.

Column 2 reports estimates from an unweighted regression. The results are similar, but quantitatively smaller, since large Atlantic ports, such as London and Amsterdam, no longer get more weight. Columns 3 and 4 report weighted and unweighted estimates from similar models, with a dummy for potential Atlantic port, that is, any city that in our balanced panel could have been used as a port for Atlantic trade. The results are similar to those in columns 1 and 2.[18] Column 5 drops London and Amsterdam to show that the results are not driven by these two major cities. The coefficients on Atlantic port times year interactions are approximately halved from 1700 onward, but they remain significant. Column 6 adds a full set of country times year interactions to show the differential growth of Atlantic ports relative to other cities in the same country. The coefficients on Atlantic port times year interactions after 1700 are about half those of column 1, but still highly statistically significant.

[18] To allow for the specification test discussed in the text, these regressions use 1300–1400 as the base period. Because there was rapid growth in a few potential—but not actual—Atlantic ports from 1400 to 1500, some of the coefficients on potential Atlantic port are higher than the corresponding coefficients on Atlantic port. However, cumulative growth between 1500 and any subsequent date is always higher for Atlantic ports than for potential Atlantic ports. It should also be noted that some potential Atlantic ports flourished as a result of secondary trade from the Atlantic.

TABLE 5—GROWTH OF ATLANTIC PORTS
Dependent variable is log city population

	Balanced panel, 1300–1850, weighted (1)	Balanced panel, 1300–1850, unweighted (2)	Balanced panel, 1300–1850, weighted (3)	Balanced panel, 1300–1850, unweighted (4)	Balanced panel, 1300–1850, weighted, without London and Amsterdam (5)	Balanced panel, 1300–1850, weighted, with full set of country × year interactions (6)	Balanced panel, weighted 1300–1850, with Asia (7)	Balanced panel, weighted 1300–1850, with Mediterranean and Atlantic ports (8)
Panel A: Flexible specification								
	Atlantic port		Potential Atlantic port		Atlantic port			
p-value for Western Europe × year dummies, 1600–1850	[0.34]	[0.05]	[0.30]	[0.16]	[0.28]	[0.30]	[0.41]	[0.32]
Atlantic port × 1500	−0.04	−0.05	0.027	0.048	−0.008	−0.072	−0.03	−0.05
	(0.19)	(0.20)	(0.17)	(0.16)	(0.20)	(0.20)	(0.20)	(0.19)
Atlantic port × 1600	0.36	0.46	0.41	0.43	0.41	0.36	0.36	0.40
	(0.16)	(0.20)	(0.14)	(0.16)	(0.17)	(0.17)	(0.16)	(0.16)
Atlantic port × 1700	0.71	0.62	0.76	0.76	0.297	0.47	0.71	0.74
	(0.14)	(0.20)	(0.13)	(0.16)	(0.17)	(0.17)	(0.15)	(0.15)
Atlantic port × 1750	0.70	0.71	0.79	0.89	0.26	0.46	0.7	0.72
	(0.14)	(0.20)	(0.13)	(0.16)	(0.16)	(0.16)	(0.15)	(0.14)
Atlantic port × 1800	0.79	0.92	0.95	1.10	0.32	0.57	0.799	0.84
	(0.14)	(0.20)	(0.12)	(0.16)	(0.15)	(0.15)	(0.14)	(0.14)
Atlantic port × 1850	1.09	1.00	1.19	1.23	0.48	0.46	1.09	1.10
	(0.13)	(0.20)	(0.12)	(0.16)	(0.14)	(0.14)	(0.14)	(0.13)
p-value for Mediterranean port × year dummies, 1500–1850								[0.19]
R-squared	0.92	0.79	0.92	0.80	0.89	0.95	0.94	0.92
Number of observations	1544	1544	1544	1544	1528	1544	1624	1544
Panel B: Structured specification								
p-value for Western Europe × year dummies, 1600–1850	[0.23]	[0.04]	[0.23]	[0.10]	[0.31]	[0.33]	[0.30]	[0.20]
Volume of Atlantic trade × Atlantic port	0.17	0.16	0.17	0.16	0.065	0.078	0.17	0.17
	(0.02)	(0.02)	(0.017)	(0.024)	(0.019)	(0.018)	(0.018)	(0.017)
p-value for Mediterranean Port × year dummies, 1500–1850								[0.14]
R-squared	0.92	0.79	0.92	0.79	0.89	0.95	0.94	0.92
Number of observations	1544	1544	1544	1544	1528	1544	1624	1544

Notes: Dependent variable is log city population, from Bairoch et al. (1988). Weighted regressions use current level of city population in each year as weights. All columns report balanced panel regressions for 1300, 1400, 1500, 1600, 1700, 1750, 1800, and 1850, using only cities for which we have data in all eight time periods. The Atlantic port dummy equals one for a city used as an Atlantic port. Potential Atlantic ports are all ports that could have been used for Atlantic trade and include Atlantic ports plus ports in Belgium, Germany, and Ireland (there are no potential Atlantic ports in Denmark or Norway in our balanced panel). Volume of Atlantic trade is log average voyages per year; this is multiplied by the Atlantic port dummy (or by the potential Atlantic port dummy); the coefficient on this interaction term is multiplied by 100. Year dummies are included for all years from 1400. Western Europe × year dummies are included for all years from 1600. For a list of Atlantic ports and potential Atlantic ports, see the Appendix of Acemoglu et al. (2002b).

Column 7 adds Asian cities from Tertius Chandler (1987), so now West European cities are being compared to both East European and Asian cities. The results are similar, but also show the differential growth of all West European cities relative to Asian cities.[19]

Is there something special about ports, or is it Atlantic ports that are behaving differently after 1500? To answer this question, Figure 4B and column 8 show that Mediterranean ports grew at similar rates to inland European cities; what we find is not a general port effect but an *Atlantic port effect.*

Was the urban and economic expansion of Atlantic nations driven solely by the growth of Atlantic ports? Figure 5A shows the expansion of Iberian (Spanish and Portuguese) Atlantic ports, other Iberian cities, and West European inland cities. Almost all of the differential growth of Spain and Portugal comes from Atlantic ports. In fact, non-Atlantic parts of Spain and Portugal grew more slowly than West European inland cities. Relevant to our hypothesis

[19] We also investigated the importance of the same controls used in Table 4 for country-level growth. The results, which are reported in Acemoglu et al. (2002b), show that the pattern in Table 5 is robust to the inclusion of these controls.

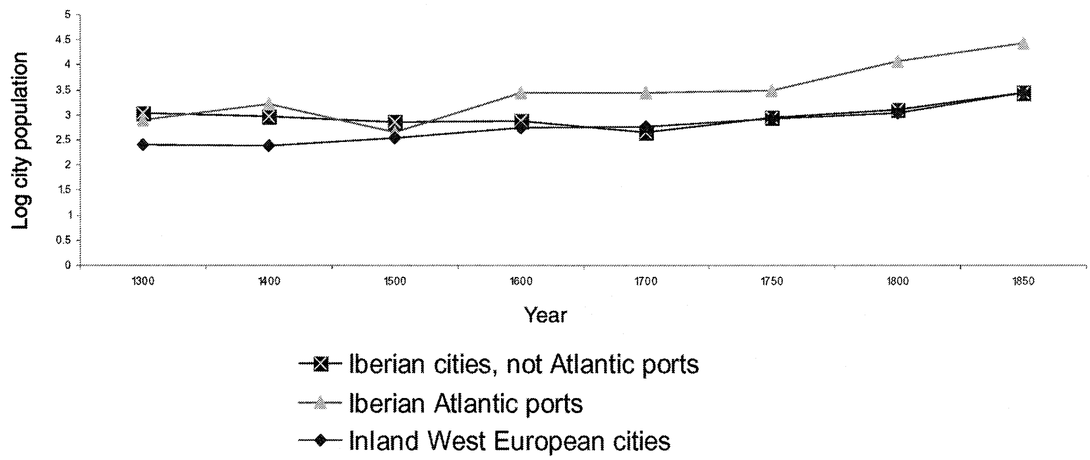

FIGURE 5A. AVERAGE OF LOG CITY POPULATION IN IBERIAN ATLANTIC PORTS, OTHER IBERIAN CITIES THAT ARE NOT ATLANTIC PORTS, AND INLAND WEST EUROPEAN CITIES (BALANCED PANEL), 1300–1850

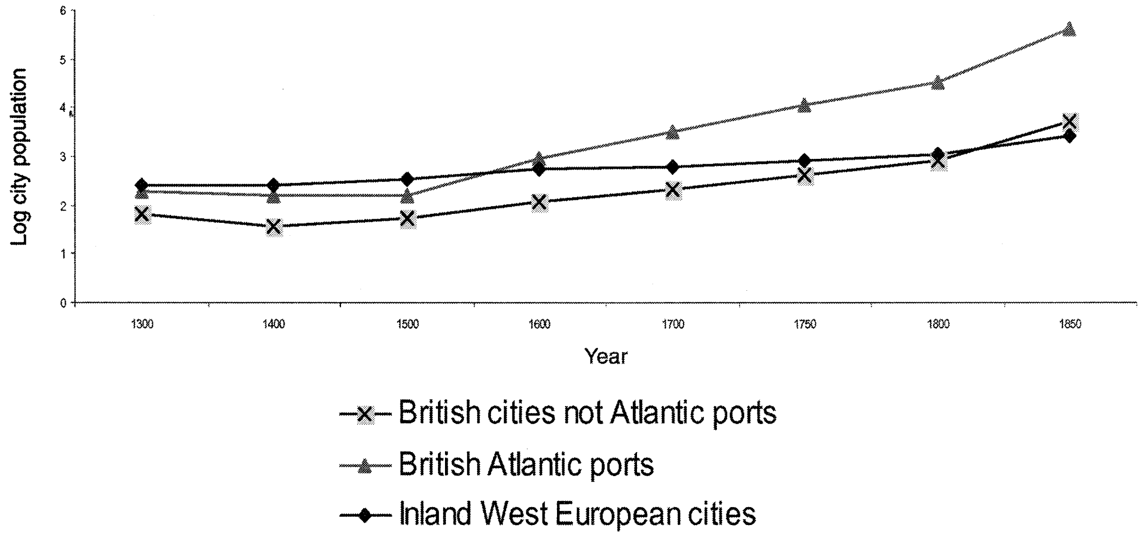

FIGURE 5B. AVERAGE OF LOG CITY POPULATION IN BRITISH ATLANTIC PORTS, OTHER BRITISH CITIES THAT ARE NOT ATLANTIC PORTS, AND INLAND WEST EUROPEAN CITIES (BALANCED PANEL), 1300–1850

below, this Iberian pattern contrasts with the steady growth of non-Atlantic British cities shown in Figure 5B. (Notice that the non-Atlantic British line starts below the West European line and overtakes it by 1850; see Acemoglu et al., 2002b, for further evidence.)

E. *Interpretation*

The evidence presented so far has established a significant relationship between the potential for Atlantic trade and post-1500 economic development, and suggests that the opportunities to trade via the Atlantic, and the associated profits from colonialism and slavery, played an important role in the rise of Europe. This evidence weighs against theories linking the rise of Western Europe to the continuation of pre-1500 trends driven by certain distinctive characteristics of European nations or cultures, such as Roman heritage or religion.

At face value, this evidence is more consistent with theories emphasizing the direct contribution of profits from Atlantic trade, colonialism, and slavery, such as those advanced by Williams (1944), Frank (1978), and Wallerstein (1974–1980). It is undoubtedly true that colonial relations with the New World and Asia contributed to European growth. Nevertheless, quantitative analyses, for example, Engerman (1972), Engerman and O'Brien (1991), O'Brien (1982), and Bairoch (1993, ch. 5), suggest that the volume of trade and the profits generated by Atlantic trade appear to be too small to account for much of European growth directly. Atlantic trade may also have played an important direct role by inducing a reallocation of resources within Europe, even if profits from trading were low (as would be the case in a competitive economy). This direct channel is unlikely to be the whole story, however, since the volume of trade was small. For example, Bairoch (1993) calculates that commodity trade between Western Europe and the rest of the world amounted to less than 4 percent of the GNP of Western Europe before 1800. Although recent work by Inikori (2002) argues that profits from colonial activities, in particular from the slave trade, were larger than those estimated by O'Brien, even with his estimates, the direct effect of Atlantic trade and colonialism could account for the rise of Europe only with significant increasing returns to scale in leading sectors.[20]

Overall, therefore, the weight of evidence inclines us toward a view in which the rise of Europe reflects not only the direct effects of Atlantic trade and colonialism but also a major social transformation induced by these opportunities.

II. Our Hypothesis

A. *The Argument*

Our hypothesis is that Atlantic trade—the opening of the sea routes to the New World, Africa, and Asia and the building of colonial empires—contributed to the process of West European growth between 1500 and 1850, not only through direct economic effects, but also indirectly by inducing fundamental institutional change. Atlantic trade in Britain and the Netherlands (or, more appropriately, in England and the Duchy of Burgundy) altered the balance of political power by enriching and strengthening commercial interests outside the royal circle, including various overseas merchants, slave traders, and various colonial planters. Through this channel, it contributed to the emergence of political institutions protecting merchants against royal power.[21] Our hypothesis also implies that the tendency for institutional change to emerge should have been much stronger in societies with existing checks on royal power than in countries with absolutist regimes and monarchy-controlled trade monopolies, because in these latter countries Atlantic trade did not enrich and strengthen merchant groups outside the royal circle as much, and did not disturb the political status quo.

This hypothesis can be broken into 4 subhypotheses:

(a) Political institutions placing limits and constraints on state power are essential for the incentives to undertake investments and for sustained economic growth;
(b) In early modern Europe, such political institutions were favored by commercial interests outside the royal circle, but were not welcome by the monarchy and its allies;
(c) Institutions favored by economically and

[20] For example, O'Brien (1982) calculates that total profits from British trade with less developed regions of the world during the late eighteenth century were approximately £5.6 million, while total gross investment during the same period stood at £10.3 million. Inikori (2002, Table 4.2) suggests that imports from the periphery around 1800 were about double O'Brien's estimate. During this period, the aggregate savings rate was between 12 and 14 percent, so if we assume that this savings rate also applies to profits from trade, the contribution of these profits to aggregate capital accumulation would be less than 15 percent, even using Inikori's estimates. Even assuming considerably higher savings rates, the contribution would remain relatively small.

[21] An additional channel via which Atlantic trade may have contributed to institutional change may be the desire of the monarchy to secure the property rights of merchants in order to encourage long-term investments in long-distance trade. Our reading of the relevant history, discussed below, makes us believe that the greater contribution of Atlantic trade to the development of capitalist institutions was by strengthening commercial interests in favor of political change in their fight against the monarchy.

politically powerful groups are more likely to prevail; and

(d) In countries with nonabsolutist initial political institutions, Atlantic trade and colonial activity enriched and strengthened commercial interests, including new groups without ties to the monarchy.

Together these four subhypotheses yield our main hypothesis. In countries with easy access to the Atlantic and without a strong absolutist monarchy, Atlantic trade provided substantial profits and political power for commercial interests outside the royal circle. This group could then demand and obtain significant institutional reforms protecting their property rights. With their newly gained power and property rights, they took advantage of the growth opportunities offered by Atlantic trade, invested more, traded more, and fueled the First Great Divergence.[22]

Initial institutions placing sufficient checks on the monarchy are essential for the fourth subhypothesis, so that merchants not directly associated with the crown benefit significantly from Atlantic trade. When the power of the crown was relatively unchecked, as in Spain, Portugal, and France, trade was largely monopolized and regulated, the crown and its allies became the main beneficiaries of the Atlantic expansion, and institutional change did not take place. Therefore, our hypothesis explains not only the major role played by Atlantic trade in West European growth, but also why economic growth took off in Britain and the Netherlands, and not in Spain and Portugal.

Acemoglu et al. (2002b) provide historical evidence consistent with these subhypotheses. Space constraints preclude us from going into details here. We refer the reader to that paper for a more detailed discussion, and briefly discuss the evidence related to the fourth subhypothesis, which is perhaps the most important for our argument.

B. *Atlantic Trade and Commercial Interests*

We now discuss the major changes in the political institutions of Britain and the Netherlands. Our argument highlights that in both cases: (a) the political institutions at the beginning of the sixteenth century, though not as absolutist as in Spain and Portugal, did not provide secure property rights to commercial interests outside the royal circle;[23] (b) there was significant conflict between these merchant groups and the monarchy; (c) Atlantic trade created large profits for some of these merchants who were in favor of institutional change, and who then used part of these profits to support the conflict against the crown.

Britain.—In the British case the two milestones in the emergence of political institutions constraining royal power are the (English) Civil War of 1642–1649, when Parliamentarian forces defeated Charles I, and the Glorious Revolution of 1688–1689, where James II was deposed by Parliament with the help of an invading Dutch army, and replaced by William of Orange and a parliamentary regime with a constitutional monarchy. Although there is no consensus among historians on the relative importance of these two events, this is secondary for our focus. What is important is that there was a major improvement in British political institutions between the mid-seventeenth and early-eighteenth centuries.

Although after the War of the Roses, Britain was never as absolutist as France, Portugal, and Spain, both the Tudor and Stuart monarchs consistently attempted to expand their powers. The insecurity of property rights was clear during the reign of Henry VIII, when there were continual attempts to regulate trade and undermine the powers of Parliament (see Geoffrey R. Elton, 1991). A significant attempt to establish a form of absolutism came during the period of so-called "personal rule" of Charles I, after he dissolved his third Parliament in 1629, raised taxes in an unconstitutional way, and used the

[22] The establishment of political institutions limiting the power of the monarchy may have also created positive spillovers in the rest of the economy, especially for industrial capitalists (consistent with the subsequent growth of non-Atlantic British cities in Figure 5B).

[23] More explicitly, these commercial interests included merchants not receiving crown-granted monopolies, slave traders, various producers in the colonies and parts of the gentry in Britain, and the majority of the Dutch merchants not allied with the Habsburg monarchy in the Netherlands.

Star Chamber to manipulate legal decisions in his favor (Kevin Sharpe, 1992).

Although undoubtedly complex social events, both the Civil War and the Glorious Revolution were also battles over the rights and prerogatives of the monarchy.[24] In both cases, commercial interests (including large segments, but not all, of the merchants and the gentry) predominantly sided with those demanding restrictions on the power of the monarchy. During the Civil War, for example, the majority of the merchants, and even many of those with royal monopolies, supported Parliament (see Brenner, 1973, 2003; Mary Keeler, 1954; Douglas Brunton and D. H. Pennington, 1954).[25] Members of the Commons from the City of London, which was the main center of mercantile activity, as well as many non-London commercial constituencies, such as Southampton, Newcastle, and Liverpool, supported Parliament against the King. David H. Sacks (1991, pp. 230–47) shows that in Bristol trading, commercial and industrial interests outside of the Merchant Adventurers (the trading company then enjoying the royal monopoly) were Parliamentarians. Brunton and Pennington (1954, p. 62) also note that "in the country as a whole there was probably a preponderance of Parliamentarian feeling among merchants."

The situation for the Glorious Revolution is similar. The East India Company under the control of Josiah Child supported James II, his claim to tax without consent of Parliament, and his right to grant trading monopolies—of which it was the main beneficiary. But the majority of commercial interests, alienated by James II's grants of various monopoly privileges, and especially the interlopers—merchants trying to break into trade with Asia—were on the side of the revolution (Bruce G. Carruthers, 1996; Pincus, 2002). These merchants also received strong support from Whigs who sought to constrain the king (Henry Horwitz, 1978). Summarizing the evidence, Pincus (2002, p. 34) concludes, "England's merchant community actively supported William's plan for invasion, and provided a key financial prop to the regime in the critical early months."

The victory of Parliament in the Civil War and after the Glorious Revolution introduced major checks on royal power and strengthened the rights of merchants. After the Civil War, the fraction of MPs who were merchants increased dramatically. Although even in the 1690s this number was not large enough to constitute a majority on its own, as David Stasavage (2003) shows, the interests of merchants were assured by the formation of the Whig coalition of merchants and Protestant landowners. This period also witnessed a series of policies favoring merchants, including the Navigation Acts of 1651 and 1660, which restricted trade with British colonies to British ships and merchants (J. E. Farnell, 1964; J. P. Cooper, 1972) and strengthened the position of British overseas traders, especially slave traders (see Geoffrey Holmes, 1993, p. 64). Similarly, the Glorious Revolution led to a series of economic reforms sought by merchants outside the royal circle, including the dismantling of all monopoly charters, except the East India Company (Perry Gauci, 2001) and the establishment of the Bank of England. The conventional wisdom in economic history emphasizes the importance of these institutional changes for the protection of property rights, and how they led to a wave of innovations in economic institutions, particularly in financial markets (e.g., North and Weingast, 1989; Carruthers, 1996; Larry Neal, 2000).

Critically for our thesis, the major changes in political institutions and the new assertiveness of merchant groups coincided with the expansion of British mercantile groups trading

[24] Other prominent interpretations of the English Civil War have emphasized various factors apart from those we stress here. Conrad Russell (1990) argues that the Civil War was a plot by the traditional aristocracy to regain power it had lost under the Tudors. Many, for example, John S. Morrill (1993), focus on the role of religious differences in determining who supported which side, and recent work by Brian Manning (1996) stresses more general class conflict. Although there are doubtless elements of truth in these approaches, the general role of mercantile interests seems undeniable (see Roger C. Richardson, 1998, for a balanced overview of the debate).

[25] Valerie Pearl's seminal study (1961) argued that there were political divisions between such groups as the Merchant Adventurers, who benefited from monopolies granted by the crown, and new merchants, who did not. For example, the two pre–Civil War MPs for Bristol, Humphrey Hooke and Richard Long, were Royalists. Robert Ashton (1979, 1996), on the other hand, documented that even merchants who enjoyed monopolies tended to oppose the crown by the time of the Civil War, and argued "the majority of the City fathers, far from being the natural supporters of Stuart absolutism at the end of the period of Charles I's personal rule in the late 1630's, were as alienated from royal policies as were the vast majority of the political nation" (1996, p. 3).

through the Atlantic. The East India Company was founded in 1600, and from 1600 to 1630 there was an unprecedented wave of investment by merchants, gentry, and even some aristocracy in overseas ventures (Theodore K. Rabb, 1967). Virginia tobacco cultivation boomed in the 1620s, and beginning in the 1640s, the highly profitable Caribbean sugar colonies developed. Finally, in the 1650s the British began to take over the Atlantic slave trade.

A number of historians, most notably Brenner (2003), have emphasized that Atlantic merchants were critical in ensuring the military victory of Parliament in the Civil War. In his famous book, Lawrence Stone also points out that "... other important merchant elements can now be identified, men interested especially in the American trades, in New England colonization, and in breaking the monopoly of the East India and Levant Companies. They were new men in new fields of entrepreneurial endeavor who chafed at the political and economic stranglehold of the older established monopolistic oligarchies. These men were important members of the group of radicals who seized control of London at a critical moment in 1641, and so swung the power and influence of the city decisively on the side of Parliament" (1973, p. 144).

Atlantic trade indeed created large profits for the fortunate who succeeded in this high-risk endeavor. In the Appendix, we use data on profits from K. N. Chaudhuri (1965) and de Vries and van der Woude (1997), on investment from Rabb (1967), on trade from Inikori (2002) and de Vries (2003), and on rates of return from Richard Grassby (1969, 1995) and O'Brien (1982) to estimate profits of various merchant companies, slave traders, and colonial planters from Atlantic trade during this period. These estimates suggest that profits from Atlantic trade were negligible before 1575, about £40,000 on average per annum from 1576 to 1600 (mostly from a few highly profitable privateering expeditions), perhaps £200,000 on average per annum from 1601 to 1650, and around £500,000 per annum from 1651 to 1675. Profits then rose with the expansion of sugar and the slave trade to around £900,000 per annum from 1676 to 1700, £1.7m per annum from 1701 to 1750, and probably about £5m per annum in the late eighteenth century (all figures adjusted to 1600 prices using the index of building craftsmen's wages from E. H. Phelps Brown and Sheila V. Hopkins, 1955). These profits were substantial relative to the personal wealth of merchants and gentry during this time period. For example, personal wealth of £10,000 in the early seventeenth century was enough to be very rich. A minimum investment of £2,000 was required to become a director of the East India Company, and £200 represented a substantial investment (Brenner, 1973, pp. 62–63; Brenner, 2003, p. 78). Moreover, because profits from Atlantic trade were highly concentrated, they created a number of very wealthy merchants (see Grassby, 1995, pp. 248 and 263). These profits were also large relative to the resources necessary to make a difference politically and militarily.[26]

Many merchants used their profits from Atlantic trade to support the conflict against the crown. For example, the Earl of Warwick, who earned at least £50,000 from privateering in one year prior to the Civil War (W. Frank Craven, 1930), applied his fortune and experience with naval warfare to effectively oppose the king.[27] More generally, Parliament during the Civil War was partly financed by taxes on, and profits from, Atlantic trade. Parliamentary leaders such as Sir Edwin Sandys and John Pym were active in colonization and trade with the Americas. James I, well aware of the links between major Atlantic trading ventures and parliamentary

[26] From 1550 to 1688, the English monarch was always short of cash, and war typically required additional funds. For example, King Charles I was forced to recall Parliament in 1640 because he needed to raise about £300,000 (£250,000 in 1600 prices) for war against Scotland—enough to pay and equip about 12,000 soldiers for a year (Ashton, 1960, p. 176). Total English government revenues were around £500,000 in 1600 and about £850,000 in 1640 (Richard Bean, 1973). Armies on both sides of the English Civil War were small, 10,000 to 20,000 men, and most of the conflict was small-scale local operations by regional forces (Geoffrey Parker, 1988, pp. 28 and 41). Parliament fielded 27,000 at the battle of Marston Moor and just 13,000 at Naseby; the presence or absence of a few thousand troops was therefore decisive (Parker, 1988, p. 41). Kennedy (1987, p. 63) estimates that the average annual cost of a soldier was around £27 in 1657 (about £20 in 1600 prices).

[27] A privateer is an armed private vessel bearing the authorization or commission of a sovereign power to attack an enemy, i.e., a privately funded and manned extension of a country's naval forces. Privateers typically engaged in trading activities as well as fighting (see, for example, the case of John Hawkins discussed in N. A. M. Rodger, 1997, p. 201).

opposition, intervened in the election of treasurer for the Virginia Company, saying, "Choose the devil if you will, but not Sir Edwin Sandys" (Rabb, 1998, p. 349). Similarly, for the Glorious Revolution, Pincus (2002, pp. 32–33) provides evidence that "the merchant community poured money into William of Orange's coffers in 1688"—perhaps around £800,000 (about £500,000 in 1600 prices), enough to pay for a sizable army.

The Netherlands.—Dutch merchants always had considerable autonomy and access to profitable trade opportunities. Nevertheless, prior to the Dutch Revolt, the Netherlands (in fact, the entire Duchy of Burgundy) was part of the Habsburg Empire, and the political power of Dutch merchants was limited. The Habsburg monarchy consistently attempted to increase its political dominance over and fiscal revenues from the Netherlands (W. Fritschy et al., 2001). The critical improvement in Dutch political institutions was therefore the establishment of the independent Dutch Republic, with political dominance and economic security for merchants, including both the established wealthy regents and the new merchants immigrating from Antwerp and Germany.[28]

Dutch politics was shaped by the conflict between Dutch merchants and the Habsburg monarchy starting in the fifteenth century, and before then by the conflict between merchants and the Duke of Burgundy. By 1493 Maximilian of Habsburg had reversed the Grand Privilege of 1477, which gave the states general the right to gather on their own initiative and curbed the right of the ruler to raise taxes. After 1552, war with France and England increased the Habsburgs' fiscal needs and led them to impose a large tax burden on the Netherlands. Growing fiscal and religious resentment in 1572 led to a series of uprisings, mostly orchestrated by commercial interests (see Jonathan I. Israel, 1995). These culminated in a war of independence, which began with the Revolt in the 1570s and did not end until 1648, punctuated by Philip II diverting resources to intervene in France after 1590, the successful Dutch offensives of 1591–1597 under the command of Maurice of Nassau, the embargoes against Dutch trade with Spain and Portugal in 1585–1590, 1598–1609, and 1621–1647, and the Twelve Years Truce from 1609 to 1621.

The major turning point came in the 1590s when important changes in Dutch military and commercial strategy became evident. New military tactics made it possible for the Dutch to hold their own against experienced Spanish infantry (Geoffrey Parker, 1988, pp. 19–20). This was combined with a fiscal and financial "revolution" that allowed states, particularly Holland, both to increase their tax revenues and borrow against future taxes in order to finance the war effort (Fritschy, 2003). At the same time, the Dutch took the critical strategic step of seeking direct access to Asian and American trade centers. This both enriched a generation of Dutch merchants and undermined Spanish and Portuguese revenues sufficiently to induce Philip III to offer peace. By 1605 it was clear to a Spanish royal councillor, the Count of Olivares, that victory would go to "whoever is left with the last escudo" (Parker, 1977, p. 238).

Merchants were naturally the primary political and economic force on the side of independence. De Vries and van der Woude (1997) argue that "urban economic interests ultimately believed it advantageous to escape the Habsburg imperial framework" (p. 369). They also note that, in the case of Amsterdam, the "[Habsburgs'] opponents included most of the city's international merchants ... . [I]n 1578 a new Amsterdam city council threw the city's lot in with the Prince of Orange ... among the merchants returning from ... exile were [those whose families] and several generations of their descendents would long dominate the city" (1997, p. 365).

Commercial interests involved in the Atlantic were particularly important in the shaping of the conflict (see, for example, Israel, 1982, 1995; Herman van der Wee, 1993, pp. 272–73). In 1609, in an attempt to prevent the creation of the Dutch West India Company, Philip III offered peace and independence in return for a Dutch withdrawal from both the West and East Indies. But these terms were "simply not feasible politically because many regents and elite merchants had invested heavily in the [Dutch East India Company]" (Israel, 1995, p. 402).

[28] By the year 1600, a third of the population of Amsterdam was immigrants (Israel, 1995, p. 309). In 1631, there were 685 citizens of Amsterdam with wealth over 25,000 florins. Only half of them were native Hollanders (Parker, 1977, p. 251).

Prominent in the anti-peace camp was the famous Dutch leader and general Maurice of Nassau, who was heavily involved in colonial trades, and "Reynier Pauw, the preeminent figure and leader of the anti-truce faction in Holland who, besides being a champion of the West India Company project, had been a founder member of the East India Company and for many years a director of its Amsterdam chamber" (Israel, 1982, p. 40).

It is therefore no surprise that independence put merchants firmly in control of the political process. De Vries and van der Woude (1997, p. 587) describe the new political elite following the Dutch Revolt as "6 to 8% of urban households with incomes in excess of 1,000 guilders per year. This was the *grote burgerij* from whom was drawn the political and commercial leadership of the country. Here we find, first and foremost, the merchants." They also point out how merchants dominated the governments of Leiden, Rotterdam, and the cities in the two largest states, Zeeland and Holland.

The Dutch economy had been expanding since the fifteenth century and experienced advances in economic institutions, including in shipping, agriculture, and finance, particularly public finance, prior to this revolt (James D. Tracy, 1985; Jan Luiten van Zanden, 1993). Nevertheless, the potential of these institutions was severely limited under the Habsburg yoke because of the threat of arbitrary taxation. For example, Marjolien Hart et al. (1997, fig. 2.3, p. 19) show that, despite the changes in financial institutions in the mid-sixteenth century, interest rates did not fall systematically until after 1600, when they declined to about one-third of their pre-revolt level. Consequently, the economy appears to have experienced a major transformation after the process of political change began. Van Zanden (1993) notes, "We can see the starting point of the rapid urbanization at 1580" (pp. 35–36), and continues, "during this transformation process, the pre-1580 proto-capitalist structure disappeared ... out of this 'unspecialised' class of small-holders, fishermen, homeworkers and sailors, separate classes of large farmers, agricultural laborers and craftsmen arose" (p. 39). Similarly, Braudel (1995, p. 547) dates the start of the divergence between the South and North of Europe to 1590 with the "explosion" of Dutch commerce and the rise of Amsterdam.

Critical was the Dutch merchants' improving economic fortunes, partly from Atlantic trade, which were used to field a powerful army against the Habsburg Empire. The Baltic trade is widely recognized as important for the Dutch economy in the sixteenth century, but profits from Atlantic trade quickly surpassed those from Baltic trade and provided the funds necessary for the Dutch military effort against the Habsburgs (Israel, 1989). De Vries and van der Woude (1997) estimate that the annual profits of the Dutch East India Company alone between 1630 and 1670, 2.1 million guilders per annum, were more than twice the total annual profits from the Baltic grain trade between 1590 and 1599 (pp. 373 and 447).

Fritschy (2003) estimates that, as a result of these developments, tax revenue per head in Holland rose nearly fivefold from 1575 to 1610, while population increased by a third (see also Tracy, 2001, Table 7.2). These revenues enabled Holland to provide 960,000 guilders for the war in 1579 and to pay five million guilders in 1599 (Parker, 1977, p. 251). Israel (1995, pp. 241–42) summarizes the basic reason for the Dutch victory as follows: "From 1590, there was a dramatic improvement in the Republic's economic circumstances. Commerce and shipping expanded enormously, as did the towns. As a result, the financial power of the states rapidly grew, and it was possible to improve the army vastly, both qualitatively, and quantitatively, within a short space of time. The army increased from 20,000 men in 1588 to 32,000 by 1595, and its artillery, methods of transportation, and training were transformed." By 1629, the Dutch were able to field an army of 77,000 men, 50 percent larger than the Spanish army of Flanders (Israel, 1995, p. 507).

Overall, both the British and Dutch evidence, therefore, appears favorable to our hypothesis that Atlantic trade enriched a group of merchants who then played a critical role in the emergence of new political institutions constraining the power of the crown.

Spain, Portugal and France.—There is general agreement that Spanish and Portuguese political institutions at the turn of the sixteenth century were more absolutist than those in

Britain and the Netherlands, and did not experience similar reform.[29]

A key difference between these cases and the British-Dutch patterns is the organization of trade which, in turn, reflected differences in political institutions. Throughout this period, the granting of trade monopolies was a central tool for the rulers to raise revenue. When the power of the monarchs was constrained, they were unable to use this fiscal tool. For example, the English Parliament successfully blocked many attempts of both Tudor and Stuart monarchs to create such monopolies (Christopher Hill, 1969). Consequently, in Britain "most trade was carried on by individuals and small partnerships, and not by the Company of Merchant Adventurers, the Levant Company ... or others of their kind" (Davis, 1973a, p. 41). At least by 1600 there was quite free entry into the British merchant class (R. G. Lang, 1974). In contrast, Rondo Cameron (1993, p. 127) describes the Portuguese situation as follows: "The spice trade in the East Indies of the Portuguese Empire was a crown monopoly; the Portuguese navy doubled as a merchant fleet, and all spices had to be sold through the *Casa da India* (India House) in Lisbon ... no commerce existed between Portugal and the East except that organized and controlled by the state." (See also Charles R. Boxer, 1985; Earl J. Hamilton, 1948.) Similarly, in Spain colonial trade was a monopoly of the Crown of Castille and was delegated to the *Casa de Contratación* (House of Trade) in Seville, which was itself closely monitored by the government (James H. Parry, 1966, ch. 2).

France, on the other hand, can be viewed as an intermediate case. Although French institutions were equally absolutist (W. F. Church, 1969; David Parrott, 2001), early Atlantic activity enriched some merchant groups, in particular the protestant Huguenots. However, the monarchy soon clashed with and defeated the Huguenots, first with the siege of La Rochelle by Louis XIII and then the outlawing of the Protestant church by Louis XIV (see, e.g., Warren C. Scoville, 1960). The monarchy then kept much of overseas trading activity as a royal monopoly, especially under Colbert (see, e.g., Davis, 1973b, pp. 222–24; William Doyle, 1974, pp. 210–11). Nevertheless, certain strong French commercial and industrial interests developed and, arguably, forced institutional change before, during, and after the French Revolution (see G. Lefebvre, 1947, and Doyle, 1988, for the debate on the origins of the French Revolution).

Overall, the evidence is therefore consistent with our thesis that in Spain and Portugal, and also largely in France, merchant interests with sufficient power to challenge the crown did not develop because the crown, and groups allied to it, were the main beneficiaries of the profits from transoceanic trade and plunder.

III. Atlantic Trade and Institutional Change

We now attempt to substantiate our hypothesis further by providing empirical evidence on the link between changes in political institutions and Atlantic trade. A prerequisite for this exercise is a measure of relevant political institutions. Unfortunately, no such measure exists for this period.[30] So as a first step, we attempted to create a measure of political institutions for European countries between 1300 and 1850, adapting the definition of "constraint on the executive" from Gurr's Polity dataset. This is a useful concept since it measures limitations on the arbitrary use of power by the executive (for the relevant time period, the monarchy), and is

[29] Davis (1973a, p. 66), for example, emphasizes the high degree of absolute control by the monarchy in Spain, as follows: [in Castille] "the king ruled subject only to weak constitutional restraints. In the first decades of the sixteenth century the crown had reduced the pretensions of the Castillian nobility and towns, so that the representative body, the Cortes, could obstruct but not in the last resort prevent royal tax raising," and contrasts this with the situation in Britain (e.g., Davis, 1973a, p. 210).

The modern literature, in particular, I. A. A. Thompson (1994) and Michael A. R. Graves (2001), suggests that the extent of Spanish absolutism has been overemphasized by scholars such as North and Thomas (1973), and points out important differences between Castille and such other parts of Iberia as Aragon and Catalonia. Nevertheless, it is certainly true that the Spanish Crown was able to create trade monopolies and raise taxes in ways that the Tudor and Stuart monarchies could not.

[30] An alternative approach would be to use the terms of finance for trading entities, as suggested by one of our reviewers. Although there are some data on this, the coverage is not broad enough for our purposes. Moreover, the terms of finance may be affected by the demand for and supply of financial resources, as well as the underlying security of property rights.

presumably correlated with the security of property rights for merchants and the control over the monopoly of overseas trade by the monarchy.[31]

We follow the Polity IV coding handbook, giving a score of between 1 and 7 for constraint on the executive to each country.[32] For 1800 and 1850, we use the Polity coding for constraint on the executive, where available. For earlier periods, we coded these measures ourselves. The main source for this exercise was William L. Langer (1972), a classic historical encyclopedia, written with a focus on constitutional events. We supplemented this work with the more recent edition by Peter N. Stearns (2001). While there may be disagreement about the precise values used in particular years, the general level of constraint on the executive does not appear to be controversial. For example, the absolutist regimes of France, Portugal, and Spain clearly had much less constraint on the executive than did the Netherlands after independence or England after the Civil War. Acemoglu et al. (2002b) give further details and report the entire series.

Table 6 documents the differential changes in institutions between Atlantic traders and other West European nations by estimating an equation similar to (1) with constraint on the executive as the left-hand-side variable. The results show significant differential improvements in institutions among Atlantic traders and no evidence of differential existing trends. Unlike our results when urbanization was the dependent variable, however, even after the inclusion of Atlantic trade interactions, there is some evidence of differential West European effects.

Other columns use the same controls and time interactions as in Table 4. Although the F-statistics show that many of these time interactions are significant, neither Protestantism, nor wars, nor Roman heritage, nor latitude appears to have led to greater institutional change after 1500 (for example, institutions in Protestant countries improved more rapidly until 1750, and significantly more slowly thereafter).

Overall, these results suggest that, following the surge in Atlantic trade, there were greater strides toward better political institutions in nations engaged in Atlantic trade and colonialism (or in those with a greater potential to engage in Atlantic trade).

IV. The Role of Initial Institutions

We now investigate whether, as implied by our hypothesis, it was predominantly societies with less absolutist initial institutions (and relatedly, those without widespread royal granted monopoly rights in overseas trade) that took advantage of the opportunities offered by Atlantic trade. We also investigate the related hypothesis of North and Thomas (1973) and Jones (1981) that post-1500 developments largely reflect divergence between societies that had very different political institutions at the turn of the fifteenth century. This differs from our hypothesis, which emphasizes the *interaction* between initial political institutions and Atlantic trade.

To investigate these ideas, we estimate models of the following form:

$$(3)\quad u_{jt} = d_t + \delta_j + \sum_{t \geq 1600} \alpha_t \cdot WE_j \cdot d_t + \beta \cdot \ln AT_t \cdot PAT_j + \sum_{t \geq 1500} \gamma_t \cdot I_{j,1415} \cdot d_t + \eta \cdot \ln AT_t \cdot PAT_j \cdot I_{j,1415} + \varepsilon_{jt}$$

[31] The measure of constraint on the executive may not be ideal for our purposes, however, since a number of significant constraints on monarchs were imposed by the nobles and did not necessarily serve to protect the rights of merchants. For example, in much of the 1500–1750 period, Poland had a highly constrained executive. But there was relatively little protection for urban merchants; most of the rights rested with the nobility. For this reason, we modified the definition of constraint on the executive to create an alternative measure, which we refer to as "protection for capital." The coding of this measure depends on the formal rights given to urban merchants, particularly their protection in the event of a dispute with the nobility or monarch. The results using this measure are similar to those using constraint on the executive, and are contained in Acemoglu et al. (2002b).

[32] A value of 1 means "there are no regular limitations on the executive's actions," 3 means "there are some real but limited restraints on the executive," 5 means "the executive has more effective authority than any accountability group, but is subject to substantial constraints by them," and 7 means "accountability groups have effective authority equal to or greater than the executive in most activity." Scores of 2, 4, and 6 are used for intermediate values. See Monty G. Marshall and Keith Jaggers (2000).

TABLE 6—ATLANTIC TRADE AND INSTITUTIONS
Dependent variable is constraint on the executive

	Panel, 1300–1850	Panel, 1300–1850	Panel, 1300–1850	Panel, 1300–1850, controlling for religion	Panel, 1300 to 1850, controlling for wars	Panel, 1300 to 1850, controlling for Roman heritage	Panel, 1300 to 1850, controlling for latitude	Panel, 1300 to 1850, using Atlantic coastline-to-area measure of potential for Atlantic trade	Panel, 1300 to 1850, using Atlantic coastline-to-area measure of potential for Atlantic trade
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
p-value for Western Europe × year dummies, 1600–1850	[0.00]	[0.35]	[0.00]	[0.00]	[0.00]	[0.26]	[0.00]	[0.00]	[0.00]
Potential for Atlantic trade × 1500		−0.42						−20.83	
		(0.47)						(22.94)	
Potential for Atlantic trade × 1600		−0.14						10.94	
		(0.52)						(22.91)	
Potential for Atlantic trade × 1700		0.29						62.12	
		(0.48)						(21.14)	
Potential for Atlantic trade × 1750		0.32						81.45	
		(0.46)						(20.78)	
Potential for Atlantic trade × 1800		2.07						79.81	
		(0.44)						(18.97)	
Potential for Atlantic trade × 1850		2.96						72.25	
		(0.41)						(17.13)	
Potential for Atlantic trade × volume of Atlantic trade			0.42	0.45	0.43	0.39	0.43		12.99
			(0.06)	(0.06)	(0.06)	(0.06)	(0.06)		(2.31)
p-value for Protestant × year effect				[0.00]					
Wars per year in preceding century					−0.034				
					(0.20)				
p-value for Roman heritage × year						[0.05]			
p-value for latitude × year							[0.49]		
R-squared	0.75	0.85	0.81	0.84	0.81	0.82	0.81	0.81	0.79
Number of observations	192	192	192	192	176	192	192	192	192

Notes: Standard errors are in parentheses. Weighted panel regressions with full set of country and year dummies. Weights are total population in each country in each year, from McEvedy and Jones (1978). Dependent variable is constraint on executive, which ranges from 1 to 7 where a higher score indicates more constraints on arbitrary action by the executive. All columns use the Atlantic trader dummy (one for Britain, France, Spain, Portugal, and the Netherlands; zero for all others) as the measure of potential for Atlantic trade, apart from columns 8 and 9, which use the ratio of Atlantic coastline to area (including Atlantic traders plus Belgium, Denmark, Germany, Ireland, and Norway). Volume of Atlantic trade is the log average number of voyages per year. Protestant is a dummy for whether country was majority Protestant in 1600. Protestant × year is the Protestant dummy interacted with year dummies for 1600 and after. Wars per year are for the preceding century through 1700, 1700–1750 for 1750, 1750–1800 for 1800, and 1800–1850 for 1850. Roman heritage is dummy for whether country was in the Roman Empire; this is interacted with year dummies for 1600 and after. Latitude is distance from the equator for capital city of this country today; this is interacted with year for 1600 and after.

where, as before, u_{jt} is the urbanization rate, $\ln AT_t$ is our measure of Atlantic trade, PAT_j is again either a dummy for Atlantic trader or the Atlantic coastline-to-area ratio, and $I_{j,1415}$ is country j's initial institutions, calculated as the average of its constraint on the executive in 1400 and 1500. We choose the average of these two dates to capture the long-term institutional differences in the pre-1500 period. The $\gamma_t \cdot I_{j,1415} \cdot d_t$ terms allow any differential economic trends related to differences in initial institutions that would apply even with no access to the Atlantic. Significant coefficients on these interaction terms would imply that at least part of the post-1500 developments in Europe reflect divergent paths taken by countries with different initial institutions, independent of the effects of Atlantic trade. The table reports the p-value from a joint significance test for all of these interaction terms. The $\ln AT_t \cdot PAT_j$ term, on the other hand, measures the effect of Atlantic trade for a given level of institutions. In the table, this term is evaluated at the lowest score of institutions, i.e., for $I_{j,1415} = 1$, so the coefficient on this term measures the growth contribution of Atlantic trade and access to the Atlantic for a society with the worst possible initial institutions.

The variable $\ln AT_t \cdot PAT_j \cdot I_{j,1415}$ tests the hypothesis of interest. A significant coefficient η implies that there were divergent paths taken by countries with different initial institutions, but this divergence relates significantly to whether they took advantage of the opportunities presented by Atlantic trade.

The results are reported in Table 7 using the Atlantic trader dummy for the potential for Atlantic trade, PAT_j (results using the coastline-

TABLE 7—INTERACTION BETWEEN INITIAL INSTITUTIONS AND ATLANTIC TRADE

	Using Atlantic trader dummy as measure of Atlantic trade									
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	Panel A: Dependent variable is urbanization									
	Panel, 1300–1850	Panel, 1300–1850	Panel, 1300–1850	Panel, 1300–1850	Panel, 1300–1850, unweighted	Panel, 1000–1850	Panel, 1000–1850	Panel, 1000–1850	Panel, 1000–1850	Panel, 1000–1850, unweighted
Atlantic trader dummy × volume of Atlantic trade		0.011	0.011	−0.0095	−0.0026		0.0082	0.0084	−0.012	−0.009
		(0.002)	(0.002)	(0.0049)	(0.0062)		(0.0020)	(0.0020)	(0.004)	(0.005)
p-value for initial institutions × year (1600, 1700, 1750, 1800, 1850)	[0.61]		[0.51]	[0.71]	[0.85]	[0.12]		[0.08]	[0.42]	[0.92]
Volume of Atlantic trade × initial institutions × Atlantic trader dummy				0.021	0.017				0.021	0.022
				(0.004)	(0.005)				(0.004)	(0.004)
R-squared	0.87	0.88	0.89	0.90	0.83	0.86	0.86	0.87	0.87	0.81
Number of observations	192	192	192	192	192	240	240	240	240	240
	Panel B: Dependent variable is Log GDP per capita									
	Panel, 1500–1820	Panel, 1500–1820	Panel, 1500–1820	Panel, 1500–1820	Panel, 1500–1820, unweighted	Panel, 1500–1870	Panel, 1500–1870	Panel, 1500–1870	Panel, 1500–1870	Panel, 1500–1870, unweighted
Atlantic trader dummy × volume of Atlantic trade		0.069	0.069	−0.068	−0.079		0.040	0.040	−0.123	−0.110
		(0.016)	(0.016)	(0.028)	(0.028)		(0.017)	(0.017)	(0.030)	(0.028)
p-value for initial institutions × year (1600, 1700, 1750, 1800, 1850)	[0.40]		[0.31]	[0.004]	[0.08]	[0.66]		[0.64]	[0.01]	[0.58]
Volume of Atlantic trade × initial institutions × Atlantic trader dummy				0.14	0.12				0.16	0.11
				(0.03)	(0.02)				(0.03)	(0.02)
R-squared	0.94	0.96	0.96	0.97	0.97	0.95	0.95	0.95	0.96	0.96
Number of observations	96	96	96	96	96	120	120	120	120	120
	Panel C: Dependent variable is constraint on the executive									
	Panel, 1300–1850	Panel, 1300–1850	Panel, 1300–1850	Panel, 1300–1850	Panel, 1300–1850, unweighted	Panel, 1500–1850	Panel, 1500–1850	Panel, 1500–1850	Panel, 1500–1850	Panel, 1500–1850, unweighted
Atlantic trader dummy × volume of Atlantic trade		0.43	0.42	−0.001	−0.096		0.35	0.34	−0.11	−0.15
		(0.06)	(0.06)	(0.12)	(0.12)		(0.05)	(0.05)	(0.10)	(0.09)
p-value for initial institutions × year (1600, 1700, 1750, 1800, 1850)	[0.27]		[0.14]	[0.008]	[0.69]	[0.43]		[0.33]	[0.01]	[0.95]
Volume of Atlantic trade × initial institutions × Atlantic trader dummy				0.44	0.26				0.47	0.29
				(0.11)	(0.09)				(0.09)	(0.07)
R-squared	0.76	0.81	0.82	0.84	0.76	0.72	0.77	0.78	0.70	0.71
Number of observations	192	192	192	192	192	240	240	240	240	240

Notes: Standard errors are in parentheses. Weighted panel regressions with full set of country and year dummies. Weights are total population in each country in each year, from McEvedy and Jones (1978). Dependent variable is urbanization in panel A, log GDP per capita in panel B, and constraint on the executive in panel C. Western Europe dummies interacted with years (from 1600) are included in all columns, but not reported to save space. Urbanization in Europe is from Bairoch et al. (1988), and urbanization in Asia is from Bairoch (1998). Log GDP per capita is from Maddison (2001). Constraint on the executive is coded from Langer (1972); initial institutions are the average of institutions in 1400 and 1500. We use the Atlantic trader dummy as the measure of potential for Atlantic trade. Volume of Atlantic Trade is the log average number of voyages per year and is demeaned. Main effects are evaluated at initial institutions equal to one. For data definitions and sources, see Appendix, Table 1.

to-area ratio measure are identical, and are contained in Acemoglu et al., 2002b). Panel A presents estimates of equation (3), while panel B presents estimates of a similar equation with log income per capita as the dependent variable. Panel C shows the role of the interaction between initial institutions and Atlantic trade for the evolution of institutions.

The results in all three panels are similar. The interaction between the aggregate measure of Atlantic trade and potential for Atlantic trade, ln $AT_t \cdot PAT_j$, is generally significant by itself, and also when entered against the $\gamma_t \cdot I_{j,1415} \cdot d_t$ terms. This shows that the ability to take advantage of Atlantic trade was of major importance for post-1500 developments. When we add the triple interaction ln $AT_t \cdot PAT_j \cdot I_{j,1415}$, this is typically the only significant term.[33]

[33] When the ln $AT_t \cdot PAT_j \cdot I_{j,1415}$ term is included, ln $AT_t \cdot PAT_j$ has typically a negative and sometimes significant

For example, the coefficient of 0.021 on this triple interaction term in column 4 implies that urbanization in an Atlantic trader with an initial constraint on the executive equal to 3, like the Netherlands, grew by 15.7 percentage points more than urbanization in an Atlantic trader country with the worst initial institutions, 1 ($0.021 \times 2 \times 3.74 \approx 0.157$, where 3.74 is the change in the log volume of Atlantic trade between 1500 and 1800).

These results imply that the patterns reported so far are explained almost entirely by the fact that countries with initially constrained rulers were able to take advantage of the opportunities presented by Atlantic trade. Although Spain and Portugal benefited from the transfer of resources from the New World during the sixteenth century, they neither developed the political institutions to support economic growth nor experienced sustained economic development. Our evidence suggests that these differential patterns are closely related to the fact that they started the post-1500 era with absolutist regimes in control of overseas activity. On the other hand, it appears that the Italian city-states, which started with relatively nonabsolutist institutions around 1500, did not experience further economic development because they did not have as easy access to the Atlantic as Britain and the Netherlands did. Britain and the Netherlands were the economic winners because they had both relatively good political institutions to start with *and* ready access to the Atlantic.

V. Conclusion

This paper documents a distinctive and interesting fact related to the process of European growth: between 1500 and 1850, the growth of nations with access to the Atlantic, and the growth of Atlantic ports, account for most of the differential growth of Western Europe relative to Eastern Europe. It therefore appears that the rise of Europe between 1500 and 1850 was largely the rise of Atlantic Europe and the rise of Atlantic ports. This fact weighs against theories of the origins of European development emphasizing distinctive European characteristics and purely internal dynamics, but is consistent with those that give a prominent role to Atlantic trade and deemphasize the continuation of pre-1500 trends or permanent European characteristics, such as religion, Roman heritage, or European culture. If these factors are important, it must be because of the interaction between them and the opportunity to trade in the Atlantic.

We suggested that Atlantic trade contributed to European growth through an indirect institutional channel as well as via its more obvious direct effects. Our hypothesis is that Atlantic trade generated large profits for commercial interests in favor of institutional change in countries that met two crucial preconditions: easy access to the Atlantic and nonabsolutist initial institutions. These profits swung the balance of political power away from the monarchy and induced significant reforms in political institutions, which introduced more secure property rights and paved the way for further innovations in economic institutions. With their newly gained property rights, English and Dutch merchant nations invested more, traded more, and spurred economic growth.

Our analysis stopped before West European industrialization, focusing instead on economic and political developments between the sixteenth and nineteenth centuries. Consequently, we did not investigate why some successful Atlantic nations, like the Dutch, did not industrialize early, while Britain and some non-Atlantic nations such as Germany did. We suspect that the answer is related to interstate competition, "defensive modernization" responses of certain European nations, and, possibly, the adverse effects of oligarchies on industrialization, but we leave further investigation of this issue for future research.

The process of early modern European growth is undoubtedly multifaceted. We are aware that our account leaves out many important aspects of the social and economic development of Western Europe. Our intention is not to offer a mono-causal explanation for the rise of Europe, but rather to suggest that Atlantic trade played a major role in this process. It is our hope that our hypothesis and the empirical patterns documented in this paper will encourage further research.

coefficient, reinforcing the conclusion that nations with absolutist institutions did not benefit much, or at all, from the opportunity to trade in the Atlantic. In addition, in three specifications in Table 7, the interactions between initial institutions and dates after 1600 are jointly significant, but the coefficients (not shown in the tables) are *negative*.

APPENDIX: CONSTRUCTION OF KEY VARIABLES

Country-Level and City-Level Urbanization Data.—Calculated from the urban population dataset of Bairoch et al. (1988) and country population estimates from McEvedy and Jones (1978). Details are provided in the Appendix of Acemoglu et al. (2002b).

Trade Measures.—Acemoglu et al. (2002b) explain in detail the construction of Atlantic and Mediterranean trade volume measures. These series are annual average voyages equivalent for ships of 400 deadweight tons. The Mediterranean trade estimates are based on information on Venetian trade levels from Frederic Chapin Lane (1934), but we also include Genoa, Catalonia, and other trading centers (Carla Rahn Phillips, 1990). Estimates exclude short-haul coastal trade and trade by the British and Dutch—these countries also engaged in Mediterranean trade as they built their naval power and trading empires after 1600.

Key sources for our Atlantic trade series are de Vries (2003), Tracy (1990), Davis (1962), and N. Steensgaard (1974). We have also constructed an alternative Atlantic trade series based on Kevin H. O'Rourke and Jeffrey G. Williamson (2002). Robustness results using this series are reported in Acemoglu et al. (2002b). The growth of our volume-based Atlantic trade series matches closely the sum of annual value of Europe-Africa-New World commerce series in Inikori (2002, Table 4.8, p. 202) and de Vries' (2003) trade flows with Asia.

Estimates of British Profits from Trade.—All figures are approximately in 1600 prices using the index of building craftsmen's wages, constructed by Phelps Brown and Hopkins (1955), which shows a doubling of wages from 1500 to 1600, then a 50 percent increase from 1600 to 1650, followed by rough stability through 1700 and a further 50 percent increase during the eighteenth century.

1576–1600:—Rabb (1967, pp. 61–62) calculates that total profits from privateering in 1585–1603 were £700,000. Dividing by 25 years gives an average of £28,000 per year, approximately £40,000 in 1600 prices.

1601–1650:—Profits for the vertically integrated Dutch East India Company from 1630–1670 were 2.1m guilders (de Vries and van der Woude, 1997, p. 447); British trade with Asia was around a half of Dutch levels in the seventeenth century (de Vries, 2003); and the guilder-pound exchange rate fluctuated around 10, so total British profits from Asian trade (including interlopers and suppliers) were likely around £100,000 per annum (which is consistent with Chaudhuri, 1965). Around £10m was invested between 1600 and 1630 in joint stock companies active in the New World and Africa (Rabb, 1967). Even when a company failed to show returns, as with the Virginia Company, individual colonists and their suppliers could earn good profits. Privateering in the 1630s and 1640s was highly profitable (Craven, 1930). We assume the same level of earnings in the New World as in East India trade, i.e., £100,000 per annum, yielding an estimate of average annual profits of £200,000 in 1600 prices.

1651–1675:—From 1650 we use the annual value of export production in British America from Inikori (2002, p. 181). This was £421,000 in 1651–1670 and £2.7m per annum for 1711–1760; we take the average value for 1651–1700 to be £1m. O'Brien's (1982) numbers suggest that profits were 50 percent of import volume, implying profits of £500,000. To this, we add £100,000 per annum from the East India trade with the same calculation as above, yielding profits of £600,000 per annum, or approximately £500,000 in 1600 prices.

1676–1700:—Inikori's British America trade estimate is £2.7m per annum for 1711–1760; we assume £2m per annum for 1676–1700, which implies profits of £1m. Adding East India profits of £100,000 gives an average annual profit estimate of £1.1m, or £900,000 in 1600 prices.

1701–1750:—Inikori's British America trade estimate is £6.8m for 1761–1780; we take the average value for 1701–1750 to be £4m, thus profits of £2m. Adding again profits of £100,000 from East India gives an average annual profit estimate of £2.1m, about £1.7m in 1600 prices.

APPENDIX, TABLE 1—VARIABLE DEFINITIONS AND SOURCES

Variable	Description	Source
Log GDP per capita in 1500, 1600, 1700, 1820, and 1870	Logarithm of GDP per capita	Maddison (2001)
Population in 1000, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, and 1850	Total population	McEvedy and Jones (1978)
Urban population in 1000, 1200, 1300, 1400, 1500, 1600, 1700, 1750, 1800, and 1850	Population living in urban areas	Bairoch et al. (1988), as described in the Appendix. We use Bairoch (1988) for urbanization in Asia and Chandler (1996) for Asian city population.
Atlantic and Mediterranean ports	City that is on the Atlantic or Mediterranean	Bairoch et al. (1988) for cities; location from Doring Kindersley (DK) Publishers (1997).
Ratio of Atlantic coastline to area	Length of Atlantic coastline divided by land area. Both assume modern borders. Atlantic coastline includes the whole coast of Portugal, Ireland, Belgium, the Netherlands, and Britain. It also includes half the coastline of Spain, two-thirds the coastline of France, half the coastline of Germany, one-quarter the coastline of Denmark, and half the coastline of Norway.	Coastline is from Integrated Coastline Management (on the Web). Land area is from the World Bank, *World Development Indicators*, CD-Rom, 1999.
Dummy for Atlantic trader	Equals one for Britain, France, the Netherlands, Portugal, and Spain	Coded by authors based on composition of Atlantic trade. Acemoglu et al. (2002b) for details.
Dummy for Atlantic port	Equals one for a city that was used as an Atlantic port; zero otherwise	Bairoch et al. (1988) for cities; location from DK Publishing (1997).
Dummy for potential Atlantic port	Equals one for a city that is on the Atlantic; zero otherwise	Bairoch et al. (1988) for cities; location from DK Publishing (1997).
Volume of Atlantic trade	Average voyages per year equivalent	See Appendix. Acemoglu et al. (2002b) provide full details.
Constraint on executive in 1800, 1850, 1960, 1970, 1990, and intervening years	A seven-category scale, from 1 to 7, with a higher score indicating more constraints. Score of 1 indicates unlimited authority; score of 3 indicates slight to moderate limitations; score of 5 indicates substantial limitations; score of 7 indicates executive parity or subordination. Scores of 2, 4, and 6 indicate intermediate values.	Polity IV dataset, downloaded from Inter-University Consortium for Political and Social Research. Variable described in Gurr (1997).
Constraint on executive from 1000 to 1800	A seven-category scale, from 1 to 7, with a higher score indicating more constraints. Score of 1 indicates unlimited authority; score of 3 indicates slight to moderate limitations; score of 5 indicates substantial limitations; score of 7 indicates executive parity or subordination. Scores of 2, 4, and 6 indicate intermediate values.	Coded by authors from Langer (1972); see Appendix for more details.
Religion variables	Majority religion of city or country	Coded by authors from Langer (1972)
Roman heritage	Coded equal to one for countries that were part of the Roman Empire and not subsequently part of the Ottoman Empire.	Coded by authors from Langer (1972)
Wars per year	Number of years of war in preceding 50 or 100 years. Civil wars and colonial wars outside Europe are excluded.	Coded by authors from Kohn (1999)
Latitude	Absolute value of the latitude of the country, scaled to take values between 0 and 1, where 0 is the equator	Country data from La Porta et al. (1999). City data from Bairoch et al. (1988).

1751–1800:—Inikori's British America trade estimates of £19,545 for 1781–1800 implies annual profits of around £10m, i.e., double O'Brien's profit estimate (approximately £5m in 1600 prices).

It is worth noting that our profit estimates would be significantly higher prior to 1650 if we also included British and Dutch trade in Asian goods passing through Portugal, Spain, and the Levant (Israel, 1989; Brenner, 2003).

Religion.—From Langer (1972) and Stearns (2001), Britain, the Czech Republic, Denmark, Finland, Germany, the Netherlands, Norway, Sweden, and Switzerland were majority Protestant in 1600. Germany was largely Protestant, but the balance remained unclear until the end of the 1600s. The results are robust to coding Germany as Catholic. We have also tried an alternative specification in which religion is coded directly as Catholic, Muslim, Orthodox, or Protestant, with essentially identical results.

Roman Heritage.—From Langer (1972) the following countries had a Roman heritage: Belgium, Britain, France, Italy, the Netherlands, Portugal, Spain, and Switzerland. Bulgaria, Greece, Romania, and Yugoslavia had their Roman traditions eradicated by a long period of Ottoman rule. If they are also coded with Roman heritage, the effect of this variable is weakened further.

Wars.—George Childs Kohn (1999) lists the dates of every European war from about AD 1000, and a brief explanation of participants, duration, intensity, and outcome. We calculate the average number of years of war in a time interval before each date in our dataset: for the preceding 100 years through 1700 and for the preceding 50 years for 1750, 1800, and 1850, excluding purely civil wars and colonial wars outside Europe. Alternative codings such as dropping "minor" wars does not affect our main results. Kohn (1999) does not provide reliable information on the wars of Finland and Greece during this period, so we drop these countries from regressions involving the "wars per year" variable.

Constraint on Executive.—This variable is coded using the method of Polity IV as described in footnote 32. Our primary source in this exercise is the historical encyclopedia of Langer (1972), supplemented with Stearns (2001). Acemoglu et al. (2002b) provide more details on our coding, the full series, and robustness checks with some reasonable alternatives. We also checked our results using the three codings of institutions in De Long and Shleifer (1993), which are somewhat different from ours, for example awarding a much better score to feudal systems than does coding based on the Polity criteria. Using their measures leads to very similar results to those reported in the text.

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Progress and poverty in early modern Europe[1]

By ROBERT C. ALLEN

At the end of the middle ages, the urban, manufacturing core of Europe was on the Mediterranean with an important offshoot in Flanders. The Netherlands were thinly populated,[2] and England was an agrarian periphery. By 1800 the situation was largely reversed. First the Netherlands and then Britain emerged as commercial and manufacturing powerhouses with the largest urban economies in Europe. Italy and Spain slipped behind. Only present-day Belgium managed to remain near the leaders, perhaps because of its proximity to the Netherlands.

Explaining this reversal in fortunes has been a central problem of social science, and the literature includes many conflicting hypotheses. This article attempts to give an integrated assessment of six: population, enclosure, empire, representative government, technology, and literacy.

Population can function in two ways to explain social and economic change in early modern Europe. First, changes in the land-labour ratio can explain differences in real wages and land rents. These, in turn, may affect other aspects of economic life such as the extent of serfdom or proto-industrialization. Second, different demographic regimes may affect development by changing population growth and income levels. Hajnal has identified differences in marriage patterns which suggest that western Europe exhibited Malthus's preventive check, while eastern Europe may have been an example of the positive check model. Historians of the 'European miracle' have argued that just such a difference accounts for Europe's lead over Asia.[3] Perhaps it explains the advance of north-western Europe as well?[4]

Modernization of traditional rural society is a long-standing explanation of the lead of north-western Europe. The enclosure movement in England is the inspiration for this theory. Liberals have emphasized that enclosure replaced communal property with private property, which they regard as more 'efficient' since it aligned the interests of farmers and landlords more tightly with the results of their decisions.[5] Marxists have emphasized

[1] I am grateful to the Social Sciences and Humanities Research Council of Canada for supporting this research through its research grants program and the Team for Advanced Research on Globalization, Education, and Technology.

[2] Van Zanden, '"Revolt of the early modernists"', has argued that the Netherlands was already advanced in 1500, and that view is supported by its relatively high agricultural productivity and urbanization: see below, tab. 1, figs. 2, 6-8.

[3] Hajnal, 'European marriage patterns'; Jones, *European miracle*; Blaut, *Colonizer's model*, pp. 128-35.

[4] Weir, 'Life under pressure'.

[5] North and Thomas, *Rise of the western world*; Hardin, *Managing the commons*.

that the three-tiered social structure—landlords, tenant farmers, and landless labourers—that emerged in the eighteenth century and that seemed to accompany enclosure was a 'capitalist' arrangement that forced farmers to innovate since high productivity was the only way to pay their landlords and their workers.[6]

Both the English and the Dutch were winners in the early modern scramble for empire, and that success is the inspiration for the imperial theory of economic development. Marx developed this theme as well as the agrarian argument. The role of empire as a source of capital and a market for manufactures has since been emphasized by 'world system theorists' including Wallerstein, Arrighi, and Frank.[7] Acemoglu and his co-authors also emphasize the importance of Asian and American trade, as does Inikori.[8]

Eighteenth-century liberals contrasted the absolutism of France with England's 'mixed monarchy' and the constitution of the Dutch Republic. Representative institutions were alleged to be economically superior, as evidenced by lower interest rates in England and the Netherlands compared with France. These arguments have been restated by recent theorists such as North and Weingast and De Long and Schleifer, who allege that absolutist kings expropriated property and raised taxes in ways that discouraged business enterprise.[9] Eckland and Tollinson have proposed complementary explanations in terms of rent seeking.[10]

Theorists have long emphasized that continuous technological progress is the only basis for sustained economic growth.[11] The relationship between the scientific revolution of the seventeenth century and the industrial revolution has often been discussed, and has been probed recently by Jacob and Mokyr, who argue that north-western Europe benefited from an 'industrial enlightenment' (in Mokyr's phrase) and England, in particular, from a distinctive scientific culture that led to economic advance.[12] But is it possible to measure technological performance and assess its contribution to economic growth?

A final candidate which might explain success was the spread of literacy. When Gutenberg invented movable type in the mid-fifteenth century, less than 10 per cent of adult Europeans could sign their names. By 1800, the proportion was higher everywhere, and it exceeded half in the economic leaders. Much recent theorizing has emphasized the importance of education and human capital accumulation for economic growth, so it makes sense to probe its importance in earlier years. Was a literate population the seed bed for economic expansion?

[6] See, for instance, Brenner, 'Agrarian class structure', and the spirited debate in Aston and Philpin, eds., *The Brenner debate*.

[7] Wallerstein, *Modern world system*; Arrighi, *Long twentieth century*; Frank, *World accumulation*; *idem*, *ReOrient*.

[8] Acemoglu et al., 'Rise of Europe'; Inikori, *Africans and the industrial revolution*.

[9] North and Weingast, 'Constitutions and commitment'; De Long and Schleifer, 'Princes and merchants'.

[10] Eckland and Tollinson, *Politicized economies*.

[11] Jones, *Introduction to economic growth*.

[12] Jacob, *Scientific culture*; Mokyr, *Gifts of Athena*.

The importance of these developments has been debated extensively, usually in terms of internal coherence. The enclosure argument, for instance, has been called into question by historians who have denied that enclosure led to much growth in agricultural productivity.[13] The empire argument has been attacked on the grounds that the extra-European markets were too small to matter, and that the same was true of the profits earned on slavery and colonial trade.[14] The representative government argument has been disputed by those who assert that France did not have particularly high interest rates or taxes. Recent research has downplayed the importance of technological progress and literacy in explaining the British industrial revolution.

This article takes a different approach to assessment by estimating a five-equation simultaneous equation model of European development. The model explains five variables—the population, the wage rate, urbanization, agricultural productivity, and the proto-industrial revolution. It is estimated with an aggregate dataset for Europe from 1300 to 1800.[15] The units of observation are countries at intervals of approximately a century. The countries are defined in terms of their boundaries in 1945 and include England and Wales, Belgium, France, the Netherlands, Spain, Italy, Germany, Poland, and Austria/Hungary/Czechoslovakia. The years include 1300, 1400, 1500, 1600, 1700, 1750, and 1800, although observations in 1300 are available only for England and Italy, and the Netherlands does not enter the dataset until 1500.

A very serious issue is whether countries are appropriate units of analysis—in particular, whether they were homogeneous enough. Was there an 'English' or an 'Italian' wage, for instance? In many respects, the countries were internally heterogeneous, and are represented here with averages. However, if world empires or agrarian institutions were powerful enough to remake societies, their effects should show up in the average experience of the countries concerned. And they do.

A second question is whether the same model fits all countries; in particular, does a single, five-equation model summarize the variety of

[13] Comparisons of open and enclosed villages and of large and small farms find that England's unique rural institutions made little contribution to productivity: Allen, *Enclosure*; Clark, 'Commons sense'. Likewise, studies of share cropping in southern Europe and the Meseta in Spain find it to have been more efficient than liberals and marxists have thought: Hayami and Otsuka, *Economics of contract choice*; Hoffman, *Growth in traditional society*; Nugent and Sanchez, 'Efficiency of the Meseta'; Simpson, *Spanish agriculture*. International comparisons also call into question the importance of 'modern' institutions. The open-field farmers of north-eastern France achieved wheat yields that were on a par with those of farmers of enclosed land in England: O'Brien and Keyder, *Economic growth*; Allen and Ó Gráda, 'On the road again'. Moreover, the farmers who accomplished the Dutch agricultural revolution were mainly owner-occupiers rather than the capitalist tenants of great estates: De Vries, *Dutch rural economy*.

[14] The debate is enormous. Relevant works showing the diversity of approaches include Williams, *Capitalism and slavery*; Wallerstein, *Modern world system*, I and II; Frank, *World accumulation*; Findlay, '"Triangular trade"'; Darity, '"Original sin"'; Engerman, 'Slave trade'; Thomas and Bean, 'Fishers of men'; O'Brien, 'European economic development'; *idem*, 'Imperialism'; O'Brien and Engerman, 'Exports'; O'Brien and Prados, 'Costs and benefits'. Morgan, *Slavery*, is a survey of some important aspects, and Inikori, *Africans and the industrial revolution*, and Ormrod, *Rise of commercial empires*, are the most recent contributions.

[15] The data are tabulated in app. I.

development experiences seen in early modern Europe, or do we need specific, different models for each country to capture the divergent paths of development on the continent? The surprising answer is that one model does fit all, and it indicates why some countries were more successful than others.

I

It is possible to distinguish the successful economies from the unsuccessful by three indicators—real wages, economic structure, and agricultural productivity. These require discussion since they are the axes around which the present analysis is constructed.

Income is fundamental and is best measured by the real wage.[16] Figure 1 plots real wages for leading European cities and highlights the differences in performance between regions. In the fifteenth century, wages in north-western Europe were already higher than elsewhere on the continent, but the advantage was comparatively small. A large gap emerged by 1750—not because of advance in the north but rather because real wages collapsed in central and southern Europe. Figure 1 shows the drop for Valencia and Vienna. Similar declines occurred in other cities in France, Spain, Italy, Germany, Austria, and Poland. Conversely, the real wage in London showed ups and downs, but the trend was stable in the long run. Wages in other English towns fell like those on the continent between 1450 and 1650, but then began to converge up to the London level. Real wages in Antwerp and Amsterdam showed little variation from 1500 to 1800.[17] Roughly speaking, real wages were constant in the leading cities of north-western Europe between 1500 and 1750, but they halved elsewhere on the continent.

Concentration on the real wage also links economic success in early modern Europe to one of the great divides of human history—the escape from the Malthusian trap. Europe took its first steps in that direction between 1500 and 1800. Previously, if an economic expansion raised the standard of living of the majority of the population, their good fortune was unsustainable since the better living conditions induced an increase in population that eventually drove the standard of living back to its

[16] Maddison, *World economy*, has estimated GDP per head for many countries in the early modern period, and some of his estimates concur with the usual view. Thus, he shows Italy to have had the highest income in Europe in 1500, but with little growth from then until 1820. Likewise, between 1500 and 1820 he finds considerable growth in the Dutch Republic and the UK, which were the two richest economies at the time. More problematic reconstructions include Spain, which, according to Maddison's figures, was a rapidly growing economy in that period. Discrepancies such as this emphasize that estimates of GDP for the early modern period must be treated with great caution. Even for the early nineteenth century, the calculation of GDP per head is fraught with difficulties. Thus, Maddison, *Monitoring*, and Prados, 'International comparisons', agree that Britain had the highest income in Europe in 1820, but they disagree significantly about the income of the US—Maddison putting it below Britain's, while Prados puts it above. The differences in ranking reflect difficulties in deflation, for which there are no simple solutions.

[17] Allen, 'Great divergence'.

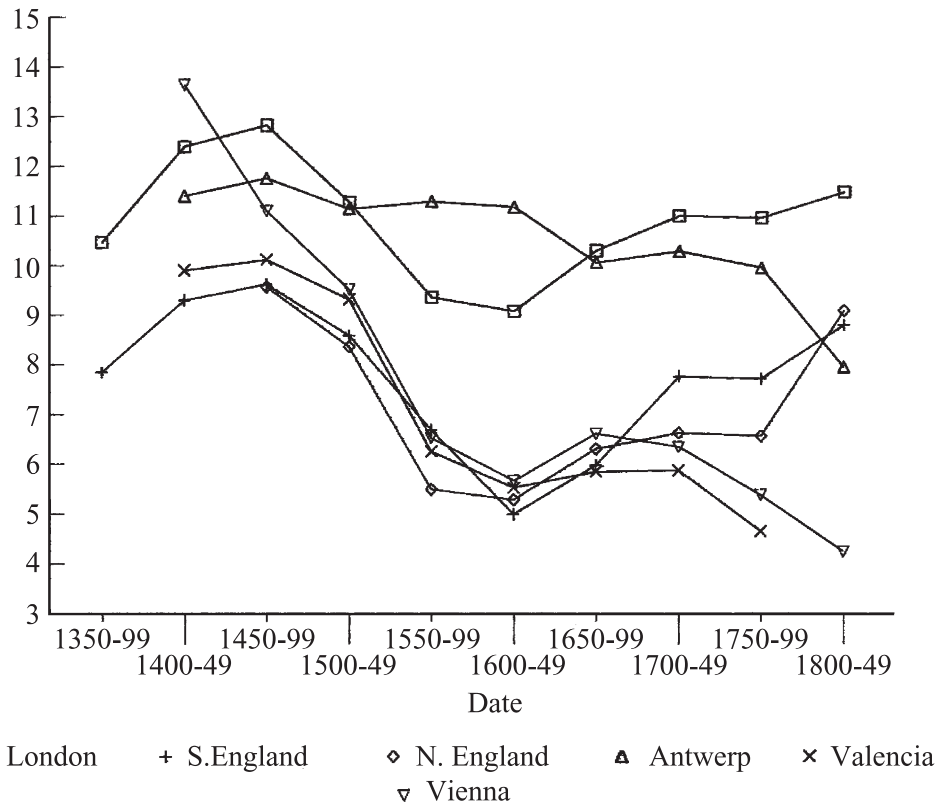

Figure 1. *Real wages, 1350-1850*
Source: Amounts are in Strasbourg prices of 1750-9 from Allen, 'Great divergence'.

earlier value.[18] The economic expansions of the Dutch and English, however, were sustained for centuries without serious falls in the standard of living. This was not because fertility was restrained; on the contrary, these countries had the most rapidly growing populations in Europe. The secret of their success was maintaining even more rapid growth in their economies.[19] The problem of combining economic growth and stable living standards was solved for the first time by vigorous economic expansion rather than by demographic restraint.

The economies that achieved high wages in 1750 were also the ones that experienced the most rapid structural change. Table 1 shows the distribution of the population in major European countries in 1500 and 1800. At the end of the middle ages, Italy, Spain, and present-day Belgium were the leading economies, and they had the smallest proportions of their populations in agriculture and the most extensive degree of urbanization. Elsewhere, about three-quarters of the population was

[18] Abel, *Agricultural fluctuations*; Le Roy Ladurie, *Peasants*; Postan, 'Agrarian evidence'; Wrigley and Schofield, *Population history*.
[19] North and Thomas, *Rise of the western world*.

Table 1. *Distribution of the population by sector, 1500-1800*

	1500	*%* *Rural*		1800	% *Rural*	
	Urban	*Non-agric*	*Agric*	*Urban*	*Non-agric*	*Agric*
Greatest transformation						
England	7	18	74	29	36	35
Significant modernization						
Netherlands	30	14	56	34	25	41
Belgium	28	14	58	22	29	49
Slight evolution						
Germany	8	18	73	9	29	62
France	9	18	73	13	28	59
Austria/Hungary	5	19	76	8	35	57
Poland	6	19	75	5	39	56
Little change						
Italy	22	16	62	22	20	58
Spain	19	16	65	20	16	64

Notes and sources: The procedures and estimates used in Wrigley, 'Urban growth', are generalized to the countries shown here. Total population and urban population are taken from McEvedy and Jones, *Atlas*, and from Bairoch, *La Population*. Census data from the nineteenth century are used to divide the rural population into agricultural and non-agricultural components in 1800. The comparable division in 1500 is made on the assumption that 80% of the rural population at that time was agricultural. Intervening years are linearly interpolated. For details, see Allen, 'Economic structure'.

agricultural—a proportion similar to that in most of the less developed countries early in the twentieth century—and the urban population was correspondingly small.

In analysing changes in the early modern period, it is useful to distinguish four groups. England was undoubtedly the most successful economy, with a drop in the agricultural population to 35 per cent of the whole and a rise in both the urban and 'rural non-agricultural' shares. The latter corresponds to the 'proto-industrial revolution', which involved the expansion of manufacturing (particularly textiles) in small villages organized in the putting-out system.[20] Belgium and the Netherlands experienced a similar transformation, with agriculture declining to a point where it employed 49 per cent and 41 per cent of the population, respectively, in 1800. Spain and Italy showed little change in economic structure, and, indeed, much of the growth in north-western Europe was at their expense as key industries such as woollen textiles relocated from the south to the north. Finally, France, Germany, Austria, and Poland experienced only modest structural transformation. The small decline in the agricultural share was reflected in rural manufacturing rather than in the growth of cities. Although historians of proto-industry have often been enthusiastic about its development potential—hence the term—it was as often associated with economic stagnation as with advance.[21]

[20] Mendels, 'Proto-industrialization'.
[21] Coleman, 'Proto-industrialization'.

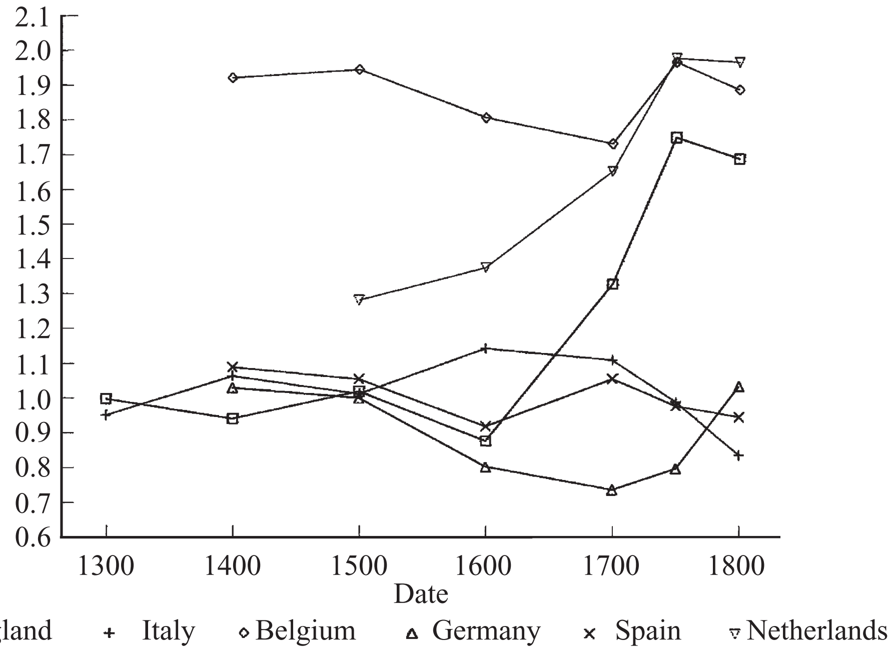

Figure 2. *Total factor productivity in agriculture, 1300-1800*
Source: see app. II.

Agricultural productivity is a third indicator of economic success in the early modern period. An immediate reason why England and the Netherlands could reduce the proportion of their population engaged in agriculture was that the productivity of farmers and cultivators increased substantially between the middle ages and the nineteenth century. In present-day Belgium, output per agriculturalist was high during the middle ages and remained so until 1800. England and the Netherlands were the two countries which experienced agricultural revolutions in the early modern period: labour productivity in both of these countries was low in the medieval period, but both closed the gap with Belgium during the seventeenth and eighteenth centuries.[22] Roughly the same was true of total factor productivity, as shown in figure 2.[23] Rising agricultural efficiency contributed to economic development by supplying food, wool, and flax to support the non-agricultural economy, by releasing labour for employment in manufacturing, and by providing a surplus that could finance investment or sustain the conspicuous consumption of the aristocracy and the state.

II

In explaining economic development, a distinction must be made between the explanatory variables and those that are explained. The model

[22] Allen, 'Economic structure'.
[23] The calculation of TFP in agriculture is explained in app. II.

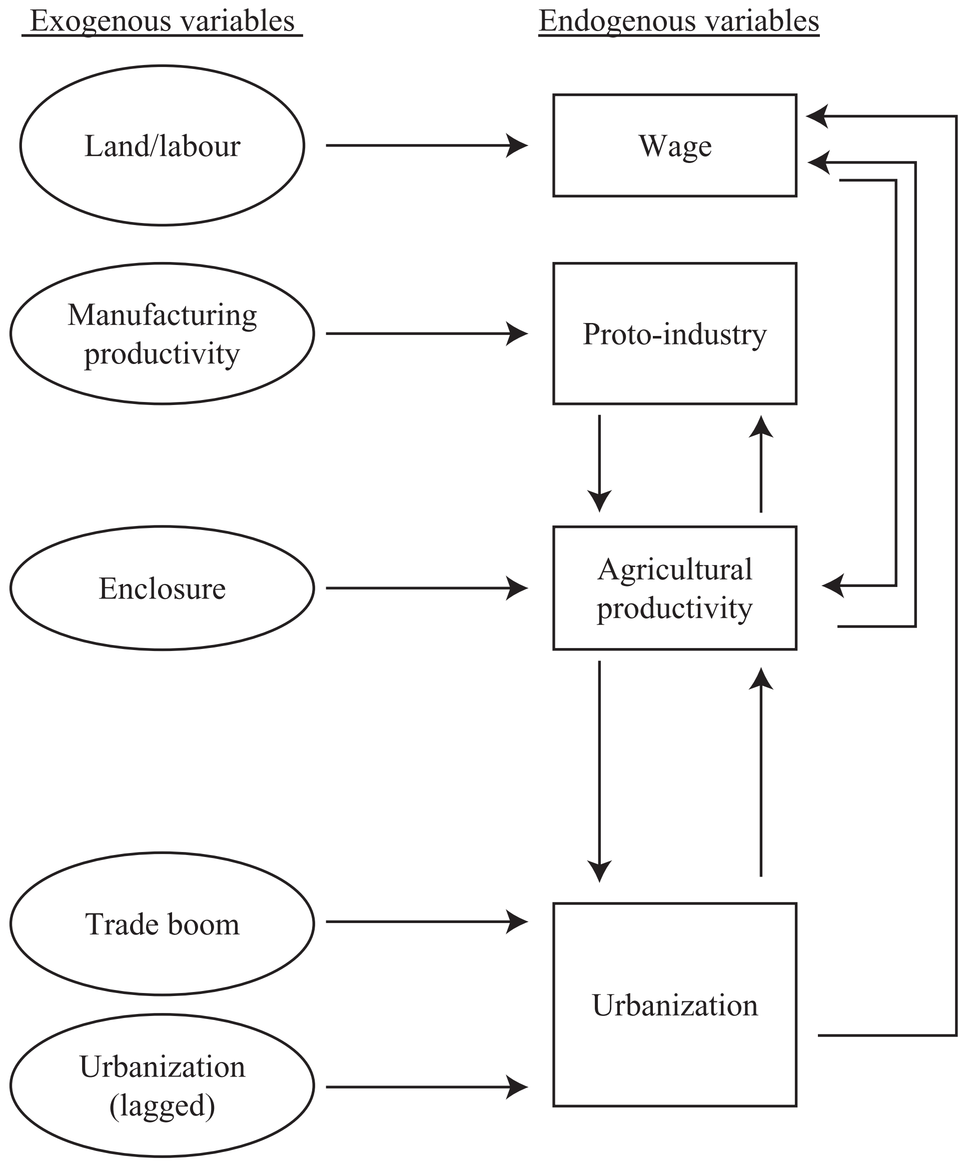

Figure 3. *Flow chart (one period) of the model*
Note: The role of population is explained on p. 411.

developed here explains five variables: population, the real wage, the urban and proto-industrial shares of the population, and agricultural productivity. They are endogenous variables; each influences the others. A productive agriculture, for instance, promoted the development of cities, while urbanization induced growth in agricultural productivity. Hence, the view of development is one in which living standards, urbanization, proto-industrialization, and agricultural revolutions were mutually reinforcing. None was a prime mover pushing all of the others forward.

All of these five variables are ultimately explained by other variables in the model—the enclosure of the open fields, for instance, and the establishment of world empires. Other prime movers include the literacy rate, a productivity variable indexing the growth of competitive advantage in the new draperies, previous levels of urbanization, and the land-labour ratio. The model contains five equations to explain the five endogenous variables in terms of the other variables.

The model works as a recursive system. In each period (century), four equations are solved to determine four endogenous variables—the real wage, the urban and proto-industrial proportions of the population, and agricultural productivity—in terms of the exogenous variables and the population. Figure 3 is a flow diagram that shows the logic of this solution. It demonstrates the links between variables that emerge as important in the statistical analyses to be discussed: many more links were examined but failed to be statistically or historically significant. The four endogenous variables are shown in rectangles and the exogenous variables in ellipses. The endogenous variables influenced each other in many ways. Higher urbanization, for instance, led to higher agricultural productivity. Causation worked in the opposite way as well, with higher agricultural productivity increasing the proportion of the population living in cities. In the model developed here, agricultural and urban revolutions are both a cause and a consequence of economic development.

Population change links successive solutions of the model summarized in figure 3: once the model is solved for one period, the implied wage and urbanization rates are used to project population forward to the next. The process is then repeated as the model is resolved to determine the wage, urbanization, agricultural productivity, and proto-industry for the new period. Urbanization was also a self-perpetuating process that linked one simulation period to the next.

Figure 3 shows the variables that were ultimately causal, and their influence is what would be expected on general grounds. They are now reviewed in turn.

The standard explanation for falling real wages in the sixteenth and seventeenth centuries is population growth in the context of a fixed supply of natural resources.[24] This diminishing returns effect is confirmed in the present model. Here the natural resource base is measured by agricultural land, T, in the 1950s. Although there were improvements in the quality of land over the period, the total did not change in most cases.[25] The labour force, L, is indexed by the population, and the model

[24] Abel, *Agricultural fluctuations*; Le Roy Ladurie, *Peasants*; Postan, 'Agrarian evidence'; *idem*, *Medieval economy*; Wrigley and Schofield, *Population history*; Wrigley, *Continuity*.

[25] Land is the area of agricultural land as given in the UN Food and Agricultural Organization, *Production year-book*, 1958, vol. 12, p. 3. (Figures for England and Wales are taken from Stamp, *Land use statistics*, p. 30. The corresponding figures for the UK agree with those of the FAO.) Agricultural land includes cropped land, meadow, pasture, and rough grazing, but not forest. This total is treated as a constant for each country from 1300 to 1800. The quality of land was certainly improved by drainage, irrigation, and so on, and the intensity of land use grew as a consequence. Nevertheless, the extent of land in the 1950s defines the potential resource base. For instance, in England and Wales between 1688 and 1960 there was a reduction in rough pasture (called 'waste

uses Bairoch's estimates, which are generally taken from McEvedy and Jones.[26] The land and population estimates supposedly relate to boundaries that applied in 1945. Dividing agricultural land by the population gives the land-labour ratio T/L.

The productivity record of early modern manufacturing was mixed, but some significant advances were made in textiles, which were the most important products of the age. These improvements affected growth through trade.

The commercial revolution of the seventeenth century was an intra-European affair, and the changing locus of textile production was central to it. In the middle ages, woollen cloth was produced in the cities of Italy and Flanders and exported across the continent. The English were also successful in exporting heavy broadcloths. By the sixteenth century, the English and the Dutch were beginning to make the 'new draperies' which were light worsteds. These were patterned after Italian fabrics. The northern imitations were so successful that English and Dutch exports drove Italian producers out of business in the seventeenth century.[27] New manufacturing industries were established in East Anglia and the Low Countries. The Norwich industry was started in the middle of the sixteenth century by Flemish refugees, although it drew on an earlier craft tradition.[28] At the end of the seventeenth century, about 40 per cent of England's woollen cloth production was exported, and woollen fabrics comprised 69 per cent of the country's exports of domestic manufactures.[29] Wool was even more important for London. The new draperies flowed out of the capital: cloth accounted for 74 per cent of its exports and re-exports in the 1660s and made a large contribution to its growth.[30]

Productivity growth in textiles can be measured by prices. Figure 4 plots an index of input prices (a geometric average of the price of wool and the wage rate) divided by the price of cloth. Throughout the early modern period, there was no growth in efficiency in the production of traditional woollen broadcloth, but productivity rose by 70 per cent in the new draperies from the inception of production until they became established in the 1620s. Since the English and Italians were paying similar wages and were buying wool and selling cloth in the same markets,

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and common' by Gregory King) and a corresponding increase in improved farm land, but the total land available for agriculture remained the same according to King and the recent estimates. Cf. Allen, 'Agriculture during the industrial revolution', p. 104; Stamp, *Land use statistics*, p. 30.

[26] Bairoch, *La Population*, p. 297; McEvedy and Jones, *Atlas*. However, Bairoch reports figures for the UK rather than for England and Wales. Population totals were taken from Hatcher, *Plague*, and from Wrigley and Schofield, *Population history*, pp. 528-9. The model follows the lead of Wrigley and Schofield, ibid., p. 566, in increasing their estimates for England (excluding Monmouthshire) by 6% to include Wales. The adjustment is rough, but agrees with the figures of de Vries, *European urbanization*, p. 36.

[27] Rapp, 'Mediterranean trade hegemony'; Harte, ed., *New draperies*.

[28] Munro, 'English "new draperies"'; Holderness, 'Reception and distribution'; Martin, 'New draperies in Norwich'.

[29] Deane, 'Output', pp. 209-10; Davis, 'English foreign trade', p. 165.

[30] Rapp, 'Unmaking of hegemony', p. 502.

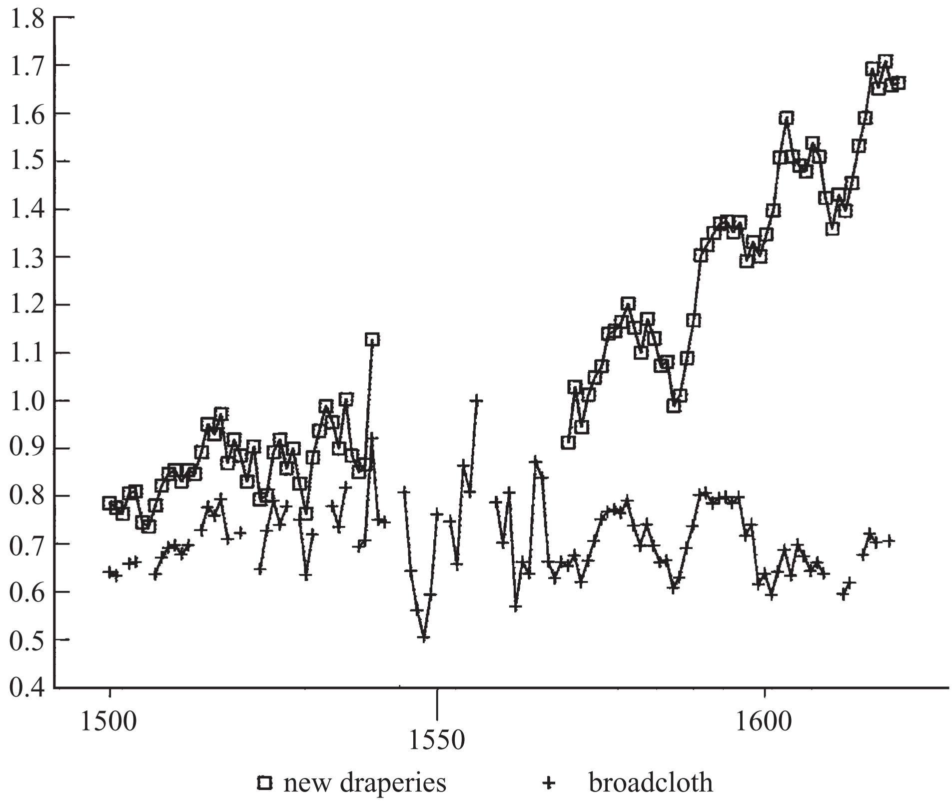

Figure 4. *Total productivity in English cloth, 1500-1620*

Sources: The indices were computed by, first, calculating a geometric average of a series of the price of raw wool and a wage rate and, then, dividing that average by a cloth price series. The raw wool series is described in Allen, *Enclosure*, pp. 327–8, and the wage rate for craftsmen in *idem*, 'Great divergence', p. 435. For the new draperies, the cloth price for Norwich is from Rogers, *History*, IV, p. 569 and V, p. 576. For broadcloth, the cloth price is series A in Beveridge, *Prices*, pp. 85–90.

their efficiency was similar before the invention of the new draperies.[31] The rising efficiency of English worsted production compared with traditional woollens is, thus, also indicative of the increasing advantage enjoyed by northern European worsted producers over the Italians.

The enclosure of the open fields and commons is the best-known aspect of the agricultural revolution in England, and it is measured by ENCL, the proportion of land enclosed. England is famous as the only country that had an enclosure movement in this period, but it was not the only country with enclosed farms. Indeed, there was considerable variation in the proportion of land enclosed as shown by Pounds.[32] For countries other than England, the proportion of land enclosed is taken from this source; for England, where the proportion grew over time,

[31] The cloth market was highly integrated, for, as Munro reports, the cost of shipping woollens between the North Sea and Mediterranean ports was 15% of their value and often less during the fourteenth century: Munro, 'English "new draperies"'.

[32] Pounds, *Historical geography*, p. 335.

Wordie's estimates have been used with slight adjustment to match the dates in the dataset.[33] Including ENCL in cross-national regressions explaining agricultural productivity provides a focused test of England's most distinctive rural institution.

Some countries were successful in the race for empire, while others were not. Spain seized a vast empire in Latin America and the Philippines; England acquired much of North America, some rich sugar islands in the Caribbean, and Bengal; the Netherlands conquered Indonesia, the original Spice Islands and Surinam; and France had important possessions in North America, the Caribbean, and India. Portugal had a substantial empire in Brazil, Africa, and South Asia but is not in the database analysed here. The other European countries were not in the running.

The effect of empire is measured by TRADEPOP, the volume of non-specie trade per caput.[34] All of the countries were mercantilist and tried to reserve trade with their colonies for their nationals. The experience of the Dutch is the exception that proves the rule. They were highly efficient in shipping and came closest to being free traders in the Atlantic economy (but not in the Asian). However, the Dutch were squeezed out of most Atlantic colonial trade by the regulations of the English, French, and Spanish. Only in times of war could the Dutch make much headway.[35] Many factors affect trade volumes, but the experience of the Dutch shows the primacy of politics in this period, and this is why trade is treated as an exogenous measure of imperial advantage.

It should be noted that trade volumes are measured exclusive of shipments of gold and silver. This affects the measurement of Spanish trade where bullion was the main cargo. While the Dutch and, especially, the English empires offered trade and markets, the Spanish may have been too successful in generating loot: the gold and silver from the Americas inflated prices and wages in Spain, rendering much manufacturing unprofitable.[36] The effects of the Spanish empire are tested in some specifications by including a dummy variable SPANEMP.

The early modern period saw the invention and spread of printing with movable type, an increase in book publishing, and a concomitant rise in the ability to read and write. The proportion of the population that could sign its name has been established for most parts of Europe in the seventeenth and eighteenth centuries, and provides a rough indi-

[33] Wordie, 'Chronology of enclosure'.

[34] Trade volumes were derived from Deane and Cole, *British economic growth*, p. 87; Levasseur, *Histoire*, I, p. 18, II, pp. 20-2, 94-6; Haudrere, *La Compagnie française*, IV, p. 1201; Villiers, 'Slave and colonial trade', p. 211; de Vries and van der Woude, *First modern economy*, pp. 393, 445, 460, 474, 478; Garcia Fuentes, *El comercio español*; Morineau, *Incroyables gazettes*, pp. 267, 494; Hamilton *American treasure*, pp. 33-4; Fisher, *Commercial relations*, pp. 67-8; *idem*, *Economic aspects*, pp. 164-70, 201-6. The English imports and exports for the eighteenth century were valued with prices of *c*. 1700, so they are quantity indices. Prices of linen and sugar were used to convert the values of exports and imports, respectively, for other countries to sterling values of 1700 comparable with the English values. For the sources of the prices, see Allen, 'Great divergence'.

[35] De Vries and van der Woude, *First modern economy*, pp. 476-9.

[36] Hamilton, *American treasure*; *idem*, *Money, prices, and wages*; *idem*, *War and prices*.

Table 2. *Adult literacy, 1500-1800*

	1500 %	*1800* %
England	6	53
Netherlands	10	68
Belgium	10	49
Germany	6	35
France	7	37
Austria/Hungary	6	21
Poland	6	21
Italy	9	22
Spain	9	20

Notes and sources: Literacy is taken as the ability to sign one's name. Figures for 1500 are estimated from the rural-urban breakdown. Rural population is assumed to be 5% literate. This is suggested by later data from Nalle, 'Literacy and culture', p. 71, and Houston, *Literacy*, pp. 140-1, 152-3, for Spain; Wyczanski, 'Alphabetisation', p. 713, for Poland; Le Roy Ladurie, *Peasants*, pp. 161-4, for Languedoc; Graff, *Legacies of literacy*, p. 106, for England.

Urban population is assumed to be 23% literate, generalizing from the estimate for Venice in 1587 given in Grendler, *Schooling*, p. 46, that 33% of the men and between 12.2% and 13.2% of the women were literate. The proportion was of the same order in Valencia (Nalle, 'Literacy and culture', p. 71), and among the nobles and bourgeoisie of Poland (Wyczanski, 'Alphabetisation', p. 713), and perhaps a little lower in fifteenth-century London (Graff, *Legacies of literacy*, p. 106). Because of the limited urbanization of countries other than Spain and Italy at this time, the urban literacy rate has no discernible impact on the national average.

Data are fuller for the seventeenth and eighteenth centuries and are taken from: Nalle, 'Literacy and culture'; Houston, *Literacy*; Graff, *Legacies of literacy*; Cressy, *Literacy and social order*; *idem*, 'Levels of literacy'; Viñao Fraga, 'Literacy in Spain'; Grendler, *Schooling*; Ruwet and Wellemans, *L'analphébetisme*; Wyczanski, 'Alphabetisation'; Furet and Ozouf, *Lire et écrire*; Gelabert, 'Niveaux d'alphabetisation'; de Vries and van der Woude, *First modern economy*; Park 'Education revolution?'; Chartier, *Lectures et lecturers*; Cipolla, *Literacy and development*; Kuijpers, 'Lezen en schrijven'; Larguie, 'L'Alphabetisation des Madrileños'.

cator of literacy (table 2). Data for 1500 are less satisfactory, but literacy was clearly far lower at that date, no matter how the material is processed. Literacy increased in all parts of Europe during the subsequent three centuries, but especially in the north where economic growth was most pronounced. Casual speculation suggests that the ability to read and write contributed to technological progress, and this opinion draws some strength from the studies of twentieth-century economic growth that identify schooling and human capital as important causes.[37] Could the same have been true of the pre-industrial economy? The answer appears to be negative, and this is why literacy does not appear in figure 3.

European political systems varied enormously between 1300 and 1800. The model here follows the classification of De Long and Schleifer who have distinguished 'princes' (absolutist monarchs) from more representative and other systems.[38] Medieval Italy, the Dutch Republic, and eighteenth-century England were the classic 'representative' states. Most of the rest were ruled by absolutist 'princes'.[39]

[37] The discussion is voluminous and runs from Denison, *Sources of economic growth*, to Barro, *Determinants*.

[38] De Long and Schleifer, 'Princes and merchants'.

[39] Ibid. Implicitly, these authors have classified Napoleon as a prince. This article does likewise. In 1800, therefore, France and the Netherlands (at that time a dependency of France) are placed in the 'prince' category.

DeLong and Schliefer did not categorize Poland, but it is necessary to do so for the present analysis. Poland is an interesting case, for its government was representative with an exceptionally weak monarch until its dismemberment, which was completed in the 1790s. For the periods before 1800, therefore, Poland is placed in the 'non-prince' category; in 1800 it is assigned to the 'prince' category, for Russia, Prussia, and Austria were all absolutist states.

III

Five equations explain the five endogenous variables—the real wage, agricultural productivity, urbanization, proto-industrialization, and the population. Since the first four of these comprise a simultaneous system, they are estimated by two-stage least squares (instrumental variables). The instruments are all the exogenous variables in the model—LNTL, TRADEPOP, SPANEMP, ENCL, ENG18, LIT, MANPROD, PRINCE, LNURBLG, and the constant. All of these variables are defined in this section. All equations are exactly identified or over identified by the order condition. The four equations solved simultaneously in each period are considered next, and then the equation explaining population growth.

The wage equation is key, for the divergence between north and south is ultimately a question of labour income. Figure 5 defines the problem. D is the demand curve for labour in pre-industrial society. Since the land area is fixed, diminishing returns to labour implies that a larger population can be employed only if the wage falls. For that reason, the demand curve slopes downwards. S represents the supply of labour, which is shown as inelastic (equivalent to the population) for simplicity. With S at a low level, the wage is high at w. In most of Europe, the population expanded between 1500 and 1800, and the wage fell from w to w_1 as shown in figure 5. In the successful economies, however, the story was different. There the demand curve for labour shifted to the right (to D_1) in step with the population growth. As a result, the wage remained at w. The key question in early modern economic history is why the demand curve for labour grew in a few countries and remained constant in the rest. Answering that question will explain the great divergence in incomes that occurred in the early modern period.

The demand curve in figure 5 shifts to the right if capital per worker increases or if efficiency rises. The model can be implemented empirically by choosing proxies for these variables. Regression 1 in table 3 provides a basic specification in which the wage[40] depends on two variables

[40] The wage is the daily wage of a craftsman converted to constant purchasing power with an international inter-temporary consumer price index. The sources of most wages and prices, and the consumer price index, are described in Allen, 'Great divergence'. The English wage is an average of London, southern towns, and northern towns. The series for southern English towns is that of Phelps Brown and Hopkins, 'Building wages', and for northern English towns, Woodward, *Men at work*, is used. For the fifteenth, sixteenth, and seventeenth centuries the York series was used, but it did not differ materially from any of the other northern series; for the eighteenth century the source was the Lancashire wages in Gilboy, *Wages*. All of the English wage series were deflated with the same consumer price index.

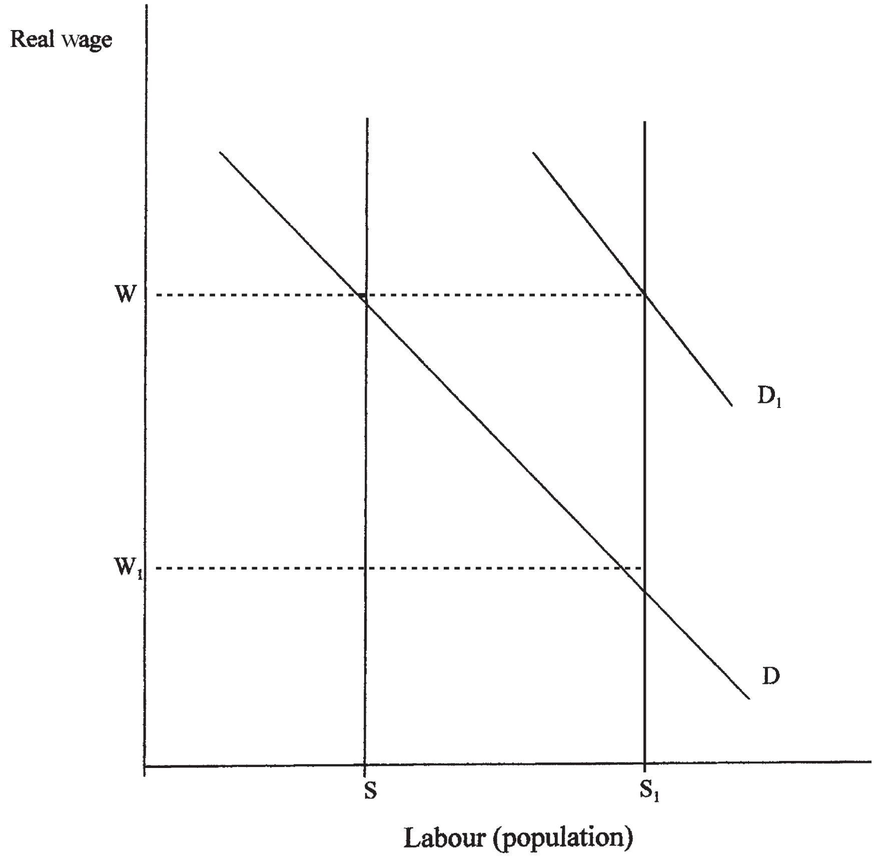

Figure 5. *The supply of and demand for labour*

indexing efficiency and capital per worker—the logarithm of total factor productivity in agriculture (LNAGTFP) and the log of the urbanization rate (LNURB)—as well as on the log of the land-labour ratio (LNTL). The last of these captures the fall-off in productivity as population presses more heavily on the resource base. This effect explains the downward slope of the demand curve in figure 5. The coefficients of all variables are positive and statistically significant, as expected, and the equation fits the data reasonably well.

More variables are added to the basic regression in other specifications. Regression 2 contains PRINCE, a dummy variable equalling 1 for absolutist monarchies. Its coefficient is negative but very small and statistically insignificant, indicating that absolutism had a negligible impact on the demand for labour. Regression 3 includes LIT (the proportion of the adult population that could sign its name), TRADEPOP (intercontinental commodity trade per caput), and LNPROTO (the proportion of the population engaged in rural, non-agricultural activities). None of these variables was statistically significant. It is particularly important that

Table 3. *Wage equation*
(*t*-ratios in parentheses)

regression	1	2	3
dep. var.	LNWAGE	LNWAGE	LNWAGE
estimator	IV	IV	IV
LNTL	.42	.40	.20
	(5.84)	(4.58)	(1.69)
LNURB	.23	.23	−.11
	(3.24)	(3.18)	(−.60)
LNAGTFP	.60	.54	1.03
	(2.68)	(1.98)	(3.25)
PRINCE		−.03	−.09
		(−.43)	(−1.08)
LNPROTO			−.66
			(−1.81)
LIT			−.01
			(−.02)
TRADEPOP			−.03
			(−.03)
constant	−.86	−.66	−.84
	(−1.51)	(−.88)	(−.83)
R^2	.60	.59	.65

Notes: The dependent variable is the real wage.

neither representative government nor literacy shifted the demand for labour to the right.

There are two approaches to explaining the growth in agricultural productivity. The traditional view, discussed above, attributes agricultural revolutions to the 'modernization' of rural institutions. This approach, however, has been called into question by the micro studies which have shown that rural institutions did not influence efficiency. If agrarian institutions, which limit the responsiveness of agriculture to new opportunities, do not explain why some countries were more productive than others, differences in the challenges faced by agriculture may explain the variation in performance. The second approach attributes high agricultural productivity to the growth of the non-agricultural economy. Large cities and rural industries increased the demand for food, flax, wool, leather, and labour, thereby providing an incentive to farmers to modernize their methods. Von Thünen noticed that agriculture was more intensive near cities, and the second approach generalizes that observation into a theory of agricultural development.[41] Hence, the growth of the non-agricultural economy may explain agricultural productivity.

This article measures the relative importance of agrarian institutions and the non-agricultural economy in raising farm efficiency by including

[41] Grantham, 'Diffusion of new husbandry'; *idem*, 'Agricultural supply'; Campbell, *English seigniorial agriculture*, pp. 411-40.

Table 4. *Agricultural productivity equation*
(*t*-ratios in parentheses)

regression	1	2	3	4
dep. var.	LNAGTFP	LNAGTFP	LNAGTFP	LNAGTFP
estimator	IV	IV	IV	IV
LNURB	.27	.24	.23	.50
	(5.67)	(4.61)	(4.27)	(1.84)
LNPROTO	.55	.43	.50	1.19
	(4.39)	(3.07)	(3.05)	(1.73)
LNWAGE	.47	.33	.44	.50
	(3.02)	(1.90)	(2.00)	(1.35)
ENG18				−.31
				(−1.04)
ENCL		.19	.18	.35
		(1.55)	(1.53)	(1.36)
PRINCE			.06	.05
			(.85)	(.37)
LIT				−1.28
				(−1.01)
constant	.63	.58	.40	2.16
	(2.03)	(1.98)	(1.10)	(1.22)
R^2	.53	.57	.58	.29

Notes: The dependent variable is total factor productivity in agriculture; see app. II.

indicators of both in the statistical model. In table 4, regression 1, TFP in agriculture is regressed on LNURB, LNPROTO, and LNWAGE. They are indices of the growth of the non-agricultural economy. All have positive and statistically significant coefficients. Larger values for the first two variables indicate greater demands on agriculture for food and fibre, while higher wages provide an incentive to shed low productivity jobs or to increase efficiency in other ways in order to generate enough net income to keep the farm labour force from migrating to the city. Regression 1 substantiates the view that a larger non-agricultural economy induced an increase in farm efficiency.

The role of agrarian institutions in limiting the response to these demands is ascertained by including two additional variables in equations 2-4. The first is ENCL, the proportion of land enclosed. Its coefficient was usually about .18. ENCL was statistically significant at about the 15 per cent level, which is low by most standards. There is, however, much to be said in favour of the coefficient. The value of .18 implies that the TFP of enclosed farms was 18 per cent higher than that of open fields. If rent accounted for one-third of revenues, then enclosure would have boosted rent by 64 per cent, e.g. a rise from 12 shillings to 20 shillings per acre. This result is consistent with rent differences similar to those observed in some districts in the south midlands but rather higher than Clark's recent findings.[42] Arthur Young would have been enthusiastic about the regression coefficient, for it is close to the doubling he often

[42] Allen, *Enclosure*, p. 172; *idem*, 'Tracking'; Clark, 'Commons sense'.

Table 5. *Urbanization equation*
(*t*-ratios in parentheses)

regression	1	2	3	4	5
dep. var.	LNURB	LNURB	LNURB	LNURB	LNURBCON
estimator	IV	IV	IV	IV	IV
LNAGTFP	.45		.31	.58	
	(2.32)		(1.47)	(.60)	
TRADEPOP		.16	.10	.10	
		(2.53)	(1.40)	(1.06)	
SPANEMP				.20	
				(.89)	
PRINCE				.02	.01
				(.22)	(.33)
LIT				−.10	
				(−.25)	
MANPROD				−.08	
				(−.13)	
LNURBLG	.82	.90	.84	.77	
	(13.77)	(23.06)	(14.49)	(5.00)	
constant	−.39	−.19	−.35	−.46	
	(−2.67)	(−2.20)	(−2.47)	(−1.35)	
R^2	.90	.92	.91	.89	.01

Note: The dependent variable in regressions 1–4 is the rate of urbanization. The dependent variable in regression 5 is LNURBCON = LNURB −.14*TRADEPOP −.79*LNURBLG −.41*LNAGTFP +.46. The values of the independent variables in this equation are thus constrained to the values in the definition of LNURBCON.

spoke of. Despite the low *t*-ratios, ENCL is included in the model both as a tribute to Young and to make sure that enclosure gets its due.

The second variable representing agrarian institutions was ENG18, a dummy variable equalling one for England in the eighteenth century, at the time when its distinctive agrarian institutions—great estates, large-scale farms, and landless labourers—reached their fully developed form. If they mattered, presumably, they would have pushed the efficiency of England above the level implied by the other variables. However, the coefficient of ENG18 is always negative, close to zero, and statistically insignificant. This finding contradicts the importance of England's eighteenth-century institutions as a source of agricultural improvement.

Finally, PRINCE and LIT were included to see whether they had any observable effect on growth in agricultural productivity. They did not, in any specification.

The proportion of the population living in cities changed very little in many countries during the early modern period, while rising in the Netherlands and, especially, in England. It is difficult to find one equation that captures both stasis and dynamism.[43] The problem is made more difficult by the collinearity among important variables in north-western Europe. This is a bigger problem for this equation than for the others.

Table 5 reports regressions that explain Europe's urbanization rate. The

[43] Magisterial overviews of European urbanization are provided by De Vries, *European urbanization*, and Bairoch, *La Population*. For recent surveys of English urbanization in this period, see Sweet, *English town*; Chalklin, *English town*; Ellis, *Georgian town*.

lagged urbanization rate LNURBLG is included in all equations to account for the persistence of cities, as will be explained below. LNAGTFP is introduced as an explanatory variable since a highly productive agriculture might have nurtured cities by providing them with food, raw materials, capital, and labour. TRADEPOP is included to measure the contributions of American and Asian empires, and SPANEMP to detect any further effects of the Spanish empire. PRINCE and LIT measure the impact of absolutism and of literacy on urbanization. MANPROD measures the productivity of the new draperies relative to traditional woollen cloth and hence the productivity advantage of northern textiles.

The log of the urbanization rate lagged by a century (LNURBLG) is a significant variable in all regressions with a coefficient of about .8. Lagged urbanization captures the persistence of city size since its coefficient means that the urban proportion would have been 80 per cent of its value a century earlier if nothing else had caused it to change.

Persistence represents several social processes. The most common case was countries such as Austria or Germany where the proportion of city dwellers was low and remained so—in other words, where growth was modest. A more interesting case is Italy where the accumulation of social capital allowed cities to renew themselves even when their economic base collapsed. In the middle ages, a major Italian industry was woollen cloth. When its manufacture was destroyed by the exports of the new draperies from northern Europe the Italian cities did not disappear. Instead, their economies were recreated on the basis of silk. This involved raising silkworms in the countryside as well as weaving silk cloth in the city. Although different technical skills were involved, business skills and networks were carried over from wool production. Italians showed tremendous enterprise in the seventeenth century, but they encountered difficulties also, and the economy as a whole did not advance.

The proportion of city dwellers also remained high in Spain throughout the early modern period, but for a different reason. The manufacturing industries that sustained the medieval cities were destroyed by the inflation caused by imports of American bullion. Their population losses were counterbalanced by the growth of Madrid as American treasure was used to build the capital.[44] These very different histories are summarized by the inclusion of the lagged urbanization rate.

Lagged urbanization does not, of course, explain the urban revolutions in England and the Netherlands. Equation 1 indicates that higher agricultural productivity significantly increases urbanization, and equation 2 indicates the same thing for intercontinental commodity trade. However, as equation 3 shows, these variables are highly correlated so they are not jointly significant. Adding PRINCE, LIT, SPANEMP, and MANPROD makes no significant contribution to the explanation (equation 4).

The collinearity problem was addressed on the basis of subsidiary simulations. They indicated that the various national histories could be successfully tracked if the coefficients of LNAGTFP, LNURBLG,

[44] Ringrose, *Madrid*.

TRADEPOP, and the intercept were set to the values noted in table 5. These are all within a standard error of their values in the rest of the table. Equation 5 shows the value implied for the coefficient of PRINCE if these restrictions are imposed, and that is also very close to its unconstrained value. Consequently, in subsequent simulations, equation 5 is used for urbanization. With this specification, urbanization depends on its lagged value, agricultural productivity, the volume of intercontinental trade, and PRINCE, the dummy variable coding absolutism. The last is not statistically significant but is included, as in the other equations, to give the representative government argument the best possible run for its money.

Proto-industry was not a direct determinant of labour demand, but it influenced wages and other variables through its impact on agricultural productivity. Proto-industry had contradictory causes that reflect its ambiguous role in early modern development. On the one hand, there were large rural manufacturing industries in the leading economies, and these industries played an important role in economic growth. The English woollen cloth industry is a case in point. On the other hand, many rural industries developed in backward regions and left no legacy for industrialization.

The dual nature of proto-industry is reflected in the statistical analysis of its causes (table 6). The negative coefficient of LNAGTFP means that proto-industrialization was a consequence of low agricultural productivity rather than of high productivity: it was often the occupation of poor peasants practising a backward agriculture as in central Europe (table 1). The negative coefficient on LNWAGE conveys the same lesson.

Why, then, was there a proto-industrial revolution in north-western

Table 6. *Proto-industry equation*

(*t*-ratios in parentheses)

regression	1	2	3
dep. var.	LNPROTO	LNPROTO	LNPROTO
estimator	IV	IV	IV
LNAGTFP	−1.14	−.93	−.94
	(−1.98)	(−1.58)	(−.83)
LNWAGE	−.84	−1.00	−1.01
	(−3.67)	(−4.02)	(−1.63)
MANPROD	1.48	1.27	1.36
	(3.29)	(2.76)	(2.59)
PRINCE		−.18	−.17
		(−1.50)	(−.99)
LIT			−.14
			(−.10)
TRADEPOP			.01
			(.08)
SPANEMP			(−.08)
			(−.20)
constant	−1.41	−.80	−.83
	(−2.01)	(−.99)	(−.57)
R^2	.37	.40	.40

Notes: The dependent variable is the rate of proto-industrialization.

Europe? Table 6 shows that MANPROD, which indexes the growth in productivity in the new draperies, offset the depressing effect of high-productivity agriculture. The proximate cause of north-western Europe's proto-industrial revolution was, thus, quite different from the cause of its urban revolution. The former was due to rising productivity in textile manufacturing in the sixteenth and seventeenth centuries, and the latter was due, in the first instance, to empire. Manufacturing productivity did not directly promote urban growth, nor did empire promote rural manufacturing. It should be emphasized, however, that these are 'first-round' effects. Allowing for feedback between the sectors means that all exogenous variables affected urbanization and proto-industrialization, sometimes in dramatic ways.

Equations 2 and 3 also include PRINCE. Its coefficient in these tables is larger in absolute value than in the other tables and almost statistically significant by the usual criteria. This is the strongest evidence that absolutism depressed economic development, and equation 2 will be used in simulations to assess its impact. LIT is included in equation 3, and it remains insignificant.

With the data at hand, it is impossible to explore the determinants of fertility and mortality separately; only the overall impact of wages on population change can be examined. As a first step, the population growth rate over a century was graphed against the real wage at the beginning of that century. Century data are of much lower frequency than the annual data usually used in such investigations, but the wage and population cycles extend over periods of several centuries, so century data can reveal the elements of the system.[45]

Graphical analysis revealed two very different demographic regimes. In England and the Netherlands, population growth clearly rose with the wage—these countries, in other words, exhibited the Malthusian preventive check. The rest of the continent did not: no relationship was discernible between population growth and wages. It may be that other data would reveal Malthusian behaviour, but it is not apparent here.

The graphical analysis was extended with regression models of population growth. Table 7 shows regressions for England and the Netherlands as well as for the rest of Europe. Mendels's view that proto-industrialization caused population growth[46] was tested with these data by including the proto-industrial share of the population as an explanatory variable, but it was never significant. Other variables included in the regressions are the wage rate, the urbanization rate, and dummy variables for the Black Death (DBD), the Thirty Years War (D30), and the Netherlands (DN). Urbanization is included in recognition of the very high mortality rate in cities.[47] The results are plausible: according to equation 2, population growth increased with the wage and decreased with urban density.

[45] For the same reason, Lee, 'Population in pre-industrial England', analysed English data at 50-year intervals.

[46] Mendels, 'Proto-industrialization'.

[47] Wrigley, 'London's importance'; van Zanden, 'Holland's economy'.

Table 7. *Population growth equations*

(*t*-ratios in parentheses)

regression	1	2	3	4	5
region	Eng/Neth	Eng/Neth	Eng/Neth	cont	cont
dep. var.	POPGROW	POPGROW	POPGROW	POPGROW	POPGROW
CONSTANT	−.47	.15	.43	1.27	1.28
	(−.89)	(.29)	(1.11)	(15.88)	(15.72)
WAGE	.21	.16	.14	−.0042	−.0016
	(3.13)	(2.65)	(2.65)	(−.44)	(−.14)
URBRATE	.68	−.62	−1.58		−.16
	(.44)	(−.43)	(−2.20)		(−.57)
DBD		−.58	−.68	−.52	−.51
		(−2.00)	(−2.70)	(−2.79)	(−3.52)
DN	−.64	−.30			
	(−1.53)	(−.80)			
D30				−.21	−.21
				(−1.53)	(−1.53)
R^2	.64	.80	.77	.36	.34

Notes: The dependent variable is the ratio of the population at one time to its value a century earlier. Equations 1-3 were estimated for England and the Netherlands, equations 4 and 5 for the remaining continental countries.
WAGE = real wage
URBRATE = proportion of the population living in cities
DBD = dummy variable for Black Death
DN = dummy variable for the Netherlands
D30 = dummy variable for the Thirty Years War

Urban density was higher in the Netherlands than in England, and so there is some collinearity between a dummy variable for the Netherlands and urbanization. The *t*-statistic on DN in equation 2 shows it to be insignificant, so equation 3 has been used in later analysis. This gives a large, negative weight to urbanization in accounting for population change.

The rest of the continent had a different demographic regime according to this regression analysis. As equations 4 and 5 indicate, neither the wage nor urban density had an appreciable impact. The equation predicts population growth of about 24 per cent per century (0.2 per cent per annum) over much of Europe irrespective of economic conditions. The fourteenth century aside, population growth in north-western Europe varied between zero and 50 per cent per century on account of changes in the wage and in urbanization. The mean was similar, but the sensitivity to economic conditions was more Malthusian.

IV

An important test of the simulation model is to see whether it can account for the different paths of development followed by different parts of Europe. If the model is simulated from 1400 onwards, do Italy and France show falling wages and limited structural transformation? Do the Netherlands and England maintain their wages and exhibit urban and agricultural revolutions? The questions have been addressed using simulations with the five-equation version of the model in which population is endogenous and with a four-equation version in which population is

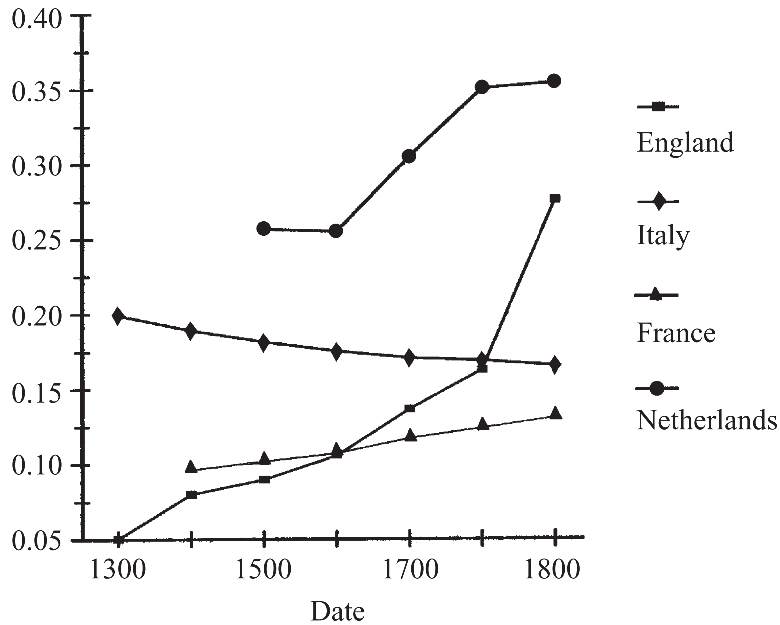

Figure 6. *Simulated urbanization rate, 1300-1800*

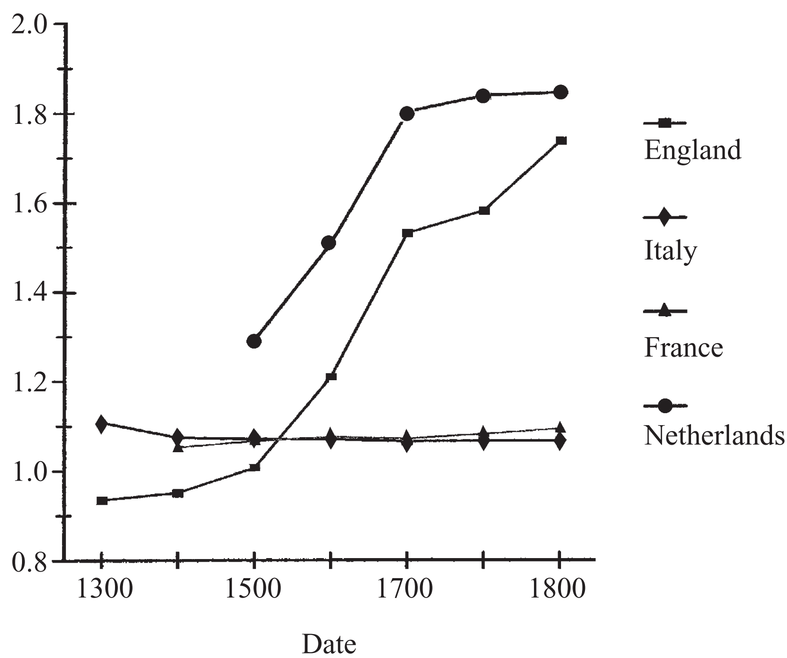

Figure 7. *Simulated total factor productivity [TFP] in agriculture, 1300-1800*

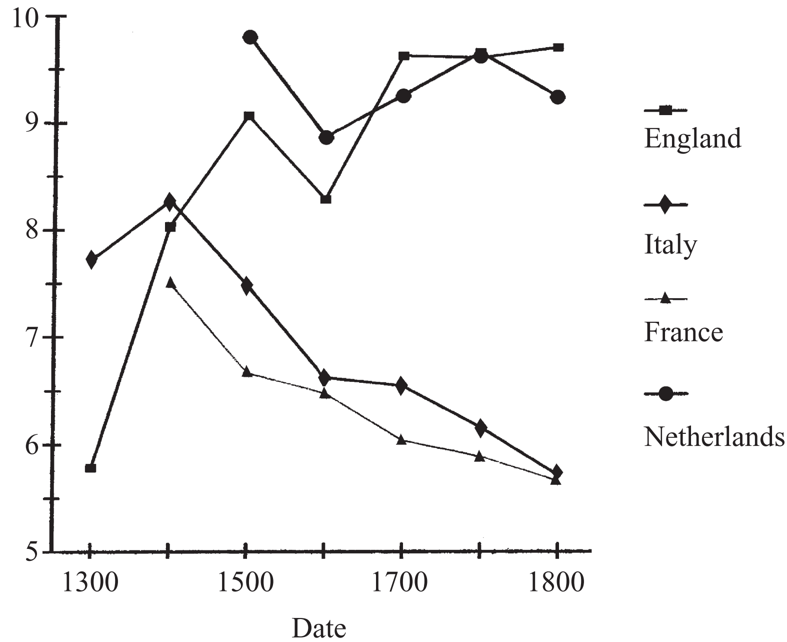

Figure 8. *Simulated real wage, 1300-1800*

treated as exogenous. The answers are similar in both cases, but the model with endogenous population introduces some erratic movements in simulated wages when there are discrepancies in simulating population. The simulations of the other variables are scarcely affected. This section concentrates on the model with exogenous population and considers the effects of endogenous population at the end of the discussion.

Figures 6-8 compare simulated trajectories for urbanization, agricultural productivity, and wages for England, Italy, France, and the Netherlands. The simulations use regression 2 in table 3, regression 3 in table 4, regression 5 in table 5, regression 2 in table 6, and regressions 3 and 4 in table 7. The simulations for France are very similar to those for Germany, Austria, and Poland. They show little cumulative urbanization, static agricultural productivity, and falling real wages. For France and the major countries of central Europe, the model predicts little economic development. The simulations for Italy and Spain are almost as bleak, although their initially higher urban shares are largely maintained.

The simulations for the Netherlands and England, on the other hand, show successful patterns of economic development. In the first place, urbanization was much more extensive. The Dutch were already more highly urbanized in 1500 than much of the continent, and the development of commerce and empire built on that base to produce the highest rate of urbanization in 1800. The English started from a much lower level of urbanization in 1500, overtook France and Italy, and almost caught up with the Dutch by 1800.

Unlike the major continental countries, both England and the Netherlands had agricultural revolutions, and the simulation model reproduces these. Revisionist historians have undermined the view that the modernization of agrarian institutions caused productivity growth in agriculture, which, in turn, spurred economic development generally. This article has taken that reassessment to its logical conclusion by modelling the growth in farm efficiency as a response to the development of the non-agricultural economy. This hypothesis works rather well. It replicates the agricultural revolutions of north-western Europe and the stagnation of productivity in much of the continent.

Urbanization, greater farm efficiency, and proto-industrialization had a pronounced impact on wages. In north-western Europe, the simulated wage remains high during the early modern period. The simulation for England shows a drop in the sixteenth century and then a rebound in the seventeenth and eighteenth centuries as economic development tightened up the labour market. This was escape from the Malthusian trap through rapid development. The contrast with most of the continent is impressive. There, simulated real wages fell as population grew and the economy stagnated.

V

The simulation model can be used to factor out the differences between successful and unsuccessful economies. This section concentrates on the comparison between England, the most successful economy, and its large continental rivals such as France and Austria. How did England maintain a high wage despite rapid population growth, while continental wages fell even though the population grew little? The possibilities—as incorporated in the model—include the replacement of absolutist by representative government in the seventeenth century, the enclosure of the open fields, the productivity advantage associated with the new draperies, and the growth in intercontinental trade consequent upon the formation of the British empire.[48] In addition, the preventive check demographic regime may have accelerated economic development. By successively removing these sources of growth and re-simulating the model, the fundamental differences between England and the continent are identified. These simulations include the ramifications of the changes throughout the economy and not simply in the sector concerned.

Figures 9-11 show alternative simulations for England of TFP in agriculture, the urbanization rate, and the real wage from 1300 to 1800. In all figures, the top line is the 'simulated actual' history of the variable, that is, the value implied by the model when it is simulated with the historical time paths of the variables describing the proportion of the land enclosed, relative textile productivity, and so forth. If the model

[48] In principle, development could also be simulated holding literacy at medieval levels. Since the sign of the coefficient of literacy was usually negative, these simulations perversely generate greater growth than actually occurred. However, they have little relevance because the negative coefficients on literacy were never statistically significant.

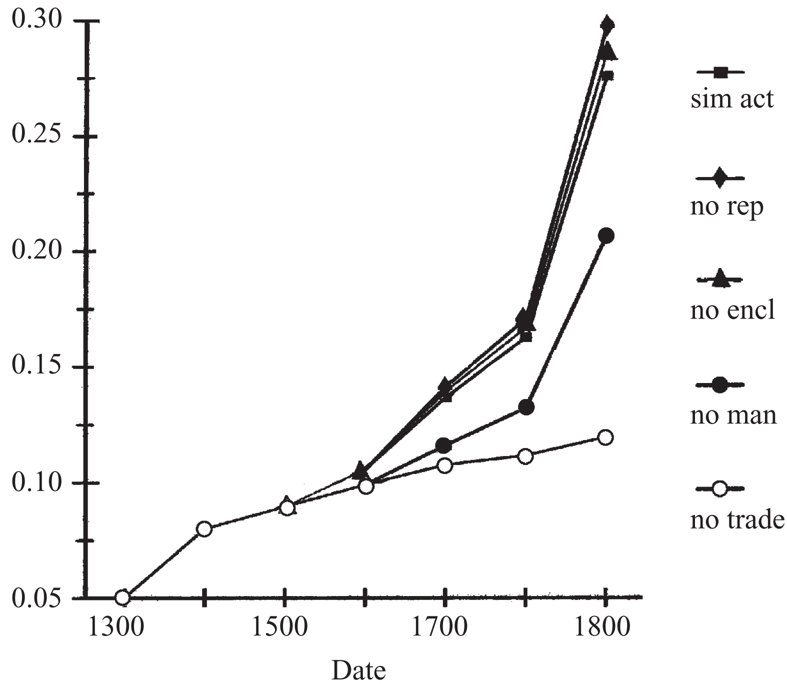

Figure 9. *Simulated urbanization rate for England, 1300-1800*
Note: The abbreviations are explained in the text

were perfect, the simulated values would equal their historical time paths. In the event, the main features are replicated.

The lower lines show the simulated value of the variables as growth-promoting factors are removed from the calculations. The line marked 'not representative' shows the course of the variable if England had remained an absolutist monarchy in the eighteenth century. The removal of exogenous factors cumulates as one moves down the graphs. Thus, the line marked 'no enclosure' keeps the proportion of enclosed land at its 1500 level, while also eliminating representative government. The difference between the 'not representative' line and the 'no enclosure' line, therefore, shows the impact of enclosure, and the difference between the 'no enclosure' line and the 'no manufacturing' line shows the effect of the new draperies. By the same reasoning, the bottom line labelled 'no intercontinental trade' shows the result of eliminating all four growth-promoting factors.

Figures 9-11 make several important points about England's success. First, the bottom lines trace out a no-growth trajectory like that of the large continental countries: little growth in agricultural productivity or in urbanization and a falling real wage. In the absence of the growth-promoting factors, in other words, the history of England would have resembled that of France, Germany, or Austria. Second, the ascendancy of parliament in the eighteenth century made little contribution to England's development. Several studies of interest rates have failed to detect any

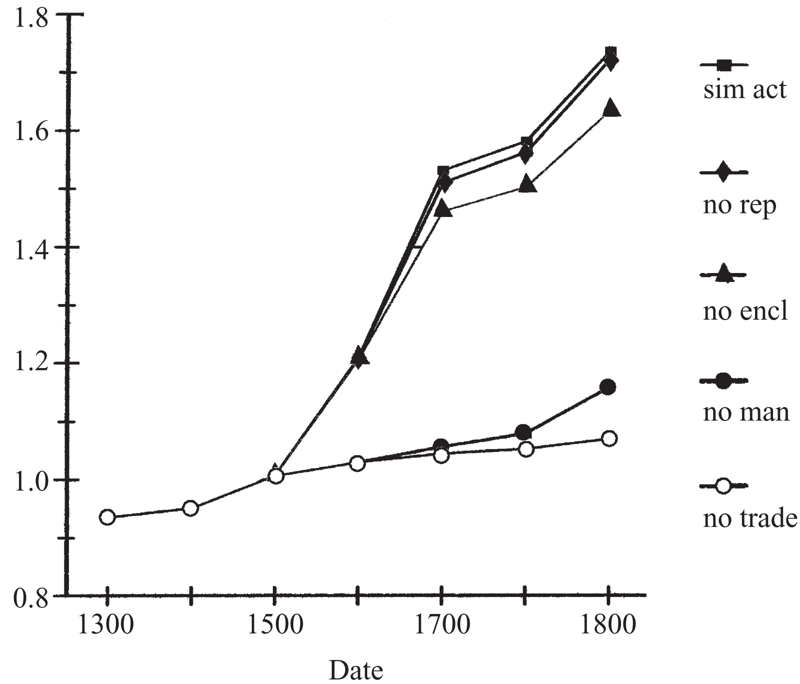

Figure 10. *Simulated total factor productivity [TFP] in English agriculture, 1300-1800*
Note: The abbreviations are explained in the text

growth-promoting result of the Glorious Revolution of 1688,[49] and the present study supports that view.

It is not surprising that representative government did not accelerate growth. Property was secure in all the leading European countries, whatever their constitution. Indeed, as Rosenthal has shown, one of France's problems was that property was too secure: the state, for instance, could not push forward profitable irrigation projects in Provence because landowners could block these initiatives in the courts.[50] Parliamentary ascendancy in England led to higher taxes than in France, contrary to the views of liberals then or now.[51] And while representative government could provide good government—England's local improvement acts are a case in point—it could also provide spectacularly bad government. The concentration of power in the diet emasculated the Polish state and ultimately destroyed it. It would be a great surprise if there were a straightforward statistical relationship between absolutism and underdevelopment, and there was not in these tests.

[49] Clark, 'Political foundations'; Epstein, *Freedom and growth*, pp. 12-37; Quinn, 'Glorious Revolution's effect'.

[50] Rosenthal, 'Irrigation in Provence'.

[51] Mathias and O'Brien, 'Taxation in England and France'; Mathias and O'Brien, 'Incidence of taxes'; Hoffman and Norberg, *Fiscal crises*; Bonney, *Fiscal state*.

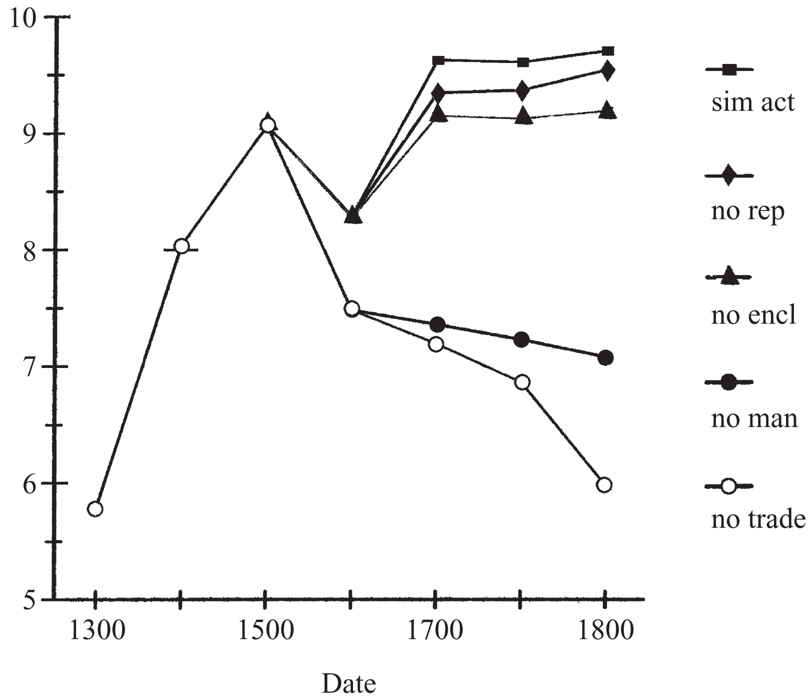

Figure 11. *Simulated real wage for England, 1300-1800*
Note: The abbreviations are explained in the text

Third, the enclosure movement made little contribution to England's progress. In all cases, the 'no enclosure' trajectory grows almost as rapidly as the 'simulated actual'. Figures 9-11 extend the findings of agricultural historians who downplay the importance of enclosure by showing that it had only a small impact on urbanization, on the real wage—and even on TFP in agriculture. This simulation includes not only the direct effect of enclosure on farm efficiency but also the feedback effect when the impact of rising farm efficiency on city growth, for instance, is taken into account. In this broad framework—as well as in the more narrowly defined study of farming methods—the enclosure movement was peripheral to English development.

The converse of this conclusion needs underlining. The success of English agriculture was a response to the growth of the urban and proto-industrial sectors and to the maintenance of a high wage economy. Farmers responded to these challenges by increasing output and by economizing on labour. The latter was effected by increasing the size of farms and by enclosing land to convert arable to pasture. To the degree that these changes, the hallmarks of the English agricultural revolution, increased productivity, they should be seen as responses to an urbanized, high wage economy rather than as autonomous causes. (Dutch agri-culture, it should be noted, developed along similar lines for similar

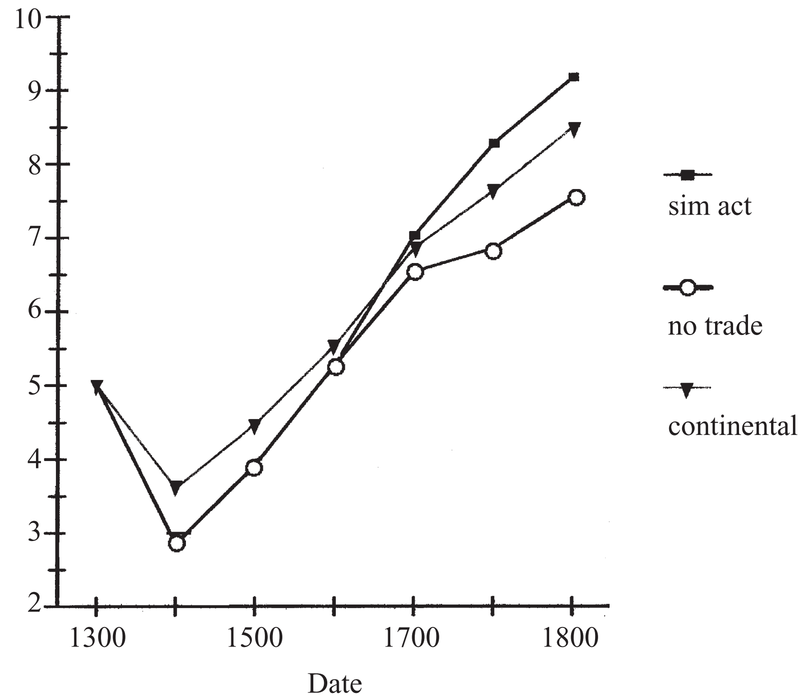

Figure 12. *Simulated population for England, 1300-1800*
Note: The abbreviations are explained in the text

reasons.) In other words, the traditional historiography should be stood on its head.[52]

Fourth, the rise in productivity underlying the success of the new draperies in the seventeenth century was of great importance for England's success. It provided a strong boost to urbanization, and the growth of rural industry. Through these effects, the success of the new draperies was responsible for a large proportion of the growth in TFP in agriculture as farmers successfully responded to the greater demand for food, wool, and labour. Without seventeenth-century success, wages, agricultural productivity, and city size would all have been lower in 1800.

Fifth, the empire established in the seventeenth and eighteenth centuries also contributed to growth. The greatest impact was on city size. Over half of England's urban expansion is attributed to empire in these simulations.

How are these conclusions affected by demographic considerations? There are two questions to consider. The first is how English population history would have been affected by changes in the development of the economy, and the second is how English history would have differed had England had a continental population regime. Figure 12 summarizes

[52] This view is not shared by Crafts and Harley, who argue that capitalist agriculture played an important role in explaining the growth of industrial employment in the British industrial revolution: N.F.R. Crafts and C.K. Harley, 'Precocious British industrialization: a general equilibrium perspective' (London School of Economics, Working Papers in Economic History, no. 67/02).

some simulations that highlight the important features. First, the rapid growth of the English economy due to the new draperies and the intercontinental trade boom had an important effect on population growth. This is indicated in figure 12 by the difference between the 'simulated actual' population history and the 'no trade' simulation, which eliminates representative government, enclosure, the new draperies, and the trade boom. Without these growth-stimulating effects, England's population would have been cut from a simulated 9.2 million in 1800 to 7.5 million. This is the expected result in a preventive check population model where population surges in response to economic expansion.

Second, the substitution of a continental demographic regime would not have had much impact on English development. With continental demography, the population would have been insensitive to the real wage and to urbanization, and so would have reached 8.5 million whatever happened to the economy. If all the growth-promoting developments occurred, the population would have remained at 8.5 million rather than rising to 9.2 million, and the real wage in England would have been somewhat higher than it actually was. There would have been very little difference in urbanization, proto-industry, or agricultural productivity. A population regime that was less responsive to economic variables would probably have benefited labour at the expense of landlords and capitalists, but would probably have had little impact on growth. Malthus and Ricardo would not have been surprised.

VI

The simulations show that a simple model captures the factors responsible for success and failure in the early modern economy. The intercontinental trade boom was a key development that propelled north-western Europe forwards. This conclusion has also been advanced by Acemoglu and his co-authors.[53] However, this article emphasizes that the ascent of north-western Europe began in the century before the American and Asian trades became important. This emphasis extends the work of historians such as Davis and particularly Rapp, who have noted that the commercial revolution began in the seventeenth century before the Atlantic trades became significant and was an intra-European reorganization in which north-west Europeans outstripped Mediterranean producers in woollen textiles.[54] On this reading of the evidence, the ascendancy of north-western Europe and the eclipse of Italy predated the rise of the Atlantic economy. The success of north-western Europe was based on a two-step advance—the first within Europe, the second in America and Asia.

This success, it might be noted, marked the first steps out of the Malthusian trap. High wages were sustainable even with pre-industrial fertility so long as the economy grew fast enough. The reason is that the population growth rate was limited to about 2 per cent per year, the

[53] Acemoglu et al., 'Rise of Europe'.
[54] Davis, 'English foreign trade'; Rapp, 'Mediterranean trade hegemony'.

difference between the maximum observed fertility rate (50 per 1,000 or 5 per cent per year) and the mortality rate, which was about 3 per cent per year in the early modern period. If the demand for labour grew faster than 2 per cent annually, wages could rise even without the fertility restraint of twentieth-century Europeans. This favourable conjuncture first occurred in England and the Low Countries in the early modern period when high wages were maintained even as the population expanded at a brisk rate. In the rest of Europe, where population grew less rapidly, wages sagged as the economy stagnated. Rapid economic development, rather than fertility reduction, was the basis of continued high wages.

The simulations reported here have some important lessons for thinking about economic growth. The dominant paradigm in economics sees sustained growth as the result of human capital accumulation and invention. These are promoted by limited government. This view receives little support from the analysis of this article.

The establishment of representative government had a negligible effect on development in early modern Europe. The stress placed on its importance links together the form of the constitution, the security of property, low taxes, and good government. These could come in many combinations, however. In England, for instance, most agricultural producers acquired the secure property that was a precondition for the agricultural revolution when royal courts created copyhold and beneficial leasehold tenures in the late fifteenth and sixteenth centuries.[55] This was judicial activism by royal officials rather than the action of parliament. Much of England's rise to pre-eminence occurred before the Glorious Revolution of 1688. The English had displaced the Italians in woollen cloth production by then, and the population of London had exploded from 55,000 in 1520 to 475,000 in 1670.[56] In eighteenth-century France, property was secure enough for the Atlantic ports to boom as a result of their involvement in intercontinental trade. Would representative government have made them grow faster? Perhaps by voting higher taxes, France could have contested mastery of the seas more successfully and expanded its empire rather than losing it. The possible gains are doubtful, however, since the population of France was three or four times that of England (and 10 times greater than that of the Netherlands), so that intercontinental trade would have needed to have been larger by the same proportion to have had the same per caput effect. French development was not held back by high taxes, the inability to enforce commercial contracts, or royal interference with private credit.[57] Good government was not cheap nor did it require a parliament.

Likewise, literacy was generally unimportant for growth. What the regression coefficients of literacy measure is its marginal value. The national adult literacy rate reached 50 per cent when labourers learned to read. Their ability probably had no economic pay-off, and Reis has argued that they

[55] Allen, *Enclosure*, pp. 55-77.
[56] Wrigley, 'Urban growth'.
[57] Hoffman et al., *Priceless markets*.

learned to read in order to study religious tracts and enjoy pulp fiction rather than as an investment.[58] The finding of a negligible economic return on the margin is consistent with literacy's having a high value to some merchants and scientists but to few others. This view is consistent with Mitch's argument that schooling had little pay-off during the industrial revolution, and Sandberg's observation that literacy was widespread in backward parts of northern Europe such as Sweden.[59]

These findings, so jarring to modern expectations, gain plausibility in the light of recent research on science and technology.[60] Mokyr, for instance, has argued that the 'knowledge economy' is a recent phenomenon. Its origins lie in the scientific revolution of the seventeenth century, but it became significant on a broad scale only in the nineteenth. Approaching the matter from a different direction, Goldin and Katz have traced the origins of 'capital-skills complementarity' to the early twentieth century.[61] Mass literacy was irrelevant to economic growth before these developments.

The results of this article are much more akin to the findings of recent work on the British industrial revolution. Crafts and Harley have argued that productivity growth was limited to agriculture and a few leading industrial sectors.[62] Most growth came from structural transformation including the remarkable release of labour from English farming. The openness of the economy to international trade was important in explaining this outcome. It might be noted that other historians—including Pomeranz, Frank, and Inikori—have also emphasized the importance of the international economy, although their theoretical frameworks are very different.[63] These conclusions all have echoes in the themes of this article.

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APPENDIX I: Data

See spreadsheet datafile.xls in table A1.
The variables are:

agland: agricultural land (thousands of hectares)
pop: population (millions)
urbpop: urban population
agpop: agricultural population

[58] J. Reis, 'Human capital, immaterial goods, and the standard of living in pre-industrial Europe' (paper delivered at a conference on new evidence on the standard of living in pre-industrial Europe and Asia, Arild, Sweden, 2000).
[59] Mitch, 'Role of human capital'; Sandberg, 'Impoverished sophisticate'.
[60] Mokyr, *Gifts of Athena*.
[61] Goldin and Katz, 'Technology-skill complementarity'.
[62] Crafts and Harley, 'Output growth'; Crafts and Harley, 'Simulating the two views'; Crafts and Harley, 'Precocious industrialization' (see above, n. 53).
[63] Pomeranz, *Great divergence*; Frank, *ReOrient*; Inikori, *Africans and the industrial revolution*.

protopop: rural, non-agricultural population
wage: real wage
agout: index of agricultural output (England in 1500 = 1)
agtfp: TFP in agriculture (see appendix II)
spanemp: dummy variable for Spanish empire
encl: proportion of agricultural land enclosed
manprod: index of productivity in textile manufacturing
urbratlg: lagged value of urbanization rate
literate: proportion of adults who were literate
eng18: dummy variable for England in eighteenth century
popgrow: ratio of population to its level a century earlier
dbd: dummy variable for Black Death in that century
d30: dummy variable for Thiry Years War in Germany
popgrowlg: lagged value of population growth
prince: dummy variable for nonrepresentative government
imports: real value of imports from Asia and Americas
exports: real value of exports to Asia and Americas
trade: imports plus exports

APPENDIX II: Total factor productivity in agriculture

TFP in agriculture was estimated as follows. First, the logarithm of output per agricultural worker was regressed on the logarithm of the land-labour ratio for those 41 observations in which productivity was manifestly low. Excluded were all observations for Belgium, the Netherlands, and for England in 1700, 1750, and 1800. The estimated regression was:

$$\begin{aligned} \text{lnlp} = {} & -3.19 + .29^{*}\text{lntagl} \\ & (-7.82) \quad (5.75) \end{aligned}$$

In this equation lnlp is the logarithm of output divided by the agricultural population and lntagl is agricultural land divided by the agricultural population. The *t*-ratios are shown in parentheses. R^2 was .45. This equation was used to predict output per worker for all observations in the sample including those excluded from the estimation. The index of TFP in agriculture is the ratio of actual output per worker to output per worker predicted by the regression equation.

Ideally, capital per worker should also be included as an independent variable in this regression, but data to measure it are not available for all of the countries and time periods. However, when the productivity indices derived here can be compared with indices of TFP based on fuller information, there are no major discrepancies.[64] That is the warrant for referring to these productivity indices as TFP.

Table A1 begins overleaf.

[64] e.g. for England as in Allen, 'Tracking'.

Table A1. *Datafile*

Country	*year*	*agland*	*pop*	*urbpop*	*agpop*	*protopop*	*wage*	*agout*	*agtfp*	*spanemp*	*encl*	*manprod*
Germany	1400	20879	7	0.78	4.976	1.244	9.4	2.311579	1.030026	0	0.25	1
	1500	20879	10.5	0.86	7.712	1.928	9.5	3.08313	1.000846	0	0.25	1
	1600	20879	12.5	1.06	8.6944	2.7456	5.2	2.699845	0.803655	0	0.25	1
	1700	20879	13	1	8.64	3.36	3.9	2.469117	0.738317	0	0.25	1
	1750	20879	16	1.4	10.22	4.38	3.9	3.01759	0.799159	0	0.25	1
	1800	20879	21.5	2.02	13.2464	6.2336	4.1	4.716973	1.035621	0	0.25	1
Spain	1400	21883	6	1.58	3.536	0.884	10.1	1.933762	1.088806	0	0.2	1
	1500	21883	7.5	1.38	4.896	1.224	10.7	2.370132	1.054748	0	0.2	1
	1600	21883	8.7	1.85	5.48	1.37	7.8	2.243574	0.920317	1	0.2	1
	1700	21883	8.6	1.75	5.4115	1.4385	9	2.552534	1.056617	1	0.2	1
	1750	21883	9.6	2.05	5.9645	1.5855	8.4	2.537206	0.978935	1	0.2	1
	1800	21883	13	2.54	8.2634	2.1966	6.3	3.110416	0.948114	1	0.2	1
France	1400	34567	12	1.29	8.568	2.142	7.5	3.498912	0.91537	0	0.5	1
	1500	34567	17	1.49	12.408	3.102	8.7	5.630037	1.126968	0	0.5	1
	1600	34567	19	2.05	12.882	4.068	6.8	4.98534	0.971236	0	0.5	1
	1700	34567	22	2.7	13.896	5.404	6.3	5.607982	1.034302	0	0.5	1
	1750	34567	24.5	3.11	14.973	6.417	5.4	6.475272	1.13152	0	0.5	1
	1800	34567	28.3	3.65	16.762	7.888	5.7	7.475945	1.204022	0	0.5	1
Italy	1300	20905	11	2.29	6.968	1.742	6.9	2.723976	0.951219	0	0	1
	1400	20905	8	1.93	4.856	1.214	7.75	2.344516	1.062936	0	0	1
	1500	20905	10	2.21	6.232	1.558	8.2	2.674996	1.012625	0	0	1
	1600	20905	13.3	3	8.034	2.266	7.99	3.627469	1.142844	0	0	1
	1700	20905	13.4	3.03	7.8812	2.4888	6.95	3.474022	1.1098	0	0	1
	1750	20905	15.5	3.49	9.1276	2.8824	5.1	3.445574	0.989866	0	0	1
	1800	20905	18.5	4.06	10.6856	3.7544	3.3	3.265904	0.83722	0	0	1
Austria[a]	1400	18619	5.4	0.28	4.096	1.024	13.5	2.227734	1.179479	0	0.2	1
	1500	18619	6.6	0.32	5.024	1.256	10.9	2.459897	1.12364	0	0.2	1
	1600	18619	8	0.39	5.6314	1.9786	4.2	1.767712	0.743513	0	0.2	1
	1700	18619	9.2	0.44	5.9568	2.8032	5.3	2.375581	0.959423	0	0.2	1
	1750	18619	10.7	0.78	6.5472	3.3728	6.5	3.210348	1.210937	0	0.2	1
	1800	18619	14	1.11	7.9918	4.8982	5.1	3.523441	1.150638	0	0.2	1

Note: a Austria includes Hungary and Czechoslovakia

Table A1. *Datafile, continued*

Country	*year*	*agland*	*pop*	*urbpop*	*agpop*	*protopop*	*wage*	*agout*	*agtfp*	*spanemp*	*encl*	*manprod*
Poland	1400	20403	2.75	0.12	2.104	0.526	9	1.148022	0.959225	0	0	1
	1500	20403	4	0.24	3.008	0.752	8.2	1.496169	0.965448	0	0	1
	1600	20403	5	0.38	3.3726	1.2474	6.5	1.432637	0.851068	0	0	1
	1700	20403	6	0.26	3.7884	1.9516	5.2	1.924188	1.050931	0	0	1
	1750	20403	7	0.31	4.1478	2.5422	6.7	2.0884	1.068279	0	0	1
	1800	20403	9	0.43	5.0563	3.5137	3.8	2.930787	1.299189	0	0	1
England	1300	13798	5	0.22	3.824	0.956	5.9	1.651504	0.998477	0	0.45	1
	1400	13798	2.5	0.2	1.84	0.46	7.8	0.917306	0.941125	0	0.45	1
	1500	13798	2.5	0.18331	1.853352	0.463338	9.3	1	1.020617	0	0.45	1
	1600	13798	4.408602	0.425	3.027538	0.956065	5.5	1.22625	0.877734	0	0.47	1.35
	1700	13798	5.208333	0.8841	2.853994	1.470239	6.9	1.779346	1.329161	0	0.71	1.7
	1750	13798	6.041667	1.39412	2.695577	1.95197	8.8	2.248834	1.75067	0	0.75	1.7
	1800	13798	9.0625	2.60838	3.22706	3.22706	7.5	2.47054	1.688644	0	0.84	1.7
Netherlands	1500	2306	0.95	0.28	0.536	0.134	11.4	0.312059	1.281979	0	1	1
	1600	2306	1.5	0.52	0.7252	0.2548	9.5	0.416902	1.376459	0	1	1.35
	1700	2306	1.9	0.74	0.7888	0.3712	9	0.532103	1.653221	0	1	1.7
	1750	2306	1.9	0.69	0.7986	0.4114	9.9	0.642213	1.977598	0	1	1.7
	1800	2306	2.14	0.73	0.8742	0.5358	8	0.682051	1.967334	0	1	1.7
Belgium	1400	1718	1	0.39	0.5795	0.0305	12.1	0.456203	1.921865	0	0.5	1
	1500	1718	1.25	0.35	0.72	0.18	11.7	0.540278	1.945474	0	0.5	1
	1600	1718	1.5	0.44	0.7844	0.2756	11.6	0.53405	1.807561	0	0.5	1.35
	1700	1718	1.7	0.52	0.8024	0.3776	9.2	0.520204	1.732055	0	0.5	1.7
	1750	1718	2.3	0.51	1.1814	0.6086	10.4	0.78136	1.966903	0	0.5	1.7
	1800	1718	3	0.65	1.457	0.893	8	0.872719	1.887879	0	0.5	1.7

Table A1. *Datafile, continued*

Country	*year*	*urbratlg*	*literate*	*eng18*	*popgrow*	*dbd*	*d30*	*popgrowlg*	*prince*	*imports*	*exports*	*trade*
Germany	1400	0.1	0.06	0		0	0	1.5	1	0	0	0
	1500	0.111429	0.06	0	1.5	0	0	1.190476	1	0	0	0
	1600	0.081905	0.12	0	1.190476	1	0	1.04	1	0	0	0
	1700	0.0848	0.19	0	1.04	0	0	1.538462	1	0	0	0
	1750	0.080766	0.27	0	1.538462	0	0	1.34375	1	0	0	0
	1800	0.0875	0.35	0	1.34375	0	0		1	0	0	0
Spain	1400	0.25	0.09	0		0	0	1.25	0	0	0	0
	1500	0.263333	0.09	0	1.25	0	0	1.16	1	0	0	0
	1600	0.184	0.4	0	1.16	0	0	0.988506	1	191.3043	0	191.3043
	1700	0.212644	0.2	0	0.988506	0	0	1.060465	1	89.79592	12.6	102.3959
	1750	0.208016	0.2	0	1.060465	0	0	1.354167	1	141.9355	41.85417	183.7897
	1800	0.213542	0.2	0	1.354167	0	0		1	161.9632	137.9737	299.9369
France	1400	0.09	0.07	0		0	0	1.416667	0	0	0	0
	1500	0.1075	0.07	0	1.416667	0	0	1.117647	0	0	0	0
	1600	0.087647	0.14	0	1.117647	0	0	1.157895	0	0	0	0
	1700	0.107895	0.21	0	1.157895	0	0	1.057955	1	983	517.44	1500.44
	1750	0.115072	0.29	0	1.057955	0	0	1.155102	1	3370.506	1897.933	5268.439
	1800	0.126939	0.37	0	1.155102	0	0		1	0	0	0
Italy	1300	0.22	0.1	0		1	0	0.727273	0	0	0	0
	1400	0.208182	0.1	0	0.727273	0	0	1.25	1	0	0	0
	1500	0.24125	0.09	0	1.25	0	0	1.33	1	0	0	0
	1600	0.221	0.14	0	1.33	0	0	1.007519	1	0	0	0
	1700	0.225564	0.18	0	1.007519	0	0	1.361445	1	0	0	0
	1750	0.225841	0.2	0	1.361445	0	0	1.193548	1	0	0	0
	1800	0.225161	0.22	0	1.193548	0	0		1	0	0	0
Austria[a]	1400	0.05	0.06	0		0	0	1.222222	0	0	0	0
	1500	0.051852	0.06	0	1.222222	0	0	1.212121	0	0	0	0
	1600	0.048485	0.11	0	1.212121	0	0	1.15	1	0	0	0
	1700	0.04875	0.16	0	1.15	0	0	1.304878	1	0	0	0
	1750	0.048286	0.19	0	1.304878	0	0	1.308411	1	0	0	0
	1800	0.072897	0.21	0	1.308411	0	0		1	0	0	0

Note: a Austria includes Hungary and Czechoslovakia

Table A1. *Datafile, continued*

Country	*year*	*urbratlg*	*literate*	*eng18*	*popgrow*	*dbd*	*d30*	*popgrowlg*	*prince*	*imports*	*exports*	*trade*
Poland	1400	0.04	0.06	0		0	0	1.454545	0	0	0	0
	1500	0.043636	0.06	0	1.454545	0	0	1.25	0	0	0	0
	1600	0.06	0.11	0	1.25	0	0	1.2	0	0	0	0
	1700	0.076	0.16	0	1.2	0	0	1.088889	0	0	0	0
	1750	0.057388	0.19	0	1.088889	0	0	1.285714	0	0	0	0
	1800	0.044286	0.21	0	1.285714	0	0		1	0	0	0
England	1300	0.04	0.06	0		1	0	0.5	1	0	0	0
	1400	0.044	0.06	0	0.5	0	0	1	1	0	0	0
	1500	0.08	0.06	0	1	0	0	1.763441	1	0	0	0
	1600	0.073324	0.19	0	1.763441	0	0	1.181402	1	0		0
	1700	0.096402	0.35	1	1.181402	0	0	1.118571	0	1956	656	2612
	1750	0.127922	0.48	1	1.118571	0	0	1.5	0	3512	2094	5606
	1800	0.230751	0.53	1	1.5	0	0		0	12520	12188	24708
Netherlands	1500	0.28	0.1	0		0	0	1.578947	0	0	0	0
	1600	0.294737	0.4	0	1.578947	0	0	1.266667	0	0	0	0
	1700	0.346667	0.53	0	1.266667	0	0	1	0	1928.542	204.82	2133.362
	1750	0.367447	0.6	0	1	0	0	1.126316	0	2144.195	256.1754	2400.371
	1800	0.363158	0.68	0	1.126316	0	0		0	0	0	0
Belgium	1400	0.39	0.12	0		0	0	1.25	1	0	0	0
	1500	0.39	0.1	0	1.25	0	0	1.2	1	0	0	0
	1600	0.28	0.23	0	1.2	0	0	1.133333	1	0	0	0
	1700	0.293333	0.36	0	1.133333	0	0	1.352941	1	0	0	0
	1750	0.299542	0.43	0	1.352941	0	0	1.304348	1	0	0	0
	1800	0.221739	0.49	0	1.304348	0	0		1	0	0	0

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The Intellectual Origins of Modern Economic Growth

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The intellectual origins of the Industrial Revolution are traced back to the Baconian program of the seventeenth century, which aimed at expanding the set of useful knowledge and applying natural philosophy to solve technological problems and bring about economic growth. The eighteenth-century Enlightenment in the West carried out this program through a series of institutional developments that both increased the amount of knowledge and its accessibility to those who could make best use of it. Without the Enlightenment, therefore, an Industrial Revolution could not have transformed itself into the sustained economic growth starting in the early nineteenth century.

Economic growth was not a novelty in 1800. In a celebrated passage, Adam Smith had noted that the "annual produce of land and labour" had been growing in Britain for a long time.[1] Yet there is something distinctive in the changes that occurred in the economies of the West after the Industrial Revolution that seem to confirm our intuition that something genuinely important had happened. To be sure, technological innovations, institutional reforms, and fresh ideas do not affect the aggregate level of economic activity abruptly: they need to diffuse from region to region, from activity to activity, cross boundaries and seas, be evaluated, adapted, and refined. Their promoters have to dislodge the entrenched, persuade the

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[1] Smith, *Wealth of Nations*, pp. 365–66. Modern economic historians have reached similar conclusions. While none of their methods are uncontroversial, their unanimity seems to indicate that the "assumption" of modern economists such as Robert Lucas and Oded Galor that there was no economic growth before 1800 is a gross oversimplification. See for instance Clark, "Secret History"; and Snooks, "New Perspectives."

skeptic, and reassure the fearful. It is not surprising, therefore, that whatever we identify precisely as the Industrial Revolution after 1760 took its sweet time to start affecting GDP per capita in the West in earnest.[2]

Modern economic growth differs from the processes that Smith identified and that made Britain and the rest of Western Europe so much richer in 1700 than they had been in 1066. To the hard-nosed scholar who insists that "it was all only a matter of degree," one response is that "in economic history, degree is everything." There is a *qualitative* difference between an economy in which GDP per capita grows at 1.5 percent and one in it which grows at 0.2 percent. Another response is that it was *not* just a matter of degree. It was *qualitatively* different in at least three fundamental aspects. First, growth gradually ceased to be a niche phenomenon. Before 1750, growth had been limited to relatively small areas or limited sectors, often a successful city state, a capital of a powerful monarchy, or a limited agricultural region. These niches had to spend much of their riches to protect their possessions against greedy neighbors, real-life manifestations of Mancur Olson's "roving bandits" who often killed entire flocks of golden-egg-laying geese. After the Industrial Revolution, it became a more aggregative phenomenon, with a substantial number of economies becoming members of the much-coveted "convergence club." Second, pre-1750 growth, such as it was, was dominated by institutional change in its widest sense: law and order, the establishment of commercial relations, credit, trust, and enforceable contracts created the preconditions for wealth to expand through more efficient allocation, exchange and investment.[3] Technological change, while never quite absent, was usually too slow and too localized to assume the dominant role it was to take later. Third, premodern growth was normally not sustainable and remained vulnerable to set-backs and shocks, both man-made and natural. The economic glories of the Dutch Republic and Venice had melted away by 1800, just as those of early sixteenth century Spain had vanished by the death of Philip II.[4] In the late eighteenth century the relative contribution of technological progress to economic growth compared to other elements began to increase, and the institutional basis supporting this progress was transformed. The result was the Industrial Revolution. It may have been slow, it may have been not all that industrial and even less revolutionary, it may not even have been wholly British, but it was the taproot of modern economic growth.

[2] There is a substantial literature that asks with Jeffrey Williamson "why was economic growth so slow during the Industrial Revolution?" although the answers tend to be different from the ones given by him. See Williamson, "Why Was British Growth," pp. 687–712. For some suggested answers see Mokyr, "Editor's Introduction," pp. 12–17.

[3] See Greif, *Institutions*.

[4] De Vries and Van Der Woude. *First Modern Economy*; and Drelichman, "American Silver."

How do we explain this change? What has been missing, so far, is a full appreciation of the importance of *useful knowledge*. Economic decisions are made by individuals on the basis of certain beliefs they hold and knowledge they possess. It recent years, it has once again become "kosher" if not quite de rigueur to speak of "cultural beliefs" following Avner Greif's pathbreaking work on the emergence of institutions that made trade possible in stateless and even largely lawless societies.[5] Douglass North refers to shared cultural beliefs and as the "scaffolds" on which institutions are built.[6] But Greif and North are primarily interested in the kind of beliefs that people hold about one another, how others will behave under certain circumstances. My interest here is about the beliefs people held about their physical milieu. In my *Gifts of Athena* I refer to these beliefs as "useful knowledge," but of course they are but beliefs about the physical environment and natural phenomena, held with higher or lower degrees of unanimity and confidence ("tightness"). Yet all societies have consensus-shaping mechanisms, which determine what kind of beliefs will predominate. I suggest in what is to follow that the change in the rate and nature of economic growth in the West must be explained through developments in the intellectual realm concerning this "useful knowledge."

The short answer as to why the West is so much richer today than it was two centuries ago is that collectively, these societies "know" more.[7] This does not necessarily mean that each *individual* on average knows more than his or her great-great grandparent (although that is almost certainly the case given the increased investment in human capital), but that the social knowledge, defined as the union of all pieces of individual knowledge, has expanded. Greater specialization, professionalization, and expertization have meant that the total amount of knowledge that society controls is vastly larger than ever before. The effective deployment of that knowledge, scientific or otherwise, in the service of production is the primary—if not the only—cause for the rapid growth of Western economies in the past centuries. The huge literature that has accumulated on the topic in recent years has been ably summarized by Helpman's recent book.[8] In what follows, I propose a slightly different approach, based largely on the experience of the Western economies in the eighteenth century.

THE INTELLECTUAL ROOTS OF THE INDUSTRIAL REVOLUTION

Economic historians like to explain economic phenomena with other economic phenomena. The Industrial Revolution, it was felt for many dec-

[5] Greif, "Cultural beliefs"; and Temin, "Is it Kosher," pp. 267–87.
[6] See North, *Understanding the Process*.
[7] For a more detailed statement on this, see Mokyr, *Gifts*.
[8] Helpman, *Mystery*.

ades, should be explained by economic factors. Relative prices, property rights, endowments, demand factors, fiscal and monetary institutions, investment, savings, exports, and changes in labor supply have all been put forward as possible explanations.[9] Between the presence of coal, the Glorious Revolution, a mobile and open society, the control of a colonial empire and a powerful navy, a greedy middle class, a productive agriculture, an unusually high supply of skilled artisans and mechanics serving the private sector, and assorted other stories, a veritable smorgasbord of explanations for Britain's success has been offered. The reader is invited to pick and choose, or just pile them one on top of the other and find the explanations satisfactory by sheer quantity. Yet these approaches have all suffered from the "endogenous growth problem": none of them can carry the weight of the explanandum without relying on technological change. If technology was at the heart of the Industrial Revolution, why was it changing at a rate more rapid and on a scale more widespread than ever before, and why did it accelerate in the nineteenth century instead of fizzle out?

One possible reason why this literature has been inconclusive is that many scholars have sought the causes for the economic change in the West as something particular to *Britain*. Yet this approach might be misleading. The Industrial Revolution was a *Western* phenomenon. It was more than just a British affair, if less than a "European" affair. The causes for the differences in technological patterns and rates of development between the several European economies that by 1914 constituted the core of the convergence club is a source of a fascinating and instructive debate, but may not hold the keys to the riddle of the Industrial Revolution. Britain's position as the lead car in the Occident Express that gathered speed in the nineteenth century and drove away from the rest of the world is of tremendous interest, but it does not tell us much about the source of power. Was Britain the engine that pulled the other European cars behind it, or was the Western world like an electric train deriving its motive power from a shared source of energy? If so, what was this source?

One answer, I submit, that thus far has not received nearly enough attention from economic historians involves the intellectual changes that occurred in Europe before the Industrial Revolution. These changes affected the sphere of useful knowledge, and its interaction with the world of production. In a sense, this statement is so obvious as to be almost trivial, but the insight has been clouded by the somewhat tedious debate on the role of science in the Industrial Revolution. As economic historians have known for many years, it is very difficult to argue that the scientific revolution of the seventeenth century we associate with Galileo, Descartes, Newton, and the like had a direct impact

[9] For a full survey, see Mokyr, "Editor's Introduction," pp. 1–127.

on the pivotal technological breakthroughs of the Industrial Revolution. To be sure, a few important inventions, especially before 1800, can be directly attributed to great scientific discoveries or were dependent in some way on scientific expertise.[10] Yet the bulk of the advances in physics, chemistry, biology, medicine, and other areas occurred too late to have an effect on the industrial changes of the last third of the eighteenth century. The scientific advances of the seventeenth century, crucial as they were to the understanding of the universe, were largely peripheral to the main thrust of eighteenth-century technology that we think of as the Industrial Revolution. During the age of Enlightenment, and especially the decades after 1750, much of Europe witnessed a flourishing of interest in the application of useful knowledge to the arts and crafts, as well as to agriculture. Yet, as Charles Gillispie has remarked, in the eighteenth century, whatever the interplay between science and production may have been, "it did not consist in the application of up-to-date theory to techniques for growing and making things."[11]

True enough: in the early stages of the Industrial Revolution, many of the important advances owed little to science in a direct way. However, had technological progress been independent of what happened at the loftier intellectual level, had it consisted purely of disseminating best-practice existing procedures, standardizing them, and hoping for learning-by-doing effects, the process would eventually have run into diminishing returns and fizzled out. What was it that prevented that from happening in the decades following the burst of macroinventions we identify with the classic Industrial Revolution? In part, it is our own thinking of "science" that is at fault, because we tend to think of science as more "analytical" than descriptive. The eighteenth century, however, spent an enormous amount of intellectual energy on describing what it could not understand. The three "C's"—counting, classifying, cataloguing—were central to the Baconian program that guided much of the growth of useful knowledge in the century before the Industrial Revolution. Heat, energy, chemical affinities, electrical tension, capacitance, resistivity and many other properties of materials from iron to bricks to molasses were measured and tabulated before they were, in some sense, "understood." Measurement itself was not novel in the eighteenth century; the accuracy, thoroughness, and reliability, the scope of phenomena and quantities being measured, and the diffusion of this knowledge surely were.

[10] The *opus classicus* on this topic remains Musson and Robinson, *Science and Technology*. For the best recent statement, see Jacob, *Scientific Culture* and "Cultural Foundations," pp. 67–85.

[11] Gillispie, *Science . . . End of Old Regime,* p. 336. For canonical statements on the "unimportance of science" see Hall, "What Did the Industrial Revolution?"; Neil McKendrick, "Role of Science"; Mathias, "Who Unbound Prometheus?" John R. Harris has been even more skeptical of the importance of science relative to "tacit" skills and has even argued that France's backwardness in steelmaking was in part due to its reliance on scientists, who at first gave misleading and later rather useless advice to steel makers; compare Harris, *Industrial Espionage*, pp. 219–21.

In the nineteenth century the connection between science and technology became gradually tighter, yet remained sufficiently uneven and heterogeneous to make any dating very hazardous. Scholars such as Nathan Rosenberg and Derek Price have argued for the causality running mainly from technology to science rather than the reverse.[12] Arguably, however, science and technology were both endogenous to a third set of factors that determined the direction and intensity of the intellectual pursuits that led to advances in both. In what follows, I shall try to identify what this set consists of, document it in some detail, and then consider to which extent these factors may be regarded as "exogenous." I propose that one source of the success of the Industrial Revolution must be found in the developments in the area of the generation and diffusion of useful knowledge that occurred in Europe before and around 1750, and specifically in the Enlightenment.

The confusion surrounding the role of science in the eighteenth century on economic developments and the rather tiresome debate regarding the merits and shortcomings of the so-called linear model (in which science supposedly "leads" to technology) stem from the narrow and possibly anachronistic definitions of the concept of useful knowledge. In addition to what the eighteenth century called "natural philosophy," it consisted of catalogs of facts, based on experience and experiment rather than on understanding or careful analysis and testing. Many of these facts were organized compilations about what worked: the right mixture of materials, the right temperature or pressure in a vessel, the correct fertilizer in a given type of soil, the optimal viscosity of a lubricant, the correct tension on a piece of fabric, the shortest way to sail across the sea while using the right trade winds and avoiding reefs, and not-so-basic facts of nature used in productive activities from medicinal herbs to cattle breeding to glass blowing to marling. It involved not only the work of people whom we regard today as scientists but also those who collected data and practices—botanists, zoologists, geographers, mineralogists, instrument-makers, and other highly skilled artisans—and placed this knowledge in the public realm. For that reason I prefer the much wider category of *propositional knowledge*.[13]

THE ENLIGHTENMENT AND EIGHTEENTH-CENTURY TECHNOLOGY

The Enlightenment of the late seventeenth and eighteenth centuries bridges the Scientific and the Industrial Revolutions. Definitions of this amorphous and often contradictory historical phenomenon are many, but

[12] Price, "Notes towards a Philosophy." Rosenberg, *Perspectives* and "How Exogenous is Science?"

[13] For more details, see Mokyr, *Gifts,* chap. 2, and "Long-term Economic Growth."

for the purposes of explaining the Industrial Revolution we need only to examine a slice of it, which I have termed the Industrial Enlightenment—a belief in the possibility and desirability of economic progress and growth through knowledge.[14] The idea of *improvement* involved much more than economic growth or technological change; it included moral and social improvement, alleviating the suffering of the poor and the unfortunate, and more generally such matters as justice and freedom. Yet the idea that production could be made more efficient through more useful knowledge gradually gained acceptance. Scotland, again, showed the way, but the idea diffused throughout Britain and the Western world.[15]

It surely is true that not all Enlightenment philosophers believed that material progress was either desirable or inevitable, or were persuaded that the rise of a commercial and industrial society was a desirable end. And yet the cultural beliefs that began to dominate the elites of the eighteenth-century West created the attitudes, the institutions, and the mechanisms by which new useful knowledge was created, diffused, and put to good use. Above all was the increasingly pervasive belief in the Baconian notion that we can attain material progress (that is, economic growth) through controlling nature, and that we can only harness nature by understanding her in order, as he himself put it, to bring about "the relief of man's estate." Francis Bacon, indeed, is a pivotal figure in understanding the Industrial Enlightenment and its impact. "Lord Bacon," as he was referred to by his eighteenth-century admirers, was cited approvingly by many of the leading lights of the Enlightenment, including Diderot, Lavoisier, Davy, and the astronomer John Herschel.[16] Modern scholars seem agreed: Bacon was the most influential mind to regard knowledge as subject to constant growth,

[14] One of the most cogent statements is by McNeil, *Under the Banner*, pp. 24–25, who notes the importance of a "faith in science that brought the legacy of the Scientific Revolution to bear on industrial society . . . it is imperative to look at the interaction between culture *and* industry, between the Enlightenment and the Industrial Revolution." As Spadafora has noted, the belief in the possibility (if not the inevitability) of progress was necessary if the West was to actually experience anything like it. Spadafora, *Idea of Progress*.

[15] The Scottish philosopher George Campbell (1719–1796) noted for example in 1776 that "for some centuries backwards, the men of every age have made great and unexpected improvements on the labours of their predecessors. And it is very probable that the subsequent age will produce discoveries and acquisitions which we of this age are as little capable of foreseeing as those who preceded us in the last century were capable of conjecturing the progress that would be made in the present" (cited by Spadafora, *Idea*, p. 56).

[16] Sargent, ed., *Francis Bacon,* pp. xxvii–xxviii. In a wonderful piece of doggerel entitled *Ode to the Royal Society,* written by the now (deservedly) neglected poet Abraham Cowley (one of the Society's co-founders) and reprinted as a preface to Thomas Sprat's celebrated *History of the Royal Society of London*, the gratefulness of the scholars of the time to Bacon was well-expressed: "From these and all long Errors of the Way; In which our wandring Predecessors went; And like the old Hebrews many Years did stray; in Desarts but of small Extent; Bacon, like Moses, led us forth at last; The barren Wilderness he past; Did on the very Border stand; of the blest promis'd Land; And from the Mountain's Top of his exalted Wit; Saw it himself and shew'd us it."

as an entity that continuously expands and adds to itself.[17] As such his influence helped inspire the Industrial Enlightenment.[18] The understanding of nature was a collective project in which the division of knowledge was similar to Adam Smith's idea of the division of labor, another enlightenment notion. Smith realized that such a division of knowledge in a civilized society "presented unique and unprecedented opportunities for further technical progress."[19] The more pragmatically inclined thinkers of the Industrial Enlightenment concurred.[20] Bacon's idea of bringing this about was through what he called a "House of Salomon"—a research academy in which teams of specialists collect data and experiment, and a higher level of scientists try to distill these into general regularities and laws. Such an institution was the Royal Society, whose initial objectives were inspired by Bacon.[21] A finer and more extensive division of knowledge could not have been attained without improved access that made it possible to share the knowledge, and then apply and adapt it to solve technical problems. Access to useful knowledge created the opportunities to recombine its components to create new forms that would expand the volume of knowledge at an ever faster rate. Bacon, indeed, placed a high value on compiling inventories and catalogues of *existing* knowledge and techniques; some of these ideas are reflected in the interest the Royal Society displayed in the

[17] As always, there were earlier expressions of such ideas, not always wholly acknowledged by Bacon. One example is the sixteenth-century French theologian Pierre de la Ramée (Peter Ramus), with whom Bacon would have agreed that "the union of mathematics and the practice of scholarly arts by artisans would bring about great civic prosperity" (Smith, *Business*, p. 36).

[18] Farrington, *Francis Bacon*. Vickers, "Francis Bacon." Bacon's influence on the Industrial Enlightenment can be readily ascertained by the deep admiration the *encyclopédistes* felt toward him, exemplified by a long article on *Baconisme* written by the Abbé Pestre and the credit given him by Diderot himself in his entries on *Art* and *Encyclopédie*. The *Journal Encyclopédique* wrote in 1756 "If this society owes everything to Chancellor Bacon, the philosopher does not owe less to the authors of the *Encyclopédie*" (cited by Kronick, *History*, p. 42). The Scottish Enlightenment philosophers Dugald Stewart and Francis Jeffrey agreed on Baconian method and goals, even if they differed on some of the interpretation (Chitnis, *Scottish Enlightenment*, pp. 214–15). A practical enlightenment scientist such as Humphry Davy had no doubt that Bacon was ". . . was the first philosopher who laid down plans for extending knowledge of universal application; who ventured to assert, that all the science could be nothing more than expressions or arrangements of facts . . . the pursuit of the new method of investigation, in a very short time, wholly altered the face of every department of natural knowledge. Davy, "Sketch," pp. 121–22. Across the channel, the French minister of the Interior, Nicolas-Louis François de Neufchâteau invoked the spirit of Francis Bacon when opening the 1798 French industrial exhibition. See Jacob, "Putting Science."

[19] Rosenberg, "Adam Smith," p. 137.

[20] A typical passage in this spirit was written by the British chemist and philosopher Joseph Priestley: "If, by this means, one art or science should grow too large for an easy comprehension in a moderate space of time, a commodious subdivision will be made. Thus all knowledge will be subdivided and extended, and *knowledge* as Lord Bacon observes, being *power*, the human powers will be increased . . . men will make their situation in this world abundantly more easy and comfortable." Priestley, *Essay*, p. 7.

[21] McClellan, *Science Reorganized*, p. 52.

"useful arts" in its early years.[22] In subsequent decades, the Royal Society accepted amateurs and dilettantes and thus became less of a pure "Baconian" institution than the French *Académie Royale*.

Of course, the eighteenth century still saw a lot of efforts that were purely epistemic or metaphysical in motivation, but the emphasis was slowly changing. The message that the Industrial Revolution inherited from the seventeenth century concerned the very purpose and objective of propositional knowledge. The result was a change in the *agenda* of research, in which the "useful arts" began to assume an equal, and eventually dominant, place alongside the liberal arts. This "Baconian Program" assumed that the main purpose of knowledge was to improve mankind's condition rather than the mere satisfaction of that most creative of human characteristics, curiosity, or the demonstration of some metaphysical point, such as illustrating the wisdom of the creator.[23] Studying and extending useful knowledge, it was increasingly felt, was respectable and suitable work for a gentleman.[24] Natural philosophy, its prestige hugely enhanced by the insights of Newton, was marketed as being useful to economic improvement.[25] Farmers, manufacturers, sailors, engineers, merchants, miners, bleachers, and army officers asked questions, and the community of learned persons, the *savants*, were more and more pressured to provide them with answers. The 'business of science," John T. Desaguliers noted in the 1730s, was "to make Art and Nature subservient to the Necessities of Life in joining proper Causes to produce the most useful Effects."[26] The great Lavoisier worked on assorted applied problems, including as a young man on the chemistry of gypsum and the problems of street lighting. Perhaps no area of propositional knowledge showed as much promise to application as mathematics, which made enormous strides after the seminal works of Descartes, Huygens, Newton, and Leibniz. Mathematical techniques following the development of calculus were applied to questions of motion and the challenges of mechanics, although these were initially not

[22] As Musson and Robinson stress in *Science and Technology*, p. 16, "Bacon's influence can be perceived everywhere among men of science in the seventeenth and eighteenth centuries, constantly encouraging them to comprehend workshop practices."

[23] Calvin in the sixteenth century still followed St. Augustine's condemnation of curiosity as a "vanity." By way of contrast, in the 1660s, Thomas Sprat felt that gentlemen were suitable to research precisely because they were "free and unconfined."

[24] Thus in 1710 the *Tatler* wrote that "It is the duty of all who make philosophy the entertainment of their lives, to turn their thoughts to practical schemes for the good of society, and not pass away their time in fruitless searches which tend rather to the ostentation of knowledge than the service of life." Cited by Shapin, "Scholar," p. 309. In a similar vein, *The Gentleman's Magazine* wrote in 1731 that "our knowledge should be in the first place that which is most useful, then that which is fashionable." Cited by Burke, *Social History*, p. 111.

[25] Cohen, "Inside Newcomen's," p. 127, points out that the Baconian ideology "went under the sainted name of Newton."

[26] Desaguliers, *Course*, vol. 1, p. iii.

the mechanics of engineers and architects as much as those of "rational mechanics," which analyzed idealized properties, rather than actual day-to-day problems loaded with ugly characteristics such as friction and resistance. Many of the leading *philosophes* of the Enlightenment, including Diderot, were pessimistic of the ability of mathematics to advance beyond its current state and contribute much to material progress.[27] Yet mathematicians were often asked to solve practical problems. Leonhard Euler, the most talented mathematician of the age, was concerned with ship design, lenses, the buckling of beams, and (with his less famous son Johann) contributed a great deal to hydraulics.[28] Naturalists and botanists, in very different ways, were equally regarded as contributing to the wealth of their nations. Linnaeus's belief that skillful naturalists could transform farming was widely shared and inspired the establishment of agricultural societies and farm improvement organizations throughout Europe. By the second half of the eighteenth century, botany, horticulture, and agronomy were working hand-in-hand through publications, meetings, and model gardens to introduce new crops, adjust rotations, improve tools, and better management.[29]

Many of the answers that mathematicians and natural philosophers gave to engineers, industrialists, and farmers were, of course, useless, misleading, or wrong. The eighteenth century was nothing at all like a steady progress of better understanding of nature and its application to agriculture and manufacturing. The alleged "usefulness" of knowledge was often an attempt by scholars to secure financial support and patronage from wealthy individuals and official sponsors.[30] But no matter how self-serving and pre-

[27] Furbank, *Diderot*, p. 110. Hankins, *Science*, p. 45. Hankins add that "Diderot was wrong . . . in the years between 1780 and 1840 . . . mathematics and mechanics found a place precisely where Diderot thought they had no place."

[28] See above all, Reynolds, *Stronger*, pp. 233–50. Another example of such an application of mathematical knowledge to a mundane problem is Colin MacLaurin's ingenious solution (1735) to the problem of measuring the quantity of molasses in irregularly shaped barrels by the use of classical geometry. Not only did he solve the rather difficult mathematical problem with uncommon elegance, he also provided simple formulas, tables, and algorithms for the customs officers, that were used for many years. See Grabiner, "Some Disputes," pp. 139–68.

[29] One source of confirmation of the belief in the possibility of economic progress may have been perceptions of agricultural progress. As John Gascoigne has recently noted, "as the land bore more, better, and increasingly diversified fruits as a consequence of patient experiment with new techniques and crops, so, too, the need to apply comparable methods to other areas of the economy and society came to seem more insistent." Gascoigne, *Joseph Banks*, p. 185.

[30] A good early example of such hope was the work of the Scottish botanist and physician, Sir Robert Sibbald (1641–1721), whose widespread interests, extensive correspondence network, and continental education were harbingers of things to come in the eighteenth century. Sibbald was extremely active in reforming the University of Edinburgh and helped establish the Royal College of Medicine as well as an early botanical garden in town. Yet as Paul Wood remarks, much of Sibbald's work failed to bear fruit in his lifetime, and his dream to turn learning into material benefit was largely disappointed in his lifetime. See Wood, "Science." For a general discussion of the

tentious the claims of those who controlled propositional knowledge were, the Industrial Enlightenment did not waver in its belief that economic growth through better and more knowledge was possible. Progress through more and better knowledge also had moral and political implications; it was believed that better-informed and more enlightened individuals would be more ethical and better-behaved citizens. "Useful knowledge" in the eighteenth century thus meant something more than it does to our wiser and sadder age.

ACCESS COSTS: SOME REFLECTIONS

The Industrial Enlightenment was in part about the expansion of useful knowledge. Knowledge exists in the final analysis within the mind of an individual, but for it to be socially productive it needs to be shared and distributed. If a vital piece of knowledge is discovered but only one individual possesses it and keeps it secret, it is by definition part of social knowledge, but has little economic value. What counted for useful knowledge to play a role in generating economic growth was therefore *access costs*, the marginal cost involved in acquiring knowledge possessed by someone else in society. The concept is in line with recent thinking about the Enlightenment which regards it above all "as a system of communication creating a public of rational individuals."[31] The economic significance of access costs has three dimensions. The first is obvious: access made it possible for producers to learn of best-practice techniques and emulate them. Needless to say, access costs are not the only wedge between best- and average-practice techniques, but it is safe to assume that ignorance will make such wedges both larger and more permanent. Secondly, technological progress depended on the knowledge of other techniques already in use. As has often been noted, much invention took the form of the "recombination" of existing techniques.[32] Moreover, technological progress often depended on "analogical" thinking, in which inventors, consciously or subconsciously, transform an idea they have already seen into something novel.[33] Furthermore, knowledge of what techniques exists will alert original and creative individuals to gaps and opportunities in the existing set of techniques, and prevent potential inventors from misspending their resources by reinvent-

quest for patronage through claims for usefulness, see especially, Spary, *Utopia's Garden*, p. 127.

[31] Censer, "Journals," p. 311, though he should have added "informed" to the "rational."

[32] The classic example of such an invention during the Industrial Revolution is surely Cort's patent for the second half of his puddling and rolling process, in which the common rolling mill was used to weld together pieces of scrap iron at a sufficiently high temperature. His invention "clearly inspired" a naval contractor named William Forbes who used grooved rollers to produce improved copper bolts for naval ships (Harris, "Copper," p. 183). For a theoretical discussion of recombination in technological change, see Weitzman, "Hybridizing," pp. 207–13.

[33] McGee, "Rethinking Invention."

ing the wheel. Thirdly, as I have stressed in my *Gifts of Athena*, lower access costs made it possible for inventors to tap the propositional knowledge on which the new technique rests—insofar as such knowledge was available and effective.[34] Understanding *why* and *how* a technique works at some level of generality made it easier to clean up bugs, adapt it to new uses and different environments, and unleashed the cumulative stream of microinventions on which nineteenth-century productivity growth rested. It streamlined the process of invention by reducing the likelihood of blind alleys such as searches for perpetual motion machines and the like. All of these suggest that the easier the access to existing propositional knowledge and to practices in use, the more likely inventions were to emerge and result in sustained economic growth. Contemporaries became slowly aware of the possibilities of bringing to bear science on production technology.[35] As one assiduous collector of facts remarked in 1772, "before a thing can be *improved* it must be *known*, hence the utility of those publications that abound in fact either in the offer of new or the elucidation of old ones."[36] Whether in agriculture, pottery, steam-engine construction, or chemical industry, leading manufacturers eagerly sought and found the advice of scientists. In and of itself this does not prove that this knowledge was instrumental in technical advances and productivity growth, as these progressive industrialists may have been successful for other reasons. But in the nineteenth century such input becomes more and more prominent.[37]

The level of access costs can be decomposed into four separate components. First, there was the cost involved in establishing that this knowledge actually existed, that is, that there was at least one individual in society who possessed it. Second, there was the cost of finding out who the lowest-cost supplier of this knowledge was and where it could be found. Third, there was the actual cost of acquiring it, which could range from a simple search through a library or catalog to the need of reading a scien-

[34] I use the term "effective" rather that "correct" because terms such as "true" or "correct" are irrelevant and inappropriate here. The best we can do is to say that a piece of knowledge held in the past was "right" or "wrong" in the sense that it is inconsistent with our beliefs. By "effective" I mean such knowledge on which certain techniques rest that perform better than techniques based on some other base according to some prespecified criterion. For instance, bloodletting might have been effective simply because it did help patients if only through a placebo effect.

[35] As Voltaire noted in his *The Age of Louis XV*, written late in his life in 1770: "pure natural philosophy has illustrated the necessary arts; and these arts have already begun to heal the wounds of the state caused by two fatal wars. Stuffs manufactured in a cheaper manner, by ingenuity of the most celebrated mechanics" (Vol. 2, pp. 369–70).

[36] Young, *Political Essays*, p. v., emphasis in original.

[37] One telling example is Neilson's hot blast (1828), a fuel-saving innovation from the "second stage" of the Industrial Revolution. Neilson had learned of Gay-Lussac's calculation of the rate of expansion of oxygen and nitrogen between 0° and 80° C and used laboratory experiments to persuade Scottish ironmasters to apply it, which proved "the salvation of the Scottish iron industry" (Clow and Clow, *Chemical Revolution*, p. 356).

tific article, visiting a site, or hiring a consultant or expert who could convey it. Fourth, there was the cost of verifying the knowledge and establishing the extent of its "tightness," that is, to what extent was this a consensus view among the experts or authorities on certain propositions and how certain were they of its truthfulness?

What determined access costs? One obvious determinant is technological: how costly was it to code, store, transmit, and receive useful knowledge, what was the best-practice technology through which it was transmitted, and in what language and terminology was it expressed? Another is social and cultural: to what extent were individuals who made a discovery willing to share such useful knowledge (for example as part of "open science" that awards credit for priority), and allow inventions to be used freely (for instance in processes of collective invention or "open source" development)? Did organizations exist that channeled knowledge from those who knew useful things to those who could and were willing to exploit such knowledge? Finally, there are economic factors: did markets for useful knowledge exist? Economists know that such markets (and the intellectual property on which they rest) will be deficient and incomplete, yet *some* of them clearly did exist and others emerged during the Industrial Revolution.

ACCESS COSTS: TECHNICAL FACTORS

The decline in access costs in the century or so before the Industrial Revolution cannot be attributed to a single factor. There is no question that the costs of transmitting information was declining already before the arrival of the railroad. Abstracting from homing pigeons and the semaphore telegraph, knowledge moved as fast and as far as people did. People and carriages carried books, periodicals, and other storage devices. All the same, much of the knowledge that counted was not written down or depicted in the (increasingly detailed and sophisticated) technical drawings of the age, but embodied in implicit forms we would call "skills," "dexterity," and other synonyms for what is known as tacit knowledge. The ratio of codified knowledge to tacit knowledge was itself a function of the technology and costs of codification and the payoff to efforts to do so, although tacit knowledge inevitably remained an essential part of knowledge.[38] Access to knowledge thus depended not only on written records, but also on personal transmission and training. Much of the tacit and practical useful knowledge in eighteenth-century Europe moved about through

[38] For a more detailed analysis of the economics of tacit knowledge, see Cowan and Foray. "Economics," pp. 595–622.

itinerant skilled artisans who taught the tricks of their trade to local craftsmen. Beyond that, the normal human proclivities for observation and imitation did their work.[39] Industrial espionage, both within an economy and across borders, became an important part of technological diffusion.[40] In Enlightenment Europe, people—including skilled craftsmen—moved about more often and further than ever before, despite the undeniable discomforts of the road. Although the great breakthroughs in transport technology were still in the future, the decline in the cost and speed of moving about in Europe in the eighteenth century are too well documented to require elaboration here.[41] Transportation improvements also sped up the mail; a great deal of scientific communication depended on personal correspondence between individuals.

The eighteenth century also witnessed the improvement of the transfer of formerly tacit knowledge. Part of it was simply the improvement of the language of technology: mathematical symbols, standardized measures, and more universal scales and notation added a great deal to the ease of communication of codified technological information. Diagrams and illustrations became more sophisticated.[42] Above all, there was printing, but in and of itself printing was not decisive, or else the Industrial Revolution might have occurred in the sixteenth century. Paper had been introduced into Europe in the thirteenth century, and as an access-cost and storage-cost reducing material it must have had few substitutes. The paper industry grew remarkably in the seventeenth century, culminating in the invention

[39] Harris, "Skills." Epstein, "Knowledge Sharing," especially pp. 15–20. Eighteenth-century Europe was crisscrossed by a variety of technological informants and spies such as Gabriel Jars (studying metalmaking) and Nicolas Desmarest (papermaking) (Gillispie, *Science . . . End of Old Regime,* pp. 429–37, 444–54). For a discussion of the importance of geographical mobility on the diffusion of artisanal skills in Italy, see Belfanti, "Guilds." The effect of traveling was also notable in the improved access to agricultural knowledge, as attested to by the many Frenchmen who visited Britain after 1750 to study farm methods and techniques. See Bourde, *Influence.*

[40] Harris, "Industrial Espionage," pp. 164–75, and *Industrial Espionage.* British legislation to prevent the outflow of skilled craftsmen and certain kinds of machinery were in the long run doomed to failure, though it is hard to disagree with Harris's assessment that they raised access costs and had a retardative effect on the diffusion of technology.

[41] In Britain, better-built roads and coaches sharply reduced internal travel time in the eighteenth century: the coach from London to Edinburgh still took 10–12 days in the mid 1750s, whereas in 1836 (just before being replaced by a railroad) it could cover the distance in 45.5 hours. In France, travel times were halved or better on many routes between 1765 and 1785. See data reported by Szostak, *Role*, p. 70.

[42] Thomas Newcomen surely must have seen Papin's sketches of his models of proto-engines and pumps, published in various issues of *Philosophical Transactions* between 1685 and 1700. One example of a book that codified a great deal of formerly tacit knowledge was Bernard de Bélidor's famed *Architecture Hydraulique*, published in four volumes in 1737. It discussed almost all fields of civil engineering, and the great British engineers John Smeaton, John Rennie, and Thomas Telford all owned copies. Charles Plumier (1646–1704) wrote a book on the art of using a lathe (*l'Art de Tourner*), which—whether of use to craftsmen or not—was sufficiently regarded to be translated into Russian, the translation attributed to Emperor Peter the Great himself.

of the *Hollander* (1670), a device that applied wind- or water power to the difficult process of ripping up the rags needed for pulping.[43] The effect of printing and paper was, as Eric L. Jones has noted, constrained in that only widespread literacy could realize its full effect throughout society. It also mattered, of course, whether the literate actually read, and what kind of texts they chose. In Enlightenment Europe, the printing press finally lived up to its full potential. It may still have been that, as Jones points out, "published ideas flowed through narrow channels bounded by limited literacy and unlimited poverty," and that the bulk of the population had little or no access to libraries and could not afford to buy books or (highly taxed) newspapers. But technical knowledge had a way of seeping through to those who needed it and could find a use for it.[44] Reading became increasingly common, as literacy rates edged upward and books became cheaper and more widely available through lending libraries and the reading rooms attached to learned societies and academies. The first free public library in Britain, Chetham's in Manchester, was founded in 1653 and prospered in the eighteenth century.[45] Coffee houses and booksellers often offered magazines to be browsed by customers.[46] Many of the scientific and scholarly societies that emerged in the eighteenth century built up their own libraries. The idea was to make useful knowledge accessible. Furthermore, in the century between Newton's *Principia* and Lavoisier's *Traité Elementaire* Latin disappeared as the language in which books were published.[47]

A telltale sign of the changing age were the scientific and other technical magazines that began appearing all over Europe. Many of these periodicals were derivative popularizations and intended to summarize and review the existing literature, and thus directly reduced access costs even if their respect for intellectual property left a lot to be desired. To be sure, only a minority of the population read, and that of those the bulk read novels, romantic potboilers turned out by hacks in what Robert Darnton has called "Grub Street," scandalous pamphlets and religious tracts. Books on

[43] For a study of Pierre Montgolfier, one of the most progressive paper manufacturers of eighteenth-century France, see Rosenband, *Papermaking*.

[44] Jones, "Culture," p. 13.

[45] Musson and Robinson, *Science and Technology*, p. 113. In 1697 the rev. Thomas Bray [1697, (1967)] called for 400 lending libraries to be established throughout Britain, believing that making knowledge more accessible would "raise a Noble Spirit of Emulation in those Leaned Societies and would excite more of the members thereof to exert themselves in being serviceable to the world" (p. 11).

[46] See Outram, *Enlightenment*, p. 21.

[47] The Swedish metallurgist Tobern Bergman published his major work, *De Praecipitatis Metallicis* (a major theoretical essay on the nature of steel) in Latin as late as 1780. An English translation, by no less a scholar than William Withering, a founding member of the Lunar Society, came out in 1783.

the useful arts, science, and mathematics were without doubt of interest to only a small minority.[48] Even within science, the majority of publications were concerned with the kind of knowledge that was not often directly concerned with the technical problems of the early stages of the Industrial Revolution.[49]

Useful knowledge was thus transmitted in codified form through "storage devices." John R. Harris, an authority on British eighteenth-century technology, has doubted the extent that codified knowledge mattered in the early stages of the Industrial Revolution. As far as skills and workmanship were concerned, it is possible to exaggerate the importance of books and periodicals as means through which technical knowledge was accessed. It surely was less important in the metal trades or mining than in medicine, agriculture, instrument-making, electricity, astronomy, or chemistry. It changed over time, with much of the volume of technical and scientific publishing concentrated in the last third of the eighteenth century.[50] Yet Harris's judgment is also affected by his narrow focus on the transmission of the techniques themselves, without fully realizing that what mattered in many industries is the diffusion of the propositional knowledge on which the techniques rested, so that they could be adapted, refined, and tweaked by the select few who accessed these knowledge bases. Moreover, artifacts and instruments were storage devices as much as descriptions and illustrations. In the eighteenth century, an international market in scientific and industrial instruments had emerged, with British instrument makers buying and selling instruments to and from all over Europe.[51] These instruments were used for scientific experimentation as well as for industrial improvement; in the eyes of the men of the Industrial Enlightenment, there was little difference between the two. Capital goods such as steam engines and spinning machines were moving about, various prohibitions on the export of machinery notwithstanding.

[48] A study of the contents of French private libraries (probably unrepresentative) shows only about 3.2 percent of all books devoted to what we may call useful knowledge, more than half being novels and 32 percent being devoted to history or theology. See Mornet, "Enseignements," p. 457.

[49] The "Natural Science" section of J. D. Reuss's *Repertorium* (Index of scientific literature) published between 1801 and 1821 (covering only a small part of the scientific journals) indicates that astronomy accounted for 19 percent of the scientific papers published between 1665 and 1800 and zoology for 18 percent, whereas mechanics accounted for 4 percent and chemistry for 6 percent. See Gascoigne, *Historical Catalogue*, p. 100.

[50] Harris, "Skills," pp. 21–23. It might be added that Harris writes specifically about mining and coal-using technology, and that outside geology and the adoption of steam-powered pumps, there was actually little technological progress in the mining sector.

[51] Thus the Portuguese instrument maker Jean Hyacinthe de Magellan—who had worked with Priestley in the 1770s—bought thermometers from Wedgwood, and sold the needed instruments to Alessandro Volta. Volta in turn used these to construct his eponymous pile (reputedly upon hints received from William Nicholson in London). See Stewart, "Laboratory," p. 13.

It could be objected that this knowledge, whether codified or tacit, was shared by only a minute percentage of the population. However, the technological thrust during the Industrial Revolution was not the result of the action of the majority of population; in the hurry of the economic history profession to get away from the absurd hero-worship of a few key inventors as having carried the Industrial Revolution, it has tended to go too far in the other direction by asserting that unless much or most of the population had access to technical knowledge, the spread of new techniques was limited. The truth is somewhere in between; it is undeniable that technological progress during the Industrial Revolution was an elite phenomenon, carried not by a dozen or two of big names who made it to the *National Dictionary of Biography*, but by the thousands of trained engineers, capable mechanics, and dexterous craftsmen on whose shoulders the inventors could stand.

Yet when all is said and done, we are talking about thousands, perhaps a few tens of thousands, not hundreds of thousands or millions of people in industrializing Europe; democratic instincts notwithstanding, what the large majority of workers knew mattered little as long as they did what they were told by those who knew more.[52] Technological advance in the period of the Industrial Revolution was a minority affair; most of the entrepreneurs of the time were not like Boulton and Wedgwood and had no knowledge of or interest in science or even innovation, just as most landowners were not improvers. But the dynamics of competition are such that in the long run the few drag along the many.

The exact composition of who these "few" were changed during the period in question. Late in the seventeenth century and in the first decades of the eighteenth, it was clearly the political elite that felt that new knowledge and the rejection of age-old sacred cows were the keys to social progress. Over the eighteenth century, conservative elements slowly gained the upper hand, especially when liberal and progressive elements were allied with both the American rebels and the French Jacobins. Especially in Britain, anti-Enlightenment sentiments flared up in the 1790s. But whatever happened in the center of power in London, it could not stop the Industrial

[52] Adam Smith expressed this kind of elitism in his "Early Draft," in which he noted that "to think or to reason comes to be, like every other employment, a particular business, which is carried on by very few people who furnish the public with all the thought and reason possessed by the vast multitudes that labour." The benefits of the "speculations of the philosopher . . . may evidently descend to the meanest of people" if they led to improvements in the mechanical arts. Smith, *Lectures on Jurisprudence*, pp. 569–72. Soame Jenyns, a mid-eighteenth-century writer, advocated ignorance for the poor as "the only opiate capable of infusing the insensibility which can enable them to endure the miseries of poverty and the fatigues of the drudgeries of life." See Jenyns, *Free Inquiry*, pp. 65–66. As Rosenberg points out, such a division of knowledge was increasingly pertinent to a sophisticated ("civilized") society in which specialized "philosophers" would account for technological progress. Compare Rosenberg, "Adam Smith," pp. 134–36.

Enlightenment from spreading into provincial society. In the European provincial societies of Manchester, Liverpool, Newcastle, Leeds, Antwerp, Lyons, Marseilles, Nantes, and Milan, J. H. Plumb has noted, we do not find Diderots and Humes, but neither do we find [reactionary thinkers] such as Samuel Johnson or Edmund Burke. Instead, "we find knots of enlightened men with a passionate regard for empirical knowledge, secular in their intellectual attitudes, although often muddled, uncertain and tentative, with . . . rational and irrational beliefs combined in the same man." Their religious feelings were quite diverse and many thoughtful and well-read minds of the enlightenment still fell for bogus and faddish ideas put out by charlatans.[53] On the whole, not all important eighteenth-century thought was enlightened, and the Enlightenment itself was a complex and often self-contradictory movement in which many different streams competed. Some scholars have found the differences between thinkers *within* the Enlightenment more important than their common denominator.[54] As Plumb put it in his inimitable style, "between the stars of the first magnitude are vast spaces of darkness."[55] Yet these spaces of "darkness" are often revealed, at closer inspection, to be filled with interesting material and some beliefs and axioms that were shared across the regions where the influence of the Enlightenment was palpable. In the end, the belief in advances in knowledge and their capability to improve the human lot was the one intellectual heritage that was critical to material progress.

ACCESS COSTS: CULTURAL AND SOCIAL FACTORS

In addition to the technology of access there was culture. The culture of "open science" that evolved in the seventeenth century meant that observation and experience were placed in the public domain and that credit was assigned by priority. Its openness manifested itself in two dimensions, both in the full disclosure of findings and methods, and in the lack of barriers to entry for competent persons willing to learn the language. Scientific knowledge became a public good, communicated freely rather than confined to a secretive exclusive few as had been the custom in medieval Europe. Openness, as Paul David and others have pointed out, had major benefits in that validation was made easy, duplication reduced, and spill-over effects could be augmented. It increasingly closed down research

[53] Well-known examples were the wondrous Dr. John Brown (1735–1788), whose popularity was based on his insistence that all diseases could be cured by either alcohol or opium, and the notorious fraud Alessandro Cagliostro (1743–1795), who peddled elixirs of youth and love powders to the high and mighty, and whose séances had become the rage of fashionable society in Paris by 1785, until he found himself in the Bastille.

[54] For example, von Hayek, "Legal and Political Philosophy," p. 106.

[55] Plumb, "Reason," pp. 5, 23.

roads that led to cul-de-sacs and bogus knowledge. Magic, occult, mystical beliefs, and simple charlatanry, while still alive and often well in the eighteenth century, found themselves on the defensive against an increasingly skeptical community that demanded to reproduce or refute their results.

Access costs depend crucially on the culture and social customs of useful knowledge. The rhetorical conventions of scientific discourse changed in the seventeenth century. Authority and trust, of course, remained essential to the pursuit of knowledge as they must, but the rules of the discourse and the criteria for "what was (believed to be) true" or "what worked" shifted toward a more empirical and verifiable direction. The community of those who added to useful knowledge demanded that it be tested, so that it could be trusted.[56] Verification and testing meant that a deliberate effort was made to make useful knowledge "tighter" and thus, all other things equal, more likely to be used.[57] This tightness is what makes modern science a strategic factor in economic growth. Inevitably, the skepticism of experts of each others' findings and the careful testing reinforced the trust of the potential users, who could assume that this knowledge had already been vetted by the very best; if it had been accepted by them, the likelihood of an error was minimized.[58] In science, as in commercial transactions, trust is an information-cost saving device and as such was essential if useful knowledge was not only to be diffused but also verified and accepted and—most important for our purposes—acted upon.[59] The sharing of knowledge within "open science" required systematic reporting of methods and materials using a common vocabulary and consensus standards, and was the major component in the decline in access costs, making

[56] Steven Shapin has outlined the changes in trust and expertise in Britain during the seventeenth century, associating expertise, for better or for worse, with social class and locality. Although the approach to science was ostensibly based on a "question authority" principle (the Royal Society's motto was *nullius in verba*—on no one's word), in fact no system of shared useful (or any kind of) knowledge can exist without some mechanism that generates trust. The apparent skepticism with which scientists treated the knowledge created by their colleagues increased the trust that outsiders could have in the findings, because they could then assume—as is still true today—that these findings had been scrutinized and checked by other "experts." See Shapin, *Social History*.

[57] By "tight," I mean knowledge that is believed to be true by a consensus, and that this consensus is based on considerable confidence.

[58] As Hilaire-Pérez put it, "the value of inventions was too important an economic stake to be left to be dissipated among the many forms of recognition and amateurs: the establishment of truth became the professional responsibility of academic science." (Hilaire-Pérez, *Invention Technique*, p. 60).

[59] In the scientific world of the late seventeenth and eighteenth centuries, a network of trust and verification emerged in the West that seems to have stood the test of time. It is well described by Polanyi; the space of useful knowledge is divided in small neighboring units. If an individual B is surrounded by neighbors A and C who can verify his work, and C is similarly surrounded by B and D and so on, the world of useful knowledge reaches an equilibrium in which science, as a whole, can be trusted even by those who are not themselves part of it. Polanyi, *Personal Knowledge*, pp. 216–22.

propositional knowledge, such as it was, available to those who might find a use for it.

This trend was reinforced by a redefinition of fact and experience: seventeenth-century and early enlightenment scientific thought became more interested in cataloguing specific events, to be reassessed and reformulated into general principles based in the best Baconian tradition, on hard empirical facts and the results of experiment. Yet there are facts and there are facts. In the second half of the eighteenth century, those in charge of augmenting the set of propositional knowledge increasingly relied on quantification and formal mathematical methods. The increasing reliance on mathematics and graphical representation in the writing of technical works supported this need for precise and effective communication. As Robin Rider puts it, "mathematics was eminently rational in eighteenth century eyes, its symbols and results were truly international . . . in an age that prized the rational and the universal, mathematics . . . offered inspiration and example to the reformers of language."[60] Formal methods and quantification are access-cost reducing devices, in that they are an efficient language to communicate facts and relationships, and that the rules are more or less universal (at least within the community that counted for the processing and application of useful knowledge). Computation and formal methods were necessary because they were an efficient way of communicating and because they lent themselves more readily to falsification. A rhetoric of precision, through meticulous procedures and sophisticated equipment, emerged and facilitated scientific consensuses, if not always in straightforward manner.[61] J. L. Heilbron submits that in the seventeenth century most of "learned Europe" was still largely innumerate, but that in the second half of the eighteenth century propositional knowledge, from temperature and rainfall tables to agricultural yields, the hardness and softness of materials, and economic and demographic information was increasingly presented in tables and expected its readers to be comfortable with that language (or at least be willing to learn).[62] Tables not only made the presentation of information more efficient, they organized and analyzed it by forcing the author to taxonomize the data. A booklet such as Smeaton's famous *Treaty on Water and Wind Mills* used tables lavishly to report his experiments, but already four decades earlier, in 1718, Henry Beighton had published a table entitled *A Calculation of the Power of the Fire (Newcomen's) engine shewing the Diameter of the*

[60] Rider, "Measure," p. 115.

[61] The triumph of Lavoisier's chemistry over its British opponents in the later 1790s is a good example. See Golinski, "Nicety."

[62] Heilbron, "Introductory Essay," p. 9. These methods soon were applied to mundane purposes. An example is Dougharty, *General Gauger*. The first half or so of the book lays out arithmetic manipulations, starting from the basics.

Cylinder, for Steam of the Pump that is Capable of Raising any Quantity of Water, from 48 to 440 Hogsheads an Hours; 15 to 100 yards.[63] Tables of astronomical, legal, historical, literary, and religious information appeared in many eighteenth-century books, but some of it was practical and mundane. John H. Desaguliers in 1734 published a (bi-lingual) set of 175 tables from which jewelers could determine the value of diamonds.[64] Later in the eighteenth century tables were complemented by graphs, and the growing sophistication of information was enhanced by visual means. William Playfair pioneered the display of data in graphical form, defending their use explicitly on the basis of a reduction in access costs.[65] This idea caught on but slowly, and oddly enough faster on the Continent than in Britain, which seems on the whole to have preferred tables.[66] That even with formal notation and well-organized data there will still be plenty of ambiguity left is something that most economists—and surely all economic historians—are all too keenly aware of.

Precisely because the Industrial Enlightenment was not limited to being a national or local phenomenon, it became increasingly felt that differences in language and standards were an impediment and increased access costs. Watt, James Keir, and the Derby clockmaker John Whitehurst, worked on a system of universal terms and standards that would make French and British experiments "speak the same language."[67] In the eighteenth century access costs fell in part because national and geographic barriers were easily crossed.[68] The Enlightenment movement as a whole was cosmopolitan, with the typical scientist or philosopher more a citizen of the Republic of Letters than of his own country.[69] Many of the central figures of the Indus-

[63] Smeaton, *Experimental Enquiry*. Beighton's Table is reproduced in Desaguliers, *Course of Experimental Philosophy*, p. 535. Desaguliers remarked that "Mr. Beighton's table agreed with all the experiments made ever since 1717." For more details on Beighton, a remarkable early example of the Industrial Enlightenment, see Stewart, *Rise*, pp. 242–51.

[64] Desaguliers, *Jewellers Accounts*.

[65] Playfair, *The Commercial and Political Atlas*. "As knowledge increases amongst mankind, and transactions multiply, it becomes more and more desirable to abbreviate and facilitate the modes of conveying information." Cited by Headrick, *When Information*, p. 127. This text does not appear in the 1786 original edition. Playfair's book was concerned with economic data, not science and technology.

[66] James Watt, Playfair's employer, advised him "that it might be proper to give in letter press the Tables from which the Charts have been constructed." Cited by Spence, "Invention," p. 78.

[67] Uglow, *Lunar Men*, p. 357.

[68] For an excellent discussion of the growing mobility of scientific and technological knowledge in the eighteenth century, see Inkster, "Mental Capital."

[69] Darnton, "Unity." The idea of the *Respublica Litteraria* goes back to the late middle ages, and by the eighteenth century had extended to mechanical and technical knowledge. John R. Harris has noted that as early as the 1720s the development of the early steam engine was the center of intense interest in the European scientific community, and "international intelligence about the engine diffused with great speed, the speed of correspondence between the scientific luminaries of Europe of that period." See Harris, *Industrial Espionage*, p. 296.

trial Enlightenment were well traveled, none more than Franklin and Rumford, and realized the importance of reading in foreign languages (language difference is a component of access costs).[70] Books on science and technology were translated quickly, even when nations were at war with one another. P. J. Macquer's encyclopedic textbook on chemistry was translated (with considerable additions) by James Keir, a member of the Lunar society, and the works of Lavoisier and Berthollet were translated in Britain within a short time of their first appearances. The British knew all too well that Continental chemists were superior to their own. In return, the French translated scientific works published in Britain, and here too, the translators were often leading experts themselves, such as the Comte de Buffon translating Stephen Hales's influential *Vegetable Staticks* in 1735 and John T. Desaguliers's translating the leading Dutch Newtonian Willem's Gravesande's *Mathematical Elements of Natural Philosophy* (1720), studied later by James Watt (whose father owned the book). Chaptal's *Elements of Chemistry* (1795) was translated into English by William Nicholson, a distinguished chemist.[71] Honor and prestige crossed national boundaries as easily as knowledge. Lavoisier was a fellow of the Royal Society, and corresponded with, among others, Josiah Wedgwood about the use of refractory clays.[72] In 1808 James Watt, Edward Jenner, and the chemist Richard Kirwan were elected foreign associates of the French Academy of Sciences (then known as the *Institut National*), war or no war. Statements such as that knowledge was supranational and that "the sciences were never at war" (as Lavoisier claimed in 1793) are of course an overidealization. Reality, especially after 1793, deviated from the ideals of the Enlightenment, and political and military considerations increasingly got in the way of the free flow of useful knowledge.[73] Useful knowledge, it was realized, could be valuable to the state when engaged in combating another.

Access costs consisted in great measure of knowing what was known, and to facilitate access, knowledge had to be classified. This turned out to be an involved project, and much intellectual capital was spent on taxon-

[70] Robert Hooke taught himself Dutch to read Leeuwenhoek's famous letters on microscopy, and a century later John Smeaton taught himself French to be able to read the papers of French hydraulic theorists such as de Parcieux and traveled to the Netherlands to study their use of wind power firsthand.

[71] Uglow, *Lunar Men*, p. 27. The movement of translations was symmetrical. In 1780 a French publisher published a whole bundle of *Ouvrages sur l'économie politique et Rurale, traduit de l'Anglais* including work by Arthur Young and John Arbuthnot (who had written an important work on ploughs). Bourde, *Influence*, p. 97. In agriculture, as Gillispie correctly points out, the impact of such information flows "beyond the circle of persons who wrote, printed and read the books," was probably small. See Gillispie, *Science . . . End of Old Regime*, p. 367.

[72] Schofield, *Lunar Society*, p. 378.

[73] de Beer, *Sciences,* passim.

omy and the organization of knowledge.[74] Access to knowledge required search engines. The new search engine of the eighteenth century was the encyclopedia, exploiting that miracle of organizational technology, alphabetization. To be sure, Diderot and d'Alembert's *Encyclopédie* did not augur the Industrial Revolution, it did not predict factories, and had little or nothing to say about mechanical cotton spinning equipment or steam engines. It catered primarily to the landowning elite and the bourgeoisie of the *ancien régime* (notaries, lawyers, local officials) rather than specifically to an innovative industrial bourgeoisie, such as it was. It was, in many ways, a conservative document.[75] Moreover, the idea of such a search engine was not altogether new, and attempts to sum up all that is known in some fashion can be found in China and in medieval Europe. However, the drive to organize knowledge in a way that made it accessible at a high level of detail yet easy to use was very much a product of the eighteenth century.[76] The *Encyclopédie* and similar works of the eighteenth century symbolized the very different way of looking at technological knowledge: instead of intuition came systematic analysis, instead of tacit dexterity came an attempt to attain an understanding of the principles at work, instead of secrets learned from a master came an open and accessible system of training and learning. It also insisted on organizing knowledge in user-friendly compilations, arranged in an accessible way, and although subscribers may not have been mostly artisans and small manufacturers, the knowledge contained in it dripped out and trickled down through a variety of leaks to those who could make use of it.[77] Encyclopedias allowed not only for faster searches, but also underlined the agnosticism of the project to biased taxonomies of knowledge. While it may be an overstatement that they were a starting point toward a new concept of knowledge, as pragmatic and heuristic documents they reflected an intellectual innovation that deliberately sought to reduce access costs.[78]

Furthermore, then as now, works that have an "encyclopedic" nature are instinctively trusted. It is believed—perhaps too optimistically—that such synthetic works reflect authority and best-practice knowledge, and that any statements reflecting baseless speculation and personal bias have been ex-

[74] Burke, *Social History*, chap. 5.

[75] Darnton, *Business*, p. 286.

[76] Heilbron, "Introductory Essay," p. 20, notes that Diderot and d'Alembert were but indolent in comparison with the massive (64 volumes) work published by J. H. Zedler, *Grosses vollständiges Universal-Lexikon aller Wissenschafte und Künste*, published 1732–1754.

[77] Pannabecker points out that the plates in the *Encyclopédie* were designed by the highly skilled Louis-Jacques Goussier who eventually became a machine designer at the Conservatoire des arts et métiers in Paris. They were meant to popularize the rational systematization of the mechanical arts to facilitate technological progress. Pannabecker, "Diderot," pp. 6–22, and "Representing Mechanical Arts."

[78] Broberg, "Broken Circle," pp. 45–71.

cised by conscientious encyclopedia editors. As such, the emergence of encyclopedias as an accessible source of useful knowledge reduced access costs on another front, namely the costs of verification. Many other works of useful knowledge were sponsored by the French Royal Academy, the British Royal Society, or similar formal institutions. Such quasi-official imprimaturs were intended to make them look more believable and tighter.[79] The age also witnessed the rise of bibliographical guides and handbooks, that helped readers find their way to the knowledge they sought.

Encyclopedias and "dictionaries" were supplemented by a variety of textbooks, manuals, compendia, gazettes, and compilations of techniques and devices that were in use somewhere, none more detailed than the over 13,000 pages of the 80 volumes of the *Descriptions des Arts et Métiers* compiled in France before the Revolution—in Gillispie's judgment the "largest body of technological literature ever produced."[80] Much more modest and affordable were the multitudinous "dictionaries" of useful arts published all over Europe.[81] In agriculture, meticulously compiled data collections looking at such topics as yields, crops, and cultivation methods were common.[82] Engineering manuals, meticulous descriptions of various "useful arts" were published, translated, pirated, and—one presumes—read on a wider scale than ever before. One of the most impressive and best-organized of such textbooks was P. J. Macquer's *Dictionnaire de Chimie* published in 1766 and, as noted, translated into English in 1771 by

[79] The "Philosophical Transactions" published by the Royal Society and the "Histoire et Mémoires" published by the *Académie Royale des Sciences* were among the most influential publications of their time. They were routinely reported on in the wide-circulation *Gentleman's Magazine* and abridged, abstracted, and translated all over the Continent.

[80] Cole and Watts, *Handicrafts*. Gillispie, *Science . . . End of Old Regime*, p. 344.

[81] For instance, Jaubert, *Dictionnaire Raisonné*; Hall, *New Royal Encyclopædia*; and Society of Gentlemen, *New and Complete Dictionary*.

[82] William Ellis's *Modern Husbandman or Practice of Farming* (1731) gave a month-by-month set of suggestions, much like Arthur Young's most successful book, *The Farmer's Kalendar* (1770). Summaries of this information often took the form of frequently updated dictionaries and compendia, such as Society of Gentlemen, *Complete Farmer* first published by the Society of Arts in 1766. Most of these writings were empirical or instructional in nature, but a few actually tried to provide the readers with some systematic analysis of the principles at work. One of those was Francis Home's *Principles of Agriculture and Vegetation* (1757). Some of the great private data collection projects of the time were Arthur Young's famed *Tours* of various parts of England and William Marshall's series on *Rural Economy* (Goddard, "Agricultural Literature"). They collected hundreds of observations on farm practice in Britain and the continent, although at times Young's conclusions were contrary to what his own data indicated. See Allen and Ó Gráda, "On the Road." In France, Duhamel de Monceau's *Traité de la Culture des Terres* (1753) found a wide readership and was translated into English and published in 1759. His textbook *Élements d'agriculture (1762)* was also widely translated and reprinted. The French repaid the honor in 1801/02 by publishing an 18-volume translation of Arthur Young's works on agriculture and politics under the title *Le Cultivateur Anglais*.

the chemist James Keir.[83] It contained over 500 articles on practical chemistry, arranged alphabetically. Keir supplemented his translation with the most recent discoveries made by Dr. Black, Mr. Cavendish, and others. It was the finest and most accessible compilation of pre-Lavoisier chemical knowledge, and indicative of the great value placed on access to knowledge believed to be potentially useful. There were other such volumes. Richard Watson, elected Professor of Chemistry at Cambridge in 1764 wrote a popular text, *Chemical Essays,* which sold thousands of copies and went through 11 editions. Elementary mathematical knowledge, especially arithmetic and geometry, had to be made accessible cheaply and reliably to a host of craftsmen and skilled artisans, from instrument makers to surveyors to accountants. Here the classic book was Francis Walkingame's *Tutor's Assistant*, which, between its first publication in 1751 and the death of its author in 1783, went through 18 editions, each consisting of between five and ten thousand copies.[84] Formal knowledge was also made more accessible by logical systematization and organization, as illustrated by the detailed indexes that became standard on works of useful knowledge. Taxonomical science was epitomized by the work of Carl Linnaeus, whose classificatory schemes were arguably the most influential scientific endeavor between Newton and Lavoisier, his binomial nomenclature reducing communication and access costs to natural history and botanical knowledge.

Furthermore, access costs had a strictly social dimension. Technological communication inevitably often took the form of personal contact, and such exchanges on knowledge were more effective when the two sides trusted one another. Historically, one of the great sources of technological stagnation had been the social divide between those who knew things ("*savants*") and those who made things ("*fabricants*"). The relationship between those who possessed useful knowledge and those who might find a use for it was changing in eighteenth-century Europe and points to a further reduction in access costs. To construct pipelines through which those two groups could communicate was at the very heart of the movement.[85] These pipelines, or *passerelles* as Hilaire-Pérez has called them, ran both

[83] Macquer, *Dictionary of Chemistry*. Originally printed in 1771, a fifth edition had already been published by 1777, indicating the success of the work.

[84] Walkingame, *Tutor's Assistant.* By the end of the century, student guidebooks to the *Tutor's Assistant* had appeared. See Wallis, "Early Best-seller," pp. 199–208. Walkingame included mathematical methods employed by glaziers, painters, plasterers, and bricklayers, pointing to the applied and pragmatic nature of the mathematics he taught.

[85] This point was first made by Edward Zilsel in 1942, who placed the beginning of this movement in the middle of the sixteenth century. Although this may be too early for the movement to have much economic effect, the insight that technological progress occurs when intellectuals communicate with producers is central to its historical explanation. Compare Zilsel, "Sociological Roots of Science," pp. 544–60. For a recent restatement, see Jacob, *Scientific Culture*.

ways; they served as a mechanism through which practical people with specific technical problems to solve could air their needs and absorb what best-practice knowledge had to offer—which, of course, at most times was rather little. At the same time, knowledge of crafts and manufactures could influence the research agenda of the scientists, as the Royal Society, at least in its first decades, stressed, by posing focused and well-defined problems. The movement of knowledge was thus bi-directional, as seems natural to us in the twenty-first century. In eighteenth-century Europe, however, such exchanges were still quite novel and it only slowly dawned on people that it would benefit and direct science as much as it would influence industry.[86] By the 1760s in much of Europe the social gap between natural philosophers and entrepreneurs had begun to close, though only very slowly, far too slowly for those who recognized its importance.[87] Social contacts between *savants* and *fabricants* were sufficiently close for Joseph Priestley to marry the sister of the great ironmonger John Wilkinson, and the doyen of British science and president of the Royal Society, Joseph Banks, corresponded with many of the leading industrialists of the time.

Open science and the sharing of useful knowledge meant, of course, that the persons who created this knowledge could not extract the rents it created. Those who added to propositional knowledge would be rewarded by honor, peer recognition, and fame—not a monetary reward proportional to their contribution. For most of the truly great scientists of the era, from Newton to Linnaeus to Lavoisier, the honor and recognition were usually enough if a certain reservation comfort constraint was satisfied. Even those scientists who discovered matters of significant import to industry, such as Claude Berthollet, Joseph Priestley, Benjamin Franklin, and Humphry Davy, often wanted credit, not profit.

[86] Thomas Sprat recognized this in the 1660s when he wrote that no New Atlantis (Bacon's ideal scientific community) was possible unless "Mechanick Labourers shall have Philosophical heads; or the Philosophers shall have Mechanical hands." See Sprat, *History,* p. 397. In its early days, the Royal Society invested heavily in the study of crafts and technology and commissioned a History of Trades, but this effort in the end failed. Compare Hunter, *Establishing the New Science.*

[87] Humphry Davy felt in 1802 that "in consequence of the multiplication of the means of instruction, the man of science and the manufacturer are daily becoming more assimilated to each other." Davy, *Discourse*, vol. 2, p. 321. Not all agreed at the time: William Thompson, Count Rumford, noted in 1799 that "there are no two classes of men in society that are more distinct, or that are more separated from each other by a more marked line, than philosophers and those who are engaged in arts and manufactures" and that this prevented "all connection and intercourse between them." He expressed hope that the Royal Institution he helped found in 1799 would "facilitate and consolidate" the union between science and art and to direct "their united efforts to the improvement of agriculture, manufactures, and commerce, and to the increase of domestic comfort." See Thompson, *Complete Works*, pp. 743–45.

ACCESS COSTS: INSTITUTIONAL FACTORS

The Industrial Enlightenment consisted in large part of the emergence of institutions devoted to the flow of ideas. Among those, it would seem, Universities should have played a major role. This was surely true for Scotland, where such leading lights as Colin McLaurin, William Cullen, Joseph Black, John Robison, and many others taught courses of considerable technical significance. At the University of Glasgow, many of these courses were opened to artisans and other townspeople interested in studying chemistry and other applied fields. The course taught by Joseph Black in Edinburgh was attended by 200 listeners, and his successor, Thomas Charles Hope, occasionally addressed over 500 auditors.[88] In Germany, a wave of new universities, included that in Göttingen, were founded in the 1740s, training future bureaucrats in agricultural science, engineering, mining, and forestry.[89]

Yet, oddly enough, the role of formal educational institutions in the reduction of access costs was quite modest in the first century of the Industrial Revolution.[90] English universities were rather ineffective in teaching applied science and mechanics in this period, although the gap was made up in part by the Scottish universities, and in part by 60 or so dissenting academies, which taught experimental science, mathematics, and botany among other subjects. Among those, Warrington Academy was one of the best, and the great chemist Joseph Priestley taught there for a while, though surprisingly he was made to teach history, grammar, and rhetoric.[91] Although these institutions reached only a thin elite, apparently that was enough. In the early nineteenth century, there were some attempts to close the educational gap between classes by means of the so-called Mechanics Institutes, inspired by George Birckbeck, which supplied adult education

[88] Wood, "Science," p. 109.

[89] Outram, *Enlightenment*, p. 60.

[90] Oxford and Cambridge have been given little credit for teaching much of value to a vibrant economy, and their enrollments declined in the eighteenth century. Adam Smith in a famous sentence remarked sarcastically that at Oxford the dons had "long ago given up all pretence of teaching," and Priestley compared them to "pools of stagnant water." There were a few exceptions, especially in Cambridge where Richard Watson was "chiefly concerned with manufacturing processes rather than with the advancement of pure science" and John Hadley who showed a "noticeable interest in industrial-chemical processes" (Musson and Robinson, *Science and Technology*, pp. 168, 36). His colleague in Magdalene College, John Rowning, was a mathematician who wrote a popular *Compendious System of Natural Philosophy* that went through seven editions between 1735 and 1772. Birse has collected data that show that out of 498 applied scientists and engineers born between 1700 and 1850, 91 were educated in Scotland, 50 at Oxbridge, and 329 (about two-thirds) had no university education at all. See Birse, *Engineering*, p. 16. Over the eighteenth century, moreover, the number of engineers and applied scientists who received a formal institutionalized education declined.

[91] Schofield, *Lunar Society*, p. 195.

in the evening, with the purpose of bridging the gap between the working class and science.[92] Contemporaries noted that these institutes by and large failed in their objective to spread scientific knowledge to the masses and mostly provided remedial education to laborers, as well as scientific knowledge to members of the skilled labor aristocracy.[93]

The other institutional mechanism emerging during the Industrial Enlightenment to connect those who possessed prescriptive knowledge to those who wanted to apply it was the emergence of meeting places where men of industry interacted with natural philosophers. Many of these meetings were ad hoc lectures and demonstrations by professional lecturers and popularizers.[94] A. E. Musson and Eric Robinson, who were among the first to recognize the significance of these lecturers point out that only a few of them were of national significance, whereas others were "mostly local" figures.[95] Much of the improved access to useful knowledge took place through informal meetings of which we have but poor records, in coffee houses and pubs, improvised lectures, and private salons.[96] By 1700 there were 2,000 coffeehouses in London, many of which were sites of learning, literary activity, and political discussions. Perhaps the most famous of

[92] Inkster, "Social Context," pp. 277–307.

[93] Roderick and Stephens, *Education*, pp. 54–60.

[94] Of the itinerant lecturers, the most famous was John T. Desaguliers. Desaguliers, a leading proponent of Newton with an international reputation (he lectured in the Netherlands) received a royal pension of £70 per annum as well as a variety of patents, fees, and prizes. His *Course of Mechanical and Experimental Philosophy* (1724) was based on his hugely popular lectures on science and technology. William Whiston, one of Newton's most distinguished proponents and successor at Cambridge "entertained his provincial listeners with combinations of scientific subjects and Providence and the Millennium." James Jurin, master of the Newcastle Grammar School, gave courses catering to the local gentlemen concerned with collieries and lead-mines. (See Stewart, *Rise,* p. 147). Other British lecturers of note were Peter Shaw, a chemist and physician, the instrument maker Benjamin Martin, Stephen Demainbray who lectured both in France and England and later became Superintendent of the King's Observatory at Kew, and the Reverend Richard Watson at Cambridge whose lectures on Chemistry in the 1760s were so successful that he drew a patronage of £100 for his impoverished chair. In France the premier lecturer and scientific celebrity of his time was Abbé Jean-Antoine Nollet, whose fame rests on early public experiments with electricity (he once passed an electrical charge from a Leyden jar through a row of Carthusian monks more than a mile long). Nollet also trained and encouraged a number of his disciples as lecturers, as well as some of the most celebrated scientists of his age, such as Lavoisier and Monge. Similarly, Guillaume-François Rouelle's lectures on chemistry in the Jardin du roi drew an audience that included Rousseau, Diderot, and even Lavoisier himself. Compare Stewart, "Laboratory." In Napoleonic France, the "best scientific minds of the day" were lecturing to the public about steam engines, and it became common to regard some scientific training as a natural prelude for entrepreneurial activity (Jacob, "Putting Science").

[95] For a magisterial survey, see Musson and Robinson, *Science*, pp. 87–189.

[96] In the closing years of the seventeenth century, the Marine Coffee House in Birchin Lane behind the Royal Exchange in London was the first location for an organized set of lectures on mathematics given by the Reverend John Harris, to be followed by a series on experimental philosophy. See Stewart, "Selling of Newton," p. 180. Among the best-known private eighteenth-century Paris *salons* were those of Mme de Tencin and Mme l'Espinasse.

these coffee house societies was the London Chapter Coffee House, the favorite of the fellows of the Royal Society, whose membership resembled (and overlapped with) the Birmingham Lunar Society.[97] Masonic lodges, too, proved a locus for the exchange of scientific and technological information even if that was not their primary mission.[98] Lecturers performed entertaining public experiments, in which electricity and magnetism played roles disproportionate to their technical significance. Needless to say, there are other explanations for the popularity of scientific lectures, not all of them persuasive.[99]

After 1750 informal meetings started to slowly dwindle in importance, as they were replaced by more formal organizations, but the demand for useful knowledge remained strong. The establishment of the Royal Society in 1662 was one of the first signs of what was to come. There had, of course, been precedents, such as the *Accademia dei Lincei* founded in 1603 in Rome and disbanded in 1630. Formal academies were founded and bankrolled by states or local governments, whereas spontaneous societies, often specialized, were organized by their participants. It is striking to what degree this phenomenon in the eighteenth century became a *provincial* phenomenon; small towns increasingly found they had the critical mass of interested persons to form a formal club devoted to scientific and technological discourse. Of those, a few have attained fame as the kind of organizations that were instrumental in bringing about the Industrial Revolution, none more so than the Birmingham Lunar Society.[100] Knowledge exchange was the very raison d'être of the Birmingham Lunar Society, which provided routine contact between scientists such as Priestley and Keir, mechanics such as Whitehurst and Watt, and entrepreneurs such as Boulton and Wedgwood.[101]

[97] Levere and Turner, *Discussing Chemistry*. Its membership reads like a veritable list of the "Who's who" of the British Industrial Enlightenment of the 1780s. Needless to say, many of these lecturers structured their lectures around topics that had no immediate or even remote applicability, presented theories that were bogus even by the standards of the time, and at times they showed a bias toward the flashy and dramatic experiment over the strictly useful. Schaffer, "Natural Philosophy," pp. 1–43. Desaguliers himself admitted that "a great many persons get a considerable knowledge of Natural Philosophy by way of amusement" (cited by Schaffer, "Machine Philosophy," p. 159). But as Stewart ("Laboratory," p. 8) remarks, "a sense of practical consequence was not immediately excluded by the spectacular."

[98] On the significance of Masonic Lodges, see Jacob, *Living the Enlightenment*; and Im Hoff, *Enlightenment*, pp. 139–45.

[99] Elliott, "Birth," p. 96, apparently influenced by notions of the "Habermasean public sphere," thinks that their attractiveness came from their being intellectually challenging, morally uplifting, and that they enhanced polite education while not being socially disruptive and offering no threat to peace and stability. This would equally apply to lectures on classical sculpture or cooking classes.

[100] This is most eloquently expressed by Uglow, *Lunar Men*. See also the classic Schofield, *Lunar Society*.

[101] In 1776 Josiah Wedgwood consulted his fellow Lunar Society member, the chemist James Keir, on matters of heating vitreous substances, and together they discovered a way to reduce the

In France, great institutions were created under royal patronage, above all the *Académie Royale des Sciences*, created by Colbert and Louis XIV in 1666 to disseminate information and resources.[102] Yet the phenomenon was nationwide: McClellan estimates that 33 official learned societies were functioning in the French provinces during the eighteenth century, counting over 6,400 members, and that overall during the eighteenth century perhaps between 10,000 and 12,000 men belonged to learned societies that dealt at least in part with science.[103] The *Académie Royale* exercised a fair amount of control over the direction of French scientific development and acted as technical advisor to the monarchy. By determining what was published and exercising control over patents, the *Académie* became a powerful administrative body, providing scientific and technical advice to government bureaus.[104] French academies had a somewhat different objective than did British: it is often argued that the *Académie* linked the aspirations of the scientific community to the utilitarian concerns of the government, creating not a Baconian society open to all comers and all disciplines but a closed academy limited primarily to Parisian scholars. French science was in some ways different from British science, both in its agenda and its methodology. Yet the difference between France and Britain was one of emphasis and nuance, not of essence: they shared a utilitarian optimism of man's ability to create wealth through knowledge. French science, as the old truism has it, was more formal, deductive, and abstract than British science, which had a pragmatic and more experimental bend.[105] But instead of a source of weakness, this diversity ultimately provided the Enlightenment project with strength through, as it were, a division of labor between various societies specializing in the areas of their comparative advantage. Rather than a set of competing players or a horse race, we should regard the European Enlightenment as a joint project in which collective knowledge was produced, increasingly accessible to the participants.

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veins and streaks that disfigured glass at the time. See Schofield, *Lunar Society*, p. 172. Henry Cort, whose invention of the puddling and rolling process was no less central than Watt's separate condenser, also consulted Joseph Black during his work. Compare Clow and Clow, *Chemical Revolution*.

[102] Its membership included most of the distinguished scientists of France in the eighteenth century including d'Alembert, Buffon, Clairaut, Condorcet, Fontenelle, Laplace, Lavoisier, and Reaumur. It published the most prestigious and substantive scientific series of the century in its annual proceedings *Histoire et Memoires* and sponsored scientific prize contests such as the Meslay prizes. It recognized achievement and rewarded success for individual discoveries and tried to enhance the social status of scientists by granting salaries and pensions. A broad range of scientific disciplines were covered, with mathematics and astronomy well represented, and botany and medicine not less prominent.

[103] McClellan, "Academie Royale des Sciences," p. 547.

[104] Hilaire-Pérez, *L'invention technique*, pp. 37, 50. Gillespie, *Science . . . End of Old Regime*, pp. 81–99, 461–63.

[105] For a recent statement, see Jacob and Stewart, *Practical Matter*, p. 119.

Elsewhere on the Continent, too, there was a growing recognition of the importance of the creation of new useful knowledge and improved access to the entire stock. In the Netherlands, rich but increasingly technologically backward, heroic efforts were made to infuse the economy with more innovativeness.[106] In Germany, provincial academies to promote industrial, agricultural, and political progress through science were founded in all the significant German states in the eighteenth century. The Berlin Academy was founded in 1700 and in its early years directed by the great Leibniz. Among its achievements was the discovery that sugar could be extracted from beets (1747). Around 200 such societies appeared in Germany during the half century spanning from the Seven Years War to the Napoleonic occupation of Germany, such as the Patriotic Society founded at Hamburg in 1765.[107] Many of the German societies were dedicated to political economy, emphasizing what they believed to be the welfare of the population at large and the country over private profit. Local and provincial societies supplemented and expanded the work of national academies.[108] Publishing played an important role in the work of societies bent on the encouragement of invention, innovation, and improvement, reflecting the growing conviction that through the diffusion of useful knowledge somehow the public good was enhanced. At the level of access to propositional knowledge, at least, there is little evidence that the *ancien régime* was incapable of generating sustained progress.

[106] The first of these was established in Haarlem in 1752, and within a few decades the phenomenon spread (much as in England) to the provincial towns. The Scientific Society of Rotterdam known oddly as the *Batavic Association for Experimental Philosophy* was the most applied of all, and advocated the use of steam engines (which were purchased in the 1770s but without success). The Amsterdam Society, known as *Felix Meritis*, carried out experiments in physics and chemistry. These societies stimulated interest in physical and experimental sciences in the Netherlands, and they organized prize-essay contests on useful applications of natural philosophy. A physicist named Benjamin Bosma for decades gave lectures on mathematics, geography, and applied physics in Amsterdam. A Dutch Society of Chemistry founded in the early 1790s helped to convert the Dutch to the new chemistry proposed by Lavoisier (see Snelders, "Professors"). The Dutch high schools, known as *Athenea,* taught mathematics, physics, astronomy, and at times counted distinguished scientists among their staff.

[107] Lowood, *Patriotism*, pp. 26–27.

[108] Lowood, *Patriotism*, has argued that the German local societies were predominantly private institutions, unlike state-controlled academies, which enabled them to be more open, with few conditions of entry, unlike the selective, elitist academies. They broke down social barriers, for the established structures of Old Regime society might impede useful work requiring a mixed contribution from the membership of practical experience, scientific knowledge, and political power. Unlike the more scientifically inclined academies, they were open to a wide circle of occupations, including farmers, peasants, artisans, craftsmen, foresters, and gardeners, and attempted to improve the productivity of these activities. Prizes rewarded tangible accomplishments, primarily in the agricultural or technical spheres. Unlike earlier academies, their goal was not to advance learning, but rather to apply useful results of human knowledge, discovery, and invention to practical and civic life.

Some of these societies fit perfectly into the idea of an Industrial Enlightenment. One such was the Society of Arts, founded in 1754, which made a point of encouraging invention by awarding prizes, publicizing new ideas, and facilitating communication between those who possessed useful knowledge and those who could use it. The Royal Institution, founded by Count Rumford and Joseph Banks in 1799, provided public lectures on scientific and technological topics. Its stated purpose in its charter summarizes what the Industrial Enlightenment was about: it was established for "diffusing the knowledge, and facilitating the general introduction, of useful mechanical inventions and improvements; and for teaching, by courses of philosophical lectures and experiments, the application of science to the common purposes of life."[109] In Britain, most of these societies were the result of private initiatives and funds, whereas on the Continent they were usually supported by local or national government. Yet these were differences of degree, not of essence, and certainly not of ideology.[110]

What did these scientific societies do to further economic development in Europe? They organized lectures, symposia, public experiments, and discussion groups, and published "proceedings" on a variety of topics. Many of them had prize essay contests. Much of the material discussed by these organizations was of course quite remote from economic applications. Many of them were meant to standardize languages, or were engaged in discussing issues of archaeology and local history. Others discussed music, the arts, poetry, and the theater. A substantial number of them were either the drinking clubs of a bored leisure class or the pet projects of local nobles, magistrates, or bourgeois busybodies to show off to the next town or county.[111] But in the course of the eighteenth century "natural history" and "experimental philosophy" increasingly started to play a role in these learned societies. Agriculture, chemistry, botany, mineralogy, geology, and medicine became topics around which entire organizations pivoted.[112] They were without any question an elite phenomenon,

[109] The lectures given by Humphry Davy were so popular that the carriages that brought his audience to hear him so clogged up Albermarle Street in London that it was turned into the first one-way street of the city.

[110] Allan, "Society," pp. 434–52.

[111] For a good summary see McClellan, "Learned Societies," pp. 371–77. See also the six entries under "academies" in id., vol. 1, pp. 4–17.

[112] The first agricultural "improvement society" in Britain was the *Scottish Honorable Society of Improvers of the Knowledge of Agriculture* (founded in 1723 and disbanded in 1745 after the rebellion). Ireland followed suit in 1731 with the Dublin Society established "to promote the development of agriculture, arts, science and industry in Ireland." The 1750s and 1760s witnessed the founding of such agricultural societies as the Scottish *Gordon's Mill Farming Club,* founded in 1758, by Thomas Gordon of Aberdeen University on the idea that "agriculture ought to be considered as a noble & important branch of natural Philosophy." The Continent was not far behind. The

and as such their direct impact was limited. However, as Jürgen Habermas has maintained, at least the theory—if not the practice—of formal and informal meeting places in the eighteenth century was for members to disregard status and wealth and treat one another as equals, recognizing only the authority of a "better argument."[113] To be sure, the bulk of their work—as in all creative processes—was wasteful, wrong-headed, and ineffective.[114] But the membership shared a desire to make useful knowledge more accessible, an important trend in the intellectual development of Europe that helped to create the foundation of sustained technological progress in the nineteenth century through reduced access costs.

ACCESS COSTS: ECONOMIC FACTORS

The economic issue of the endogeneity of access costs must be confronted head-on. The decline in access costs was not, of course, a purely supply-driven process. The demand for such technical knowledge by the inventors of the time is exemplified by the rise in technical publications and technical essays in general-purpose periodicals that popularized and summarized best-practice research, and did not publish original findings but popularized and summarized (and often plagiarized) best-practice research published elsewhere. The influence of the Industrial Enlightenment came from both sides, the desire of the *savants* to give and the desire of the *fabricants* to receive. The only attempt to date to try to estimate the impact of exogenous variables such as population and relative prices on the diffusion of knowledge in agriculture is an important and neglected paper by L. Simon and Richard Sullivan.[115] Thinking of it in a supply and demand framework may, however, not be the only way to think of the mechanisms

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idea of agricultural progress on the eighteenth-century Continent was personified in the work of Duhamel du Monceau, a French *agronome* and "specialist in things English" and in that of the German Albrecht Thaer. The Florence *Accademia dei Georgofili* (1753) and the *Société d'Agriculture, de Commerce et des Arts de Bretagne* (1757) in Rennes were followed by the *Académie d'Agriculture de la France* (1761), the Royal Danish agricultural society (1769) and many others. Terms such as "useful knowledge" start cropping up increasingly after 1750, in the names and charters of institutions such as the *Akademie Gemeinnütziger Wissenschaften zu Erfurt* and the British *Society for the Encouragement of Arts, Manufactures and Commerce* (both founded in 1754).

[113] Habermas, *Structural Transformation*, p. 36.

[114] This was well expressed by Eric Jones 20 years ago: "Much of the activity of the science subculture, the club meetings, the flooding exchange of information by mail, fell by the wayside as far as material gain was concerned at the hands of tired or dilettantish or unlucky individuals . . . Nevertheless there was so very much activity . . . that some seeds from hobby science and technological curiosity were almost certain not to fall on stony ground." Jones, "Subculture," p. 877.

[115] Simon and Sullivan, "Population Size," pp. 21–44. They find the growth of publications and patenting to depend on population size and the relative price of food products. The problem of course is that if the relative price of agricultural goods explains publication of tracts on farming technology, how can we explain the increase of works in chemistry, mechanics, and mathematics?

leading to the Industrial Enlightenment. An alternative view would regard it as an evolutionary process, in which elements of an entity called "useful knowledge" multiplied and were "selected for" in a environment conducive to growth and diffusion of knowledge that eventually became economically productive.

In any event, in the closing decades of the seventeenth century and the first half of the eighteenth, a market for "commodified" useful knowledge started to emerge and became a hallmark of the Industrial Enlightenment. Professional scientists such as John Harris, James Hodgson, William Whiston, and John T. Desaguliers made money by lecturing, consulting, and publishing.[116] Larry Stewart has referred to these men as "entrepreneurs of science" who found that they had a commodity to sell that people with money found attractive.[117] During the Industrial Revolution, these markets for consultants expanded and became more formal.[118] Intellectual property rights in useful knowledge tend on the whole to enhance such markets, because by taking out a patent, the inventor placed the invention in the public realm and had an incentive to publicize it rather than keep it secret.

Some Enlightenment figures made a career (and often a good living) out of specializing in building such bridges between propositional and prescriptive knowledge, and might therefore be called access-cost reducers or facilitators. Among them was William Shipley, famous for founding the Society of Arts, but also the Maidstone Society, which was expanded later into the Kentish Society for Promoting Useful Arts. Not a very creative or original individual himself, he was highly active in the management of the Society of Arts and in agricultural improvements in Kent where he had a country home, a hotbed of farm innovation. His credo is summed up in his "plan" for the establishment of the Society of Arts: "Whereas the Riches, Honour, Strength and Prosperity of a Nation depend in a great Measure on Knowledge and Improvement of useful Arts, Manufactures, Etc. . . . sev-

[116] For details on their careers, see Jacob and Stewart, *Practical Matter*, pp. 61–92

[117] Stewart, "Selling," p. 181.

[118] Such markets often concerned technical consultants such as the great John Smeaton and the "Smeatonian" engineers that followed his example. Soho-trained engineers traveled widely through Britain, dispensing expertise. The clock- and instrument maker John Whitehurst, a charter member of the Lunar Society, consulted for every major industrial undertaking in Derbyshire, where his skills in pneumatics, mechanics, and hydraulics were in great demand; Joseph Priestley worked as a paid consultant for his fellow "lunatics" Wedgwood and Boulton. See Elliott, "Birth," p. 83. Schofield, *Lunar Society*, pp. 22, 201. Another striking example is the emergence of so-called coal viewers who advised coal mine owners on the optimal location and structure of coal mines, the use of equipment, and similar specific issues. Sidney Pollard recounts that these consultants were often called to check on one another, which clearly enhanced their credibility, and that they were generally the "fountain-head" of managerial and engineering talent in the engineering industry. Pollard, *Genesis*, p. 153.

eral [persons], being fully sensible that due Encouragements and Rewards are greatly conducive to excite a Spirit of Emulation and Industry have resolved to form [the Society of Arts] for such Productions, Inventions or Improvements as shall tend to the employing of the Poor and the Increase of Trade."[119] A second was John Coakley Lettsom, famous for being one of London's most successful and prosperous physicians and for liberating his family's slaves in the Caribbean. He corresponded with many other Enlightenment figures including Benjamin Franklin, Erasmus Darwin, and the noted Swiss physiologist Albrecht von Haller. He wrote a book about the natural history of tea and was a tireless advocate of the introduction of mangel-wurzel into British agriculture.[120] Another was William Nicholson, the founder and editor of the first truly scientific journal, namely *Journal of Natural Philosophy, Chemistry, and the Arts* (more generally known at the time as *Nicholson's Journal*), which commenced publication in 1797.[121] It published the works of most of the leading scientists of the time, and functioned much as do today's *Nature* or *Science*, that is, to announce important discoveries in short communications.[122] Or consider Richard Kirwan, the living spirit behind the London Chapter Coffee House Society in the 1780s. An Irish lawyer, chemist, and mineralogist, trained in France and close to many French scientists, Kirwan brought together scientists, instrument makers, and industrialists to discuss how science could be applied. Like other facilitators, he was an ardent letter writer, who corresponded with all the leading *savants* of Europe, even the Russian Empress Catherine. He wrote the first systematic treatise on Mineralogy (1784), which was soon translated into French, German, and Russian. Elected president of the Royal Irish Academy from 1799 to 1812, he contributed to the introduction of chlorine bleaching into Ireland. Kirwan, too, despite being one of the most respected chemists of his age, was no pioneering scientist and fought a doomed rear-guard action against the anti-phlogiston chemistry imported from France.[123] A fifth Briton who fits this description

[119] Allan, *William Shipley,* p. 192.

[120] Lettsom, *Natural History.* Lettsom was only one of many who translated experimental and empirical data about tea into positive medical recommendations. See MacFarlane, *Savage Wars*, pp. 146–47.

[121] Nicholson was also a patent agent, representing other inventors. Around 1800 he ran a "scientific establishment for pupils" on London's Soho square. The school's advertisement announced that "this institution affords a degree of practical knowledge of the sciences which is seldom acquired in the early part of life," and promised to deliver weekly lectures on natural philosophy and chemistry "illustrated by frequent exhibition and explanations of the tools, processes and operations of the useful arts and common operations of society."

[122] In it, leading scientists including John Dalton, Berzelius, Davy, Rumford, and George Cayley communicated their findings and opinions. Yet it also contained essays on highly practical matters, such as an "Easy Way of churning Butter" or a "Description of a new Lamp upon M. Argand's Principle."

[123] His "Essay on Phlogiston" was translated by none other than Mme. Lavoisier herself, with adverse commentaries appended by her husband, as well as Berthollet, Monge, and Morveau. In 1791

as a mediator between the world of propositional knowledge and that of technology was Joseph Banks, one of the most distinguished and respected botanists of his time whose life was more or less coincident with the Industrial Revolution. Wealthy and politically well connected, Banks was a co-founder (with Rumford) of the Royal Institution in 1799, a friend and scientific consultant to George III, and president of the Royal Society for 42 years. Banks labored tirelessly to help bring about the social and economic improvement the Baconian program advocated, corresponded with many people, supported every innovative branch of manufacturing and agriculture, and was the dominant political figure in Britain's world of science for much of his life. Among his close friends were the agricultural improvers John Sinclair and Arthur Young, as well as two pillars of the Industrial Revolution, Matthew Boulton and Josiah Wedgwood. He was associated with, among others, the Society for the Arts, before taking over the Royal Society, which he ruled with an iron if benign hand.[124] He was every inch an enlightenment figure, devoting his time and wealth to advancing learning and to using that learning to create wealth, "an awfully English *philosophe*" in Roy Porter's memorable phrase.[125]

Britain had no monopoly on such facilitators, The same traditions can be observed on the Continent, although after 1789 some talented persons were distracted by and diverted into political or military careers. Among the more notable of them was Henri-Louis Duhamel de Monceau, a noted *agronome* and the chief editor of the massive *Descriptions des Arts et Métiers*.[126] François Rozier (1734–1793), another *agronome* and scientific entrepreneur, "a clergyman whose vocation was the enlightenment" in Gillispie's succinct characterization, publisher of the *Observations sur la Physique, sur l'Histoire Naturelle, et sure les Arts,* widely regarded as the first independent periodical to be concerned wholly with advances in cutting-edge science.[127] Jean-Antoine Chaptal, a noted chemist, successful entrepreneur, and Minister of the Interior early in the rule of Bonaparte, played a major part in the founding of the *Societé d'Encouragement pour l'Industrie Nationale* and "sought to instill a new scientific ideology to educate entrepreneurs in applied science and engineers in business

Kirwan admitted his conversion to the antiphlogistonist position. Lever and Turner, *Discussing Chemistry,* passim. See also Reilly and O'Flynn, "Richard Kirwan," pp. 298–319.

[124] Drayton, *Nature's Government*, chap. 4. Gascoigne, *Joseph Banks*, passim.

[125] Porter, *Creation*, p. 149.

[126] For details see Bourde, *Agronomie*, pp. 253–76, 313–68. Gillispie, who also studied Duhamel in some detail summarized his intellectual persona: "his hallmark was neither style nor wit but usefulness." Condorcet, in his eulogy, wrote of him that in his writings he expected little prior knowledge of his readers and composed his works, not for scientists but for persons who would put what they had learned to use. See Gillispie, *Science . . . End of Old Regime*, p. 338.

[127] McClellan, "Scientific Journals," pp. 45–46. Gillispie, *Science . . . End of Old Regime*, p. 188.

savvy."[128] His *Chimie appliqée aux arts,* published in four volumes in 1807, became the standard work in industrial chemistry in the early decades of the nineteenth century. Another was Alexandre Vandermonde, a mathematician who was deeply attracted to machinery and technology and collaborated with the famed French inventor Jacques Vaucanson. His most famous contribution was to be the "principal organizer" behind the research project that resulted in the first major industrial application of Lavoisier's new chemistry, namely the *"mémoire sur le fer"* (published jointly with the more famous Gaspard Monge and Claude Berthollet in 1786).[129] Less well known was Henri de Goyon de la Plomanie, who in 1762 published a two-volume work, *La France Agricole et Marchande,* popularizing a number of inventions in the field of farm implements and hydraulics.[130] In Germany, an early figure in this tradition was Johann Joachim Becher (1635–1682), an alchemist, engineer, mathematician, physician, and courtier.[131] On the Continent, courts played a far more central role in this process than in Britain, where this intellectual arbitrage was largely carried out by the private sector.

As might be expected, in some cases the bridge between propositional and prescriptive knowledge occurred within the same mind: the very same people who also were contributing to science made some critical inventions (even if the exact connection between their science and their ingenuity is not always clear).[132] In doing so, they not only facilitated the bidirectional flows of knowledge, but also created hybrid practices in which the standards and methods of one sphere were applied to another. The spheres were always overlapping, but during the nineteenth century some specialization did set in.[133] Among the inventions made by people whose main fame rests on their scientific accomplishments were the chlorine

[128] Jacob, "Putting Science to Work." An excellent survey of Chaptal's career and importance is contained in Horn and Jacob, "Jean-Antoine Chaptal," pp. 671–98. See also Gillispie, *Science . . . Napoleonic Years,* pp. 611–34.

[129] The paper established beyond any doubt the chemical differences between cast iron, steel, and wrought iron, and attributed the differences in physical properties to differences in carbon content without the use of phlogiston. See Gillispie, *Science . . . End of Old Regime*, pp. 438–44.

[130] de la Plombanie, *La France Agricole*, pp. 342–462. In Bourde's assessment, he combined beauty with truth in his description and depiction of these tools.

[131] Smith, *Business*, characterizes his career as "halfway between the world of artisans and that of scholars, he became an intermediary—both physical and intellectual—between them" (p. 5, see also pp. 71–77).

[132] Kranakis, "Hybrid Careers," pp. 177–204. One of her examples is the French engineer and mathematician Claude-Louis Navier (1785–1836), who, among others, used the recently developed Fourier analysis to analyze the vibration in suspension bridges, and did pioneering work in fluid dynamics for which he is still famous. His work, and that of other *polytechniciens*, was highly abstract and mathematical, and of long-term rather than immediate applicability.

[133] As I have argued elsewhere, the adoption of the scientific *method* by inventors and engineers in the eighteenth century was central to the acceleration of technological progress. See Mokyr, *Gifts*, pp. 36–38.

bleaching process, first suggested by Lavoisier's most illustrious student, Claude Berthollet, the invention of carbonated (sparkling) water and rubber erasers by Joseph Priestley, and the "miners friend," the safety lamp to be used in collieries invented by the leading scientist of his age, Humphry Davy (who also wrote a textbook on agricultural chemistry and discovered that a tropical plant named catechu was a useful additive to tanning). As noted already, many of those "dual" career minds seemed uninterested in making money from their inventions, presumably applying the ethics of open science to the diffusion of technology.[134] Incentives were, as always, central to the actions of the figures of the Industrial Enlightenment, but rather we should not assume that these incentives were the same for all. Nor were they necessarily the same in the age of Enlightenment and in the modern age. In our own post-Schumpeterian world, in which most R&D is carried out by corporate entities, the financial bottom line may well be the dominant motive; in an earlier day, when the decisions were made largely by independent individuals, ambition, curiosity, and altruism may have had a larger role relative to naked greed.

THE INDUSTRIAL ENLIGHTENMENT AND ECONOMIC GROWTH

The Industrial Enlightenment, thus, had two dimensions. One was to expand the body of propositional knowledge and to steer it in those directions that might turn out to be useful, that is, both to increase research and to adjust its agenda to make it more likely for discoveries to have useful applications. The second was a deliberate effort to reduce access costs to *existing* knowledge. As noted, those two objectives were not independent, but rather neatly complemented one another. Although they were, of course, like the rest of the Enlightenment, confined to a small elite in the West and never constituted a mass movement, that elite was pivotal in igniting the processes that brought about the Industrial Revolution. Natural philosophers, physicians, engineers, skilled mechanics, and entrepreneurs combined to change the rate and direction in which new useful knowledge was accumulated and diffused.

How much did all this matter? To dwell on one example of the effect of the improved access to knowledge, consider the development of steam power. There is little doubt that the scientific milieu of Glasgow in which Watt lived was indispensable to his technical abilities. He maintained di-

[134] Richard Kirwan was "philosophically indifferent to money," and William Nicholson was "continually occupied in useful work but failed to derive any material advantages from his labour." (Dictionary of National Biography, vol. 11, p. 229; vol. 14, p. 475. Not all scientists eschewed such profits: the brilliant Scottish aristocrat Archibald Cochrane (Earl of Dundonald) made a huge effort to render the coal tar process he patented profitable, but failed and ended up losing his fortune.

rect contact with the Scottish scientists Joseph Black and John Robison, and as H. W. Dickinson and Rhys Jenkins note in their memorial volume, "one can only say that Black gave, Robison gave, and Watt received."[135] Whether or not Watt's crucial insight of the separate condenser was due to Black's theory of latent heat, there can be little doubt that the give-and-take between the scientific community in Glasgow and the creativity of men such as Watt was essential in smoothing the path of technological progress.[136] Much the same can be observed in Cornwall a bit later.[137] Decades later, the work of Mancunians Joule and Rankine on thermodynamics led to the development of the two cylinder compound marine steam engine.[138] The growth of a machine culture in the eighteenth century involved a close collaboration and interaction between natural philosophy and highly skilled craftsmen, grappling with difficult mechanical issues such as heat, power, inertia, and friction, recently described by Larry Stewart.[139] The same is true in many other key industries, especially chemical and engineering, and although it is not nearly as obvious in textiles, access to developments in one industry inspired and stimulated inventors elsewhere.[140]

Nothing of the sort, I submit, can be detected at this time in the Ottoman Empire, Japan, India, Africa, or China. Floris Cohen, indeed, has argued flat-out that Francis Bacon was a typically European figure, who could not possibly have come from anywhere else.[141] The Enlightenment touched lightly (and with a substantial delay) upon Iberia, Russia, and South Amer-

[135] Dickinson and Jenkins, *James Watt*, p. 16.

[136] Hills explains that Black's theory of latent heat helped Watt compute the optimal amount of water to be injected without cooling the cylinder too much. More interesting, however, was his reliance on William Cullen's finding that in a vacuum, water would boil at much lower, even tepid temperatures, releasing steam that would ruin the vacuum in a cylinder. In some sense that piece of propositional knowledge was essential to his realization that he needed a separate condenser. Hills, *Power*, p. 53.

[137] Richard Trevithick, the Cornish inventor of the high pressure engine, posed sharp questions to his scientist acquaintance Davies Gilbert (later President of the Royal Society), and received answers that supported and encouraged his work. See Burton, *Richard Trevithick*, pp. 59–60.

[138] Thermodynamics not only made essential contributions to the design of steam engines, such as pointing to the advantages of compounding and steam-jacketing, but also created an entirely new way of thinking about what thermal efficiency was and how to measure it. Most important, the widening of the understanding of power technology in this direction pointed to what could *not* be done, for example the realization that John Ericsson's caloric engine (1853) based on the idea that energy could be "regenerated" (that is, used over and over again) was impossible. See Bryant, "Role."

[139] Stewart, "Meaning."

[140] In Leeds, for instance, both the flax-spinner John Marshall and the woolen manufacturer Benjamin Gott had wide-ranging interests in hydraulics, bleaching, mechanics, and related topics. In Manchester, M'Connell and Kennedy, one of the most successful early cotton manufacturers were highly technologically "literate" and closely involved with the Manchester Philosophical and Literary society.

[141] Cohen, "Causes." In a similar vein, Mark Elvin, "Some Reflections," p. 58, notes whereas Giambattista Dellaporta, who dominated the *Accademia dei Lincei* in its early days, can be compared to a Chinese intellectual of that time, he was replaced by Galileo, who cannot.

ica, but in many of these areas it encountered powerful resistance and retreated. Science, ingenuity, and invention, as many scholars have rightly stressed, had never been a European monopoly, and much of their technological creativity originated with adopting ideas and techniques the Europeans had observed from others. But by discovering the fundamental processes through which knowledge can create more knowledge and creating the institutional environment that facilitated these processes, the Industrial Enlightenment unlocked the path to cumulative growth in the West. The hard question that needs to be answered is not so much why this movement emerged at all, but what explains its triumph in the societies we now associate with "the West." That victory was at times attained through violent revolution imposed by foreign occupiers, but in Britain the success of the Enlightenment, on the whole, met little determined opposition, and as a result has tended to be underrated by historians of the eighteenth century.[142] With the success of the Enlightenment program came rising living standards, power, comfort, and wealth in the societies in which it was victorious. The stationary state was replaced by the steady state. It is Europe's intellectual development rather than its coal or its colonial ghost acreage that answers Pomeranz's query of why Chinese science and technology—which did not "stagnate"—"did not revolutionize the Chinese economy."[143]

The Industrial Enlightenment insisted on asking not just "which techniques work" but also "why techniques work" (that is, what natural regularities explain their success). The search for higher levels of generality and encompassing natural regularities were inherent in the massive intellectual heritage of Isaac Newton. The influence of the Newtonians grew steadily through Western Europe in the first half of the eighteenth century, often overlapping with the Enlightenment. Access costs to Newton's work was high because, as Voltaire said, to read Newton the student must be deeply skilled in mathematics and many Enlightenment thinkers worked hard to make Newton's writings more accessible.[144] Newton's philosophy of Nature went far beyond his mathematics and physics; it was an essentially empirical approach in which facts and phenomena were primary and

[142] As J. H. Plumb has noted, "Too much attention . . . is paid to the intellectual giants, too little to their social acceptance. Ideas acquire dynamism when they become social attitudes, and this was happening in England," compare Plumb, "Reason," p. 24.

[143] Pomeranz, *Great Divergence,* p. 48.

[144] Reprinted in Jacob, *Enlightenment,* p. 104. Voltaire himself did as much as anyone to popularize Newton's work on the Continent, including his *Elémens*. An interesting case in this regard is the career of Voltaire's companion, the Marquise de Châtelet (1706–1749), one of the most remarkable female Enlightenment figures, who published one of the more user-friendly translations of Newton's work into French. In a touching preface, Voltaire dedicated his work to this "*vaste et puisante génie, Minerve de la France, immortelle Emilie, disciple de Neuton & de la Verité.*"

any generalizations and principles were constrained by them rather than true *a priori* as the Cartesians held.[145]

The men and women of the Industrial Enlightenment increasingly felt that a research program based on an empirical-experimentalist approach held the key to continuing economic and social progress. Physicists, engineers, chemists, botanists, medical doctors, and agricultural improvers made sincere efforts to generalize from the observations they made, to fit observed facts and regularities (including successful techniques) to the formal propositional knowledge of the time. The bewildering complexity and diversity of the world of techniques in use was to be reduced to a finite set of general principles governing them. The success of such attempts varied enormously with the complexity of the matter at hand.[146]

Posing the questions *why* and *how* a technique worked was of course much easier than answering them. In the longer term, however, raising the questions and developing the tools to get to the answers were essential if technical progress was not to fizzle out.[147] The way to phrase the question was set out by Newton: he never explained *why* gravity existed, but its generality was the explanation of a bewildering host of real-world phenomena. Priestley and Lavoisier followed the same methodology. It is interesting that the late Enlightenment was willing to concede the depth of understanding for greater effectiveness. The Standard Model of physics, formulated by Laplace at the end of half a century of research, was something that gave reasonable and workable approximations rather than had any claims to the "truth." As Heilbron puts it, quantifying chemists and physicists surrendered their claims to "Truth" in exchange for convenience of thought and ease of computation.[148] An instrumentalist approach to propositional knowledge looked for exploitable empirical relations between natural forces and phenomena without wondering too deep and too hard about the metaphysics. As Gillispie has noted, if science was of any help to production, it was descriptive and experimental rather than analytical science. The triumph of that approach was in the revolution that Antoine Lavoisier brought about in chemistry. His *Élements*, complemented by

[145] Cassirer, *Philosophy*, pp. 51–56.

[146] Thus Erasmus Darwin, grandfather of the biologist and himself a charter member of the Lunar Society and an archetypical member of the British Industrial Enlightenment, complained in 1800 that Agriculture and Gardening had remained only Arts without a true theory to connect them. For details about Darwin, see especially McNeil, *Under the Banner*; and Uglow, *Lunar Men*.

[147] George Campbell, an important representative of the Scottish Enlightenment noted that "All art [including mechanical art or technology] is founded in science, and practical skills lack complete beauty and utility when they do not originate in knowledge" (cited by Spadafora, *Idea*, p. 31).

[148] Heilbron, "Introductory Essay," p. 5. This tradition, of course, goes back in a sense to Newton and is central to the methodologies of mid-eighteenth-century chemists such as William Cullen and Joseph Black, who insisted on separating empirical knowledge and theoretical explanation—and often did little of the latter.

Dalton's atomic weights, created a pragmatic and useable set of tricks and techniques that soon enough found industrial and other applications, yet did not hypothesize about the deep structure of matter and why the observed regularities were in fact true.[149]

Once such knowledge had been established and found to be helpful, it needed to be made available to the men in the workshops. From the widely felt need to rationalize and standardize weights and measures, to the insistence on writing in vernacular languages, to the launching of scientific societies and academies, to the construction of botanical gardens by enthusiasts such as Georges-Louis Buffon and Joseph Banks to teach the knowledge of plants, to that most paradigmatic Enlightenment triumph, the *Grande Encyclopédie*, the notion of the diffusion and accessibility of shared knowledge found itself at the center of attention among intellectuals.[150] Taxonomies and classifications were invented to organize and systematize the new facts gathered, and new forms of mathematical and chemical notation were proposed to standardize the languages of science and make propositional knowledge more accessible. To understand these languages, it was realized that increased technical and mathematical education was required, and mathematics teaching and research expanded from the establishment of chairs in mathematics in the Scottish universities in the late seventeenth century to the founding of the *école polytechnique* in 1794.[151]

To summarize, then, the *philosophes* realized that, in order for useful knowledge to be economically meaningful, low access costs were crucial and useful knowledge should not be confined to a select few but should be disseminated to those who could put it to productive use. Some Enlightenment thinkers believed that this was already happening in their time: the philosopher and psychologist David Hartley believed that "the diffusion of knowledge to all ranks and orders of men, to all nations, kindred and tongues and peoples . . . cannot be stopped but proceeds with an ever accelerating velocity."[152] Diffusion needed help, however, and much of the

[149] Lundgren, "Changing Role," pp. 263–64.

[150] See especially Headrick, *When Information,* pp. 142–43. Daniel Roche (*France*, pp. 574–75) notes that "if the *Encyclopédie* was able to reach nearly all of society (although . . . peasants and most of the urban poor had access to the work only indirectly), it was because the project was broadly conceived as a work of popularization, of useful diffusion of knowledge." The cheaper versions of the Diderot-d'Alembert masterpiece, printed in Switzerland, sold extremely well; the Geneva (quarto) editions sold around 8,000 copies and the Lausanne (octavo) editions as many as 6,000.

[151] See Jacob, "Putting Science."

[152] Hartley, a deeply religious man, made this point in the context of the diffusion of Christian beliefs, but then added that "the great increase in knowledge, literary and philosophical, which has been made in this and the two last centuries . . . must contribute to promote every great truth . . . the coincidence of the three remarkable events, of the reformation, the invention of printing, and the restoration of letters . . . deserves particular notice here." See Hartley, *Observations*, p. 528.

Industrial Enlightenment was dedicated to making access to useful knowledge easier and cheaper.[153] Intellectual factors never operate alone; institutional change was equally necessary. The importance of property rights, incentives, factor markets, natural resources, law and order, market integration, and many other economic elements is not in question. But without an understanding of the changes in attitudes and beliefs of the key players in the growth of useful knowledge, the technological elements will remain inside a black box.

QUANTIFYING THE ENLIGHTENMENT

To quantify the Enlightenment seems to violate Einstein's dictum that not everything that counts can be counted and that not everything that can be counted counts. Yet it would be useful to get a measure of the quantitative dimensions of the growth of the Enlightenment as an intellectual movement and to get a sense of the degree to which this was a local or a continent-wide phenomenon.[154] It also might be useful to examine the argument that the Industrial Revolution and technological progress were independent of the Enlightenment because of the widely repeated belief that France was the *locus classicus* of the Enlightenment whereas Britain was the cradle of the Industrial Revolution, and the two were separate, perhaps even orthogonal, historical developments.[155] The Enlightenment, unlike the Middle Ages, was not a concept invented by historians many centuries later, and while in 1784 Kant could note that the "age of Enlightenment" in which he lived was not yet "an Enlightened age," it was a concept that contemporaries were aware of. Nonetheless, historians today are better positioned to assess where the Enlightenment was of substantial importance. To derive a measure of this, I have relied on the recently published *Encyclopedia of the Enlightenment*. To count the importance of the Enlightenment, every geographical item (country, city, region, etc.) in the index was compiled and weighted by the number of lines devoted to it.[156] In Table 1,

[153] The best summary of this aspect of the Industrial Enlightenment was given by Diderot in his widely quoted article on "Arts" in the *Encyclopédie*: "We need a man to rise in the academies and go down to the workshops and gather material about the [mechanical] arts to be set out in a book that will persuade the artisans to read, philosophers to think along useful lines, and the great to make at least some worthwhile use of their authority and wealth."

[154] A few quantitative assessments exist, though it is not clear how they were arrived at. Thus Richard Herr has estimated that less than 1 percent of the Spanish population "welcomed" the Enlightenment, a tenth as many as in France. See Herr, *Eighteenth-Century Revolution*, pp. 198–200.

[155] For a devastating rebuttal to the first of these two statements, see Porter, *Creation*. For a qualification of the latter, see Mokyr, "Long-term Economic Growth."

[156] Kors, ed., *Encyclopedia*. The procedure followed the extensive index in vol. 4. If an essay on a general topic mentioned a country or region, we counted the lines that discussed that area only. If an article was devoted to a geographical concept (e.g., "Scandinavia" in vol. 4, pp. 20–25) we

I include two measures of the Enlightenment: an exclusive measure that counts only the number of lines that mention a country (e.g., "England") and an inclusive measure that counts both measures of a country and of regions in it (e.g., includes both "Italy" and "Tuscany"). The latter count has the advantage of including areas that would be underrepresented otherwise because they were only geographical and not political concepts in eighteenth-century Europe, but it contains some measure of double counting. The data in no way represent a scientific measure of anything except the editorial judgment of a group of modern enlightenment scholars (mostly Americans), but as such it provides us with at least a rough estimate of the regional distribution.[157]

The striking thing about Table 1 is, of course, that France's alleged supremacy in the enlightenment movement is not confirmed. Leaving out North America (which may well be biased by the fact that so many of the contributors are North Americans and the publisher is in New York), the image of Table 1 is that Britain and the Low Countries represent a higher level of the Enlightenment than a group of Western Continental countries that includes Germany, Scandinavia, Central Europe, and in which France occupies a less than overwhelming middle position. The importance of France is reflected in the fact that Paris (991 lines) is more heavily mentioned than any other town, but British towns between them covered more lines (London, Glasgow, and Edinburgh alone had 1,168), and France's population was three times Britain's in 1750. Adding the mentions of cities does change the numbers a bit (and worsens double counting if we add lines that mention a town to those that mention a country), but does not seriously change the overall picture.

The *Encyclopedia* index is of course biased and flawed in many other ways; the many references to "Greece" clearly refer to ancient Greece rather than indicate a hitherto unknown flourishing of the enlightenment in Ottoman-occupied Greece.[158] It is in no case an index that makes any

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counted all the lines in that article. The article on "academies" includes a subheading on "Scandinavia" (vol. 1, pp. 18–19) which was then counted in its entirety. The article on "Education, reform" (vol. 1, p. 385) has a three line sentence that mentions Scandinavia, as well as France, England, and Scotland; those three lines were then entered for all four countries.

[157] Of the nine members of the board of editors, six are affiliated with universities in the United States, one in Canada, one in Ireland, and one in France. The composition of the board, however, cannot be accused of anti-French bias, as two of its American members are noted experts on eighteenth-century France and the French revolution. In that limited sense it is a more unbiased source to study the spread of the enlightenment than Delon, ed., *Encyclopedia*, which is written by a preponderant majority of French scholars. The Delon volumes, in any case, did not have an index that was useful for our purpose, so no direct comparison could be made.

[158] Some of these towns reflect topics of classical rather than eighteenth-century interest, e.g., the 174 lines devoted to Pompeii and Herculaneum or the 31 devoted to Sparta. Neither of those were included.

TABLE 1
GEOGRAPHICAL DISTRIBUTION OF ENLIGHTENMENT CONCEPTS AS REFLECTED IN THE *ENCYCLOPEDIA OF THE ENLIGHTENMENT*
(lines per million of 1750 population)

Country	Lines Counted (exclusive)	Lines Counted (inclusive of regions)	Lines Counted (inclusive of regions and urban)	Enlightenment Index (exclusive)	Enlightenment Index (inclusive of regions only)	Enlightenment Index (inclusive of regions and towns)
France	2,065	2,085	3,145	86	86.8	131
England	2,348	2,362	3,138	391.3	393.7	523
Scotland	701	709	1,207	701	709	1,207
Ireland	210	210	224	70	70	75
Germany	1,618	1,863	2,389	107.9	124.2	159
Netherlands	1,042	1,066	1,236	245.2	250.8	291
Switzerland	471	471	716	314	314	477
Scandinavia	344	436	789	116.3	208	210
Italy	503	700	1600	33.5	46.7	106
Spain	689	689	706	72.5	72.5	74
Portugal	264	264	264	117.3	117.3	117
Austria	391	407	483	142.2	148	175
Hungary	253	253	253	126.5	126.5	126
Poland	435	435	435	62.2	62.2	62
Russia	762	817	831	29.3	31.4	32
Balkans	17	17	17	2.1	2.1	2.1
Greece	282	282	282	161.1	161.1	161
Latin America	448	608	611	32.6	44.2	44.4
North America	712	1,717	1,903	323	780.4	865
Ottoman Emp.	182	235	238	7.6	9.8	9.9

Note: For details on the computation, see footnote 156.

claims to cardinality. It would be absurd to claim that just because Scotland has nine times the index that France had, it in any shape or form could claim to be nine times more enlightened than France. But even if we do not deflate by population (a process that appreciably weakens France's relative position), the ordinal values of the index suggest that a Francocentrist position in the Enlightenment seems untenable: even in *absolute* terms (which is what may have counted). Britain still exceeds France, and Germany is but a hair behind. Perhaps, however, the real objection to this measure is that it pertains to the *Enlightenment* as commonly used, and thus obviously does not deal with the *Industrial* enlightenment as defined above. For the purposes of technological change, we may be less concerned with the philosophical or political concerns that dominated much Enlightenment thinking and instead focus on the growth of science and other forms of useful knowledge, their application to industry and agriculture, and the diffusion of best-practice techniques among the population of artisans and farmers.

To capture at least the first of these, we can look at the geographical incidence of scientific and technological periodicals, the publication of which became increasingly associated with the European enlightenment in the eighteenth century.[159] A useful source is the list of all scientific and technical journals published in Europe between 1600 and 1800. David Kronick meticulously compiled this difficult and often confusing source, and whereas some aspects of his work and conclusions bear reexamination, much of what is to follow is indebted to his data collection.[160] An analysis of these journals is inevitably deficient in that it disregards the number of readers of these periodicals and the number of copies printed and circulated, and does not assess the content beyond Kronick's label.[161] Yet it allows us to measure publication dates, place, and the general topic of the periodical. As such, it gives us a rough but instructive indicator of the "degree" of industrial enlightenment prevalent.[162] As Kronick notes, "by far the largest part of this literature represented not original research or contributions but a derivative form of journalism which served the purpose of the dissemination of information."[163] That kind of publication is of course precisely descriptive of an activity that was primarily aimed at a reduction of access costs. There can be little doubt that the importance of periodicals as a means of access to useful knowledge underwent a revolution during the age of Enlightenment.[164]

There are three major findings to report. The first, unsurprisingly, is that the number of new journals published accelerated rapidly after 1650; indeed, the new journals published in the last three decades of the eighteenth century account for 68 percent of all journals published in this period. This is demonstrated clearly in Figure 1. Second, the distribution by topic, roughly defined, shows some interesting changes during this period. On the whole, Science and Medicine each account for about 30 percent of all

[159] See especially McClellan, "Scientific Journals."

[160] Kronick, *Scientific and Technical Periodicals* and *History*

[161] At times, periodical titles could be misleading. The *Ladies' Diary,* edited by the engineer, surveyor, and mathematician Henry Beighton, was full of essays on mathematical and physical topics including his famous 1718 table on the capacity of the Newcomen engine cited previously. The *Gentleman's Diary*, edited by Thomas Peat between 1756 and 1780, was similarly largely devoted to the solution of mathematical problems See Musson and Robinson, *Science*, p. 47; and *Dictionary of National Biography*, vol. 15, p. 625.

[162] The analysis here differs somewhat from the one Kronick conducts himself in that I make no distinction between "substantive" journals, "society proceedings," and journals of abstracts and reviews. My main purpose here is to illustrate the decline in access costs, and journals that published abstracts and reviews served a similar purpose.

[163] Kronick, *History,* p. 239.

[164] Gascoigne's sample of the most important scientists born in the period 1665–1780 shows that a full 65 percent of them published in scientific journals, though there is no real way of telling whether such journals were their main channel of communication. The percentages rises steeply over time: for scientists born in 1600–1609 it is 17 percent, for those born in 1700–1709 it is 65 percent and for those born in 1770–1779 it is 85 percent. These statistics entirely exclude engineering, medical, and agricultural journals. See Gascoigne, *Historical Catalogue,* p. 92.

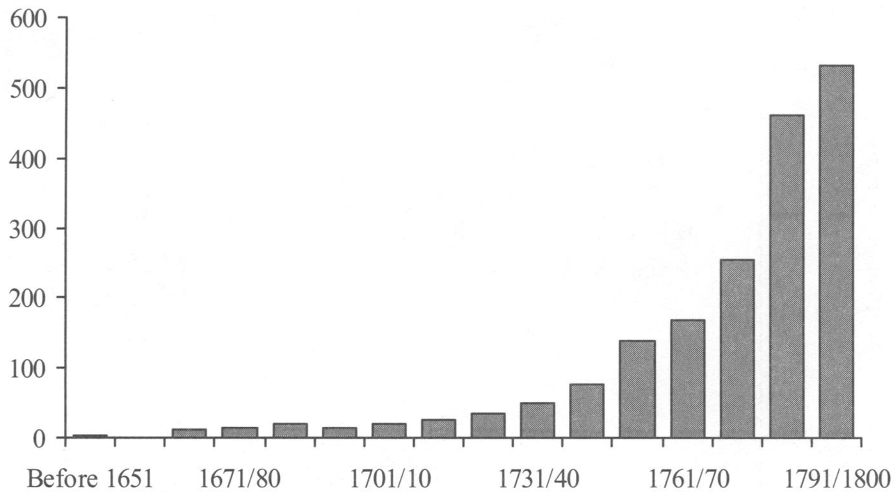

FIGURE 1
SCIENTIFIC PERIODICALS BY YEAR OF FIRST APPEARANCE

Source: Computed from Kronick, *Scientific and Technical Periodicals*.

journals, and this total remains fairly stable over the entire period (Figure 2). What is remarkable is the steep rise in the journals devoted to political economy and social science, from essentially nil to a substantial number in the second half of the eighteenth century, especially in Germany where interest in political economy and the science of government was substantial. The same is true for journals dedicated to technology and engineering (including agriculture). This increase comes at the expense of more general and philosophical journals, whose share declines despite an increase in absolute numbers.

The geographical distribution of journals shows an interesting pattern. Europe as a whole seems to divide into three regions: areas with a high rate of publication relative to population (Scandinavia, Low Countries, Switzerland), an intermediate group including France and Britain, and the expectedly low-intensity countries such as Spain and Austria, not to mention Russia. In absolute terms, German periodicals had a large advantage, but their mean life expectancy was only about seven years, as opposed to the 16 or 17 years for the average periodical in Britain or France.[165] Some areas do surprisingly poorly: Scotland counts only ten periodicals, Belgium only seven. To some extent this reflects their dependence on

[165] This is pointed out by Kronick, *History,* pp. 86–87. Elsewhere (p. 160) he notes that in Germany "the lack of political centralization was reflected in the large number of regional journals, every intellectual center or University town in Germany had its own journal of learned and scholarly news."

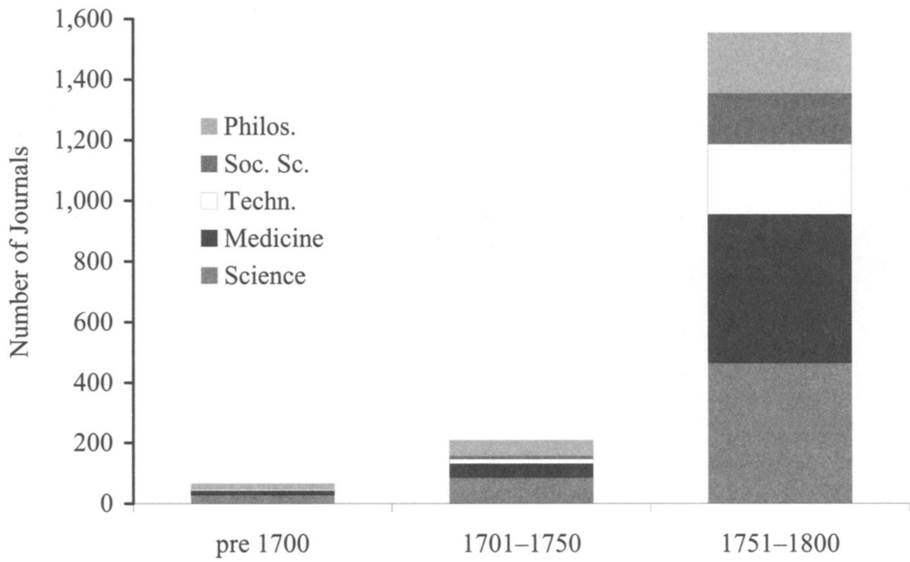

FIGURE 2
NEW SCIENTIFIC JOURNALS, BY GENERAL SUBJECT AND DATE

Source: Computed from Kronick, *Scientific and Technical Periodicals*.

periodicals coming in from elsewhere. All the same, Scotland outranks France in per capita weighted publications (Figure 3), but both are considerably behind the Netherlands and Switzerland, two countries with flourishing publishing industries (catering no doubt in part to foreign markets). The distribution of new journals by subject matter does not show Britain as in any way unusual; the only odd phenomenon is the very high proclivity of Scandinavian countries for science and the high frequency of medical and social science journals in Germany (Figure 4). As far as technology, agriculture, and engineering are concerned, remarkably enough France was in the lead. None of these results are materially different whether we count journals by first appearance only or whether we weight them by years of survival, except that German periodicals become less important as average periodical life in Germany was substantially shorter.

Finally, to get a better quantitative handle on the development of the formal institutions that were meant to reduce access costs, I utilize a database that relies heavily on the website "Scholarly Societies" collected by the University of Waterloo.[166] The Waterloo database used covers 200 years (1600–1799) and contains 236 societies founded in Europe in those years (Figure 5). As the database is still incomplete, it was supplemented

[166] http://www.scholarly-societies.org. The database was put together by its editor Jim Parrott. I am grateful to Mr. Parrott for his advice and assistance.

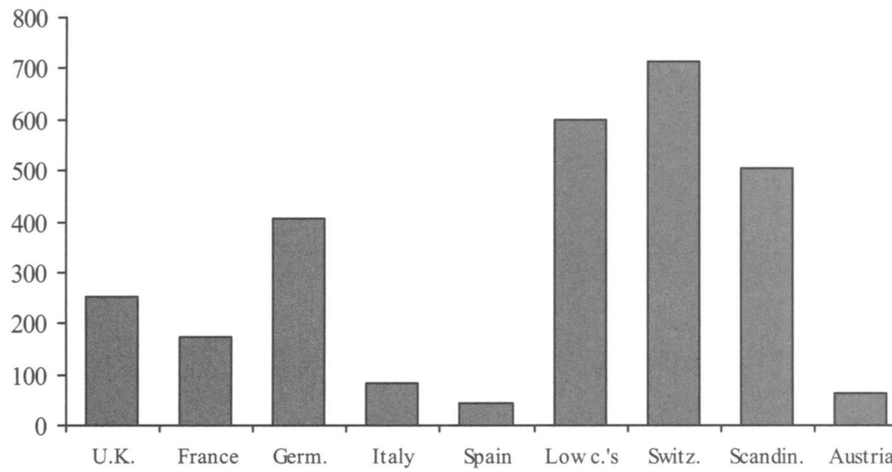

FIGURE 3
NUMBER OF SCIENTIFIC JOURNALS PER CAPITA, WEIGHTED BY YEARS OF PUBLICATION

Source: Computed from Kronick, *Scientific and Technical Periodicals*.

by a set of standard works that deal with scientific academies and societies, yielding a total of 349 societies.[167] There is no presumption that the data-base is complete, though it is likely that any omitted formal societies were of tertiary importance. Counting such organizations without weighting is of course a crude procedure. Yet the movement over time between 1600 and 1800 and the differences in cross section display three trends, all of which are indicative of the impact of the Industrial Enlightenment on European intellectual life. First, as shown by Figure 6, there is a clear time trend: after an efflorescence in the 1650s and 1660s there is a slowing down in the founding of these learned societies until the 1730s, when the phenomenon takes off. Secondly, as Figure 7 shows, learned academies and societies were a Continent-wide phenomenon. Indeed, the advantage of the British Isles in learned societies is not particularly striking by comparison with economically backward Italy and Germany: in the two centuries before 1800, Britain accounted only for 30 societies whereas France had 54 and Germany and Italy counted 31 each. Yet in the second half of the eighteenth century Britain experienced a flourishing of intellectual life as measured by the number of formal learned societies established there. At the same time, a veritable explosion occurred in the "small countries" of Europe (Iberia, Scandinavia, Low Countries, and Switzerland). Deflating by population, as in Figure 7, yields a somewhat different picture. Western

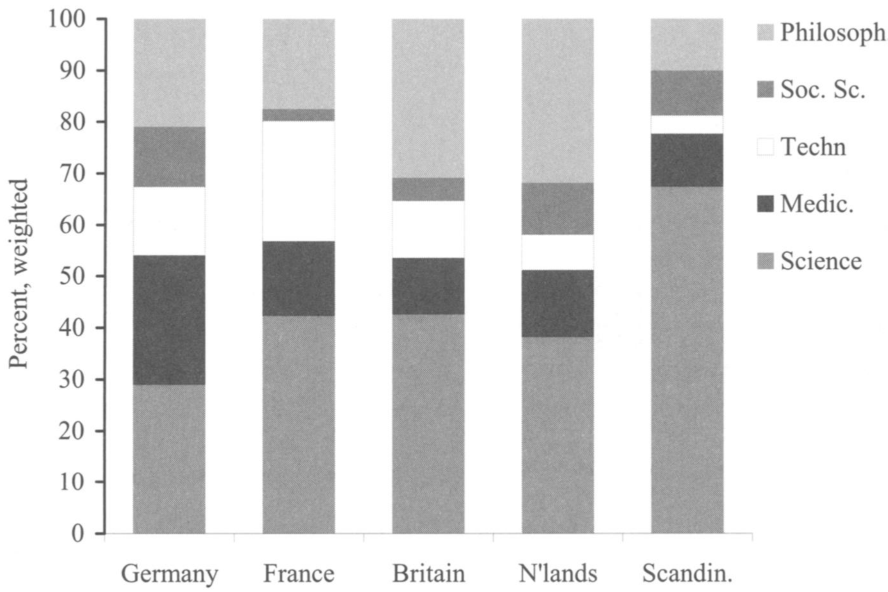

FIGURE 4
SUBJECT AREA OF NEW PERIODICALS, BY COUNTRY

Source: Computed from Kronick, *Scientific and Technical Periodicals*.

Europe's small countries and Germany clearly took the lead in this kind of intellectual activity after 1750, with Italy and to a lesser extent France falling behind. Within the "small countries," the literate nations in Scandinavia and the Netherlands experienced a veritable outburst of such societies after 1750. Third, as Figure 6 shows, there was a considerable growth in the number of societies interested primarily in applied and science-oriented nature after 1750, although all three categories experienced considerable growth in the second half of the eighteenth century. As can be seen from Figure 6, Britain had perhaps a slight advantage in terms of the relative importance of societies classified as "scientific," but this difference is far from overwhelming.

Such numbers, taken at face value, are misleading. In Italy and Germany many of the local societies reflect the political fragmentation of the countries, in which local aristocrats or magistrates had to display their independence, accounting for some provincial societies in small towns such as Cortona, Palermo, and Rovereto. Yet similar provincial institutions are found in France and Spain. It is also true that some societies were of an ephemeral nature and duplicated others.[168] One interesting finding is that

[168] A good example is the *Societas Disputatoria Medica Haunienis* (Medical Debating Society of Copenhagen), founded in 1785 as the result of a disagreement between two Danish physicians. It folded two years later.

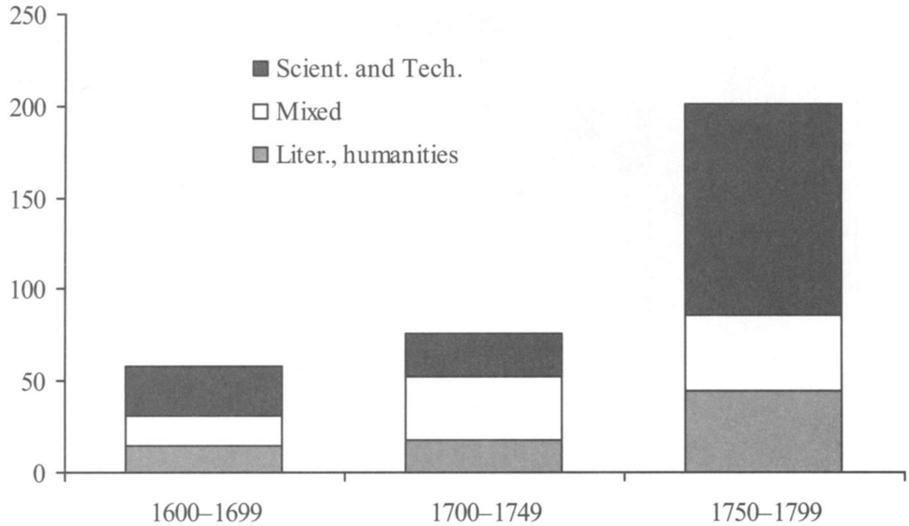

FIGURE 5
SCIENTIFIC SOCIETIES BY PERIOD AND MAIN PURPOSE

Source: See notes 166 and 167.

Figure 7 shows, oddly, that the number of societies was higher in the second half of the eighteenth century than in the previous century and a half except in Italy; this may indicate the growing importance of private, spontaneously founded scientific societies in the later period. Italian societies were predominantly established by local authorities.

To summarize these findings, two things stand out. The first is that the eighteenth century found a variety of mechanisms to reduce access costs, and that all measures we can find point to a rapid acceleration in the institutions that brought this about. Second, differences among the national styles and emphases among the main societies that later were to constitute the "convergence club" can be discerned, but most of them were secondary to their partaking in the more general movements of the Industrial Enlightenment. There is little in the quantifiable evidence to single out the Enlightenment movement in Britain as being unusual or particularly conducive to economic success. The historical factors that explain the rise of the Industrial West are thus not the same as the ones that explain Britain's leadership.

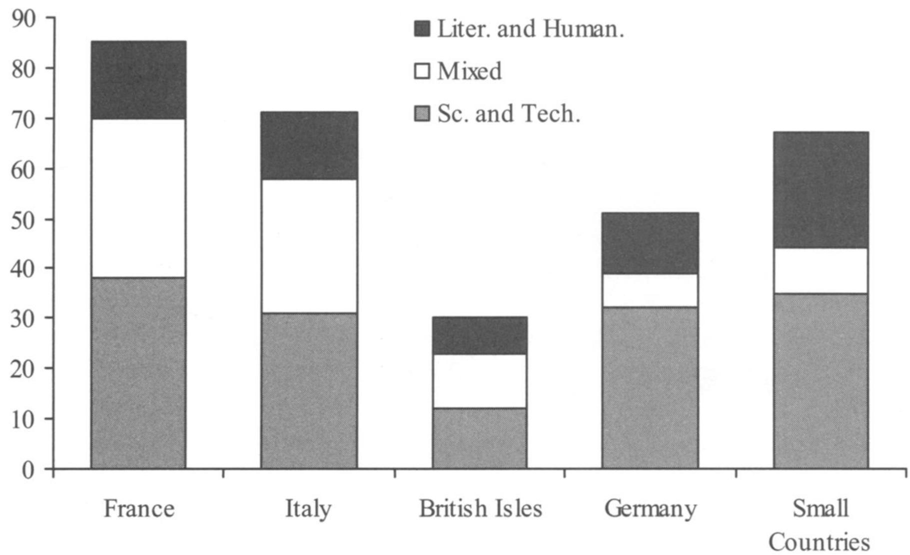

FIGURE 6
SCIENTIFIC SOCIETIES, 1600–1800, BY COUNTRY AND PURPOSE

Source: See notes 166 and 167.

CONCLUSIONS

The Enlightenment in the West is the only intellectual movement in human history that owed its irreversibility to the ability to transform itself into economic growth. It did so by fueling the engine of economic growth with the sustained supply of useful knowledge and the miraculous ability to apply this knowledge eventually to the nitty-gritty of production in the fields and workshops where the GDP is ultimately produced. It did so also by providing the economies with institutional steering wheels that on the whole prevented them from crashing the vehicle of economic growth into the trees of rent seeking, war, and other forms of destructive behavior.[169] It is safe to say that the vehicle had a few fender-benders and near misses on the way, and here and there had to swerve hard to avoid the semi-trailers of total war and totalitarianism.

The Industrial Enlightenment produced technological progress, but there was no guarantee that it would have resulted in sustained economic growth. In addition to the Baconian program, the Enlightenment produced what might best be called a doctrine of *economic reasonableness*, which became embodied in the tenets of political economy, and eventually influenced policy makers in most Western economies. Economic reasonableness

[169] On this see Mokyr, "Mercantilism."

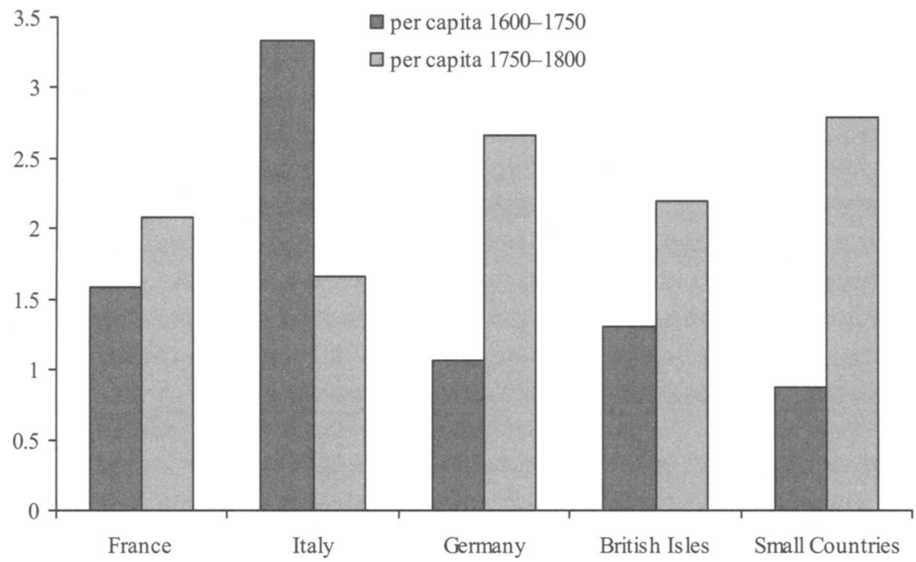

FIGURE 7
SCIENTIFIC SOCIETIES PER CAPITA , 1600–1800

Source: See notes 166 and 167.

concerned issues of political economy such as free trade, improved infrastructure, law and order's effect on commerce, and more efficient, less distortionary taxes. Above all is the Enlightenment idea that when individuals work for their own good, they normally also contribute to the welfare of society, unless they choose to engage in redistribution and rent seeking. It redefined the role of the public sphere in the economic game, pointing to the delicate balance between those who lubricate the wheels of economic activity and those who manipulate them for their own private profit. It recognized the possibility of what we might call today coordination failures and suggested policies to rectify them.

Without institutional progress to complement the technological progress, the sustainability of economic improvement would have been limited and in the end might have been frittered away and eliminated by the relentless erosion of rent seeking. Needless to say, the growth of economic reasonableness was far less monotonic and irreversible than technological progress. Opportunistic and selfish behavior did not go away simply because Enlightenment intellectuals denounced it. The cosmopolitan, internationalist subtext of the most progressive wings of the Enlightenment was constantly struggling with the traditions of mercantilism and the instincts of economic rivalry and political hostility between the major European powers. As long as the Enlightenment was a movement of elites, who saw themselves as members of the Republic of Letters, it could maintain a cosmopolitan character. By its own logic, however, as it spread to larger and larger circles, nationalist and romantic sentiments inevitably clashed with the enlightened internationalist instincts of the *philosophes*, threatening the great synergy between institutional and technological elements of the Enlightenment.

The interactions between these elements is of course complex and makes positive identification of causal factors difficult. The impact of enlightenment thought on institutional reforms took place with long lags and over a very long period of time.[170] Moreover, such economic liberalization—not to be confused with political liberalization and franchise extension—took a long time to affect output growth. In any event, its impact was largely in what it prevented, not in what it caused. As such the exact effects may be hard to trace with much accuracy. Indeed, the great irony of the European Enlightenment is that the attempts by France to adopt more "enlightened institutions" led to a prolonged military conflict with the nation that had already adopted many of those. In the process, enlightenment ideas were put on the back burner. After 1815, however, the *Pax Britannica* heralded in a new culture of peace and trade. It, too, was not to last. In the best Hegelian traditions, it created forces that challenged it. Nationalism, protectionism, and economic *étatism* were responses to the Enlightenment, not an inevitable corollary. The Enlightenment itself can by no stretch of the imagination be held responsible for the twentieth-century horrors that Theodore Adorno and Max Horkheimer and their modern-day postmodern epigones such as John Gray blame them for.[171] One of the oddest phenomena in modern historiography, indeed, are the vitriolic and nasty attacks on the Enlightenment, which perversely is being blamed for modern-day Barbarism but not given credit for bringing about modern-day prosperity.[172]

The central fact of modern economic growth is the ultimate irreversibility of the accumulation of useful knowledge paired with ever-falling access costs. As long as knowledge was confined to a small number of specialists with high access costs for everyone else, there was a serious risk that it could be lost. Many of the great inventions of China and Classical

[170] Indeed, John Nye has argued that the impact of political economy on trade liberalization in Britain has traditionally been misdated and took place much later than hitherto supposed. Nye, *Wars*.

[171] Horkheimer and Adorno, *Dialectic*. Gray, *Enlightenment's Wake*.

[172] This revulsion has deep philosophical roots in the works of Nietzsche and Heidegger, but the usefulness of the critique to historians interested in economic progress is doubtful. Even left-wing historians are embarrassed by notions that the Enlightenment inevitably led in some way to male-domination, imperialism, totalitarianism, environmental degradation, and exploitation. Eric Hobsbawm notes with some disdain that this literature describes the Enlightenment as "anything from superficial and intellectually naive to a conspiracy of dead white men in periwigs to provide the intellectual foundation for Western Imperialism." See Hobsbawm, "Barbarism," pp, 253–65.

Antiquity were no longer available to subsequent generations. The decline in access costs meant that knowledge was spread over many more minds and storage devices, so that any reversals in technological progress after the Industrial Revolution were ruled out. If the continued growth of the West was ever in danger, it came from the imbalance between rapid progress in the accumulation of useful knowledge and the more halting and ambiguous changes in supporting institutions.

Such an approach to modern growth would imply that the differences between the nations of the West should be less important than their basic commonalities. The point is not so much that there were no national differences in the institutions and culture that generated useful knowledge in France, Germany, or Britain, as that when the knowledge was accepted, it was readily diffused within the world in which the Enlightenment had taken root through periodicals, translations, international exhibitions and conferences, and personal communications. Stressing national differences in style and emphasis within the West is to miss the fundamental unity of the world affected by this intellectual movement. In this view of the Industrial Revolution, Britain had a first-mover advantage that was extended by the political upheavals of the Revolutionary and Napoleonic era, but the convergence of technology and income in the later nineteenth century was inherent in the nature of the movement that generated economic growth.

All this leaves in the middle what explains the Enlightenment itself. It surely was no autonomous shock like the Black Death or a Mongol invasion that altered the course of European history without requiring an explanation itself. The Enlightenment had roots in the commercial capitalism of the later middle ages and the sixteenth century. Many of the elements of a progressive society—such as individualism, man-made formal law, corporatism, self governance, and rules that were determined through an institutionalized process (in which those who were subject to them could be heard and have an input)—already existed in late medieval Europe.[173] Pre-1750 economic growth created the economic surpluses that made it possible for a considerable number of people to move to urban areas and nonagricultural occupations, including by becoming full-time intellectuals. Yet despite the stimuli of the Great Discoveries and the technical advances of the fifteenth century, Renaissance Europe did not generate anything like modern growth. Many highly commercial societies of the past, for one reason or another, failed to switch from trade-based growth to technology-based growth. Even the great Dutch prosperity of the seventeenth century dissipated and petered out in the end.

[173] Greif, *Institutions*, chap. xiii–17.

In order for commercial expansion and Smithian growth to transform themselves into a self-sustaining process of rapid growth something more was required. The ultimate economic significance of the Enlightenment was to bring this about. But whence the Industrial Enlightenment itself? Understanding its intellectual origins is a daunting task. Of the many explanations that have been proposed, it is worth mentioning a powerful argument made by the late B. J. T. Dobbs that when a period of relative stability settled on Europe's social and political life in the later seventeenth century, hopes for an imminent millennium were becoming dimmer, and open useful knowledge with utilitarian purposes (inspired by Bacon) replaced the more mystical and secretive activities of the late Renaissance alchemists. It is also plausible that an impulse to the Industrial Enlightenment came from below, from artisanal writers writing about mechanical arts such as mining and architecture in the previous centuries.[174]

Yet such purely intellectual explanations need to be complemented by institutional ones. In coming to grips with the oversimplified question of "why there was a European Enlightenment," a starting point is to ask not so much why some people emerged who elucidated ideas and policies we now consider to be "enlightened," as much as why these people succeeded. It is highly probable that men and women with novel ideas emerged outside the West, and would have been part of an Islamic Enlightenment or a Chinese Enlightenment, had these grown to become movements of historical importance.[175] Europe differed in that the seeds of innovation sprouted and flourished. In part, therefore, the triumph of the Enlightenment was contingent, the result not of sheer accident or random variables as much as of a set of political and social struggles that could have gone the other way. The counter-reformation led by the reactionary forces of Spain was de-

[174] Dobbs, "From the Secrecy." Long, *Openness*.

[175] It could well be argued that seeds of an Enlightenment were sown by Fang Yi-Chih (1611–1671), the author of a book meaningfully entitled *Small Encyclopedia of the Principles of Things*, which discussed potentially useful forms of propositional knowledge such as meteorology and geography. He was a harbinger of the eighteenth-century school of *kaozheng,* or school of "evidentiary research," which sounds promising until we realize that it was primarily interested in linguistics and historical studies, "confident that these would lead to greater certainty about what the true words and intentions of China's ancient sages had been and, hence, to a better understanding of how to live in the present" (Spence, *Search for Modern China,* p. 103). Similarly, the great scholar Tai Chen who was "a truly scientific spirit . . . whose principles hardly differed from those which in the West made possible the progress of the exact sciences. But this scientific spirit was applied almost exclusively to the investigation of the past" (Gernet, *History*, p. 513). The vast efforts of the Chinese Ch'ing emperors in publishing encyclopedias and compilations of knowledge under K'ang Chi and Qian Long, above all the massive *Gujin tushu jicheng* compiled by Chen Menglei and published in 1726 (one of the largest books ever produced with 10,000 chapters, 800,000 pages and 5,000 figures) indicate an awareness of the importance of access cost. It is meaningful, however, that Chen was arrested and deported (twice), that his name was removed from the project, and that the entire project was done under imperial auspices. Altogether about 60 copies were made of it, a number that pales in comparison with the 25,000 copies sold of the *encyclopédie.*

feated in a set of wars that left Europe bleeding and divided, but that also marked a sizeable part of the Continent that was open to fresh ideas introduced in the competitive intellectual marketplace.[176]

If so, there was nothing inevitable or inexorable about modern economic growth. Much like the emergence of *homo sapiens sapiens* in the Pleistocene after some 60 million years of mammal development, and not, say, in the long period (50 million years) between the Eocene and the end of the Miocene, a long period of "prehistory" occurred before the dramatic phase transition that changed the face of the planet forever. There is nothing in evolutionary theory that makes the rise of homo sapiens inevitable or its precise timing an explicable phenomenon. Although metaphors may mislead, the parallel points to the possibility that radical and irreversible historical change may occur as a contingency. That does not absolve us from the possibility of thinking about its causes—contingency does not mean randomness.

To understand the origins of the triumphs of Enlightenment thought, we must understand the victory of skepticism and rebellion against authority in the centuries of early modern Europe. Aside from the obvious cases of Luther and his fellow reformers, we may point to the growing proclivity of Europeans to question traditions that had ruled during centuries in which original scholarship had rarely consisted of more than exegesis and commentary on the classics.[177] Of course, Francis Bacon himself was a leader among those skeptics.[178] Criticism of authority was prevalent in every society, no matter how reactionary and repressive, but the question of essence must be what explains the survival and success of this movement. Here, part of the answer must be sought in the system of political fragmentation and countervailing power in which those who contested the "truth" as perceived by the status quo could normally find protection against the

[176] See Lebow, Parker, and Tetlock, eds., *Unmaking the West.*

[177] Illustrative of this inclination is the career of Lorenzo Valla (1407–1457). Humanist, philologist, and professional rebel, most famous for his demonstration that the "Donation of Constantine" was a forgery, he attacked other sacrosanct icons such as Cicero's style, Livy's history, and St. Thomas's theology. He seemed to "delight in challenging established authorities" and his work was "an attempt by a humanist intellectual to change rhetorical study from a process that involved the 'passive' acquisition of erudition into an 'active' discipline that would be capable of engaging practical problems" (Connell, "Introduction," pp. 1, 6).

[178] In an unpublished work, oddly entitled *The Masculine Birth of Time,* Bacon launched a sharp and severe attack on Aristotelian philosophy. The entire canon of classical thought, from Plato to Hippocrates and from Thomas Aquinas to Peter Ramus was denounced. Their sin was, above all, moral: they were, in Bacon's view, indifferent to the mastery of man over nature, which was the only way to alleviate the plight of mankind "with new discoveries and powers." See Farrington, *Francis Bacon*, pp. 62–68. Ramus (1515–1572) himself, an influential Calvinist philosopher, had been similarly disrespectful of accepted orthodoxy (his 1536 thesis was entitled *Everything that Aristotle Taught is False*), but had the bad fortune to find himself in Paris on St. Bartholomew's Day in 1572, where he was murdered.

persecution they could face.[179] What is unique in the European experience is not what happened to Jan Hus and Giordano Bruno, but that the same fate was not ordained for the many others who shamelessly slaughtered sacred cows in natural philosophy and metaphysics.[180] Skepticism, rebelliousness, and disrespect were as much the taproots of innovation as economic incentives. In the European environment, these sentiments survived largely because their propagators were able to play different political units, as well as spiritual and temporal authorities, against one another. Multicentrism made it possible for original thinkers to move between different regions and spheres of influence, to seek and change protectors and patrons. When some centers were destroyed by political events, the center of gravity shifted elsewhere.[181] Moreover, competition by courts and patrons of science for the "superstars" led to informational and reputational difficulties that in the end may have helped bring about the system of open science.[182] Political fragmentation had its costs, of course, and it was not a sufficient condition for intellectual innovation. All the same, what made the European Enlightenment succeed, was the combination of political multicentricity and sharpening intellectual competition thanks to falling access costs. It did not succeed everywhere, but it did not have to. By 1680 or so this skepticism, though by no means unchallenged, had become sufficiently widespread to become irresistible. It evolved into an intellectual *movement*.

In the end, the Enlightenment delivered perhaps less than what the more naive idealists of the Enlightenment had hoped for. The more ambitious and optimistic schemes of such *philosophes* as Condorcet or David Hartley are not to be confused with the whole of Enlightenment thought and work in the eighteenth century.[183] Humphry Davy, by 1802, had no more illu-

[179] Valla himself was protected by King Alphonso of Naples from the recriminations of Pope Eugenius V and the Naples Inquisition. So fragmented were the politics of Europe at the time that Eugenius's successor, Nicholas V, appointed him Papal secretary.

[180] The most outspoken example was the pugnacious German physician Paracelsus (1493–1541), sometimes referred to as a "medical Luther," who in 1527 publicly burned the books of Galen and Avicenna, the medical authorities he despised.

[181] Britain's supremacy in the late eighteenth century may well have benefited from the adventitious events that spared it the fate that befell the scientific and intellectual center of pre-1620 Prague. It seems not unreasonable to speculate that had the Czech Renaissance not been destroyed by the Thirty-Years War, it might have evolved into a center of a Central European Enlightenment and the innovative thrust of the eighteenth century might have had a different locational pattern. For a discussion of the intellectual glories of the Habsburg court around 1600, see Evans, *Rudolf II.* The Moravian religious leader and educational reformer Jan Amos Comenius, fleeing his native Czech lands from the Imperial forces, repeatedly found himself in politically uncomfortable circumstances and spent time in Poland, London, Paris, Sweden, and Amsterdam.

[182] David, "Patronage."

[183] Broadie has noted that the optimism of most Enlightenment "literati" was guarded and that there was no serious streak of utopianism in the Scottish Enlightenment. Broadie, *Scottish Enlightenment*, p. 39.

sions that we should "amuse ourselves with brilliant though delusive dreams concerning the infinite improveability of man, the annihilation of labour, disease, and even death . . . we consider only a state of human progression arising out of its present progression" and then added prophetically, "we look for a time that we may reasonably expect, for a bright day of which we already behold the dawn."[184] The optimists may have overestimated the ability of people to reason in many social settings, they may have been naive about the objective function that rulers and people of power and wealth were maximizing, and surely even the more cynical political thinkers such as Hume and Smith did not fully realize how strategic behavior and collective action in nonrepeated settings could lead to Pareto-dominated equilibria. The hyper-rational assumptions about the perfectibility of the human environment and the restructuring of institutions may seem ingenuous to us.

And yet the Baconian program succeeded beyond the wildest dreams of the natural philosophers and engineers who made the Industrial Enlightenment. The Enlightenment believed that human improvement could be attained through reason and knowledge. But as belief in reason has become more and more qualified in the centuries after Davy, the notion that the growth of useful knowledge is the mainspring of economic growth has proven to be an overwhelming truth. The result has been what Robert Darnton has termed "progress with a little p," distinct from the ambitious utopianism and political sentimentalism characteristic of some Enlightenment thinkers, but conforming to the economist's prosaic and sober notion that economic growth is not an undivided blessing but the best we can hope for in a second-best world.[185] It consists of the modest and incremental gains of pleasure over pain, of health over sickness, of abundance over want, of comfort over physical misery. It is what the history of economic growth is all about.

[184] Davy, *Discourse*, vol. 2, p. 323.
[185] Darnton, "Case," p. 23.

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American Exceptionalism as a Problem in Global History

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Abstract

The causes of the USA's exceptional economic performance are investigated by comparing American wages and prices with wages and prices in Great Britain, Egypt, and India. Habakkuk's views on the causes of American industrial pre-eminence are reassessed. While the USA had abundant natural resources, they did not promote manufacturing since international trade equalized prices in Britain and the USA or American tariffs made resources dearer in the USA. Wages were higher in the USA than in Britain since labor markets were tightly integrated and labor was drawn to the USA as the continent was settled. Capital services were also more expensive in USA. American industrialization required tariffs since virtually all input prices were higher than in Britain and industrial productivity was comparable. America's comparative advantage shifted from agriculture to manufacturing after 1895 was industrial productivity soured. This was due to a fall in energy prices in the USA, the American policy of mass schooling which increased the supply of skilled adults and induced firms to invent technology to raise their productivity since the supply of child labor was restricted in comparison to Britain, and the great growth of manufacturing investment induced by the tariff which provide a large market for inventions and generated technical knowledge through learning by doing. Egypt and India could not have industrialized by following American policies since their wages were so low and their energy costs so high that the modern technology that was cost effective in Britain and the USA would not have paid in their circumstances. The development of Egypt and India required more draconian state intervention than a protective tariff, mass education, and infrastructure investment–the American model.

American exceptionalism' is a long standing theme in academic and popular culture.[1] It has also been controversial, at least on the academic plain. Sometimes, exceptionalism is taken to mean that Americans are morally superior to other people and are, therefore, entitled–perhaps obliged–to intervene in their affairs. I am not concerned with these claims here. At other times, exceptionalism means that American history is exempt from the usual laws and regularities of social science. On the contrary, my aim here is to assess and account for remarkable features in American economic history with normal social scientific explanations. One of those remarkable features has been rapid economic growth, and another has been the flourishing of democracy. Sometimes, indeed, the two are linked by claiming that the economic success has been the result of the democratic commitment.

How exceptional has American economic history been? The question is fundamentally comparative, and one obvious comparator is Great Britain. Indeed, it is just half a century since Habakkuk published his influential *American and British Technology in the Nineteenth Century: The Search for Labour-Saving Inventions* (1962). It was written when America was the world's economic hegemon, and the question was how to account for that great lead. Habakkuk found the answer in an extended path of development that ran back to the early nineteenth century when the USA had an abundance of land and natural resources. He believed that these advantages led to exceptionally high wages and 'the search for labour-saving inventions.' These ideas provoked tremendous debate for some time.[2] Today America's economic lead is not so pronounced, so it is a good time to reconsider how deep exceptionalism runs in American economic history.

Comparisons should not be confined to Britain. The study of long run economic development has 'gone global,' so that we must consider progress and stagnation in a world wide frame work. In addition, to Britain, I will compare the USA to Egypt and India. These are interesting comparators since both countries were major cotton exporters as was the USA.

American economic history can be divided into two phases each with impressive economic accomplishments. Before 1895, economic growth was extensive. Between 1820 and 1913, the American population grew by a factor of ten, while the populations of India, Egypt, and the United Kingdom approximately doubled. The USA had a similar lead in GDP growth. American growth required mass immigration and was based on the settlement of the continent and the development of its agricultural potential. There was also a large growth in manufacture that catered to the domestic market. The size and growth of this sector was important for the later surge in productivity even if it was not the main driver before 1895. In this period, American GDP per head grew slowly and trailed that of Britain (Figure 1).

The character of American growth changed at the end of the nineteenth century. Figure 2 shows the shares of American exports that were agricultural or processed agricultural products versus manufactured goods. Between 1820 and 1895, farm products made up a steady 80% of American exports with manufactured goods accounting for the other

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[1]The literature is vast. Recent contributions include Lipset (1997), Bacevich (2010), Hodgson (2009), Pease (2009), Baldwin (2009), Marry (2013), and Zinn (2005). Joe Ferrie and Jason Long have interpreted American exceptionalism in terms of social mobility and studied that phenomenon as a problem in economic history: Ferrie (2005), Long and Ferrie (2007), Ferrie and Long (2013). Temin (1991) tackles the question but not the term.

[2]The literature is very large and includes David (1975), Temin (1966b, 1971a, 1971b), James (1981a), James and Skinner (1985), Field (1983), Rosenberg (1967), Ames and Rosenberg (1968), Rothbart (1946).

20%. The stability ended abruptly in 1895 when the share of manufactures began to rise towards the value of 75% after the Second World War. Improved American performance is also apparent in the GDP figures. According to Maddison's (2006, pp. 436-43, 465-7) estimates, the USA overtook Britain in GDP per head in 1901. Britain regained the lead as all resources were mobilized during the First World War, but demobilization left the USA far ahead.[3] An important aspect of the American lead was very strong productivity performance in manufacturing. There is no doubt that labour productivity in USA manufacturing was double that of British in the first decade of the twentieth century (Broadberry 1997). When this lead emerged is controversial, and I will argue that it was a feature of the late nineteenth century. These accomplishments are more significant than the extensive growth realized earlier when the continent was settled.

Figure 1 conveys another lesson that must be born in mind in assessing US performance. The most striking feature of the graph is the gap between Britain and the USA, on the one hand, and India and Egypt on the other. Anglo-American differences shrink to insignificance compared to this gap, which is the result of the great divergence in the world economy. Seen from a global perspective, it is the West as a whole that is exceptional. The USA is exceptional since it is part of the West–and why it is so is a problem that must be solved–but it is hardly unique.

How can we explain these features of American economic history? My approach is based on comparative wage and price history.[4] This approach has thrown new light on the causes of the British Industrial Revolution (Allen 2009). I argued that eighteenth century Britain was unique in having particularly high wages and low energy prices. The breakthrough technologies of the industrial revolution increased the use of capital and energy per worker. These techniques, in their earliest, crudest forms were profitable to use in Britain but not abroad in view of Britain's unusual factor prices. I even argued that eighteenth century Britain was the prequel to Habakkuk's nineteenth century America where cheap resources and dear labour made labour saving technology profitable. Here I want to examine that claim more carefully by comparing the USA, Britain, Egypt, and India in terms of wages, living costs, the prices of natural resources, energy, and capital services. Was nineteenth century America really the sequel to industrializing Britain, as I had supposed?

My approach differs from many others that emphasize culture or institutions or some combination of the two. Cultural explanations attribute American success to a 'nation of

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[3]The comparative history of national income in the USA and UK is still, after decades of research, highly contested. See, for instance, Prados de la Escosura (2000), Ward and Devereux (2003), Broadberry (2003), and Lindert and Williamson (2011). The argument of this paper does not place much emphasis on specific national income estimates or related indicators like sectoral labour productivity. Factor prices and industry specific estimates are preferred.

[4]Price history has a long history, beginning with Rogers (1866-1902). Recent contributions focussing on wage history include Allen (1994), Williamson (1995), van Zanden (1999), Allen (2001), Özmucur and Pamuk (2002), Allen, Bassino, Ma Moll-Murata, van Zanden (2011), Allen, Murphy, Schneider (2012), Abad, Davies, van Zanden (2012).

tinkerers' or 'the enterprise of a free people.'[5] Political institutions are the main stream explanation in economics today.[6] What these theories have in common is a focus on the responsiveness of economic actors to the incentives they face. Good culture means that businessmen and inventors respond vigorously and effectively to those incentives. Good institutions ensure that economic actors correctly perceive the 'true' incentives generated by endowments, technology, preferences, and markets, while bad institutions are either like a smoke screen that obscures the true economic incentives or, worse, like a signal pointing the wrong way that actively generates misleading incentives that lead to unproductive rent seeking. In either case, entrepreneurs and inventors go off in the wrong direction. The limitation of these approaches is that they leave unanalysed the true incentives arising from markets, endowments, and so forth. The implicit assumption is that these incentives were the same in all times and places. But were they? Were the incentives that Americans faced the same as those faced by Brits, Egyptians, or Indians? Was America's economic success the result of an unusual responsiveness to incentives or was it the result of unusual incentives?

Three features of nineteenth century economic history play roles in this discussion. One, already mentioned, is technology, in particular, the idea that advances in technology were biased and consisted of new machines that raised capital and energy per worker as they increased output per worker. These machines were profitable to use where labour was dear and energy cheap. A second is globalization. Over the course of the nineteenth century, transportation costs fell, the institutions relevant to international trade improved, and prices converged.[7] The third is economic policy. As global markets became more tightly integrated, comparative advantage came more forcefully into play in shaping an international division of labour. As Britain's comparative advantage shifted more towards manufacturing, other countries' shifted towards agriculture, and they de-industrialized or failed to industrialize.[8] How countries could respond to the environment was an important question, and a standard development model was elaborated in the USA, in the first instance (Allen 2011). This model consisted of four imperatives: Create a large internal market by eliminating internal barriers to trade and constructing infrastructure. Erect an external tariff to protect your industries from British competition. Establish an effective banking system to stabilize the currency and promote investment. Found a system of universal education to prepare the citizens for industrial employment. How successful were these policies in the USA? Nationalists around the world wanted these policies, too. Would they have worked well had they been adopted in Egypt and India?

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[5]Weber (1904-5) is a well known, powerful cultural explanation. Clark (2007) proposes a bio-cultural explanation.

[6]North led the way in many publications including North and Thomas (1973), North (1981, 1990), North, Wallis, Weingast (2009). Acemoglu and Robinson (2012) is a recent contribution.

[7]Harley (1971, 1973, 1988), Jacks (2006), O'Rourke and Williamson (2001, 2009), Findlay and O'Rourke (2007).

[8]Pamuk and Williamson (2011), Williamson (2012), Wallerstein (1974, 1980, 1989, 2011).

Natural Resources and Globalization

America's success is plausibly attributed to geographical features of which 'abundant natural resources' are an important case in point. Natural resources, of course, are not entirely natural, for they require discovery, development, and transportation before they can be abundant. Those investments depended on public policy as well as private initiative. How were the abundant resources supposed to have promoted American development? There are several arguments. Habakkuk (1962), for instance, thought that the availability of farmsteads on the frontier raised the wage of unskilled labour in eastern cities and induced labour saving technical change. I will consider this argument shortly. Here I take up the long standing argument that abundant natural resources underpinned American industrialization by providing industry with essential raw materials (Rostas 1948, Melman 1956, Frankel 1957, Franko 1976, Nelson and Wright 1992, Broadberry 1997, pp. 98-102). Gavin Wright (1990) has argued for this interpretation by analysing the factor intensity of American exports.

Wright's work focuses on *quantities*. Here I analyse *prices*. Resource abundance could promote industrialization by providing manufacturers with cheap raw material inputs. Did abundance have that effect? Here globalization enters the picture. In the nineteenth century world markets became more integrated. Britain was the centre of the world economy and imported many resource products from peripheral countries like the USA (Lewis 1978). In the absence of a British tariff, transport costs defined the difference between the price of an American export in the USA and in Britain. With non-traded goods or goods that the USA imported, the price in the USA could be higher than the British price, especially if the USA imposed a high tariff on the item. These considerations raise the possibility that American industrialization was not based on cheap natural resources, and that, indeed, was the case generally.

Cotton is an important example, as it was the most important American export, and the raw material input for the core industry of the Industrial Revolution. Precise comparisons of prices require close attention to the terms of sale and systems of product grading. Harley (1992) has attended to those matters in comparing the prices of cotton in New York and Liverpool in the antebellum period (Figure 3). Evidently, in the 1850s, there was virtually no difference in the price of raw cotton in Britain and the American northern states. The reason is that there was little difference in the cost of shipping from New Orleans to either destination. This situation continued throughout the nineteenth century as Figure 22 makes clear.

I have compared US and British prices for many natural resource products. The only case where American prices are substantially below British prices was lumber, and the American advantage disappeared by the twentieth century. Figure 4 shows the price of soft wood lumber for general construction in the two countries. The US price was about half of the British price until about 1905 after which they were similar. It is always a worry that grades and terms of sale may not be exactly matched, so it is reassuring that the same differential appears in comparisons of pine flooring and oak timbers. Indeed, the price differential in the nineteenth century equals the cost of transporting timber across the Atlantic (Potter 1955, pp. 125-6). Some discussions of Habakkuk's views suggested that machine technology may have been favoured in America since such methods were wasteful of wood even as they economized on labour (Ames and Rosenberg 1968, p. 831, Church 1975, p. 619). This view receives some support from a comparison of lumber prices.

With all other products, the opposite result obtains, i.e. American prices exceeded

British prices in the nineteenth century and were very similar in the twentieth. Figures 5-7 make the point for copper, lead, and even tin. Both countries imported much or all of their tin from southeast Asia, but even in that case, nineteenth century American purchasers were at a slight disadvantage vis-a-vis British buyers. The playing field was only leveled in the twentieth century.

American blacksmiths and metal using industries were at an even greater disadvantage in so far as iron and steel products were concerned. Britain had abundant coal and iron ore conveniently located near major metropolitan areas. With the advent of coke smelting, puddling and rolling, and the hot blast, Britain became the world's low cost producer of iron, and a major supplier to the USA for most of the nineteenth century (Temin 1964). While the USA had charcoal, coal, and iron ore, they were mainly in remote locations. The country did develop a large industry, however, by placing high tariffs on British imports (Fogel and Engerman 1969, Davis and Irwin 2008, Irwin 2000). As a result, iron was often two to three times as expensive in the USA as it was in Britain (Figure 8).

This situation lasted until the mid-1890s when Mesabi iron ore became available at low cost in Pittsburgh and midwestern steel mills. The Mesasbi range was the last of the iron ore ranges surrounding Lake Superior to be brought into production. Its exploitation was facilitated by the US and Canadian governments building deep locks at Sault Saint Marie–an example of the important role played by government infrastructure programs (Allen 1979).

While Mesabi ore gave Pittsburgh (along with the Ruhr district in Germany) the cheapest raw materials for steel production in the world, there were no advantages for the US automobile and engineering industries. The reason was the US Steel merger in 1901. US Steel owned much of the Mesabi range and realized much of the potential of its market power by raising the price of iron ore to itself and other midwestern producers. Figure 9 shows the cost of the ore and coke needed for a ton of acid Bessemer steel on Britain's north east coast and at Pittsburgh. Before 1895, Britain had the lowest raw material costs. After 1895 costs in Britain and the US were about the same *when the ore was valued at its market price*. This equality led to roughly equal prices for finished steel (Figure 8). However, when the ore is valued at cost price, US Steel's costs are shown to have been much lower than British costs (Allen 1978, p. 63). Rather than passing on the cost saving of the Mesabi range to steel fabricators, US Steel expropriated the savings as monopoly profits. Cheap raw materials conveyed no advantage to American auto producers or steel fabricators generally.[9]

The final industrial input to consider is the most general–namely, energy. There was not much trade in fuel between the USA and Britain in the nineteenth century, so prices in these countries reflected domestic demand and supply. Comparisons are complicated because there were several sources of energy. Wood was used as a fuel in Britain in the eighteenth century and was widely used in some places in the USA in the nineteenth (Warde 2007). The odd quotations for cord wood in the seventeenth century show that energy was very cheap in the American colonies. This was probably also true in the Mississippi valley in the antebellum period. However, by the nineteenth century, the forests near eastern cities had been cleared, and the wood sold in Philadelphia or Boston was more expensive per BTU than coal. Likewise, falling water was a cheap source of industrial power on the east coast of the USA and, indeed, in British manufacturing districts, where it remained the predominant source of power until the 1840s. (Kanefsky 1979, Kanefsky and Robey 1980, Crafts 2004,

[9] For an alternative view, see Irwin (2003a).

Temin 1966, Hunter 1979-91) In both countries, however, coal was the ‘backstop’ fuel once the good water power sites were occupied. We can compare the prices of energy from coal in Britain and on the east coast of the USA (Figure 10). Up until about 1880, British manufacturing districts had cheaper energy than Philadelphia or New York. This was true of both bituminous and anthracite sold in the region.

After 1880, America’s energy situation improved. Bituminous coal dropped in price on the east coast and sold for a similar price to British coal. Equality extended to one of the great new fuels of the period–petroleum. While the USA had ‘abundant’ supplies of crude oil, and the British had (at the time) none, oil was traded internationally, and trade equalized prices in the two countries. The US export prices of gasoline and kerosene, at any rate, were only slightly below the British import prices. The development of electricity, the other great fuel of the twentieth century, did, however, confer positive advantages on the USA. Electricity was not traded across the Atlantic, so prices in North America and Europe could diverge. In the 1920s and 1930s, American manufacturers paid half as much for electricity as their British competitors (Melman 1956, p. 206).

So what was the impact of America’s abundant natural resources on the country’s economic development? The integration of world commodity markets meant that American industry did not benefit from cheap resources. When the effects of tariffs (eg. iron) and non-traded goods (eg energy) are taken into consideration, American firms probably paid more for natural resources than did British firms. Indeed, the point is more far reaching. America’s abundant natural resources meant that the country’s comparative advantage lay unequivocally in agriculture and forestry. Manufacturing should not have been profitable, and, indeed, it was not. Or, to make the point in monetary terms, the very large volumes of exports of farm and forest products were inflationary–they produced a ‘Dutch disease’ situation in which the prices of non-tradeables, protected imports, and labour were raised to levels that made manufacturing uncompetitive. The effect of abundant natural resources in a global economy was to retard the industrialization of the USA–not to promote it.

Labour Markets and Living Standards

Abundant natural resources is one way in which geography might have influenced American economic history. There are others. A second was proximity to Europe. Even in the colonial period, the future USA was close enough to Britain to make the export of agricultural products a basis for economic growth. This is a marked difference from Mexico, Peru, Brazil, or Argentine, which were too remote from Europe for such development to have been possible (Allen 2011) Another geographical consideration was that the continent was very large but had only a small native population. There were perhaps 250,000 aboriginals in the thirteen colonies on the eve of European settlement, and their number dropped dramatically due to disease, war, and mistreatment (Thornton 1987, p. 29). The small size and high mortality of the native population has been an underappreciated feature of American history since Acemoglu, Johnson, and Robinson (2001) placed so much emphasis on settler mortality. There were not enough natives to exploit as a labour force, so extraction was limited to seizing their land. Forced labor was a cheap way for European settlers to develop an (almost) empty continent (Domar 1970), so an ersatz native labor force was created by importing slaves from Africa to grow cotton and sugar in the South (Fogel and Engerman 1974, Engerman and Sokoloff 2011).

White settlers were attracted from Europe, and wages in America had to be high enough to make settling in an empty wilderness an attractive option. The implications of this proposition are clear in the data.

I begin with nominal wages, which are plotted for London, Lancashire, Massachusetts, and Philadelphia in Figure 11. The wages in the figure are those of labourers, generally in the construction industry. Similar results are obtained with craftsmen like carpenters. Before 1776, London had the highest wages although Philadelphia occasionally took the lead. Nominal wages converged at the end of the eighteenth century, and in the nineteenth American wages were generally higher than British wages. The high nominal wage in the United States was the result of the Dutch disease just discussed.

The significance of the high wage depends on the cost of living (among other things). The cost of living can be computed in many ways. In a paper on colonial living standards, a 'bare bones basket' based on the cheapest available grain (maize in the Americas, oats in England) was used as the deflator (Allen, Murphy, Schneider 2012). However, since the early nineteenth century, workers in Britain and America have been well enough off to be eating products made from wheat flour rather than the cheaper grains. Consequently, wheat flour has been substituted for the other grains in the deflator (Table 1). Figure 12 shows the deflator for England, Philadelphia, and Massachusetts in the eighteenth and nineteenth centuries. There was little difference in the cost of living. This is surprising since the USA was exporting wheat to England at the time. However, the cost of living index depends on the retail price of wheat flour and not on the wholesale price of wheat. The higher nominal wage in the United States meant that processing, transportation, and trade margins were higher, and they offset the advantage of cheaper wheat.

The real wage is measured as the ratio of a labourer's annual earnings divided by the cost of maintaining a family of four people at the subsistence level defined by the basket in Table 1. When the real wage, computed in this manner, equalled one, a fully employed labourer could just keep his family at that standard, which also corresponds to the World Bank's famous 'dollar a day' poverty line (Allen 2013). In the colonial period, London and Philadelphia had the highest real wages, and Lancashire hand the lowest. Real wages converged by the end of the eighteenth century. Thereafter, they were often highest in the American cities. In both countries real wage growth accelerated over the nineteenth century.

The real wage series in Figure 13 look correlated with each other, and, indeed, they were. Error correction models (Table 2) have been estimated for these series, and Granger causality tests used to explore their interconnection. These result indicate that the series were co-integrated and causation between them shifted back and forth. My interpretation of these results is that the British and American labour markets were closely integrated. Of course, people came to the USA from many countries often fleeing desperate situations. Nonetheless, British and Irish immigrants were a always a significant share of the total (US *Historical Statistics*, series C90-C92). Since they had the option of going to Lancashire or London, wages in those cities became the foregone income of the marginal migrant. This situation lasted until the mass migration from southern and eastern Europe at the end of the nineteenth century. Until then, we can regard the United States as an outlying, if rapidly developing, region of Britain. The unskilled wage rate was not determined by farm income on the frontier, as Habakkuk supposed, but rather in the British Isles. The labor market in the USA was not exceptional after all.

The finding of a unified, trans-Atlantic market for unskilled men immediately raises the question of how general that result might have been. Does it hold for other types of workers? The situation for skilled craftsman appears similar, but the question requires further investigation. One category of worker, however, for which the conclusion does not hold is the 'average factory worker.' Nominal and real average annual earnings in manufacturing were both very much higher in the USA than in Britain. The finding raises obvious questions regarding the invention of labour saving machinery in the two countries.

Why were average earnings in manufacturing in the US so high? While the data are imperfect, the structure of the workforce in the two countries appears to have been very different at least from the middle of the nineteenth century onwards. Tables 3 and 4 show breakdowns of the manufacturing workforce in the USA and Britain in the 1860s. On the face of it, a far higher proportion of the British workforce was women and especially children. Tables 3 and 4 may overstate the differences between the two countries as children may be more broadly defined in Britain (although the division between males and females should be accurate), but the results are still striking. Goldin and Sokoloff (1982, 1984) have argued that many women and children were employed in US manufacturing in the antebellum period, but their employment looks to have been relatively more widespread in Britain after 1850.

In any event, the difference in average manufacturing earnings between the two countries in the 1860s is due to the different shares of male, female, and child labour as shown in the tables. The average earnings of men in the two tables are similar to the average earnings of male labourers at the time (roughly \$1.50 per day in the USA versus \$1.00 in Britain) and the earnings of women and children were roughly in proportion. The differences in composition explain the differences in average earnings in manufacturing.

The result raises questions of cause and consequence. As to cause, the most likely explanation is the greater provision of education in the USA. Throughout the nineteenth century, enrollment rates were much lower in England and Wales than they were in the USA especially outside the South. The difference was pronounced in the years when the USA was building its technological lead. In 1880, for instance, 90% of school aged children in the USA were enrolled in schools in contrast to only 55% in England and Wales (Lindert 2004, p. 92, Engerman and Sokoloff 2011, pp. 121-67). The child proletariat was much bigger in England than in the USA.

Why did the USA lead in this regard? The answer comes down to differences in public educational policy. Policies differed in the two countries for three reasons. First, the USA was more democratic (Engerman and Sokoloff 2011, p. 166). Indeed, England only got universal, free primary education in 1891–six years after the Third Reform Act expanded the franchise from 31% to 63% of adult males (Lindert 2004, p.114). Second, the American Revolution eliminated established churches, and the Church of England was an important opponent of universal education. Universal education is a concrete example of one way political exceptionalism contributed to economic exceptionalism. Third, manufacturing interests were probably more favourable to public universal education in the USA than they were in England. The difficulty of assimilating a large, immigrant population disposed Massachusetts business interests to support the common school movement that began in 1837 and that aimed to require all children to attend school. (A large Irish population in northern British cities did not have the same result.) There was also a technological difference between the countries that may have played a role. In England, spinning was done with mules, and many boys were employed as piecers assisting in their operation. American mills, in contrast, spun with throstles, and they did not require piecers. English employers may have been more opposed to universal schooling, as it would have prevented them from employing a large part of their work force. We will consider the consequences of the educational differences shortly.

Relative factor prices and technological progress

What did the history of factor prices in Britain and America imply for the invention and adoption of technology? The answer depends on relative factor prices. I concentrate on the wage relative to both the price of energy and to the price of capital services. The more expensive was labour relative to energy and capital, the greater was the incentive to use–and ultimately to invent–techniques that substituted energy and capital for labour.

Figure 14 shows wages relative to the price of energy derived from coal. Before 1880 both wage rates and energy prices were higher in the USA than in Britain by roughly the same proportions, and Figure 14 shows that labour was only marginally more expensive relative to energy in Britain in this period. Before 1880 the incentives to adopt coal based steam technology on the east coast of the USA and in northern Britain were similar. After 1880, wages grew much faster than energy prices in the USA, and the incentives to adopt a more power intensive technology were greater on the west of the Atlantic at this time. An examination of electricity prices shows that the situation was similar with this new form of energy (Mellman 1956, p. 204, Broadberry 1997, p. 101). After 1880, the incentives to increase the use of power per worker were greater in the USA than in the UK.

Before considering the ratio of wages to the price of capital services, I compare the price of capital services themselves. They are measured as an interest rate plus a depreciation rate multiplied by the price of capital inputs. The latter, in turn, is measured as a geometric average of the wage rate of construction labour and the simple average of the prices of iron bars, softwood lumber, bricks, and copper ingots. Wage rates, interest rates, and the prices of iron, copper, and bricks were all greater in the USA than in Britain. Only softwood lumber was cheaper in America. It is no surprise then that capital services were more expensive in the USA (Figure 15)–a result anticipated by Temin (1971a, 1971b) in his general equilibrium formulation of Habakkuk's views.

What of the ratio of wages to capital service prices? The answer depends on which wage is used. If we use the wage of male labourers, then the wage rate relative to the price of capital services turns out to have been about the same in both countries over the entire nineteenth century (Figure 16). In both countries, wages rose relative to capital using costs between 1860 and 1900–thus increasing the incentive to mechanize on both sides of the Atlantic. The differences between the countries were negligible–thus calling into question Habakkuk's analysis of American technological history.

On the other hand, if we compare the average earnings of manufacturing workers to the price of capital services in the two countries (Figure 17), we find that labour was, indeed, more expensive in the USA than in the UK. What to make of this is not so clear. On the one hand, the wages of women and of children relative to capital services were, like those of men, about the same in the two countries, so perhaps the 'average factory worker' is a misleading aggregate. On the other hand, one could argue in the manner of Acemoglu (2002, 2012) that it was not the relative wages that were important but rather the relative quantities of labour. The argument might go like this: wide spread primary education in the USA reduced the supply of child labour relative to adult labour and that induced American firms to invent technology that augmented the productivity of adult labour. British firms were full of child tying strings together and otherwise performing menial tasks amongst the machines. In

America, their counterparts were in school, so American firms from an early date invented automatic shut-offs and other control devices to take the place of children. This commitment to automatic technology lead to higher productivity of the adult workers.

Can these considerations explain the history of American and British technology in the nineteenth century? We have firm comparisons of relative efficiency only at the end of the period. Comparisons of the 1907 British census of production with US censuses of manufactures show that in the early twentieth century labour productivity in American manufacturing was about twice the British level (Broadberry 1997). The situation in earlier years is not so clear. Broadberry (1994) and Broadberry and Irwin (2006) have argued that the USA had much higher productivity as early as the 1830s. An important part of the argument is that historical national accounts for the USA and Britain indicate that manufacturing valued added per worker grew at similar rates from 1870 to 1907, so America must have been twice as productive throughout. However, the employment figures are not standardized for changes in the age, sex, or educational attainment of the workforce, and in all of these regards we have seen that there were major differences between the countries and changes over time. The matter warrants more research with industry level data. My own calculations indicate that there was little difference in labour productivity between Britain and the USA in iron technology in the middle of the nineteenth century (Allen 1979, p. 922). Furthermore, there seems to have been little difference in the spinning and weaving of cotton in factories. Figure 18 uses data from the US censuses and a little known investigation of Wood (1903, p. 302) to compare output per worker in spinning and weaving analysed as an integrated activity in the two countries. In 1830, labour productivity in Britain looks much lower than it was in the USA if we define the British industry to include handloom weaving–a point made by Broadberry (1994). However, that sector was obsolete and about to disappear. Confining the comparison to the factory sector in both countries indicates very similar levels of productivity from 1830 until 1880 after which American labour productivity grew more rapidly than British.

This pattern makes good sense in terms of the factor price history. Up until 1880 the incentives to mechanize production in the two countries were similar. Relative factor prices did not inhibit the adoption by Americans of the cutting edge technology of the industrial revolution nor did it give them particularly pronounced incentives to invent more capital or energy intensive technology. As the labour market evidence shows, the USA was an outlying province of Britain operating in a similar environment. It is not surprising that Americans occasionally invented path breaking technology, but they had no particular incentive to do so.

After 1880, however, the incentives to invent higher productivity technology led to an American lead. The incentives to use more power per worker in America increased significantly in this period–without a corresponding change in Britain. As well, the restricted supply of child labour may have created a long run tendency in American industry to invent technology that took the place of the children who populated British factories.

There is a third factor that probably also contributed to America's growth in manufacturing productivity, and that was the rapid growth in industry attendant upon the settlement of the continent. The rapid growth in agricultural production during the phase of extensive growth led to the expansion of cities and manufacturing since the American tariff ensured that most manufactures consumed in the country were produced there. While per capita GDP did not exceed the British level, the growth in GDP and population themselves were much more rapid than in the UK. This expansion also entailed an extremely rapid growth in the American capital stock. In 1870, the capital stock of the USA was about 25%

greater than that UK's; in 1910 the US capital stock was almost four times larger. Over that period the increase in the US capital stock was six times greater than the growth of the British stock (Allen 2012). Rapid growth in the demand for capital goods provided a great market for inventors. Improvement in technology (including organization methods, eg Chandler 1977) depends on experimental data, and that data is often generated as a by product of investment. For instance, in industries like iron and steel the effects of changes in the lay out of blast furnaces or steel mills could only be observed by building new mills. That kind of experimental knowledge was generated in the USA as a consequence of the rapid growth in GDP and the capital stock. It was not generated in Britain. Technology surged ahead in the USA both because high investment led to the growth in the demand for new machinery but also because the erection of new capacity generated the knowledge that made later new capacity more productive. Firms learned from each other and advanced together through collective invention (Temin 1966a, Allen 1983). By 1907 America had developed a strong lead in labour productivity in manufacturing.

It is important to notice that this lead was underpinned in important ways by government policies. Transportation and educational policy have already been mentioned. It is difficult to image how this pattern of development could have been realized without a protective tariff. Nominal wages, the price of capital services, and most industrial raw materials were more expensive in the USA than they were in Britain. This was a consequence of America's comparative advantage in farm and forest products. Without a tariff, how could manufacturing have paid? A tariff undoubtedly raised the price of consumer goods; however, the good news was that it did not lead to intrinsically inefficient industries. With relative factor prices similar in the USA and the UK, it paid to adopt advanced technology in America, so American firms did that–once the tariff allowed their existence.[10]

Egypt and India

Comparisons of the US and the UK show that it is hard to find much that was exceptional about the American economy in the nineteenth century. Both of those countries, however, look exceptional in comparison to Egypt and India. They were much poorer over the whole period considered here. Can we explain their persisting poverty in the same terms that we have used to analyse the USA and Great Britain? The answer is yes.

Bad institutions or culture is the common explanation for stagnation in poor countries. The theory is that bad institutions reduce a country's response to the gains from growth by obscuring them. But were there really gains to be had? My claim is that it would not have paid to install the productivity boosting technology that would have alleviated their poverty.

In 1800, Egypt and India differed fundamentally from USA in their circumstances. India had a large population, and both were governed by Malthusian dynamics, so the wage was at bare bones subsistence. India was an important exporter of cotton textiles, and both countries had substantial manufacturing industries. Since the wage was low, they used

[10]General discussions from different perspectives include Taussig (1931),O'Rourke (2000), Irwin (2003b, 2007). General equilibrium models of the Americans include Temin (1971a), James (1978, 1981b), Harley (1992b), and Williamson (1974). There are many studies of the impact of tariffs on particular industries. For cotton these include David (1970), Temin (1988), Harley (1992a), Irwin and Temin (2001), and subsequent exchanges.

handicraft methods.

Nominal wages were low in both Egypt and India as Figure 19 shows. Food prices were also much lower than they were in Britain or America. Nonetheless, real wages were also low in the third world (Figure 20). Male labourers in Egypt earned just enough to support families at bare bones subsistence. Labourers in India were even more poorly paid with the result that all family members had to work in order for the family to survive (Allen 2007, Broadberry and Gupta 2006).

Globalization disrupted the economies of many poor countries by integrating markets and increasing trading opportunities. Figure 21 shows the evolution of wheat prices in Britain, the USA, Egypt, and India from 1820 to the First World War. The differences were substantial in the antebellum period, and prices were highest in Britain and lowest in Egypt and India. By the twentieth century, the differences had collapsed. Prices fell in Britain and America to the benefit of their consumers. The history of raw cotton prices was similar (Figure 22) with large differentials early in the nineteenth century that disappeared after 1875. Prices were highest in Liverpool and fell the most there. The gains from globalization accrued mainly to buyers in Britain and (to a lesser extent) the USA, Farmers were never gainers.

There were parallel developments in manufactured goods prices that benefited consumers in most places. Figure 23 shows the history of cotton cloth prices in the four countries. Prices were highest in the USA at the end of the eighteenth century followed by England. India, which at the time exported cloth, and Egypt had the lowest prices. The mechanization of textile production in Britain and the establishment of a machine industry in the USA drove down prices in both countries. This downward pressure forced down prices in India and Egypt as the price they paid for British textiles declined. As a result of this competition cotton spinning was largely driven out of business in Africa and Asia and weaving was increasingly depressed.

With falling prices of manufactured goods and steady or rising prices for farm products, labour left manufacturing in India and Egypt and entered agriculture. The production of raw cotton for export increased. India and Egypt became important suppliers of raw cotton to European markets, although not to the same extent as the USA. Globalization transformed Egypt and India into modern 'underdeveloped countries,' that exported primary products and imported manufactured goods from the West.

Why didn't Egypt or India industrialize by adopting British technology like the USA did? Could Egypt or India have turned its low wages into a competitive advantage? One problem was that labour in these countries was not trained for factory work, and that lowered its efficiency in modern industry (Clark 1987). Even allowing for that, labour was cheap in poor countries. The bigger problem was that, at the low wage, handicraft methods were the cost minimizing choice of technique for most products.

To explore the choice of technique, we must compare relative factor prices in India and Egypt to those in Britain and America. The price of capital services was a composite that depended on interest rates, building labour, and the prices of inputs like iron, timber, copper, and bricks. Interest rates were much higher in Egypt and India than they were in rich countries, while wages were much lower. Inputs like iron and timber were similar in Egypt and in Britain as these were internationally traded goods (Figures 24 and 25). Bricks were much cheaper in Egypt as they were locally produced with low wage labour (Figure 26). The somewhat surprising upshot of these considerations is that the user cost of capital was similar in Egypt, Britain, and the USA (Figure 27). Since wages were much lower in Egypt than in the rich countries, labour relative to capital services was much lower in Egypt (Figure 28). The incentive to use machinery in Egypt (let alone to invent it) was very much lower than in the USA or Britain.

The situation was similar with energy. Neither country possessed a coal industry at the time, and most energy came from wood. The price of charcoal in Cairo was very high as it was made by Bedouins in the Sinai and carried by camel to the capital (Rabinowitz 1985). Wood was also expensive in India (Figure 29). As a result, the ratio of the wage rate to the price of energy in Britain or America was vastly higher than in the Third World (Figure 30). The incentives to use steam power to boost the productivity of human labour in Egypt or India were nonexistent.

India and Egypt would not have spontaneously industrialized since it did not pay their firms to use most modern technology. Labour was cheap relative to energy and capital. It did not pay to adopt the technology that would have alleviated their poverty. In the USA a tariff was necessary to make industry pay, but once in place American industry chose the modern methods. Development of the third world required policies that ignored comparative advantage.

From this perspective, Egypt is one of history's great missed opportunities. In 1805 Mohammed Ali seized power and tried to turn Egypt into a modern military-industrial power. A Soviet style procurement policy financed stated led industrialization. It all came undone in 1838 when the British forced a treaty on the Ottoman overlords that ended the fiscal system. The Egyptian economy reverted to the pattern implied by comparative advantage, and Egypt remained an underdeveloped country (Rivlin 1961, Panza.and Williamson 2013).

Conclusion

Was American economic development 'exceptional'? Before 1895, it consisted of settling a vast continent with only a small indigenous population. This was an impressive achievement but not unusual. Population movements into remote areas have been a recurrent feature of world history. After 1895, America became a leading industrial power by developing high productivity manufacturing. This was a more unusual achievement that rested on three factors–(1) cheap energy, (2) universal public schooling that induced firms to develop technology to raise the productivity of adult labor while at the same time training children to meet that demand, and (3) the rapid growth of manufacturing before 1895. While the nineteenth century industrial sector was not internationally competitive, the high rate of capital accumulation led to a rapidly growing demand for capital goods as well as learning by doing and collective invention. The accumulation of engineering experience provided knowledge inputs for the inventions that augmented adult labour.

Likewise, the American development model was exceptional in the sense that it would not have delivered similar results if applied in poor countries. The model consisted of transportation investment, universal schooling, and tariff protection. Consider the tariff. In nineteenth century America, it was necessary for the development of a modern manufacturing sector since all input prices (with the exception of wood) were higher in the USA than they were in Britain. This was because resource abundance meant that the USA's comparative advantage lay in agriculture. The tariff raised prices for consumers but did not lead to inefficient production, however, since relative factor prices were similar to those in Britain, so the transfer of advanced technology was profit maximizing. On the other hand, countries like Egypt and India appeared to offer better prospects for industrial development since their wages, at least, were much lower than those in Britain. Some of this difference was due to the lower efficiency of poorly trained workers in these countries. Beyond that, low wages not accounted for in this way reduced the incentive to adopt modern technology since it was not worth investing large sums to save cheap labour. In many cases, the traditional hand technology remained the least cost choice of technique. In that circumstance, the American model was a non-starter, and more draconian policies were necessary for successful industrialization.

While the differences between the USA and Britain have exercised generations of historians, the differences between the two economies were small when seen from a global perspective. For much of its history, the USA was an outlying province of Britain–albeit an increasingly dynamic one. Both Britain and the USA were rich, while much of the rest of the world was poor. Indeed, globalization and the character of technological change widened the gap between rich and poor. The USA and Britain were winners in a global process of economic divergence. America has been a leader in that development, and that is the essence of American exceptionalism.

Table 1

Subsistence Basket

flour	kg	195
beans/peas	kg	20
meat	kg	5
butter	kg	3
soap	kg	1.3
cloth	metres	3
candles	kg	1.3
lamp oil	litres	1.3
fuel	Mill BTU	2
calories/day		2103

Table 2

Co-integration between wages in US and UK cities (Error Correction Models)

		London-Massachusetts			London-Philadelphia	
		1781-1802	1836-1913		1727-1802	1836-1913
$\Delta wage_{UK}$		0.31	0.72***		0.34**	0.38**
		(0.25)	(0.17)		(0.13)	(0.16)
ECT (z_{t-1})		-0.64***	-0.32***		-0.51***	-0.52
		(0.22)	(0.10)		(0.13)	(0.12)
N		21	62		51	51
r^2		0.32	0.30		0.38	0.34
F		4.31	12.76		14.92	12.60

		Lancashire-Massachusetts			Lancashire-Philadelphia	
		1781-1802	1836-1913		1727-1802	1836-1913
$\Delta wage_{UK}$		0.42*	0.66***		0.25*	0.32**
		(0.23)	(0.15)		(0.13)	(0.14)
ECT (z_{t-1})		-0.63***	-0.28***		-0.48***	-0.58***
		(0.22)	(0.10)		(0.13)	(0.12)
N		21	62		51	51
r^2		0.35	0.31		0.32	0.32
F		4.89	13.10		11.37	11.37

Note: the dependent variable is changes in wages in the US city. The ECT (error correction term) equals the difference between the actual and the equilibrium wage in the previous period where the equilibrium wage is determined by the co-integrating regression.

Table 3

Employment in British Manufacturing in the 1860s

	% workers	Earnings (£/year)	Earnings ($/year)
men	45%	51.5	250.68
women	29%	22.1	107.72
boys	13%	16.4	79.90
girls	13%	12.5	60.93
average		33.3	161.96

Source: Baxter (1868, pp. 88-95) and Peter Lindert’s (1997) spreadsheet ‘Baxter EW & UK 1867".

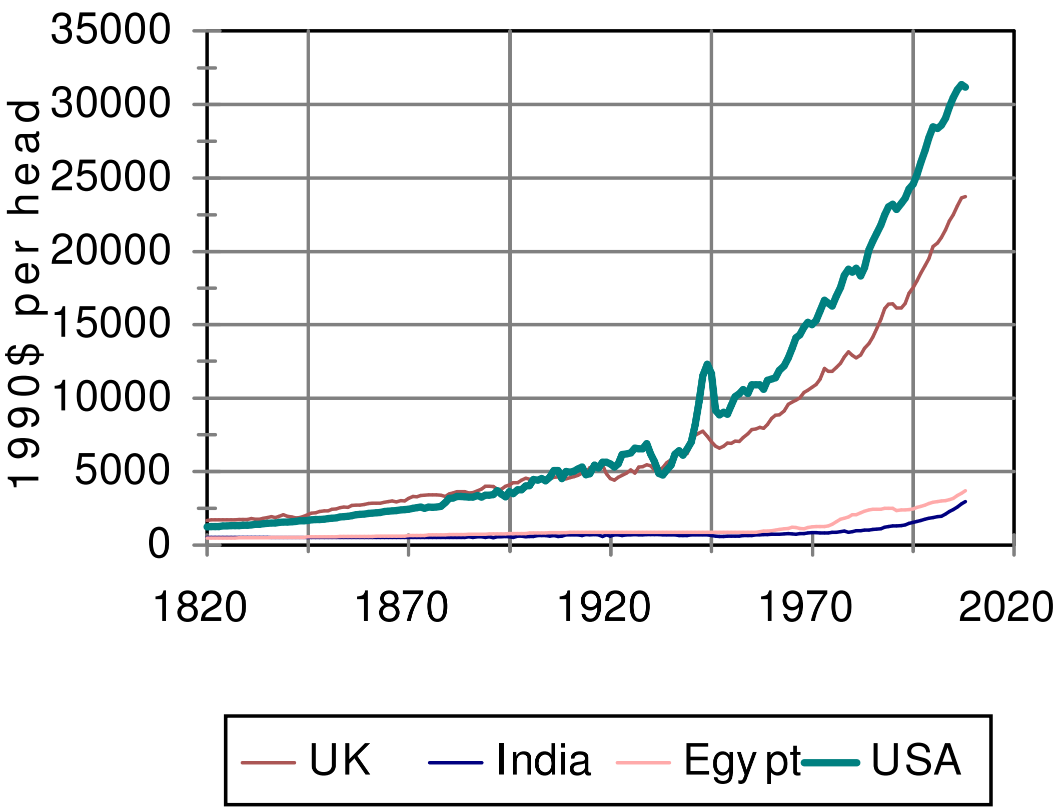
Table 4

	% workers	Earnings ($/year)	USA/UK	
Men>16	79%	343.64	1.37	
Women>15	16%	171.82	1.60	
youths	5%	85.91	1.22	
average		302.18	1.87	

Employment in USA Manufacturing in 1869
U.S. Census, *Compendium of the Ninth Census*, 1872, pp. 796-7.

Figure 1

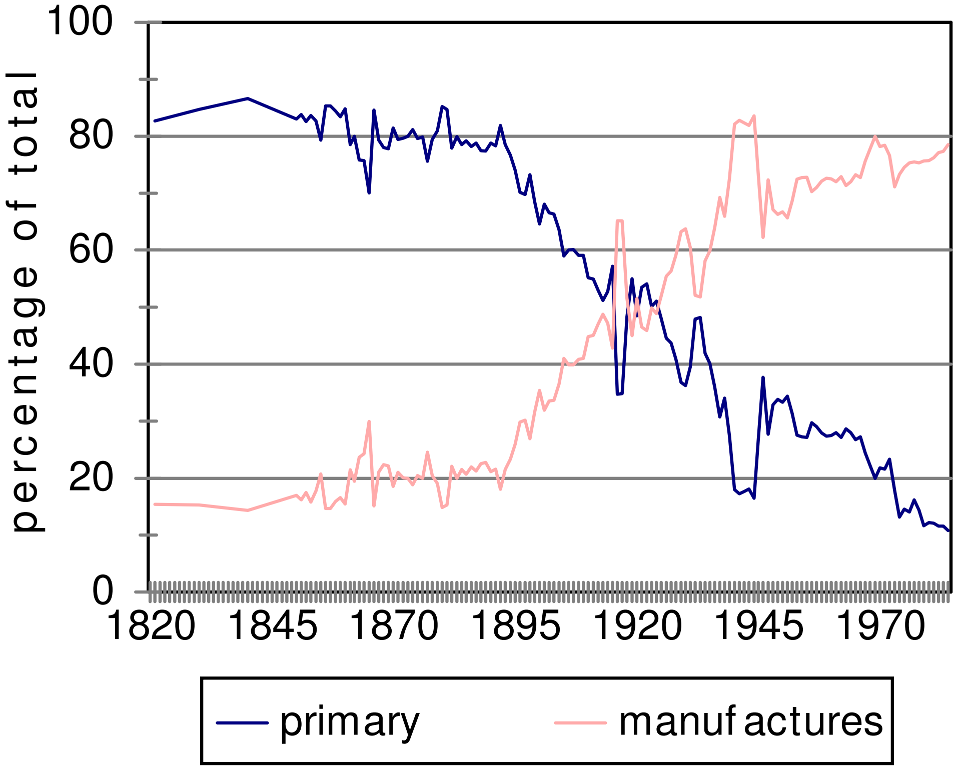
GDP per Capita



Source: Maddison (2006)

Figure 2

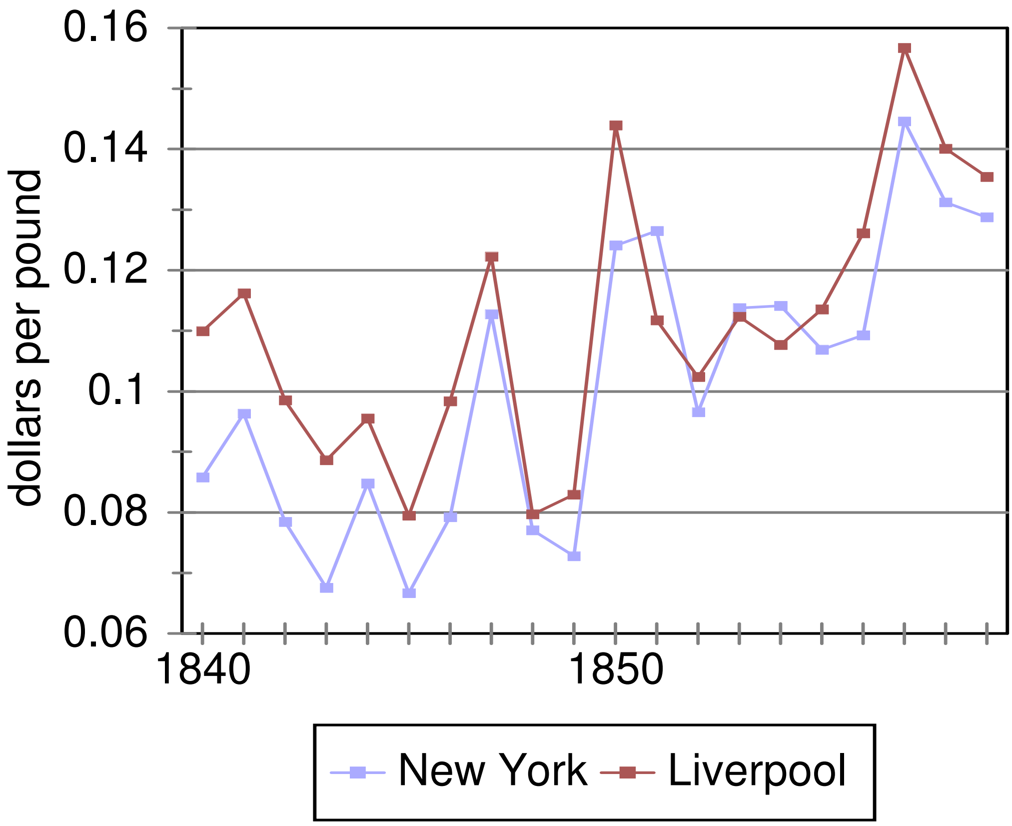
Percentage Composition of American Exports



Hist Stat
primary is sum of series Ee447, Ed448, and Ed449.
Manufactures is sum of series Ed450 and Ee451.

Figure 3

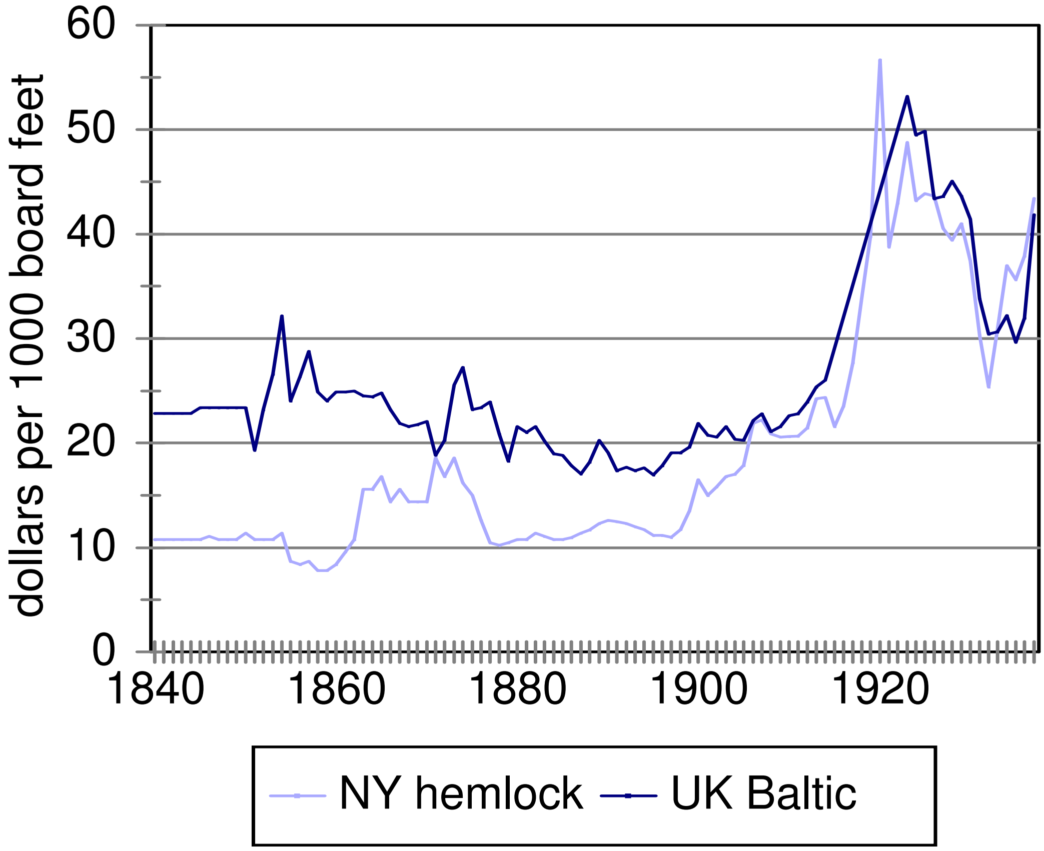
Price of Raw Cotton in New York and Liverpool



Source: Harley (1992, p. 573).

Figure 4

Price of Softwood Structural Lumber

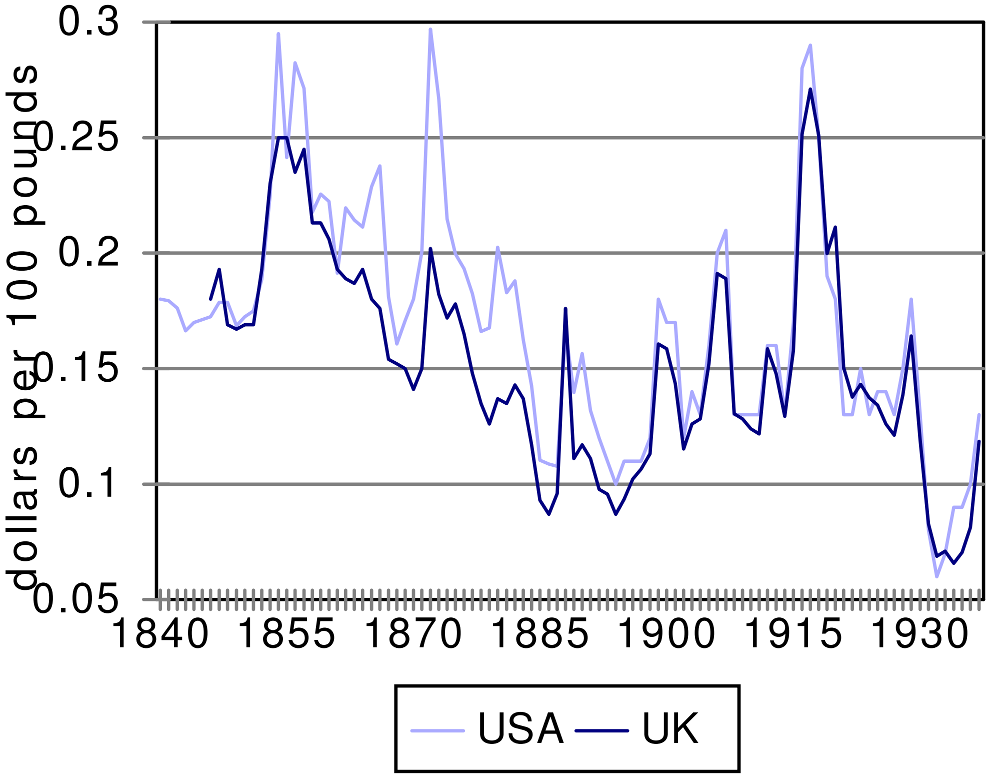


source:
New York Hemlock–
1890-1920: United States, Department of Labor, Bureau of Labor Statistics (1922. p. 184, Table 9), ‘New York Market, average price per M feet’.
1840-1890: extrapolated with Aldrich (1893, Vol. I, p. 46), ‘one inch first quality hemlock boards not planed’.
1921-39: extrapolated with Potter and Christy (1962, p. 244, series L).

UK Baltic–
1840-60 extrapolated with *Economist* series of price of Canadian yellow pine from Aldrich (1893, Vol. I, pp. 213-4).
1861-1937 UK Stat Abst and Sauerbeck,, unit value of imported timber, sawn or split, shillings per load of 50 cubic feet.

Figure 5

Price of Copper

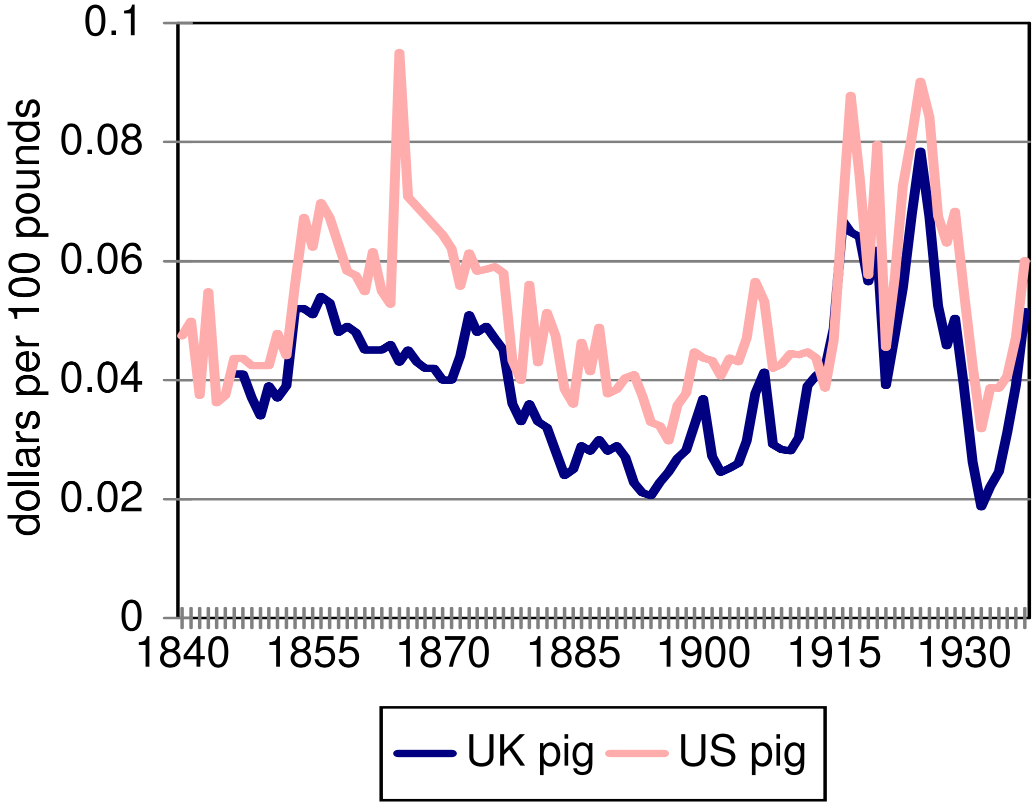


Source:
USA
1840-1891: Aldrich (1893, Vol. I, p. 40) copper ingots
1892-1939: US Hist Stats

Britain
1846-91: Aldrich (1893, Vol.I, p. 234), Saurbeck's prices of copper bars from Chile.
1892-1937: Sauerbeck.

Figure 6

Price of Lead

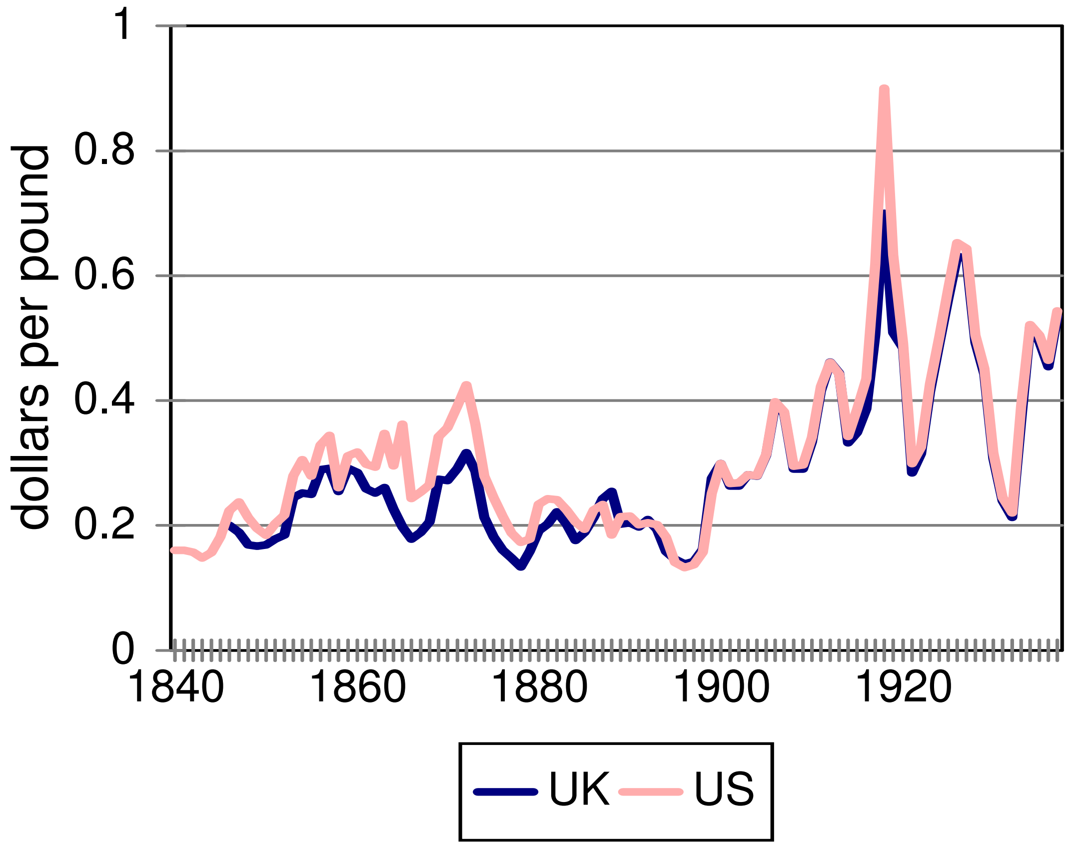


Source:
USA
1840-1891: Aldrich, I, p. 41, lead pig, second series
1892-1937: Schmitz 1979, p. 278, series 27.3

Britain
1846-91: Aldrich, I, p. 234, Saurbeck's prices of copper bars from Chile.
1892-1937: Schmitz 1979, p.278-9 series 27.2

Figure 7

Price of Tin

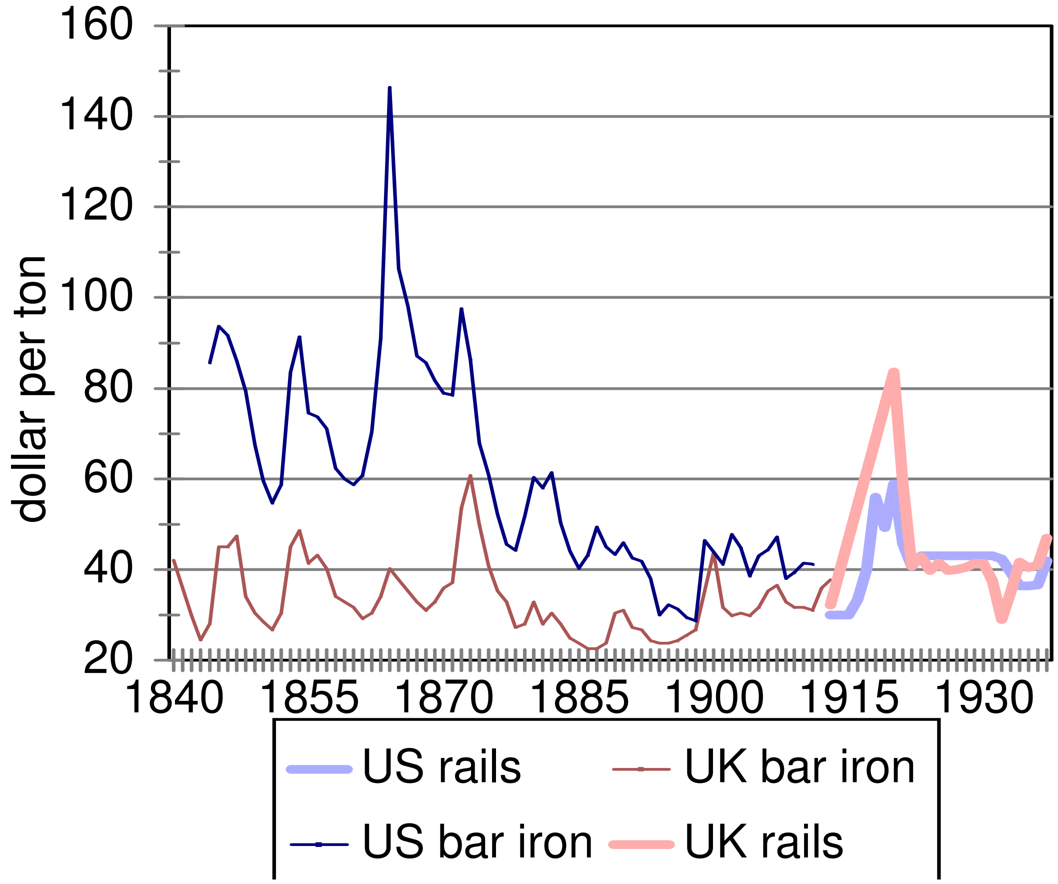


Source:

USA
1840-91 Aldrich, II, pp. 215-6
1892-1937 Schmitz 1979, p.297-8 series 34.4
Britain
1846-91: Aldrich, I, p. 235, Saurbeck's prices of Straits tin
1892-1937: Schmitz 1979, p.297-8 series 34.3

Figure 8

Prices of Iron and Steel

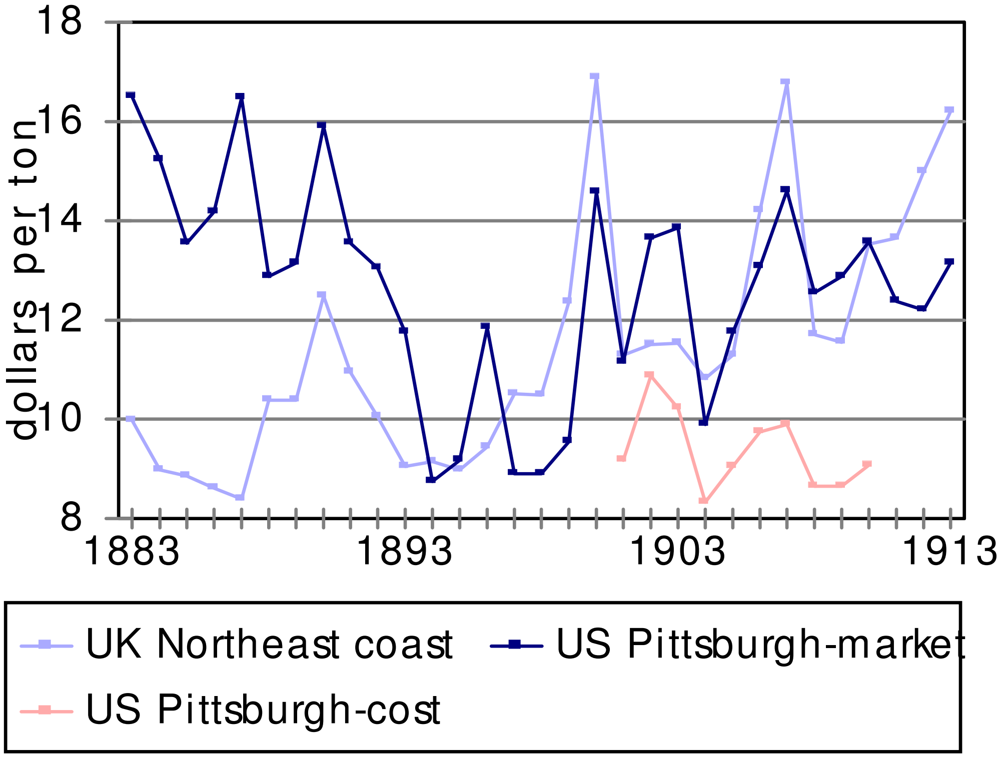


Sources:
US rails–Hist Stat Cc245 open hearth steel rails
US bar iron–Philadelphia, best refined bar iron, US Stat Abst.

UK rails–UK Stat Abst. unit value of exported heavy steel rails
UK bar iron–common bars, Mitchell and Deane (1971, pp.493-4).

Figure 9

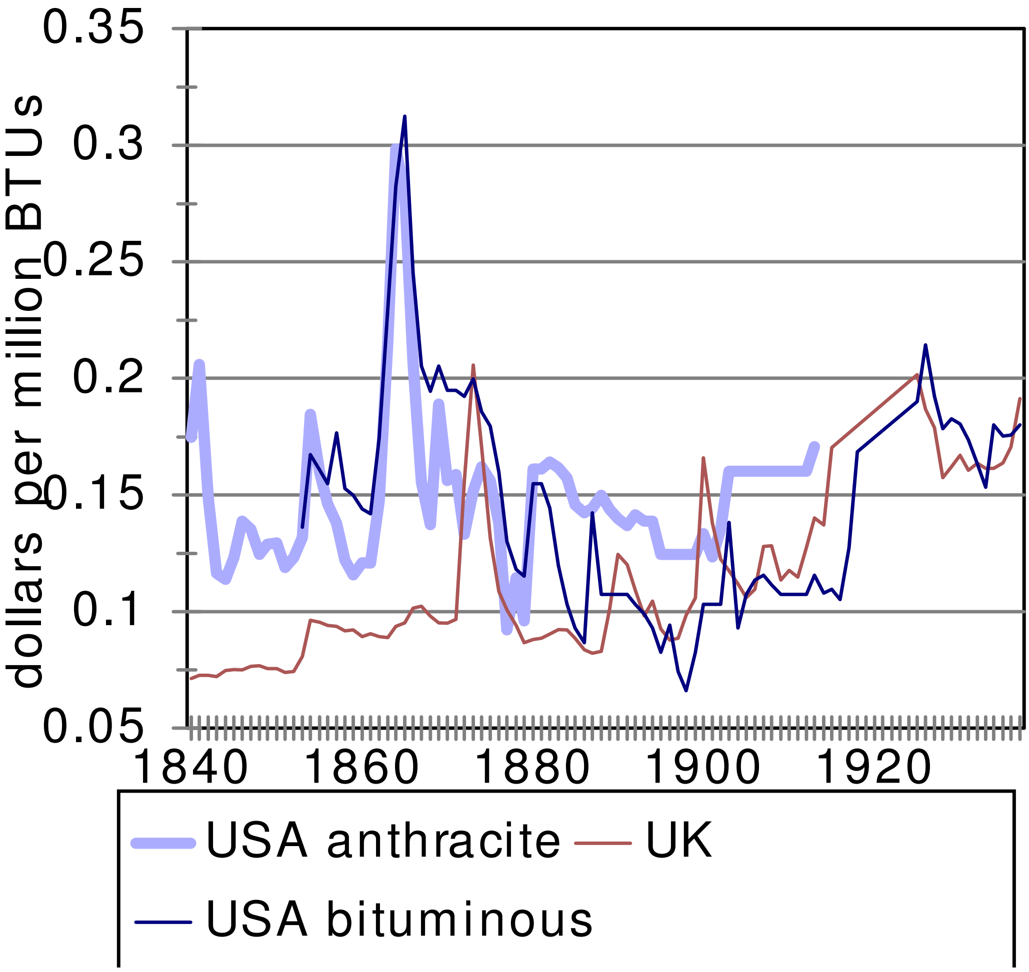
Ore and Coke Cost per ton of Acid Bessmer Pig Iron



Source: Allen (1978, p. 66).

Figure 10

Cost of Energy from Coal

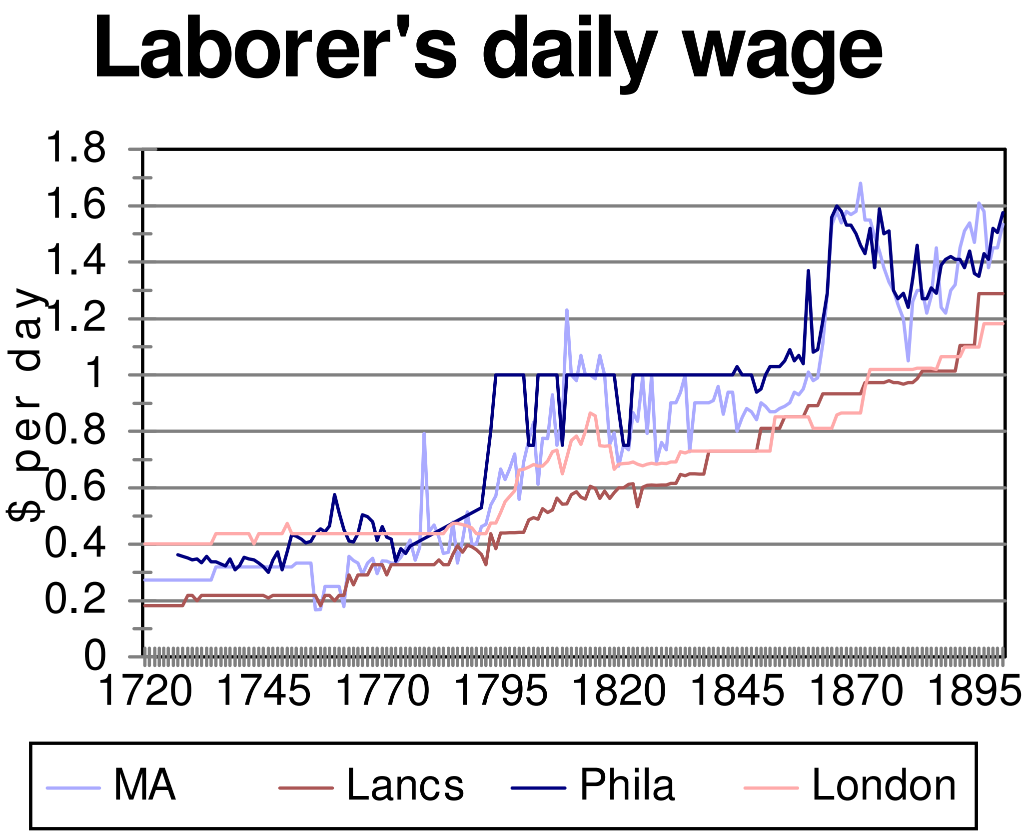


Sources:
UK: average export price of coal
1840-1902, WRP, 13
1903-37: Sauerbeck series 26

USA anthracite (white ash lump)
1840-1890 US Hist Stats, on line, series Cc237
1891-1913, US Stat Abst, 1913, p. 495.

USA bituminous
1853-1913: Bituminous coal in Baltimore: US Stat Abst
1914-37: extrapolated forward with unit value of US exported coal (very similar price in overlap) from US Stat Abst

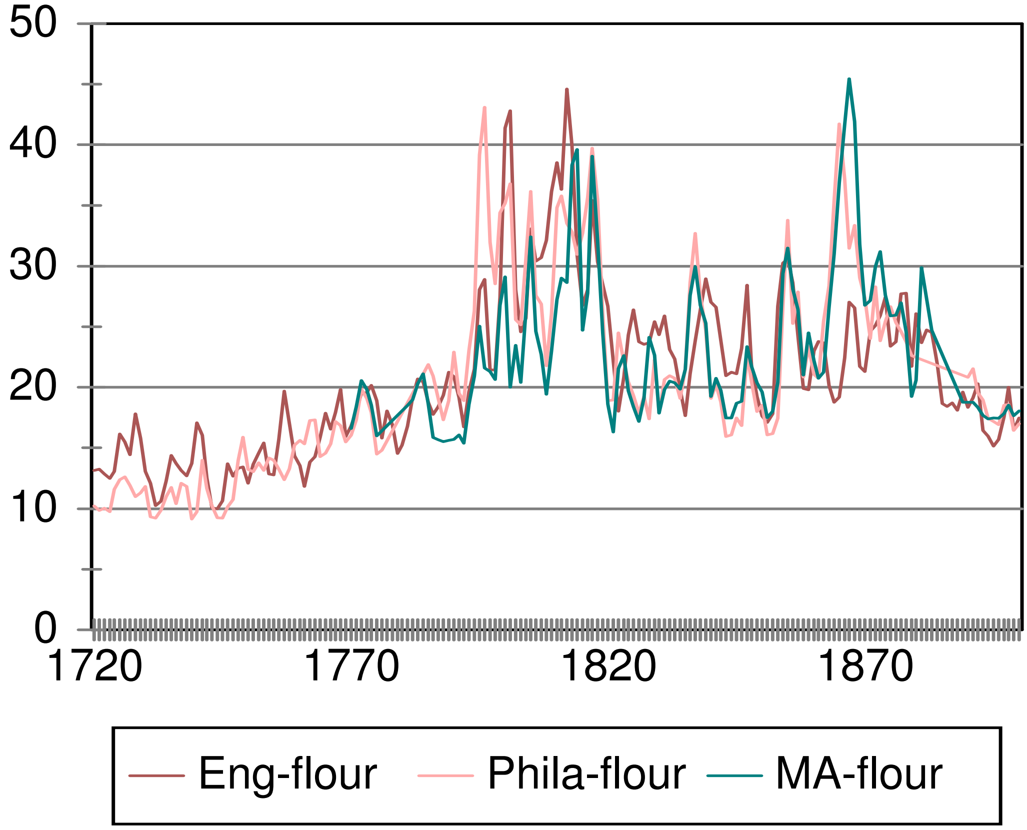
Figure 11



source:
Philadelphia
1727-1776: Nash (1979, pp. 392-4) and Smith (1981, p. 184).
1785-1830: Adams [1968: 420]
1840-99: BLS 604, pp. 253-60
1900-28: BLS 604, p. 186 (wage per hour multiplied by hours per week and divided by six).
Massachusetts
1720-1839 Wright series for 1752-1839 extrapolated backwards using Main (1994, p. 48).
1752-1839 Wright (1885, pp.323-5).
1840-98: BLS 604, pp. 253-60
1900-28: BLS 604, p. 185 (wage per hour multiplied by hours per week and divided by six).
London
1720-1860 Schwartz (1985, pp.36-8).
1860-1900 Bowley (1901, pp. 104).
1900-36 Bowley (1937, pp. 10, 15). missing values interpolated
Lancashire
1810-25: United Kingdom, House of Commons, *Tables of the revenue, population, commerce, &c. of the United Kingdom and its dependencies. Part I. From 1820 to 1831, both inclusive. British Parliamentary Papers*, 1833, Vol. 41, p. 165.
1839-1900 Bowley (1900, pp. 310-11).

Figure 12

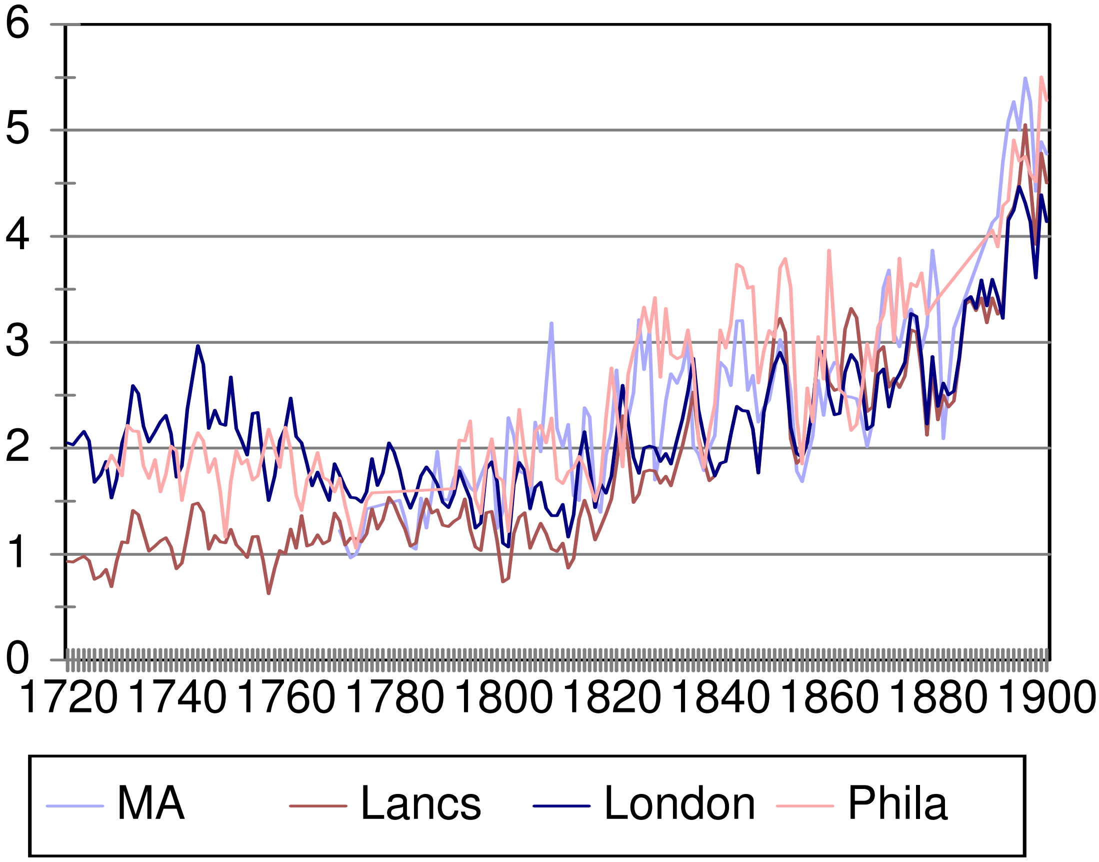
Cost of a Subsistence Basket based on Flour



Source:
cost of the basket shown in Table 1. See Data Appendix.

Figure 13

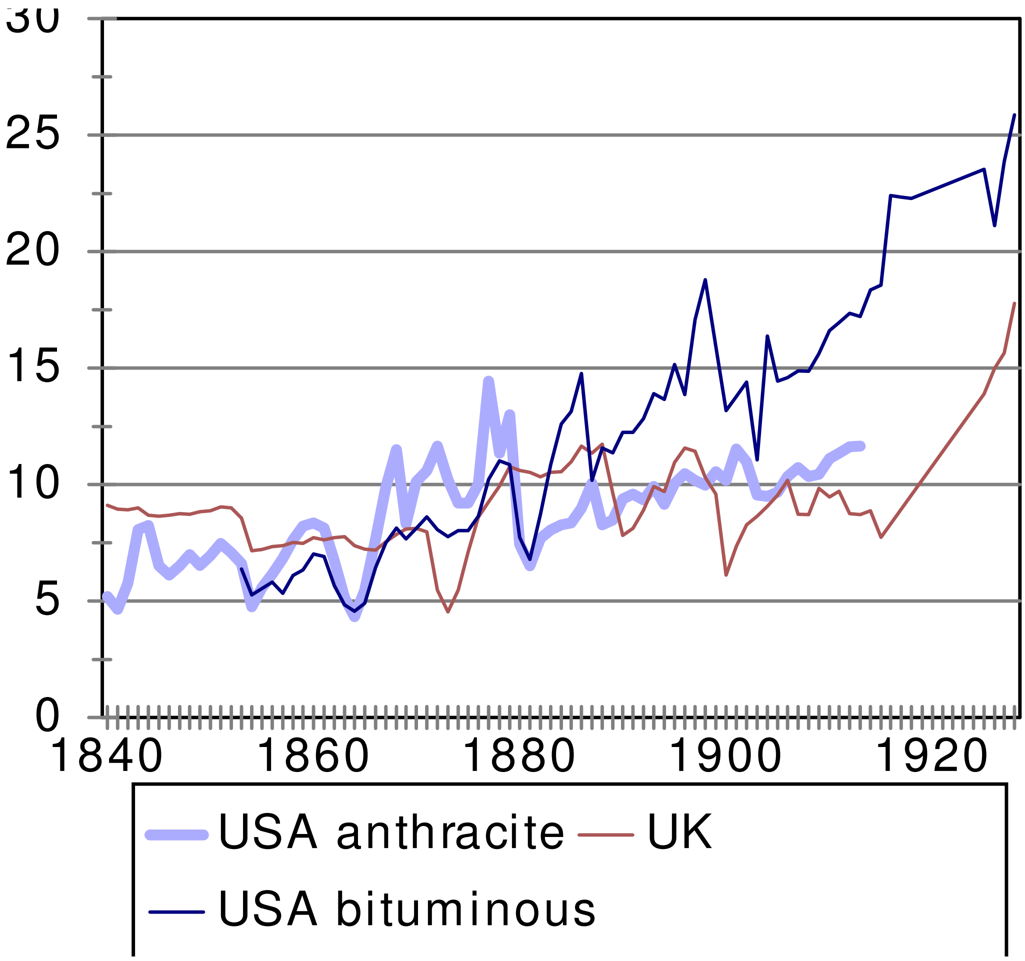
Real Wages as Multiples of Subsistence
Source: nominal wage multiplied by 250 divided by cost of subsistence basket



multiplied by 4 people per household and by 1.05 as an allowance for rent.

Figure 14

Wage relative to the Price of Energy



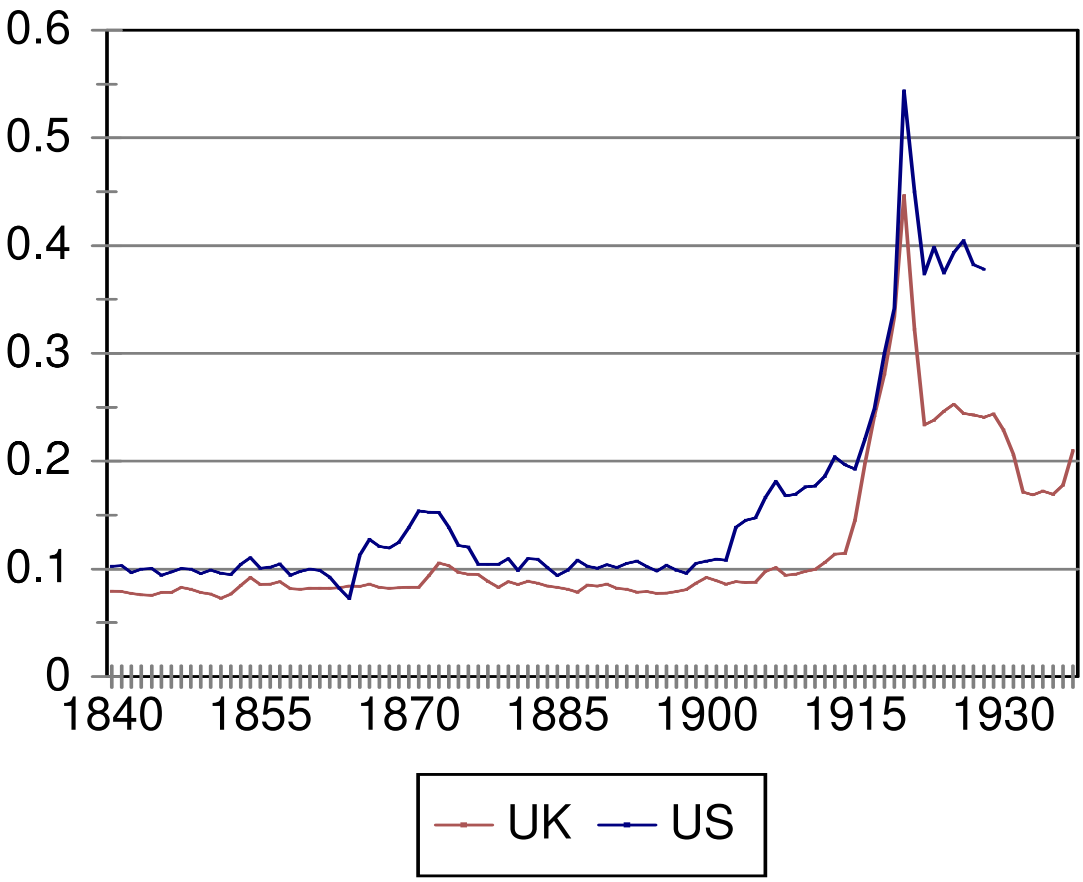
nominal wage shown in Figure 11 divided by cost of energy shown in Figure 10.

UK: southern England building labourer Phelps Brown and Hopkins (1955).

USA:
1840-1889: MA building labourer BLS 604, pp. 253-60
1890-1937: Rees' (1959, pp. 15-6, col. 3) average hourly earnings in manufacturing multiplied by .9 to match labourer series and by 9 hours per day

Figure 15

Price of Capital Services



Source:

index equals (interest rate + depreciation rate)*index of cost of capital goods

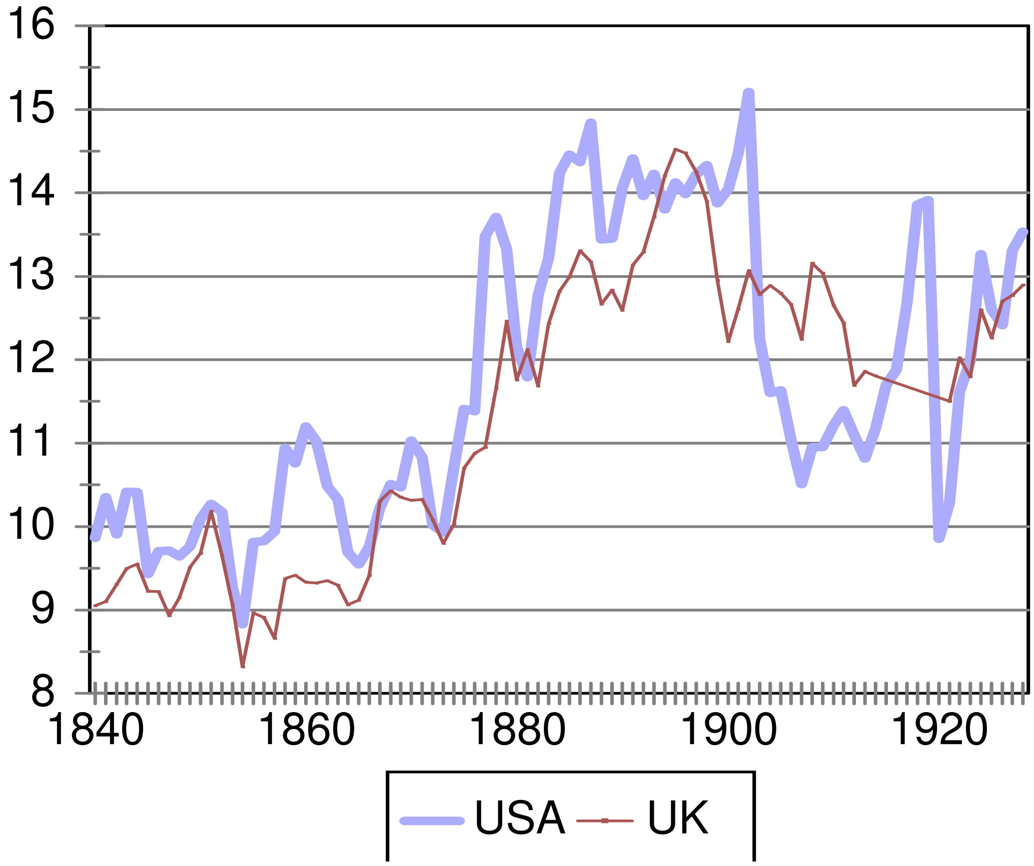
interest rate:
USA new England municipal bonds, Homer and Sylla (1996, pp. 287-8, 342, 350).
UK yield on long term government bonds, Homer and Sylla (1996, pp. 196-7, 444-5).

depreciation rate: assumed to be 5%

index of cost of capital goods = geometric average of building labour wage rate and arithmetic average of prices of bar iron, copper, soft wood building lumber, and bricks. Sources of prices of bar iron, copper, and lumber have already been given (with the addition that the US bar iron price was extrapolated to 1937 using the price of steel rails).
Bricks–
USA: New York, 1849-1933: Hist Stats Cc264.
UK: Glasgow, 1863-1902, WRP, p. 199

Figure 16

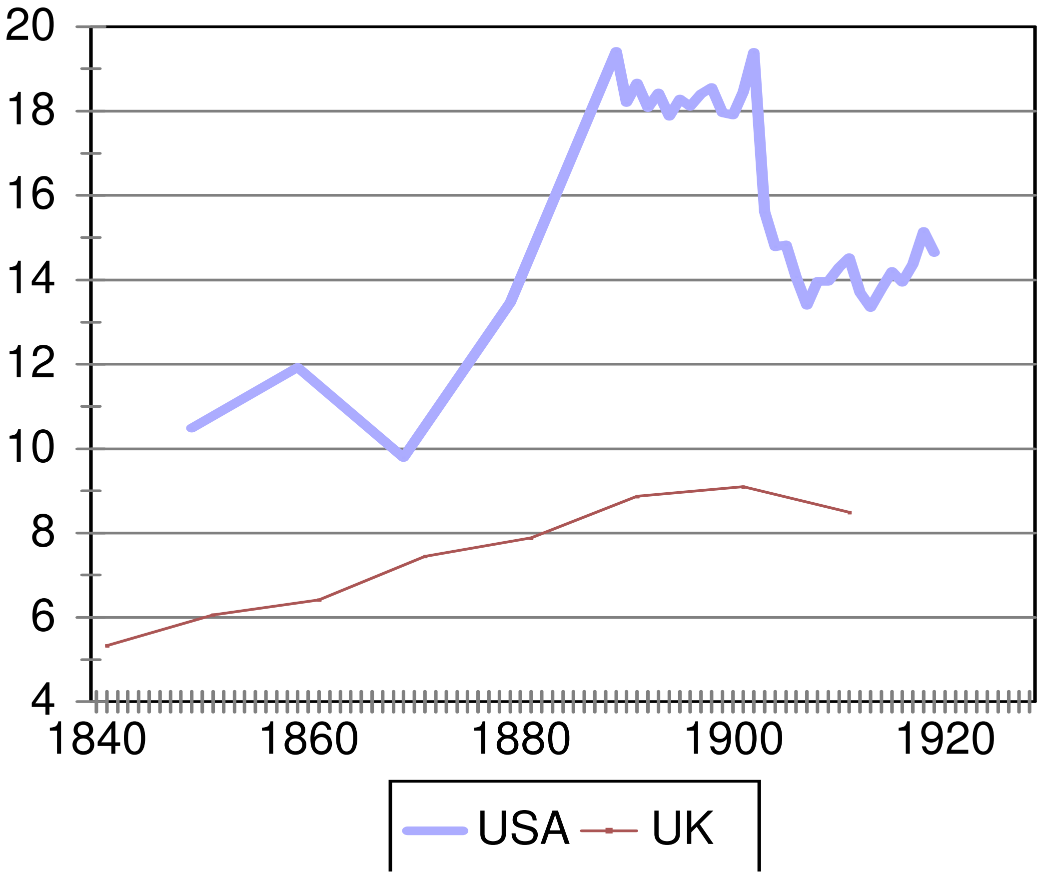
Male Laborer's Wage relative to Price of Capital Services



Source:
male wage for MA and southern England divided by price of capital services.

Figure 17

Average Earnings in Manufacturing relative to the Price of Capital Services.



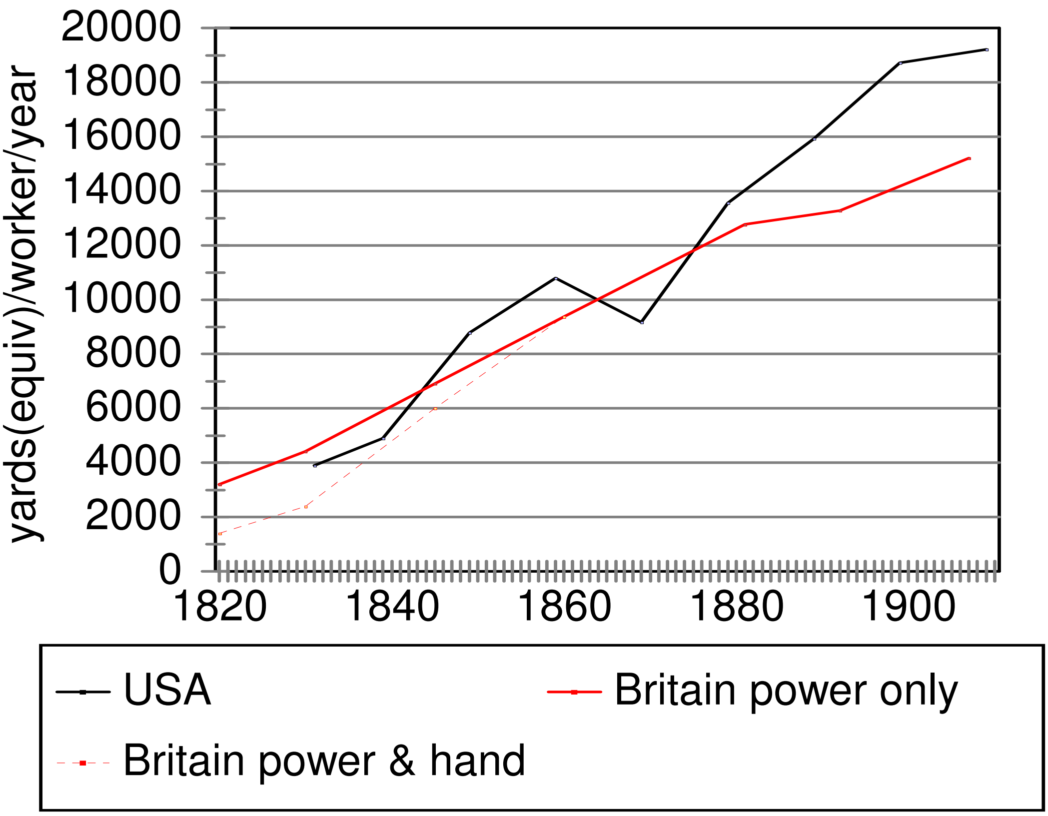
average annual earnings in manufacturing divided by price of capital services plotted in Figure 15.

Average annual earnings in manufacturing:
UK: Deane and Cole (1969, pp. 143, 152), total wages and salaries in manufacturing divided by labour force in manufacturing.

USA: total wages paid in manufacturing divided by manufacturing employment. Data from US censuses of manufactures as summarized in US Hist Stat series Dd5 and Dd9.
1889-1920: Average hourly earnings in manufacturing from Rees (1959, pp. 15-6, col. 3) multiplied by estimate of hours worked per year. This was worked out for census years by dividing census annual earnings by Rees' hourly earnings. Intervening years interpolated.

Figure 18

Labor Productivity in Cotton Spinning and Weaving combined



Data sources: US *Census of Manufactures*, various years and Wood (1903, p. 302).

Labour productivity was computed as

price*yards per lb*(lbs of yarn woven+relprice*lbs of yarn sold)/employment

Price was 1 for UK and .9 for USA in view of differences in the quality of the product. US cloth was made of coarser yarn than British cloth. Average yarn count in Britain was in the range 40-50, while average count in USA was on the order of 20. (Temin 1988, Harley 1992a). American cloths sold at lower average price per yard. Harley (1992a, pp. 566, 581) pointed out that *The Economist* reported the price of 'red end long cloth,' a fabric comparable to typical US cloth, in its weekly market reports in the 1850s, as well as print cloths typical of British production. The price per square yard of the American-style cloth was 90% or less of the price of typical British cloths.

yards per lb was taken to be 4 in the United States and 5 in Britain in view of the different qualities of cloth made. These ratios are born out by the incomplete data in the sources.

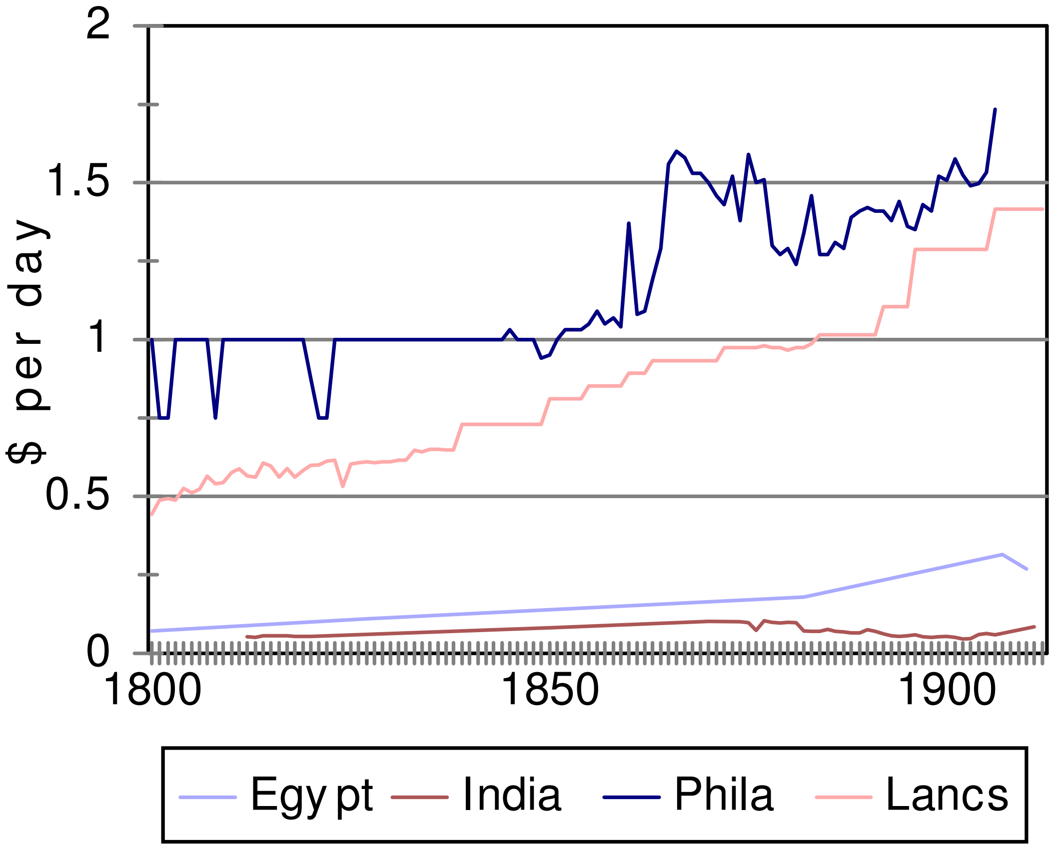
lbs of yarn woven and lbs of yarn sold were computed by dividing the weight of cotton spun into the two categories. In the case of the USA 85% of spun cotton was assumed to have been woven; in the case of Britain the proportion was 75%. These proportions were representative of the years for which they could be computed in the two countries. Wood reported the weight of cotton spun in Britain. For the USA, it was computed as 90% of the weight of cotton consumed by cotton mills, as this was the typical fraction in those years for which it could be computed.

Relprice was the price per pound of yarn relative to the price per pound of cloth made from the yarn. This equalled .75 for much of the nineteenth century, and that price was used throughout.

Employment in the USA was total employment in cotton mills. Wood reports the number of employees in cotton spinning mills, power weaving mills, and hand loom weavers. Employment was the sum of the three for the series showing the productivity of the whole sector. Labor productivity in the factory sector alone was computed by excluding the weight of yarn woven by hand from the calculation as well as the number of handloom weavers. In addition, employment in spinning mills was reduced in proportion to the weight of cotton yarn woven in power mills plus the weight of yarn sold as final product all relative to the total production of yarn.

Figure 19

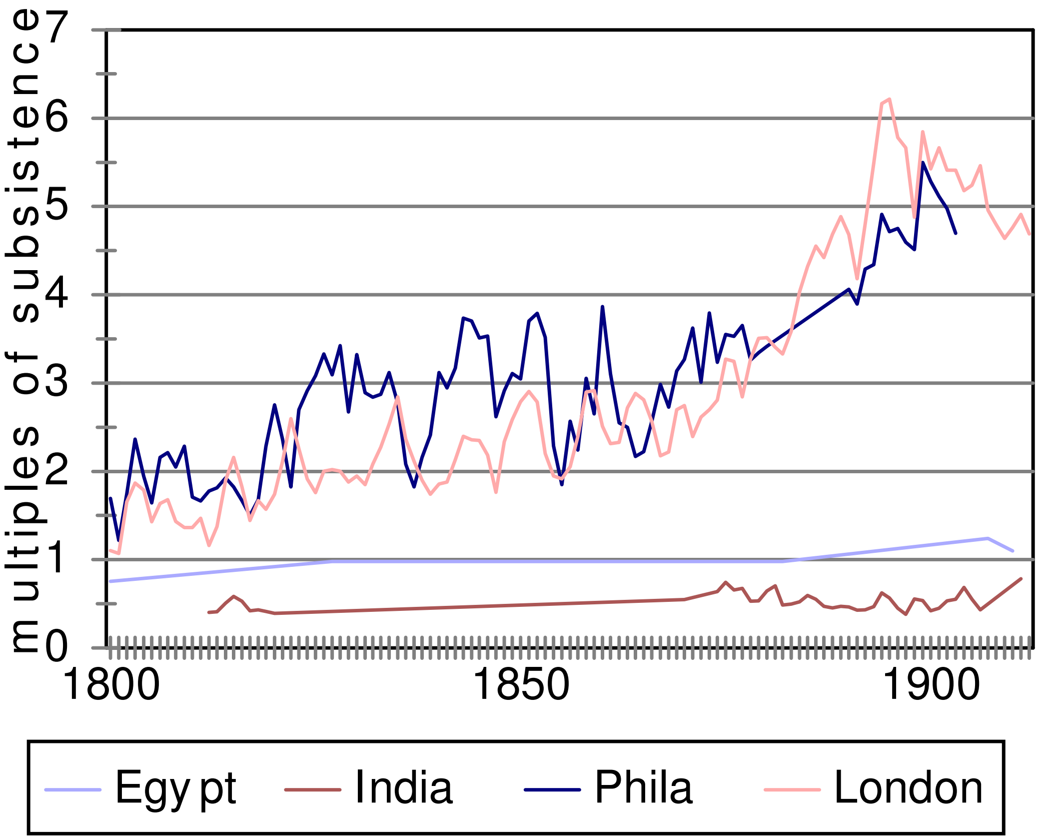
Laborers' Wages at the Exchange Rate



Source:
Philadelphia and Lancashire: as already reported.
India: see Allen (2007).
Egypt: Artin (1907, p. 125, ourvrier), Girard (1824), Wilkinson (1835, p. 286)

Figure 20

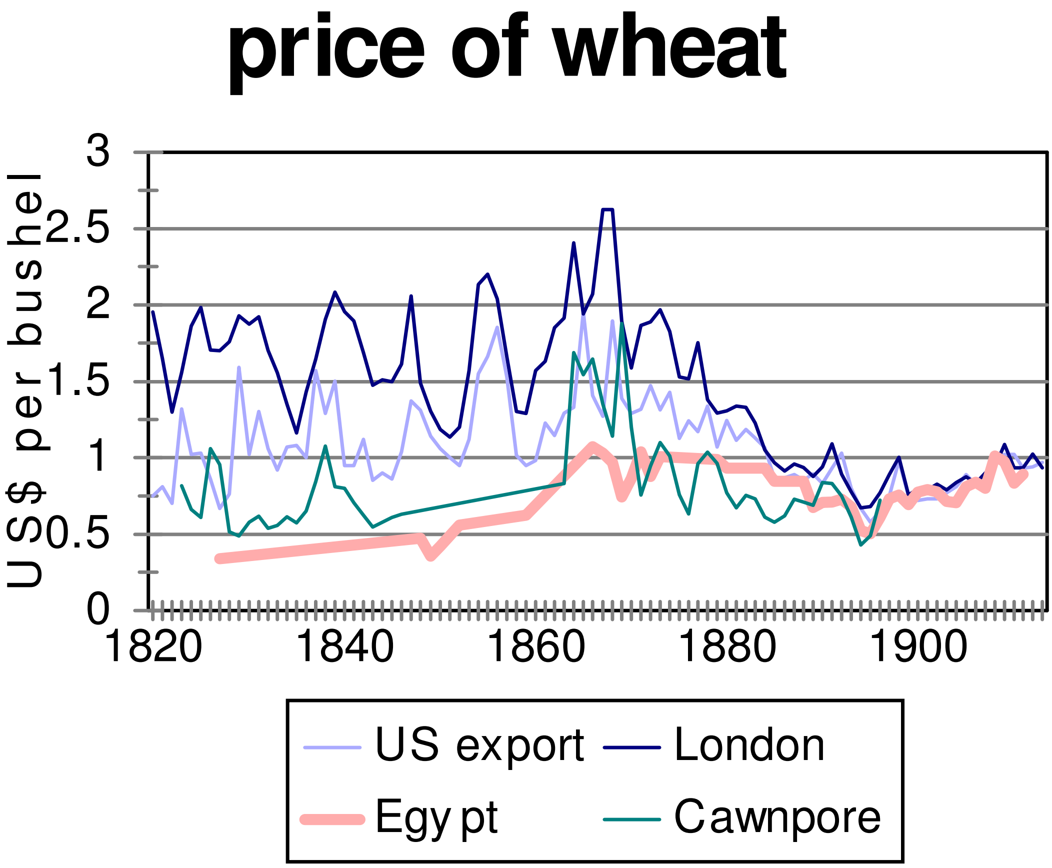
Real Wages as Multiples of Subsistence



sources:

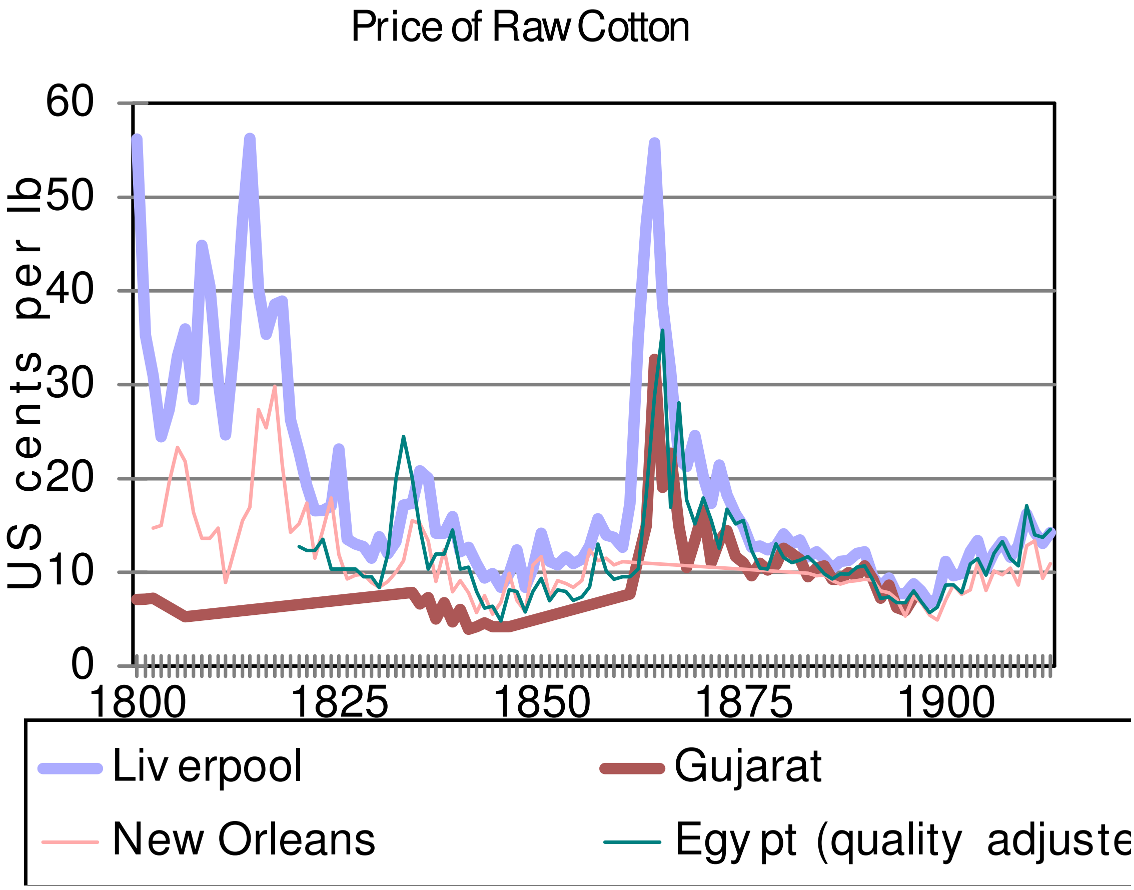
Philadelphia and Lancashire: as already reported.
London: See Appendix.
India: see Allen (2007, p. 29, ftn. 1). The cost of living was recomputed using the basket in Table 1.
Egypt:
prices from Artin (1907, p. 118-30), Girard (1824), Wilkinson (1835, p. 283-5). Flour price in 1800 was extrapolated from Wilkinson's price for 1827 in proportion to change in wheat price.
Fuel–using the market price of charcoal in the normal calculation produces an unreasonably expensive budget. Vallet (1911, p. 61, 107) reports that most households paid a baker to bake their bread rather than buying fuel and doing it themselves. I have followed Vallet's lead and assessed the fuel charge 10% of the price of the flour.

Figure 21



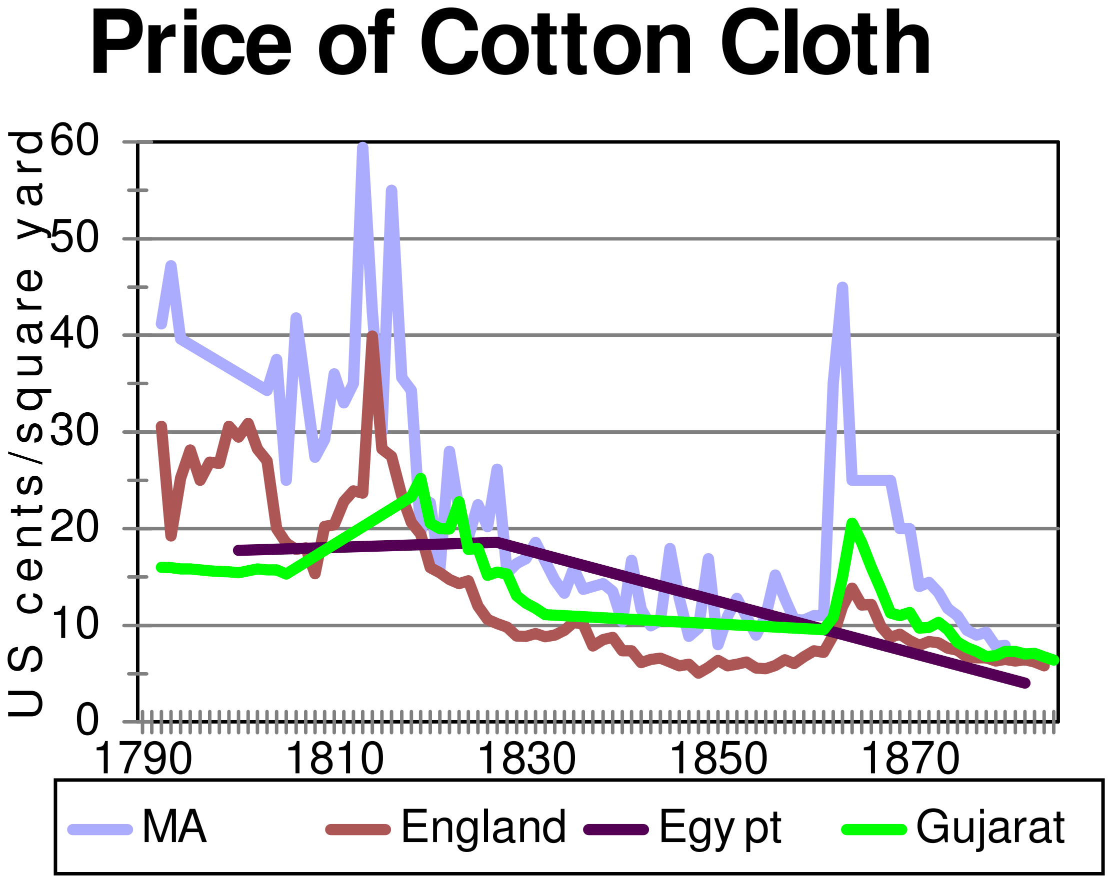
sources:
USA average price per bushel of exported wheat–US Stat Abst
London–gazette price from Mitchell and Deane (1971, pp. 488-9)
Cawnpore– Montgomery (1849, Appendix VI), *Statistical Abstract Relating to British India*, various years (available on http://dsal.uchicago.edu/statistics/)
Egypt–Owen (1969, pp. 80, 126, 263), Stat Abst Foreign Countries, 1888-97/8 and 1900-10/11.

Figure 22



sources:
England–Liverpool, upland or middling American, Mitchell and Dean (1971, p.491)
New Orleans–
1802-1860: short staple cotton, Bruchey (1967, Table 3P).
1883-1928: !860 price extrapolated using export price of US cotton from Bruchey (1967, Tables 3A and 3K for antebellum period and US Stat Abst for 1883-1928)
Gujarat:
1800-1806: Hariharan (2002, p. 329).
1834-1846:Guha (1972, p. 39).
1861-1931:Indian export price of cotton from *Index Numbers of Indian Prices* (1933, Table V).
Egypt (quality adjusted):
1820-1837: Issawi (1966, pp. 447-8) ($ per qantar of 99 lbs)
1838-59: Owen (1969, p. 73)
1860-1914; Richards (1982, pp. 32-3-132).
Egyptian cotton was longer staple than American cotton and sold at a higher price. To make comparison simpler, the Egyptian prices were reduced by the average premium between 1883 and 1899 when both cottons were quoted in Liverpool. The American price from Mitchell and Dean (1971, p.491), and the Egyptian price in Liverpool from Issawi (1966, pp. 447-8).

Figure 23

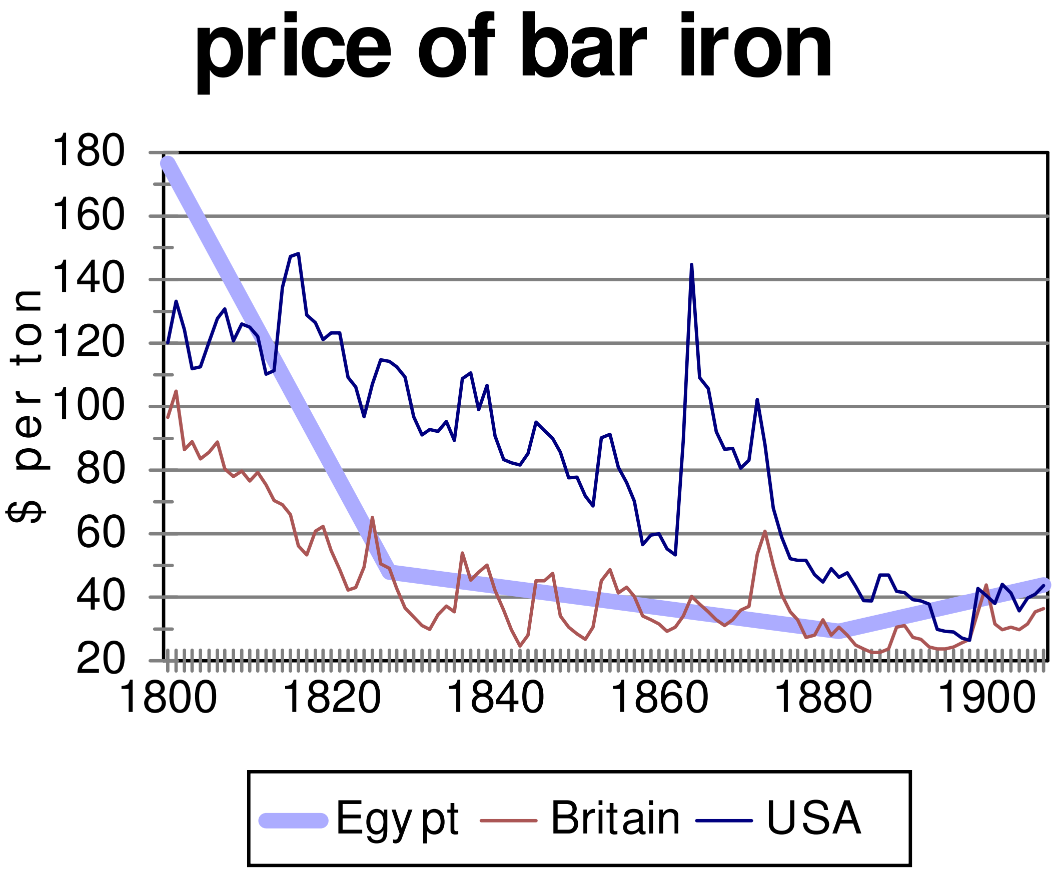


Source:
Massachusetts:
Wright (1885, p. 373, 429) and Weeks (1883, pp. 12-3) and the wholesale price of Russian brown shirting in New York from US Stat Abst.

England:
1790-1860 Neild printing cloth from Neild (1861, pp. 495-6) and Harley (1998, pp. 78, 80-81)
1861-1884 Neild series extrapolated with average price of piece goods exported from Ellison (1886, Table 2).

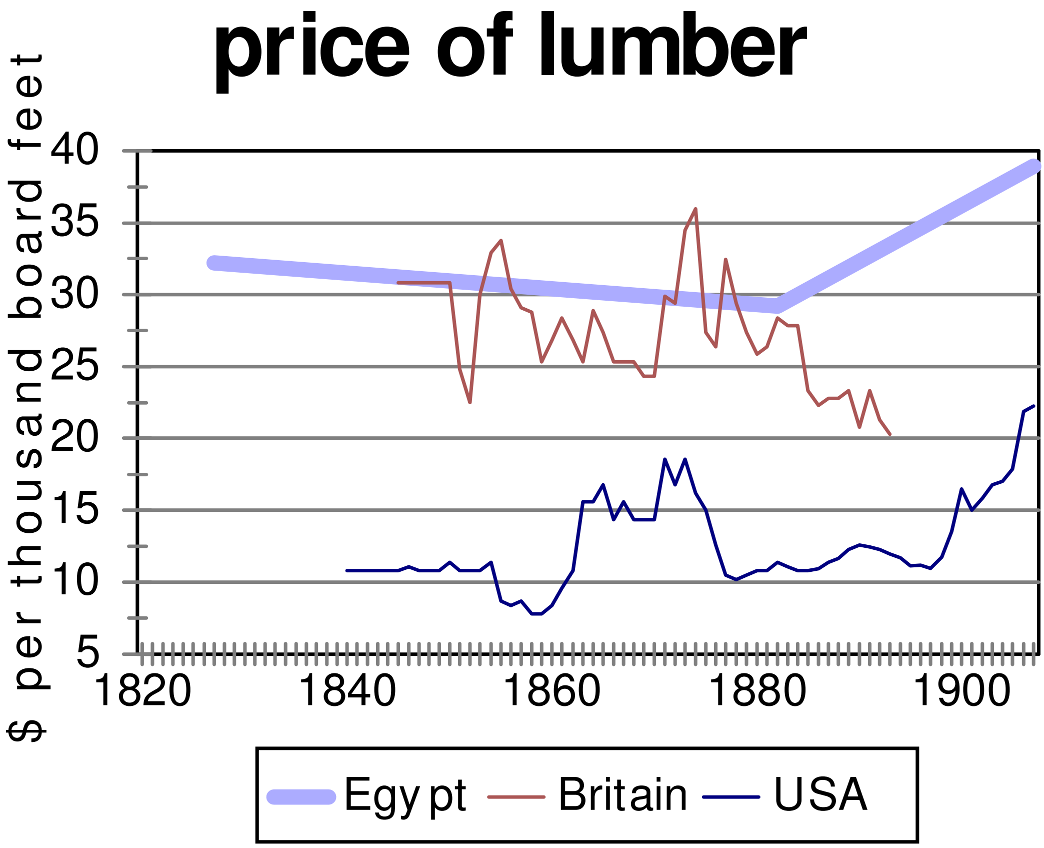
India:
1800-1805: baftas in Gujarat from Hariharan (2002, 297-302)
1818-32: calicos imported into India Desai (1971, 346-7).
1861-1913: Calcutta, price of Indian imports, *Index Numbers of Indian Prices* (1933, Table V).
Egypt:
Artin (1907, p. 120 coton, tissu de), Girard (1824, pp. 207-25), Wilkinson (1835, p. 283).

Figure 24



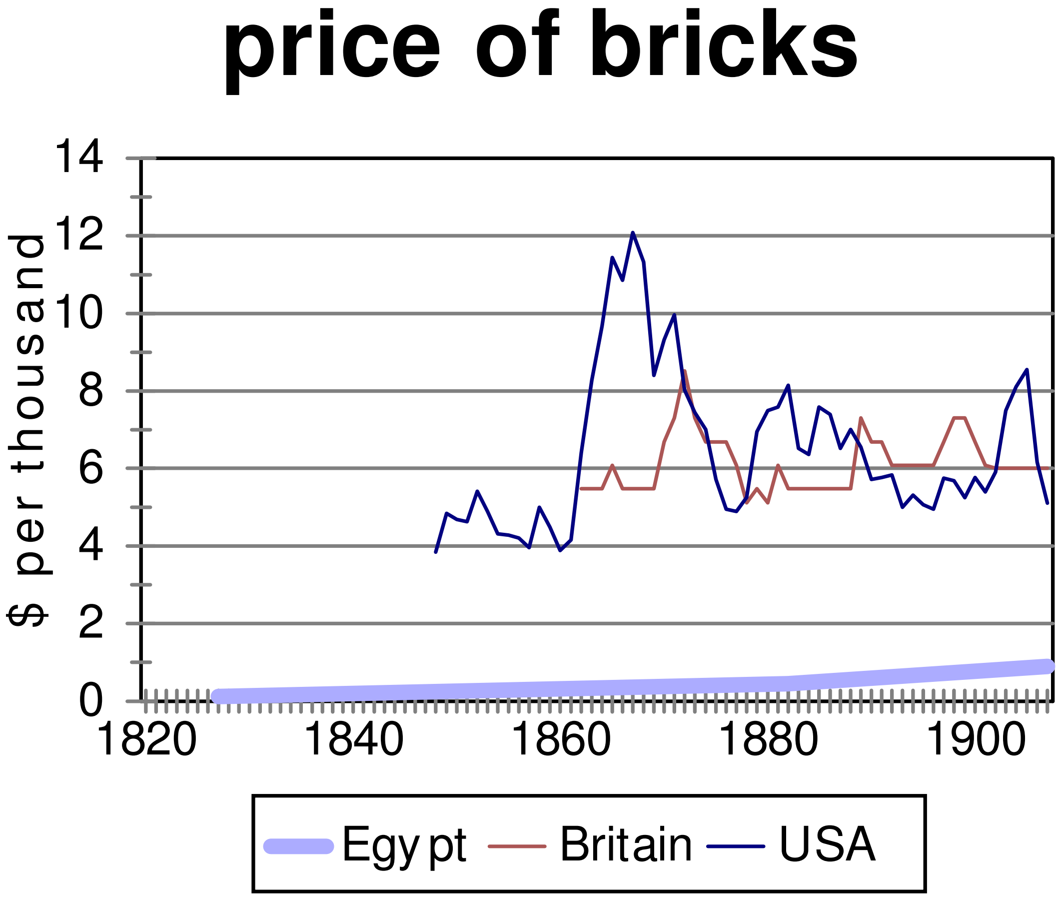
sources:
Britain and USA as in Figure 8.
Egypt–Artin (1907, p. 122).

Figure 25



sources:
Britain and USA as in Figure 4.
Egypt–Artin (1907, p. 118, bois de construction), Wilkinson (1835, p. 285). Prices reported for a 10 foot plank, which I assumed to be one inch thick and one food wide.

Figure 26



source:
sources:
Britain and USA as given previously.
Egypt–Artin (1907, p. 119, briques cuites), Girard (1824, pp. 199-207), Wilkinson (1835, p. 285). The prices of baked rather than sun dried bricks were used.

Figure 27

Price of Capital Services

source: computed as in Figure 15.

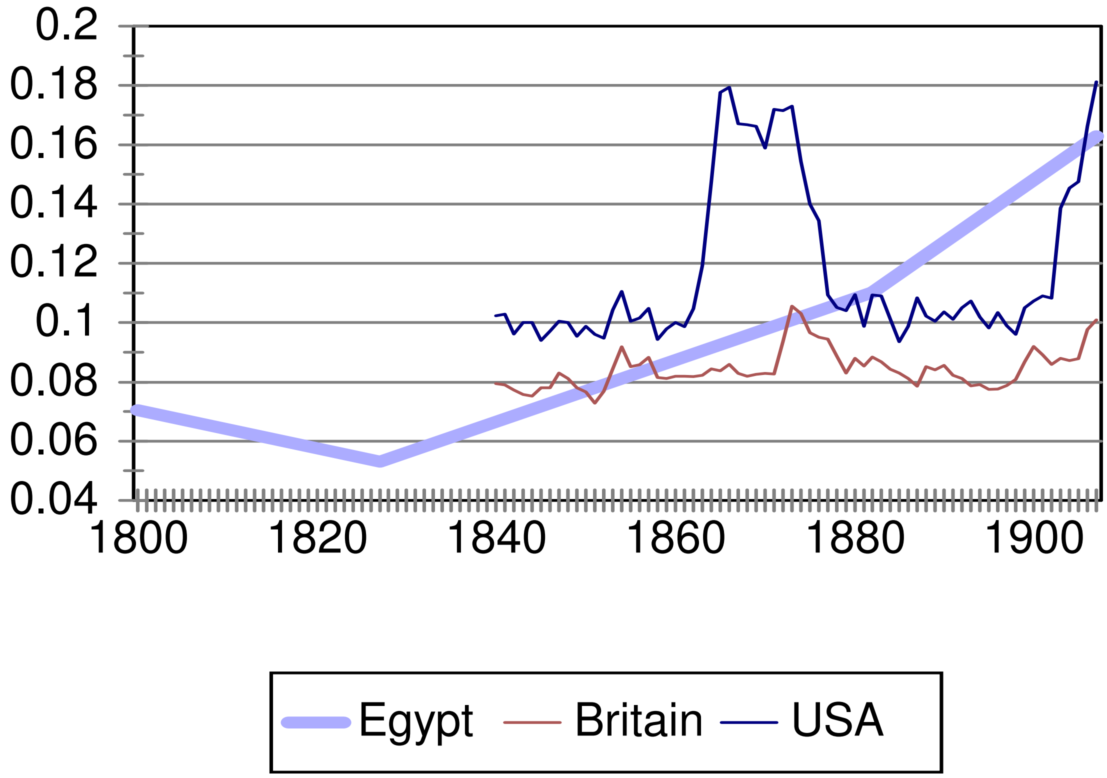
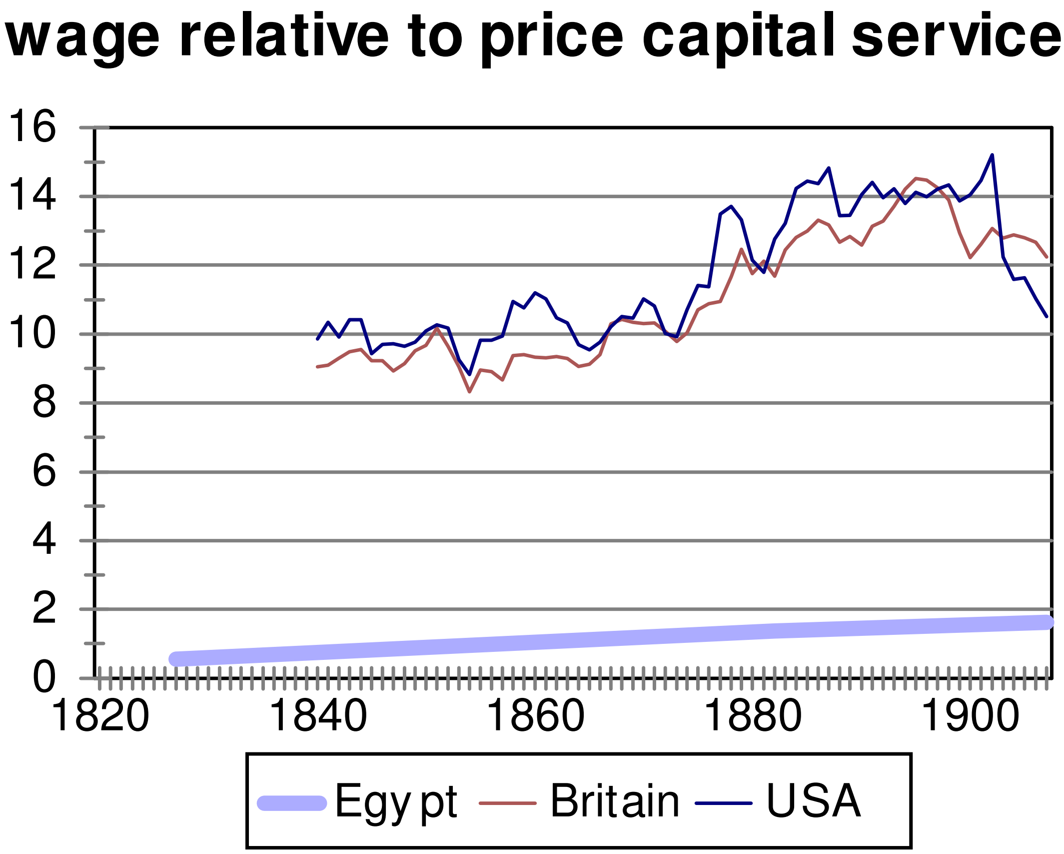


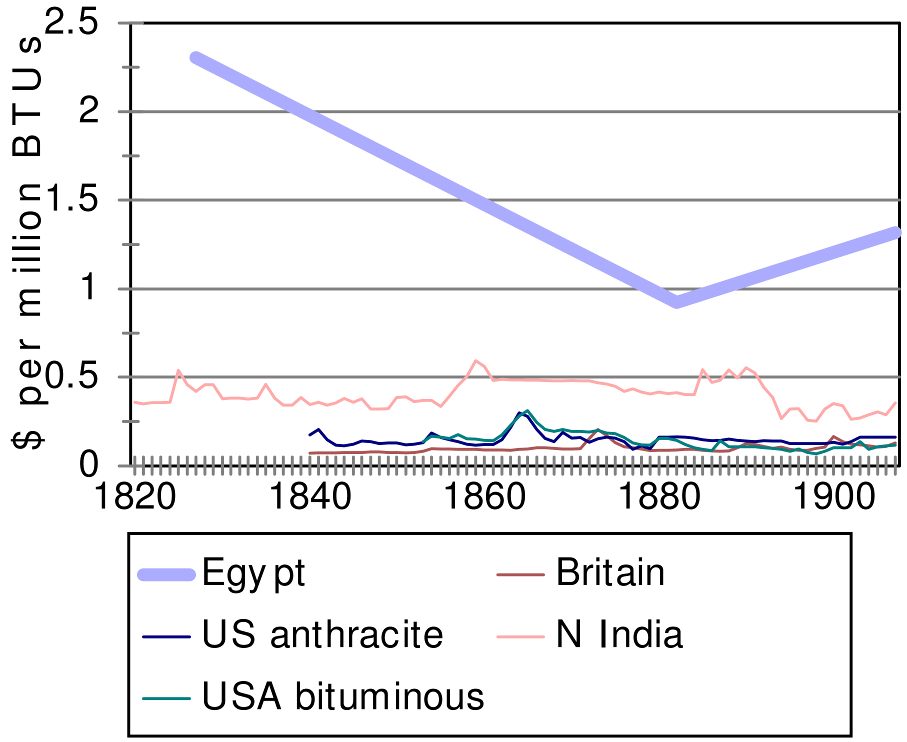
Figure 28



computed as previously.
Egyptian interest rate assumed to be 24% based on Wilkinson (1835,.p. 286–'interest of money, with security')

Figure 29

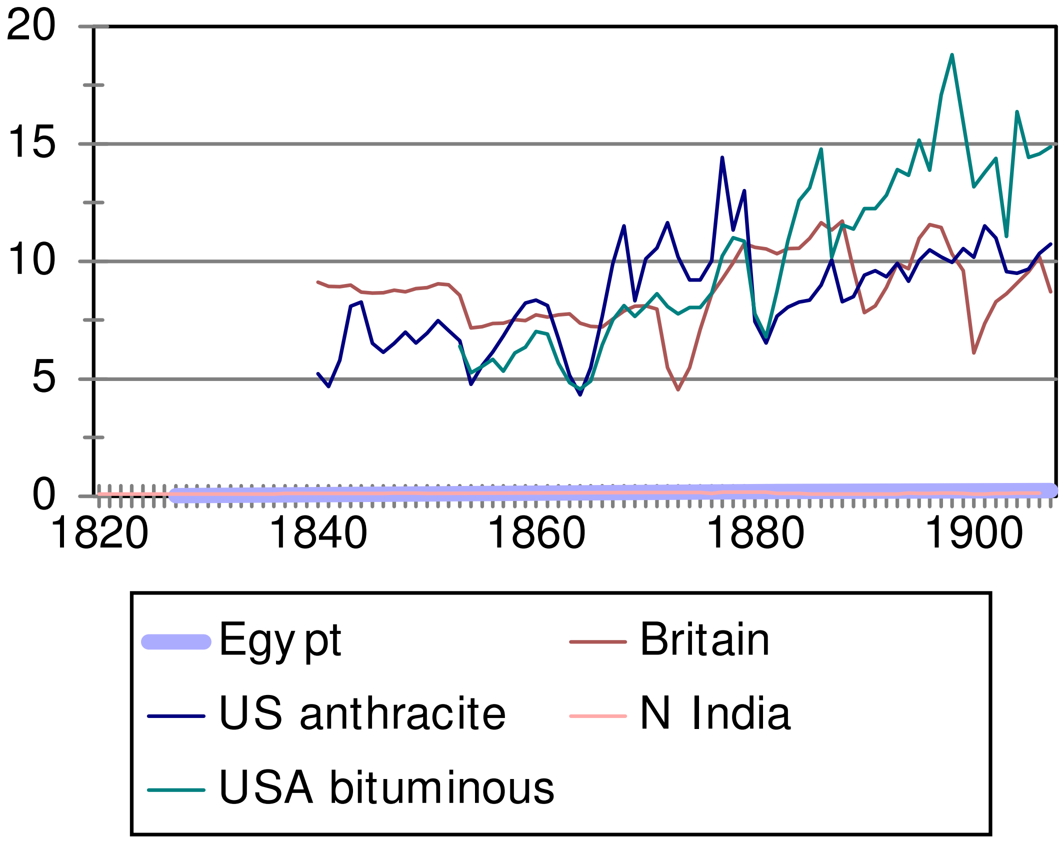
Price of Energy



sources:
Britain and USA as given previously.
Egypt–Artin (1907, p. 119), Girard (1824), Wilkinson (1835, p. 283). The price is based on the price of charcoal in Cairo. One can also compute the price from imported coal from 1889 to 1911 from import quantities and values in UK, *Statistical Abstract of Principal & Foreign Countries*.. This was a cheaper source of energy than charcoal but still twice the cost of coal energy in Britain.
India–
1761-1860:firewood in Pune.from Divekar, et al. (1989, Appendix).
1873-1910 firewood in Calcutta from *Prices and Wages in India*, 1893, 1910.

Figure 30

The Wage of Unskilled Labor relative to the Price of Energy



Source: computed data graphed previously.

Data Appendix: Sources for English cost of Living Index

flour

1700–1877: The underlying series is Kirkland's (1917). Its level is close to that of the naval victualling and Greenwich Hospital series reported by Beveridge (1939, 574-5 and 721-3). Comparison with some short series for retail sales in shops indicates that shop prices were about 8% higher, and the Kirkland series was increased by that proportion. (See the Manchester prices for 1810-25 for 'good seconds' in 12 lb contains in *Tables of Revenue, Population, and Commerce*, Parliamentary papers, 1833, Vol. 41, p. 165, and WRP, p. 235 (hotel prices) for 1858-69.)
1878-1902: WRP, p. 236 (households, per 7 lbs).
1903-13: Flour price extended with flour price index in UK, Board of Trade (1925, Vol. III, p. 21).

peas

1712-1902: price of peas, Greenwich hospital (Beveridge 1939, pp. 292-4, McCulloch 1880, pp. 1138-40, WRP, p. 102)
1903-13: extrapolated forward with price of haricot beans (See Allen 1994, p. 133-4).

beef
1712-1868: Greenwich Hospital 'flesh' (Beveridge 1939, pp. 293-5, McCulloch 1880, pp. 1138-40)
1869-1913: extrapolated forward with Clark's (2004) beef price series.

butter
1729-1902: Greenwich Hospital (McCulloch 1880, pp. 1138-40, WRP, p. 139)
1903-13: See Allen (1994, p. 133-4).

fuel
1700-1800: average of London coal price series and northern fuel price series. The northern fuel price series was a weighted average of a northern wood and northern coal price series. The weights shifted smoothly from 50% coal, 505 wood in 1700 to 100% coal in 1800.
1800-1913: average of London coal and northern coal price series
London coal price series: 1700-1830: coal delivered to Westminster school, Mitchell and Deane (1971, pp.479-80). Extrapolated forward with series for best coals at ships' side, London, and Wallsend, Hetton in London series from Mitchell and Deane (1971, pp. 482-3).

Northern coal price set equal to one quarter of London price.

Northern wood price–price of charcoal at blast furnace from Hyde (1977, pp. 39, 44, 58, 59, 79).

lamp oil
1700-1808: train oil Beveridge (1939, pp. 670, 672, 674, 680)
1809-1856: train oil Tooke and Newmarch (1928, Vol. II, p. 407, Vol. III, p. 297, Vol. IV, pp.

429-30, Vol. VI, pp. 163, 405-5).
1857-1876: train oil Aldrich I, pp. 211)
1877-1913: See Allen (1994, p. 133-4).

candles
1712-1867: Greenwich Hospital (Beveridge 1939, pp. 293-5, McCulloch 1880, pp. 1138-40)
1870-1913: See Allen (1994, p. 133-4).

soap
1700-68: Beveridge (1939,p. 667) many interpolations.
1769-1839: candle series
1840–1869: export price of soap from WRP, p. 207 increased by 25%, the mark-up implied by overlap with series for 1870-1913.
1870-1913: See Allen (1994, p. 133-4).

cloth
1700-1783, fustian, d/yd:
1783-1840: printer's cloth, Harley (1998, p. 78)
1841-1913: extrapolated forward with average price per yard of British exports of white or plain cotton cloth, Ellison (1886, Table 2).

Sources Referred to with Abbreviations

Hist Stat =*Historical Statistics of the United States: Millenium Edition*, Cambridge, Cambridge University Press, on line.

Saurerbeck =Sauerbeck (1886, 1907), Editor of the Statist (1918, 1938).

UK Stat Abst =United Kingdom, Board of Trade, *Statistical Abstract for the United Kingdom*, London, HMSO, various years.

US Stat Abst=United States of America, Department of Commerce, Bureau of the Census, *Statistical Abstract of the United States*, Washington, Government Printing Office, various years.

WRP= United Kingdom, Board of Trade, *Report on Wholesale and Retail Prices in the United Kingdom in 1902, with comparative statistical tables for a series of years,* House of Commons Parliamentary Papers, 1903, Vol. 68.

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The Rise and Fall of American Technological Leadership: The Postwar Era in Historical Perspective

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I. *Introduction*

DURING THE QUARTER CENTURY following World War II, the United States was the world's most productive economy by virtually any measure. U.S. output per worker was higher by margins of 30 to 50 percent over the other leading industrial nations, and the gap in total factor productivity was nearly as large (Edward Denison 1967). These differences held not just in the aggregate but in almost all industries (David Dollar and Edward Wolff 1988). Many factors lay behind the U.S. edge, but it seems evident that the country's position of world leadership in advanced technology was an important one. The U.S. technology lead was partly reflected in the productivity statistics but is not the same thing. On the one hand, measured total factor productivity is affected by many elements, command over technology being only one of them. On the other hand, the productivity measures fail to reflect the fact that American output included sophisticated goods that could not be produced abroad. While in this essay we sometimes use productivity data as part sometimes use productivity data as part of the evidence about technological leadership, our concern is with the latter rather than the former. A wide variety of measures, backed by the commentary of informed observers, provides solid evidence that during the period in question the U.S. technological lead was real. U.S. firms were significantly ahead in developing and employing the leading edge technologies, their exports accounted for the largest share of world trade in their product fields, and their overseas branches often were dominant firms in their host countries.

No longer. The U.S. technological lead has been eroded in many industries, and in some the U.S. is now a laggard. A growing volume of studies, books, commission reports, and popular media accounts bemoans this loss of leadership and looks for causes and cures (e.g., Michael Dertouzos, Richard Lester, and Robert Solow 1989; James Womak, Daniel Jones, and Daniel Roos 1991). This paper is motivated by the apparent weakening, perhaps loss of American technological leadership, but more basically by the observation that relatively little of the current discussion is informed by an understanding of the sources of America's unique position in the mid-twentieth century economic world. How can policies respond appropriately to "what we have lost" without a clear knowledge of what it was that we had and how we got it?

However, the questions of how the postwar American lead came about, and how and why it has eroded, pose deeper questions in turn. There has in recent decades been a striking convergence among the most advanced industrial nations in per capita income, and in output per man hour, both in the aggregate and in a wide spectrum of industries (Figure 1). This phenomenon has spawned a thriving new literature on "convergence"

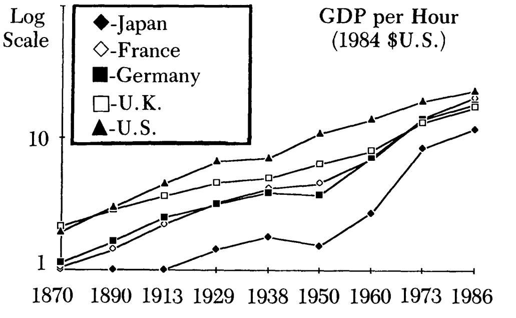

Figure 1. Gross Domestic Product per Hour, 1870–1986

Source: Angus Maddison (1987, 1989)

(Moses Abramovitz 1986; William Baumol 1986; J. Bradford De Long 1988; Dollar and Wolff 1988; Baumol, Sue Anne Batey Blackman, and Wolff 1989; Robert Barro 1991). While a portion of the analytic apparatus and a few of the ideas in this recent literature are new, the general questions being explored have been around for a long time. Historical economists have long been interested in why Britian forged ahead of the Continent in the new technologies of the first industrial revolution, and the process through which other economies later caught up (Bernard Elbaum and William Lazonick 1986). More generally, how can one explain why certain countries take a significant technological lead in key industries in certain eras, and maintain it for some time? How do other countries catch on? Is convergence really the dominant process over long epochs, with history punctuated from time to time by new leadership surges from formerly backward nations? If so, why the "punctuations"?

But these questions pose still deeper ones. In what sense can one talk about "national" technological capabilities? In what ways do borders and citizenship matter? What is the role of the nation-state in technological development, and has this role changed historically? Is the recent trend to convergence mainly an equilibration process among nations, or is it a sign of decline in the importance of nationalities and borders?

As we see it, the recent literature on these topics contains three broad perspectives, often implicit. One, associated with the convergence literature, sees the U.S. postwar lead as inherently transient, attributable partly to the late start of many of our present rivals, and partly to the destruction of our major industrial rivals during the war; convergence was therefore relatively automatic and inevitable. A second view sees not convergence but rather U.S. industry losing out in a competitive struggle with other national industries. In this view, the United States is now falling below the pack of leading countries as England did a century ago, with Japan and perhaps Germany taking on new leadership roles. The authors of this school vary in the reasons they stress. For Paul Kennedy (1987) it is the burden of defense spending. For Christopher Freeman (1987), Michael Piore and Charles Sabel (1984), James Womack, Daniel Jones, and Daniel Roos (1991), and Lazonick (1990), relative U.S. decline reflects the rise in other nations of new and better ways of organizing aspects of economic activity, with the U.S. stuck in its old ruts. A third interpretation posits a more fundamental decline in the role of national borders and nationally based industrial centers. Convergence has occurred, in this view, but not simply as a result of postwar recovery or international technological diffusion and imitation, or the rise of superior new national systems. Rather, the argument is that just as markets and business have become more global, the network of individuals and organizations generating and improving new science-based technologies have become less national and more transnational, so that convergence reflects a diminution of the saliency of nation-states as technological and economic entities.

We do not claim that these three frameworks are neatly distinguishable, and we certainly do not claim to have answered our own questions definitively. But we believe there is value in posing these questions carefully and clearly, and we attempt to marshal analysis and evidence bearing on them. This we have tried to do in the context of the U.S. experience, within the limits of our own competence and the space allocated by the *Journal*.

Let us tip our hand by stating where we come out on some of the critical issues. First, the U.S. lead of the early postwar era was not merely a temporary result of the war but stemmed from two relatively distinct sources. Part of the lead reflected long standing American dominance in mass production industries, which in turn derived from uniquely favorable historical access to natural resources and to the world's largest domestic market. The other part of the American lead, in high technology industries, was new, and reflected the massive private and public investments in R&D and scientific and technical education that the United States made after World War II. Though these investments built on older institutional foundations, broadly based world leadership by the United States in basic science and in technologies drawing on new scientific frontiers was largely a postwar development. Thus, there were two components to U.S. leadership, and they have weakened for conceptually different but institutionally connected reasons. Growing domestic markets outside the United States, and the opening of the world as a common market in resource commodities as well as consumer and producer goods have virtually eliminated the advantages American firms used to have in mass production. And as the networks of technological development and communication have become more oriented to professional peer-group communities, which have themselves become increasingly international, technology has become more accessible to companies that make the requisite investments in research and development, regardless of their nationality. Increasingly, such investments have been made by firms based in other countries. These developments are associated with the fact that large industrial firms are increasingly transnational. Where national industries become tradition-bound and fall behind, international convergence is still advanced by the migration of capital, management, and personnel across international borders. The net result of these developments is a world in which national borders and citizenship mean significantly less technologically than they used to.

Our discussion is organized as follows. We begin by examining the rise of American strength in the mass production industries during the nineteenth century, considering especially the reasons why American technology came to differ from, and in an important sense to surpass, that of the Europeans. We also describe the rise during the early twentieth century of the American chemical and electrical products industries. Then we turn to the interwar period when the U.S. consolidated its lead in mass production and laid the basis for its advances in "high tech" after World War II, by establishing a solid base in organized research, and by providing the experience of post secondary education to a broad segment of the population. Then we consider the early postwar era, focusing particularly on how U.S. primacy was achieved in such fields as microelectronics. Finally, in light of our analysis of the nature of U.S. leads in mass production and high tech, and the factors that maintained the U.S. advantages, we present our diagnosis of how and why the twin leads have declined since the late 1950s, and our views of what might lie ahead.

II. *Long Standing American Strengths*

In this section we deal with that part of the American postwar lead in manufacturing that had been there for a long time: mass production industries. We shall distinguish the reasons for the U.S. advantage in these industries rather sharply from the factors behind U.S. dominance after World War II in fields like semiconductors and computers. But before we get into the discussion of American leadership in mass production, it is important to consider the senses in which we can talk at all about national technological capabilities. What does it mean to say that (firms in) one country has a technological lead over (firms in) other countries?

A. *National Technologies and Technological Leadership*

If technology were a pure public good, as economists are wont to assume in elementary versions of microeconomic theory, then the proposition that firms in certain countries are able to employ technologies that lie beyond the ken of firms elsewhere would make no sense. The input and output mixes of firms located in different countries might be different, but such divergence would merely reflect differences in market or other environmental conditions that influence what firms choose to do. Thus during the nineteenth century the special U.S. conditions of cheap resources, high wage rates, and large markets, could be understood to induce the high labor productivity, large-scale, capital-intensive production methods that became known as characteristically American. But the contrast with European practice would be ascribable entirely to economic choices rather than to differences in the technology choice set.

Of course economists have long recognized that firms are sometimes able to bar others from using their technology through threats of a patent infringement suit, or by tightly held trade secrets. But there is little evidence that patent suits were effective barriers to technological transfer in the metal working and mass production industries where nineteenth-century American firms achieved their greatest advantage. Some American firms certainly tried to guard key trade secrets, but high interfirm mobility among technically informed personnel made firms into relatively leaky institutions for technical information that could be carried in the heads of knowledgeable individuals. Just as British restrictions in an earlier era did not stop Samuel Slater and a host of followers from carrying their understanding of textile technology across the Atlantic (David Jeremy 1981), American firms of the late nineteenth and early twentieth centuries were seldom able to block technological secrets from international dissemination.

Nonetheless we argue that the concept of a "national technology" is a useful and defensible analytical abstraction, appropriate for much of modern history if decreasingly so in recent times. Our proposition rests on three intertwined arguments. First, the technologies in question were complex, involving different kinds of machines and a variety of learned skills, and often requiring relatively sophisticated coordination and management. While certain features of these complex operations were described in writing, or more generally were familiar to the experts in the field, to get the technologies under control and operating well generally required a lot of learning-by-doing on the part of many interacting people, from engineers to managers to machine operators, as well as investment in plant and equipment. Thus "technology transfer" involved much more than what one or a few men could carry away in their heads, or in a few drawings or models. These could provide a start on technology transfer but real command of the technology required a considerable amount of trial-and-error organizational learning. Thus the technology was not really a public good in the standard sense. American firms had a command of it that others did not, and could not master without significant time and effort.

Second, to a considerable extent technical advance in these fields was local and incremental, building from and improving on prevailing practice. The knowledge useful for advancing technology included, prominently, experience with the existing technology so as to be aware of its strengths and weaknesses, and to know how it actually worked. Thus those at the forefront of the technology were in the best position to further advance it. Economic historians have long been aware of this kind of technological learning. Nathan Rosenberg (1963) recounts the evolution of American machine-tool technology in the nineteenth century as a sequence of problem solving challenges. At any given point, progress was constrained by a particular bottleneck known mainly by those experiencing it, yet each new solution shifted the focus to another technical constraint or phase of production. With frontier technology rapidly changing and new applications being spun off, physical presence in the active area was virtually indispensable for anyone who hoped to improve on the prevailing best-practice.

Third, sustained technological advance was not the result of one person or firm pushing things ahead, but involved many interacting people and firms. One learned from another's invention and went a step further. Robert C. Allen (1983) describes this process of "collective invention" in some detail, in his study of British Bessemer steel producers in the Cleveland district, and Elting Morison (1974) describes a similar process among American Bessemer producers. The interdependencies went well beyond mere aggregation of achievements over time. As demonstrated in Ross Thomson's account of the origins and diffusion of the sewing machine (Thomson 1989), the success of new technical breakthroughs required that they mesh with prevailing complementary technologies, and that they fit into a complex chain of contingent production and exchange activities, from raw material to final distribution. Any number of *technically* successful mechanical stitchers had been invented in the 60 years prior to Elias Howe's officially recognized invention of 1846, but none succeeded commercially. Howe's machine did succeed, because it fit in with complementary technologies and skills, and because it initiated a process in which new firms formed nodes in a communication network linked to other innovators. In turn, the principles and the networks of interdependence that came out of sewing machine development became applicable to a host of related industries.

In short, technological progress is a network phenomenon replete with "network externalities" of the sort that have now come in for intensive theoretical scrutiny (Michael Katz and Carl Shapiro 1985), by *path-dependence*, i.e., dependence of successive developments on prior events (Paul David 1975, 1988; Richard Nelson and Sidney Winter 1982), and a tendency for particular systems to become "locked in" beyond a certain point (W. Brian Arthur 1988, 1989). A striking historical feature of these networks of cumulative technological learning is that down to recent times their scope has been largely defined by national borders. Why should this have been so?

In the first place, for reasons of geographical proximity. The networks described by Allen, Morison, and Thomson all involved inventors and tinkerers living in the same general area and having intimate contact with each others' inventions if not each other. Second, to the extent that technological communications networks follow in the tracks of previously established linguistic and cultural communities, it would be entirely natural for technologies to have something of a national character. Such a primary basis might well be reinforced by the existence of centralized or uniform national institutions for technical training, though this was a less striking feature of American development than it was in European countries like France and Germany. Even in the absence of officially mandated uniformity, however, American scientists and engineers displayed early signs of national identity, rooted in the distinctness and commonality of their problem solving environment: the resource base, the product market, and the legal/institutional conditions were markedly different from those in European countries. The key elements of such networks are common terms and reference points, methods of measurement, and standards of technical performance. A Scottish visitor during 1849–50 complained that American mineralogists disdained to label their formations with the names of European localities, but insisted on an independent national terminology. Nathan Rosenberg (1985) points out that most of what we now call science-based progress did not deploy "frontier" scientific concepts, but involved largely mundane and elementary tasks, such as grading and testing of materials, for which scientific training was needed but where the learning was specific to the materials at hand. Standardizing such measurements, and physically embodying them in instruments and apparatus (as well as procedures) were among the main tasks of the distinctly American scientific and engineering associations which emerged in this country at the end of the nineteenth century (Edward Constant 1983). Critics of American capitalism complain that by the 1920s, American engineers themselves had become standardized commodities, through the close links between corporations and institutions of higher education (David Noble 1977). As the American technology was by that time the envy of the industrial world, however, aspiring young engineers could hardly have done better than to gain the training that would give them access to the national technological network.

Of course not all countries had such indigenous national technological communities, for reasons of scale, political stability, or historical accident. We do not address ultimate questions of historical economic development in this essay, but focus instead on the narrower task of describing the emergence of a distinctive American technology from the end of the nineteenth century onward, and tracing the course of that national characteristic in the twentieth century.

B. *The Rise of Mass Production in the Nineteenth Century*

American technology began to make a splash in the world at least as early as the mid-nineteenth century. Mechanical reapers, mass-produced firearms, and many other American novelties created a noticeable stir at the Crystal Palace Exhibition in London in 1851. In this early period, however, the impressive technical achievements of the "American System of Manufactures" pertained only to a small subset of industries, while in other major areas (such as iron-making) the U.S. was clearly behind European countries (John James and Jonathan Skinner 1985).

Nonetheless, across the nineteenth century the country did develop the sine qua non for advanced technological status, an indigenous technological community able to adapt European techniques to American conditions. Though the process of technological search was decentralized and competitive, flows of information through trade channels, printed media, and informal contacts served to establish a distinctive American problem solving network. An important early institutional manifestation was the emergence of a specialized machine-tool industry, which evolved from machine shops linked to New England textile mills in the 1820s and 1830s and became a "machinery industry" generating and diffusing new technologies for a wide range of consumer goods industries (Nathan Rosenberg 1963). Economic historians have traced remarkable threads of continuity in the histories of firms and individual machinists, as steady improvements in machine speeds, power transmission, lubrication, gearing mechanisms, precision metal cutting, and many other dimensions of performance were applied in one industrial setting after another: textiles, sewing machines, farm machinery, locks, clocks, firearms, boots and shoes, locomotives, bicycles, cigarettes, sewing machines, and so on (David Hounshell 1984; Thomson 1989). This distinctively American development represented a type of collective learning, which fed into the twentieth century technologies that formed the basis of U.S. world leadership.

By the end of the nineteenth century, American industry assumed a qualitatively different place in the world. A number of important innovations concentrated in the 1880s took advantage of the opportunities for mass production and mass marketing offered by the national rail and telegraph networks. These included new branded and packaged consumer products (cigarettes, canned goods, flour and grain products, beer, dairy products, soaps and drugs); mass-produced light machinery (sewing machines, typewriters, cameras); electrical equipment; and standardized industrial machinery such as boilers, pumps, and printing presses (Alfred Chandler 1990, pp. 62–71). Although most of these products were developed for the domestic market, many of them became exports as well. The first wave of alarmist European books on "Americanization" dates from 1901 and 1902, with titles and themes about an "American invasion" which would again became familiar in the 1920s and 1960s (e.g., Frederick MacKenzie 1901). Particularly noteworthy were growing American exports of industrial machinery, farm equipment, hardware and other engineering goods, producers' goods which embodied mass-production principles and which in many cases posed a new competitive challenge abroad. In addition, by 1900 the American steel industry had become a world leader, and the country was exporting an extensive array of iron and steel products (Allen 1977). This international standing was new. Prior to the 1890s, American steel rails would not have survived in the domestic market without tariff protection (Allen 1981).

These new turn-of-the-century achievements may be thought of as the confluence of two technological streams: the ongoing advance of mechanical and metal-working skills and performance, focused on high-volume production of standardized commodities; and the process of exploring, developing, and utilizing the mineral resource base of the national economy. As surprising as it may seem from a modern perspective, the rise of American industry to world leadership was intimately connected with the rise of the country to world leadership in the production of coal, iron ore, copper, petroleum, and virtually every other major industrial raw material of that era. To cite one important example, the breakthrough in the steel industry coincided with the opening of the rich Mesabi iron range in the 1890s, and to concomitant adaptations in technology and transportation (Allen 1977). Analysis of trade in manufactures reveals that intensity in nonreproducible resources was one of the most robust characteristics of American goods, and this relative intensity was in fact *increasing* across the critical period from 1880 to 1930 (Wright 1990). Louis Cain and Donald Paterson (1986) find that material-using technological biases were significant in nine of twenty American sectors, including those with the strongest export performance.

It would be a mistake to imply that the country's industrial performance rested on resource abundance and scale economies *as opposed to* technology, because mineral discovery, extraction, and metallurgy drew upon, stimulated, and focused some of the most advanced engineering developments of the time, as did mass production. The U.S. Geological Survey was the most ambitious and successful government science project of the nineteenth century, and the country quickly rose to world leadership in the training of mining engineers (David and Wright 1991). New processes of electrolytic smelting and refining had a dramatic impact on the industrial potential of copper, nickel, zinc, and aluminum. The oft-noted complementarity between capital and natural resources in that era was not merely an exogenous technological relationship, but may be viewed as a measure of the successful accomplishment of a technology in which Americans pioneered. Mass production industries were also intensive in their use of fuels and materials. Not only did the capital stock itself embody domestic materials, but "high-throughput" methods, to maximize the sustainable rate of capacity utilization, imply high ratios of physical materials and fuels to labor. For these reasons, although they were highly profitable given the economic conditions in the United States, American technologies were often not well adapted to other localities. Robert Allen (1979, p. 919) estimates that in 1907–09 the ratio of horsepower to workers was twice as large in America as in either Germany or Great Britain. On the other hand, American total factor productivity in this industry was only about 15 percent ahead of Great Britain, and approximately equal to that in Germany. This statistic does not imply that German steel makers could have matched American labor productivity levels "simply" by operating at the American level of capital and resource intensity. Our central point is that there is nothing "simple" about the processes through which firms come to adopt and learn to control technologies that have been in use elsewhere for some time. Rather, the numbers illustrate the particular kinds of new technological developments that the Americans developed. Accounts of the course of technological progress in Germany suggest an entirely different orientation governed by "the desire to find substitutes for expensive and uncertain imports" (Peter Hayes 1987, p. 1).

American manufacturing firms and their technologies not only were resource and capital intensive, but operated at much greater scale than did their counterparts in the United Kingdom and on the Continent. Large scale operation was well tuned to the particularities of the large affluent American market. By 1900 total national income in the United States was twice as large as that of the U.K., about four times as large as France or Germany. Per capita income had also surpassed that of Great Britain and was well ahead of continental Europe. American language and culture were reasonably homogeneous, and internal transportation and communications systems were well developed. Perhaps because of their relative freedom from traditional class standards, American consumers readily took to standardized products, a development which came much later in Europe. Further, this large American market was effectively off limits to European producers because of high prevailing levels of tariff protection. Although the size of the U.S. domestic market may have been partially offset by the greater relative importance of exports for the European countries, foreign markets were highly diverse and much less receptive to standardized goods than they later became. Oriented mainly toward the domestic market, American firms tended to produce a narrow range of product specifications. In the steel industry, for example, though the U.S. was dominant in mass-produced products, in specialty steels the U.S. performance was "a story of false starts, technological backwardness, commercial failures, and continued dependence on foreign steel" (Geoffrey Tweedale 1986, p. 221). American harvesting machinery and locomotives (like automobiles at a later point) were technically impressive but inappropriate for most of the world's markets. Many European engineers held a low opinion of their American counterparts, for emphasizing production and speed over quality and durability (Daniel Headrick 1988, pp. 75, 84).

It has often been argued that the distinctive strength of American corporations lay less in technology per se than in organizational efficiencies associated with mass production and mass distribution. The success abroad of the Singer Sewing Machine Company, for example, was not based on highly sophisticated product design or factory technology, but in the efficiency of its production, sales, and service organization (Fred Carstensen 1984, p. 26). Singer's ventures abroad came relatively early; but in general, the interest of American firms in foreign markets emerged belatedly, only after they had established national distribution networks (Mira Wilkins 1970). Here again, we should not think of organizational strength as an *alternative* but as a complement to advanced technology. As Alfred Chandler has argued, modern corporate enterprise tended to arise in sectors which had undergone prior technological transformation, and the new organizational form served to make more effective use of these new technological possibilities (Chandler 1977). Chandler's new comparative work, *Scale and Scope*, emphasizes that the United States had far more of these new technically and managerially advanced corporate institutions much earlier than any other country. Chandler's account of the "organizational capabilities" within large American firms is compelling and persuasive, but we would place more emphasis than he does on system-wide features of the economy, and on the ongoing development of the technology itself. The large American companies were not just efficiently streamlined organizations; they were part and parcel of an emerging technological and managerial network, engaged in a collective learning process with a strongly national character. By the late nineteenth century the management style in American manufacturing companies had become very different from that in Great Britain and continental Europe.

The concept and practice of "professional management" first arose in the United States, and by 1900 it was common for a large American firm to be staffed by a cadre of professional, educated, middle managers, a phenomenon that seems to have been almost exclusively American. In his recent book, Lazonick (1990) argues that American management increasingly took control of the job floor at this time, in contrast to Britain, where management had little control over the details of work. The "scientific management" movement was singularly American, and closely associated with the professionalization of management. In a fascinating recent paper, Kogut (1992) stresses the importance of basic principles of management and organization, which he argues take on a strikingly national character, or at least used to. He proposes that it was the style of management and organization, far more than the simple economies of scale and scope, that led to the pre-eminence of American corporations in the early years of the twentieth century, although the former was essential to the latter. In his empirical examination of American corporations that establishes overseas branches, Kogut found many large companies, but also some middle-sized ones. Almost all of them, however, were marked by strong adherence to the management and organizational principles described above, which formed a distinctly American style.

We note here that relatively little of the American performance during this era was based in science, nor even on advanced technical education. American technology was practical, shop-floor oriented, built on experience. The level of advanced training in German industry was substantially higher (Jürgen Kocka 1980, pp. 95–96). As prominent an American engineer as Frederick W. Taylor, who played a major role in developing high-speed tool steel years before he invented "scientific management," had only an undergraduate degree and was deeply skeptical of the practical value of university training. The search for valu-

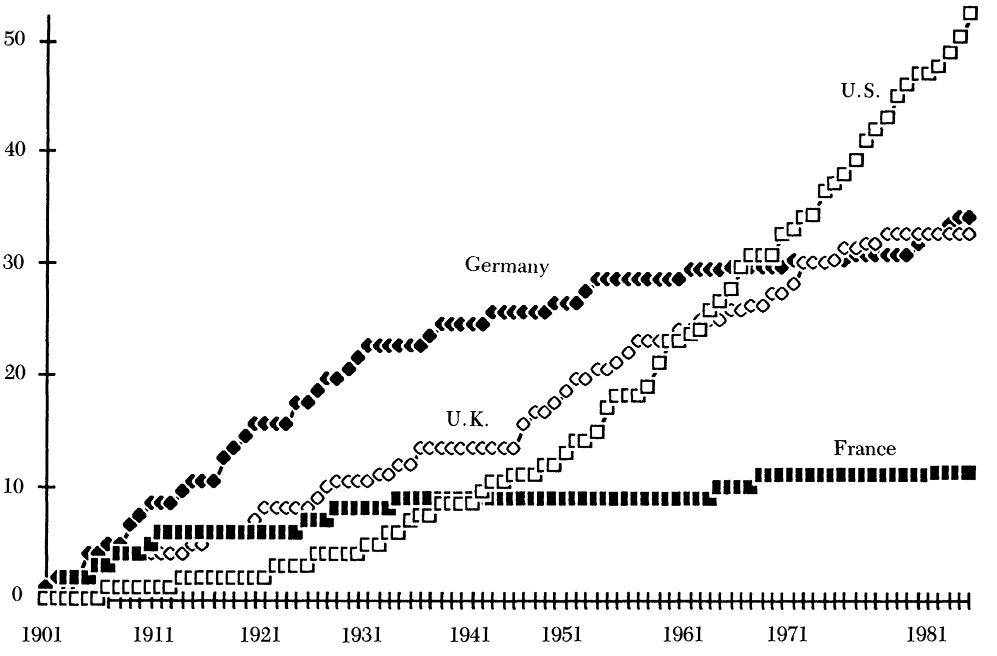

Figure 2. Cumulative Nobel Prizes in Physics and Chemistry, 1901–1990

able petroleum by-products was carried out by people with only a smattering of chemical education (Nathan Rosenberg 1985, p. 43). Many of the industries in which American strength was clearest and strongest, such as nonelectrical machinery, steel, and vehicles, were distinguished well into the twentieth century by an aversion to organized science-based research. American universities did have areas of strength in certain applied fields, but an aspiring student who sought the best available academic education in scientific disciplines like physics and chemistry would have been advised to study in Germany, Britain, or France. As Figure 2 shows, the U.S. did not surpass these countries in scientific Nobel Prizes until long after World War II.

These observations are intended to delineate rather than to downplay the magnitude of what American industry had achieved by the early 20th century. American firms were the clear leaders in productivity across the range of mass production industries. This lead in manufacturing combined with highly productive American agriculture to support wage rates and living standards higher than those in England, and higher still than on the Continent (Ernest Henry Phelps Brown 1973). In turn, high wage rates and living standards induced and supported large scale, capital- and resource-intensive production. And while the particular technologies and structures adopted by U.S. manufacturing firms reflected these unique aspects of the American scene, by and large where American industry went, Europe followed, if often with a pronounced lag.

C. *Building the Infrastructure for Science-based Industry*

By the start of World War I, the United States had established a position of leadership in mass production and mass distribution industries, a technology characterized by scale economies, capital intensity, standardization, and the intensive use of natural resources. Though the United States was not the world leader in science nor in the use of science-based technologies at that time, the country had developed much of the private organization and public infrastructure needed to operate effectively in the science-based industries that were coming into prominence.

Federal government support for university programs in agriculture and the practical arts dates from the Morrill Land Grant College Act of 1862. Though this act led directly to the founding of several major state universities and the strengthening of others, little significant research could be credited to it prior to the Hatch Act of 1887, which provided each state with funding for an agricultural experiment station. The level of support for research was doubled by the Adams Act of 1906, and unique institutions for the dissemination of knowledge among farmers were in place with the establishment of the cooperative extension service in 1914. At this juncture the U.S. was well behind Europe in the deployment of "scientific agriculture"—soil chemistry, plant biology, animal husbandry. But a generation later these investments in infrastructure had unprecedented payoffs in agricultural productivity.

The Morrill Act also provided a federal stimulus to engineering education; within a decade after its passage, the number of engineering schools increased from six to seventy, growing further to 126 in 1917. The number of graduates from engineering colleges grew from 100 in 1870 to 4300 at the outbreak of World War I (Noble 1977, p. 24). Like their agricultural counterparts, engineers and scientists at American universities were under continuing pressure to demonstrate the practical benefits of their efforts. "Merely theoretical" research was openly belittled, and the areas of applied science which did show some strength in the nineteenth century were mainly those linked to state-specific economic interests, such as geology and industrial chemistry (Robert Bruce 1987). Nonetheless, by the turn of the century a network of research universities had come into being, striking an institutional balance between the demand for immediate usefulness and the ethos of academic independence espoused by the emerging scientific disciplines. According to Roger Geiger (1986), the main elements in this balance were the provision of large-scale undergraduate teaching as a means of financing research and graduate training; and the successful mobilization of nationalistic sentiments in support of science. A watershed of sorts was passed with the founding of the American Association of Universities in 1900, to bolster academic standards, establish uniformity in requirements for the Ph.D., and achieve foreign recognition for U.S. doctorates. Though business-university cooperation has continued to be an important part of American technological history, the prospect of world-class research universities came only after a certain social distance from industry had been established.

At the same time, American industry was building its own technological infrastructure. In the wake of the great merger wave in American business (1897–1902), which established many of today's well-known corporations in positions of national market power for the first time, an unprecedented expansion of private-sector research laboratories occurred, a trend that accelerated over the next half-century (Figure 3). General Electric, DuPont, AT&T, and Kodak all set up formal research laboratories before World War I. Here too, the lasting institutional implications may have been very different from the original motivations of

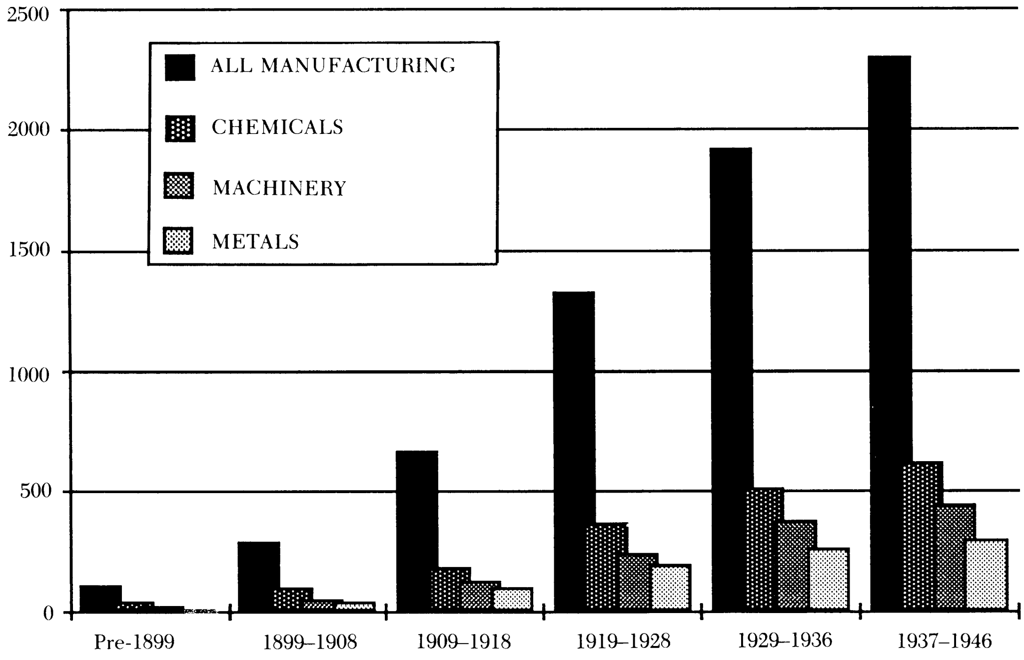

Figure 3. Laboratory Foundations in U.S. Manufacturing

Source: David Mowery and Nathan Rosenberg (1989, Table 4.1)

the founders. Business historians have argued that these early firms were not looking to do pioneering research in new technologies, but to control innovation and protect an established patent position (Leonard Reich 1985; John Kenly Smith 1990). Once established, however, a science-based research tradition evolved, often with considerable autonomy from the immediate objectives of the employer.

Only in chemistry had there been any substantial use of scientifically trained personnel prior to 1900. In 1875 the Pennsylvania Railroad hired a Yale Ph.D. chemist to organize a laboratory for testing and analysis of materials brought from suppliers. As Nathan Rosenberg argues, much of the early use of science by industry was of just this sort, a relatively mundane application of laboratory procedures for testing materials, well within the frontiers of existing science. Institutionalizing such procedures, however, often led to unexpected results. The Pennsylvania Railroad laboratory, for example, went on to develop an improved lubrication composition for locomotives. A Ph.D. chemist hired by the Carnegie Steel Company not only helped to identify high quality ores, but found ways to make better iron and steel. Increasingly, chemists came to play an important part in technological innovation in iron and steel making, in traditional inorganic chemicals like soda, and in new organic chemical substances like dyes and later plastics.

The German chemical industry unquestionably was the leader in dyestuffs, plastics, and other new products based on organic chemistry. Christopher Freeman's data show that through 1945, I. G. Farben was by far the largest patentor in plastics. By 1910 or so, however, the leading American companies like Du-

Pont, Dow, and Kodak had established R&D laboratories and had developed the capacity to produce a full range of industrial chemicals and a wide range of fine chemicals (Noble 1977; Hounshell and John Smith 1988). These companies were able to draw upon the newly emerging specialty of chemical engineering, an American professional hybrid. They were thus organizationally well positioned to take advantage of the cutoff of trade with the Germans during World War I, and to respond to the need to provide a variety of products for the military. The abrogation of German patents brought the American companies close to technological parity with the Germans by the 1920s.

The story in the new electrical industry is similar, except that here American strength was apparent somewhat earlier. As in chemistry, performance was clearly not rooted in any American advantage in fundamental science; U.S. universities were significantly behind those in Germany and other continental countries in teaching and research in physics. But American industry had early access to trained personnel in electrical *engineering*. By the last decades of the nineteenth century in universities like M.I.T. and Cornell, physics and mechanical engineering had been self-consciously combined as a field of training (Robert Rosenberg 1984). Thomas Hughes has argued that in the new electrical industries, the Americans excelled in the conception, design, development, and implementation of large scale systems (Hughes 1987). In addition, the U.S. industry benefited from scientifically educated European emigres like Thomson, Tesla, Steinmetz, and Alexanderson.

Here again one may see the influence of the large, affluent American market, not as an *alternative* to technology, but as an influence on the directions taken by American technology, and a source of unique advantages in international comparisons. There are numerous examples of innovations which were European in origin, but whose development progressed most rapidly in the United States because of the scale economies accessible in the American market (Hans-Joachim Braun 1983).

III. *The Interwar Period*

In the 1920s and 1930s, American industry consolidated its position of leadership in mass production industries, while joining these longer-term strengths to organized research and advanced training in important new industries such as chemical and electrical engineering. Some of the circumstances were historically fortuitous. The United States escaped damage and even enjoyed industrial stimulation from World War I. After the war, the institutions of international trade and finance remained in disarray, stumbling toward their complete collapse in the 1930s. Industrial countries that depended on foreign markets had a hard time of it (though Japan managed to continue its industrial growth despite these obstacles). American industries were largely insulated from these problems. The country was highly protectionist from the time of the Civil War. In the 1920s, despite the emerging strength of American industry, import barriers were increased, first by the Fordney-McCumber Tariff of 1922, and then by the notorious Hawley-Smoot Tariff of 1930. But the domestic market was more than sufficient to support rapid productivity growth and the ongoing development and diffusion of new technologies and new products.

A. *The Marriage of Old and New Industrial Strengths*

The automobile industry was the most spectacular American success story of the interwar period, a striking blend of mass production methods, cheap ma-

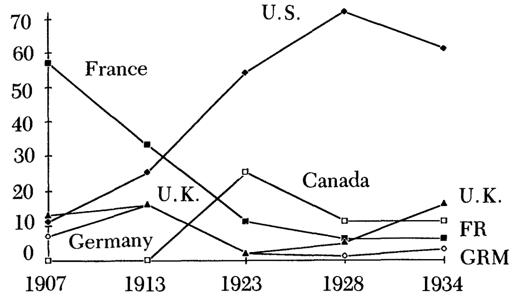

Figure 4. Shares of World Motor Vehicle Exports, 1907–1934

Source: James Foreman-Peck (1982, p. 868).

terials, and fuels. The distinct lead of American producers over French and British rivals really dates only from the advent of the assembly line at Ford between 1908 and 1913, but the ascendancy was rapid thereafter. Though the historical origins of this performance may be traced back to characteristics of the domestic market, the extent of American leadership is clearly indicated by the high volume of exports, notwithstanding the fact that the size and fuel requirements of American cars were poorly suited to foreign demand. Despite barriers to trade and weak world demand, U.S. cars dominated world trade during the 1920s, and motor vehicles dominated American manufacturing exports (Figure 4). Henry Ford's books were best sellers abroad, and "Fordism" developed a cult technocratic following in both Germany and the Soviet Union (Hughes 1989). The components of the U.S. cost advantage are difficult to measure with precision, however, because the large-scale auto firm came as a package: organizational, managerial, financial, and technological. The branch plants of American firms were also dominant abroad, though during the interwar period they were not fully able to replicate performance at home (Foreman-Peck 1982). The process of global diffusion and adaptation of American methods would surely have continued, however, either by imitation or by direct foreign investment, if it had not been interrupted by World War II.

In many ways a more lasting and significant basis for technological leadership was established in those industries that were able to marry mass production methods to organized science-based research, such as the electrical industries and chemical engineering. Though the fundamental scientific breakthroughs in electricity had come earlier, the interwar period saw the realization of this potential through full electrification of factories and households. Paul David (1989) has called attention recently to electrification as an example of an innovation whose productivity impact was delayed for a full generation, because of the need to disseminate and adapt the underlying knowledge, and to restructure physical plants and work routines. The percentage of factories using electric power grew from 25 in 1910 to 75 in 1930 (Warren Devine 1983), a development essential for the acceleration of productivity growth at this time. A similar infusion occurred in the household, where the use of electric lighting rose from 33 percent of urban families in 1909 to 96 percent in 1939 (Stanley Lebergott 1976). Large firms like GE, Westinghouse, and AT&T established advanced research organizations that generated an ongoing flow of innovative new electrical products, sometimes advancing the frontiers of science in the process.

The rise of chemical engineering was also a marriage of old and new strengths. Ralph Landau and Nathan Rosenberg (1990) point out that this professional category was an American innovation, combining chemistry with training in industrial processes. It was also relatively new, emerging as a course of study at MIT in the first two decades of the twentieth century, becoming a separate department only in 1920. The American surge was also closely associated with a shift in the basic feedstock for chemical plants from coal to petroleum, a primary product in which the U.S. dominated world production. As technology developed, the production of organic chemicals was carried on most effectively as a by-product of general petroleum refining, hence closely connected with the location of petroleum supplies. Prior to the 1920s, there was little contact between petroleum companies and the chemical industry. In that decade, however, important connections emerged, through mergers, research establishments, and industry-university associations. Working in close partnership with M.I.T., New Jersey Standard's research organization in Baton Rouge, Louisiana, produced such important process innovations as hydroforming, fluid flex coking, and fluid catalytic cracking (Landau 1990a). Here we have a remarkable blend of mass production, advanced science, and American resources. As the chemical engineer Peter Spitz has written: "Regardless of the fact that Europe's chemical industry was for a long time more advanced than that in the United States, the future of organic chemicals was going to be related to petroleum, not coal, as soon as companies such as Union Carbide, Standard Oil (New Jersey), Shell, and Dow turned their attention to the production of petrochemicals" (Spitz 1988, p. xiii). Petroleum led the way in the use of scientifically trained personnel in the first half of the century (Figure 5).

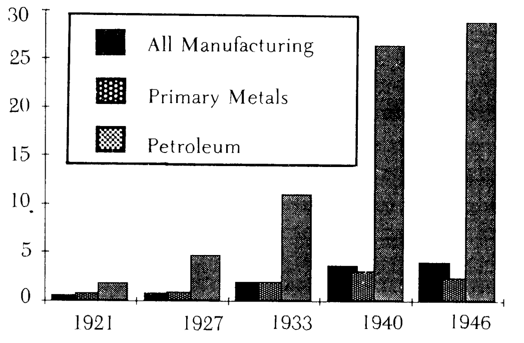

Figure 5. Scientists and Engineers per 1000 Wage Earners

Source: Mowery and Nathan Rosenberg (1989, Tables 4.2, 4.3, 4.4, 4.5, 4.6)

B. *Education and Technology*

Sooner or later, discussions of American industrial and technological performance generally come around to the educational system. Americans seem to believe in a golden age during which the country led the world in mass public schooling, and that this enlightened leadership in education was also closely associated with leadership in technology. There is some truth in this account, but the story is less straightforward than commonly imagined. It is true that the United States was an early leader in literacy and primary education, achieving close to universal elementary enrollment before the Civil War (outside of the South), well ahead of France and Britain (Richard Easterlin 1981). Only Germany (where in Prussia compulsory education dated from 1763) approached these levels. Because basic education has a clear effect on the capacity to conduct commercial operations and process written information (Theodore Schultz 1975), the diffusion of schooling among the American farming population undoubtedly had a positive influence on its responsiveness to new opportunities and its receptivity to innovations. But these benefits pertained largely to a population of farm proprietors, which for the most part was not the source of the labor for American factories during the country's surge to world industrial leadership. From the time of the Irish influx in the 1840s, the bulk of the industrial labor force came from immigration, mostly from non-English-speaking countries with far lower educational standards than those prevailing

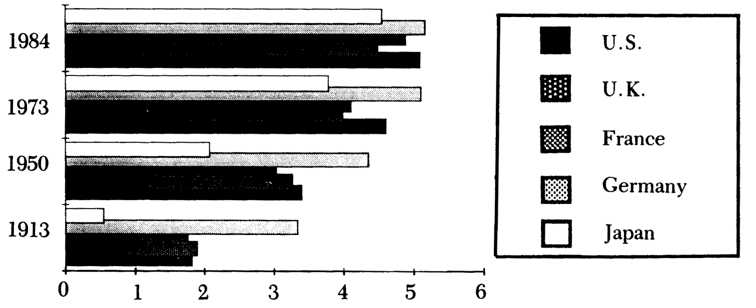

Figure 6. Average Years Secondary Education, 1913–1984 (Pop. 15–64)
Source: Maddison (1987, Table A-12)

among the native born. In 1910 the foreign born and the sons of the foreign born were more than 60 percent of the machine operatives in the country, and more than two-thirds of the laborers in mining and manufacturing (U.S. Senate 1911, pp. 332–34). There is no reason to believe that this labor force was particularly well educated by world standards. This may not have been a drawback. It has been argued that the workpace in American factories was uniquely high (Gregory Clark 1987), an intensity of effort that one might well associate with "high-throughput" production strategy, but not necessarily with high levels of education on the part of workers. To be sure, the educational background of overhead and administrative personnel undoubtedly contributed to rising productivity; but the combination of a well-educated staff at the top and hard-driving workers at the bottom is very different from the success formulas of today's world. The upgrading of educational standards for production workers came largely after the cutoff of immigration in the early 1920s.

Educational attainment did indeed increase rapidly, as much of the country moved towards the norm of a high school degree. As job qualifications were raised and mechanization tended to eliminate jobs requiring mere brute strength and exertion, it is reasonable to hold that higher educational standards contributed to the remarkable rates of productivity growth maintained by American industry between 1920 and 1960, though we have no detailed understanding of this process. It is appropriate to note, however, that the expansion of secondary education in the twentieth century was not particularly unique to the United States. Similar trends were recorded in virtually all of the "advanced" countries of the world, and as of 1950 there was no marked difference in average years of secondary education among the United States, France, and Britain, all of them still well behind Germany (Figure 6). This does not gainsay the contribution of secondary education to American performance, but it underscores the point that broadly based education contributes to technological leadership only as these skills are effectively utilized by industrial employers. The disrupted conditions of world trade between 1914 and 1950 very likely constrained many countries from exploiting their educational potential.

The respect in which the United States was distinct among the nations of the world was the percentage of the population gaining access to a college education (Figure 7). As early as 1890, the ratio of university students per 1000 primary students in America was two to three times

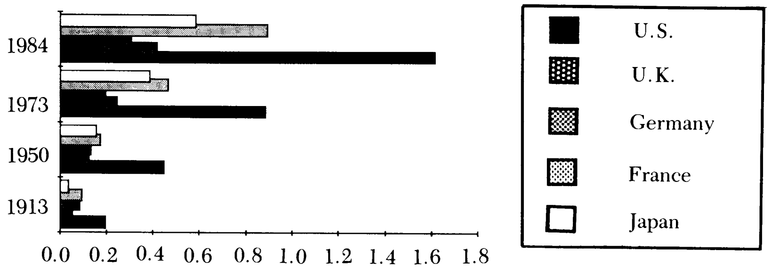

Figure 7. Average Years Higher Education, 1870–1984 (Pop. 15–64)
Source: Maddison (1987, Table A-12)

that of any other country, and this gap was maintained and increased through the period of American industrial ascendancy. After 1900, the surge in enrollment was particularly robust in applied sciences and engineering (Geiger 1986, p. 14); in new specialties like electrical engineering, American institutions such as M.I.T. were reputed to be the best in the world by World War I. Advanced training in business management also experienced rapid post-1900 growth (Chandler 1990, p. 83). Though university-trained engineers, scientists, and managers were no more than a small percentage of those employed in American industry, here if anywhere is a specific institutional basis for American technological leadership. Utilization of such personnel grew steadily through the twentieth century (Mowery and Nathan Rosenberg 1989).

So also did employment of college-trained people in a wide range of activities ancillary to R&D and production. Employment in marketing, accounting, legal service, finance, insurance, and communications grew rapidly over the interwar period, some of it in manufacturing firms, some of it in other sectors. By and large American organizations were able to tap a more highly educated population for these jobs than their European counterparts.

There are reasons to believe that the numbers somewhat exaggerate the American educational advantage "at the top." The elite grammar schools of the United Kingdom, the gymnasium of Germany, and the lycée of France, tended to teach subjects beyond what was taught in all but the best American high schools, and Americans graduating from high school tended to be younger and to have fewer years of education than their European counterparts coming out of the secondary institutions listed above. A number of commentators (e.g., Geiger) have noted that American university faculty often complained that their students were far less educated when they came to university than were students entering university in Europe. However, particularly with the advantage of hindsight, it is clear that long before the Europeans, Americans developed a tradition where a significant fraction of the sons (and later the daughters) of middle class families went on to education beyond high school. And the American middle class wanted "practical education."

Though the significance of university education for technology may seem self-evident, we have to acknowledge that we lack a clear understanding of the specific linkages. As with education more generally, what is important is not the sheer number of students or the quantity of their training, but the effectiveness with which that training is integrated into the process of improving the technology of operating firms. In interwar America that coordination was advanced to a high state of refinement, as the curricula of educational institutions came to be closely adapted to the requirements of the "positions" that graduates would be taking; and vice versa (Lazonick 1990, pp. 230–32). A 1921 survey made note of the "progressive dependence [of corporations] upon higher education institutions as sources of employee supply . . . the prejudice of many businessmen to higher education as a factor in employment is being rapidly overcome" (quoted in Noble 1977, p. 243). Political critics have complained that the process of national standardization in the specifications for products and processes came to be extended to personnel, as engineers "automatically integrated professional requirements with industrial and corporate requirements" (Noble 1977, p. 168). In 1919, for example, MIT launched its Cooperative Course in electrical engineering, a program that divided the students' time between courses at the Institute and at General Electric, which hired one-half of the students after graduation. The program was later joined by AT&T, Bell Labs, Western Electric, and other firms (Noble 1977, p. 192). Whatever the merits of Noble's reservation about the close links between universities and private firms, what he describes is an effective network of training and utilization, operating efficiently at a national level because it was self-contained, internalizing the resource base and market demands of the national economy.

We have noted that in recent years a sizeable literature on economic "convergence" has emerged, oriented around the proposition that large technological gaps between countries, and the associated gaps in productivity and income, are not sustainable if the lagging countries have the requisite "social capabilities." Abramovitz (1986) has suggested that these include, prominently, a well-educated work force including competence at the top in the major sciences and technologies of the era, adequate firm management and organization, and financial institutions and governments capable of keeping their fiscal and monetary houses in order. It is arguable that during the interwar period the major European economies were not significantly outmatched by the United States in these dimensions, although we have highlighted some important differences. It is noteworthy, however, that there was little if any tendency toward systematic convergence in command of mass production technologies during this period, nor in levels of labor productivity and per capita income relative to the United States. Although general dispersion narrowed, the mean productivity of Maddison's fifteen successful countries was no higher in 1938 as a percentage of the U.S. level than it had been in 1929, 1913, or 1890 (Abramovitz 1986, p. 391).

There are a number of reasons. One was the chaotic economic climate that affected most economies over this interval. Indeed Maddison's data show a sharp drop in the growth of world exports from nearly 4.0 percent per year between 1870 and 1913, to about 1.0 percent per year on average between 1913 and 1950. The average ratio of merchandise exports to GDP in the countries he examined fell from 11.2 percent in 1913 to 8.3 percent in 1950, and the number was almost certainly even lower during the 1930s. Thus during the interwar period nations were even more self-contained than they had been in the thirty years or so before World War I, and far more so than they became after World War II. This meant that the mass production methods used by American producers, which were highly productive and efficient on the

American scene, were less attractive to European firms facing their own home markets. Convergence is far from an automatic phenomenon. It requires not only that the lagging nations have requisite social capabilities, but also that their firms face an economic and political environment conducive to adopting technology used in the leading country. Rather than refining procedures for testing the "convergence hypothesis" as a universal tendency, it seems more fruitful to examine the new features of the postwar era that have encouraged and facilitated convergence among the world's leading countries.

IV. *The Postwar Era: The American Breakaway at the Technological Frontiers*

Just as after WWI, the United States came out of WWII buoyant, with technological capabilities extended by wartime production experience, while Europe came out prostrate. In contrast to the 1920s, after WWII Japan too was a demolished economy and nation. By the mid 1950s, most of the war-devastated countries had regained and surpassed prewar productivity and income levels, but as Figure 1 shows, the U.S. productivity and income edge remained enormous. While some Europeans seemed surprised at the lead of the Americans even after European recovery, they should not have been. The U.S. productivity lead in general, and in mass production industries in particular, had been around since the turn of the century. What was new was U.S. dominance in the "high technology" industries of the postwar era. Several intertwined but distinguishable reasons lay behind this development.

A. *National Technology and National Leadership in Science-based Fields*

Like the mass production technologies, newer "science based" technologies are advanced through community efforts. But to a far greater extent, chemical and electrical technologies, and nowadays fields like aircraft and semiconductors, require university-trained scientists and engineers, engaged in teamwork aimed to achieve new and better production process designs, through activities that have come to be called research and development. As a result, possession of university training, and involvement in organized R&D define the relevant technological communities.

Put another way, in science-based technologies the skills and experience needed to advance a technology include much more than can be acquired simply by working with that technology and learning from experience. In some cases the two components are completely disjoined. A chemist working on a new drug in a laboratory owned by a pharmaceutical company may know little about how pharmaceuticals are produced or even how the drug works on the human body. In other cases both kinds of understanding are needed. Thus a chemical engineer working on a way to produce a new plastic must know both standard production practice and a lot of formal chemistry. If the two types of understanding are separated too widely, problems of execution can easily result. But whatever the optimal mixture or practice, the industries in which the U.S. forged ahead after World War II required experience, specialized training, and organized research and development for effective advancement of the technology.

How then did the U.S. achieve its new lead in high technology industry? By investing more than other nations in training scientists and engineers, and in R&D in these technologies. The groundwork for these massive investments had been well laid earlier. We have described the rise of industrial R&D, and the rise of higher education. By World War II the U.S. had a number of world class firms in science-based industries, and several universities doing world class research. But the U.S. was not dominant in high technology industries.

B. *The Surge of Investment in R&D*

World War II changed the context. Victory brought a new sense of confidence and pride in America's strength, an awe for the power of science and technology engendered by their role in winning the war, and a burning belief in their capabilities for opening new horizons for the future. The write-ups of wartime science clearly were designed to kindle this appreciation on the part of the public (e.g., James Baxter 1946). Vannevar Bush's *Science, The Endless Frontier* (1945) gave the trumpet call, and the United States was off to levels of investment in science and technology that were historically unprecedented.

Before the war Americans had on average roughly double the years of post-secondary education as did the Europeans, although as we have noted the statistics may exaggerate the actual size of the educational gap. Between 1950 and 1973 the average number of years of American post-secondary education again doubled, further widening the gap. In part this was a simple consequence of affluence and a belief in the value of education. But the trend was also strongly encouraged by government policies. The G.I. bill of rights, which guaranteed educational funding to all qualified veterans, was both emblematic and an important factor in its own right. College fellowships became available through a number of other public programs. The state-supported part of the American higher education system provided significant additional funding and subsidy. Only a relatively small share of the new wave of university students went into natural science and engineering. But the sheer numbers meant that there was a large increase in the supply of trained scientists and engineers.

The expansion of supply was also supported, and in part propelled, by major increases in demand, from several sources. A small but important fraction was employed by the rapidly expanding U.S. university research system. The scientists and engineers who had engaged in the war effort had striking success in their argument that university science warranted public support, and during the half decade after the war the government put into place machinery to provide that support. The new research support programs of the National Science Foundation and the National Institutes of Health provided public funding of university basic research across a wide spectrum of fields. However, the bulk of government support for university research came not from these agencies but from agencies pursuing particular missions and using university research as an instrument in that endeavor. Thus, the Department of Defense and the Atomic Energy Commission provided large scale research funding in fields of particular interest to them. And the support was not just for basic research. These agencies funded research that involved applied science and engineering departments in work at the forefront of technologies in materials and electronics. By the middle 1950s the American research universities clearly were ahead of those in the rest of the world in most fields. Just as young American scholars flocked to German universities to learn science during the late 19th century, so young students from Europe, Japan, and other parts of the world came to the United States for their training.

The largest share of the increased demand for engineers and scientists, however, came from a vast expansion in the number of American companies doing R&D and in the size of their R&D programs (Mowery and Nathan Rosenberg 1989). Figure 8 displays estimates of the

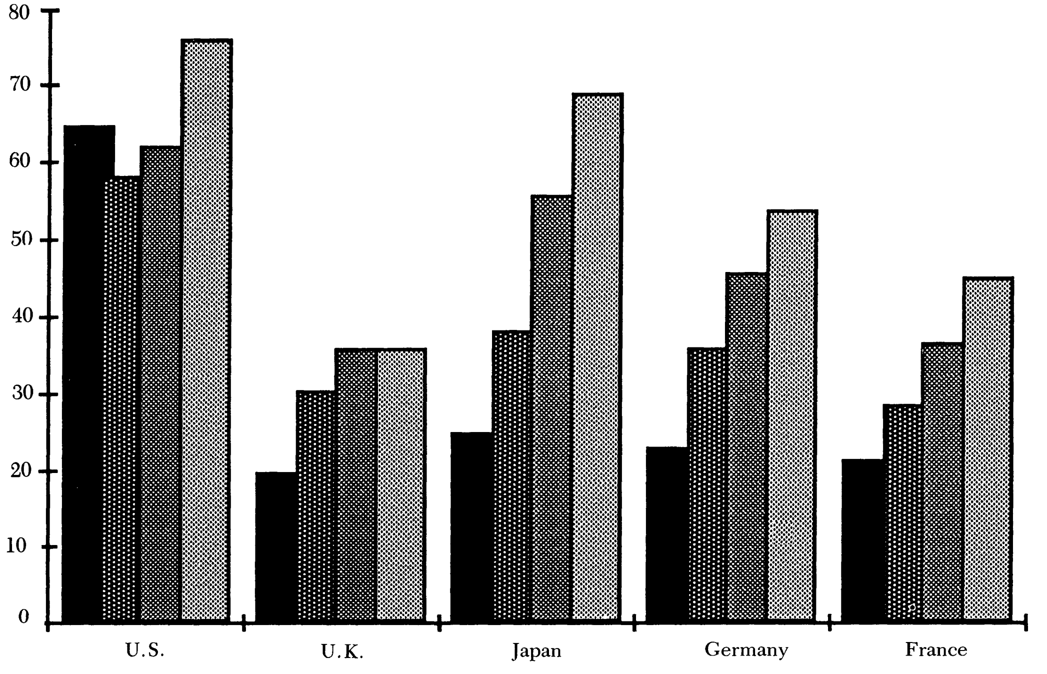

Figure 8. Scientists and Engineers Engaged in R&D per 10,000 Workers: 1965, 1972, 1981, 1987
Source: U.S. National Science Board, (1989 and 1991, Appendix Table 3–19).

number of scientists and engineers engaged in R&D (including corporate, university and other organizations) as a fraction of the workforce. Figure 9 shows the same phenomenon in terms of R&D as a fraction of GNP. Between 1953 and 1960 total R&D expenditures (in constant dollars) more than doubled, and the ratio to GNP nearly doubled. Employment of scientists and engineers in industrial research grew from fewer than 50,000 in 1946 to roughly 300,000 in 1962. Other countries lagged in increasing these kinds of investments. As late as 1969, total U.S. expenditure on R&D was more than double that of the U.K., Germany, France, and Japan combined. But by then the slowdown in U.S. productivity growth had already begun.

The R&D figures exaggerate somewhat the increase in investments in technical progress (Luc Soete et al. 1989). While formal R&D is the principal vehicle for technological advance in the science based industries, a good share of the work of improving manufacturing processes goes on outside formal R&D organizations, and often is not included in the R&D statistics. For example, a major part of improvement is often in design, usually done in an engineering department and often not counted as R&D despite the fact that it involves comparable activities. Many small firms engage in inventing, design, and development work without a formal R&D department and often without reporting any R&D. During the period in question the term R&D was becoming fashionable, and it is likely that a growing fraction of that work was so labeled. With all of these qualifications, however, it is clear that the increase in resources allocated to advancing technology was massive, and not matched in other countries.

The rise of corporate R&D in the U.S.

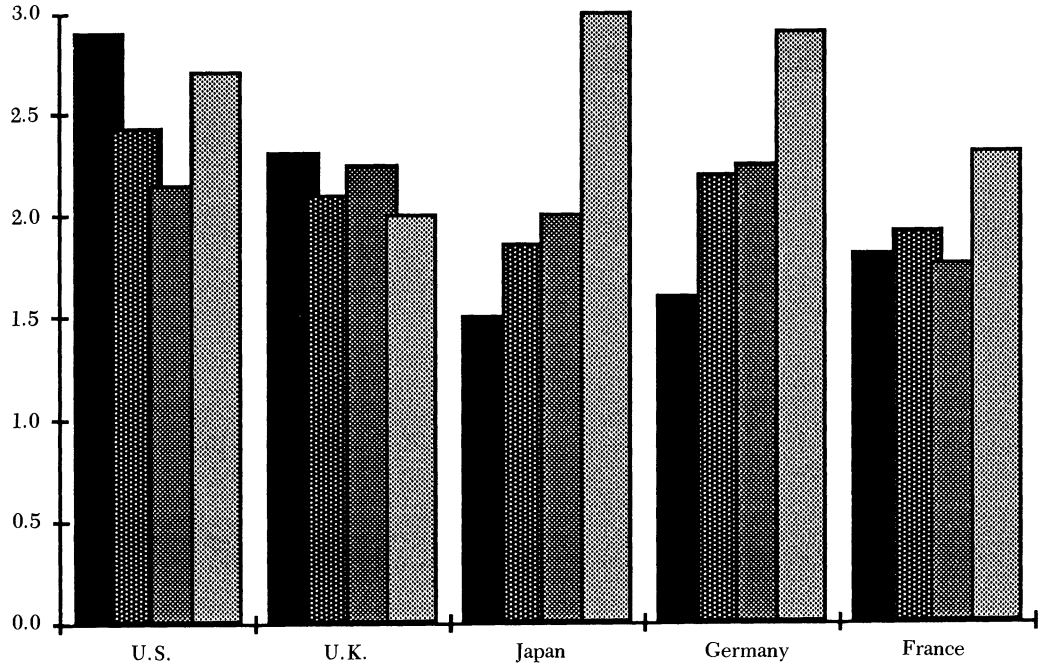

Figure 9. Expenditures for R&D as Percentage of GNP: 1964, 1971, 1978, 1989

Source: U.S. National Science Board (1989, Appendix Table 4–19; 1991, Appendix Table 4–26).

had two sources. Partly it was the result of major increases in private corporate R&D funding, based on optimistic beliefs in the profitability of such investments, a belief which by and large was well founded. Partly the rise came from large DoD, and later NASA, investments in new systems. In the mid 1960s private funds accounted for about half of corporate R&D, government funds the other half. In some industries, such as pharmaceuticals and other chemical industries, corporate funds provided almost all the support. In others, such as electronics, there was both strong private effort in such firms as AT&T and IBM, and large scale DoD funding. In industries like jet engines and space systems almost all the funding was DoD or NASA.

American dominance in computer and semiconductor technologies gained most European attention and concern during the 1950s and 1960s. These were considered the leading edge technologies of the era, and many foreign observers attributed the American advantage to defense support. Military and to a lesser extent space R&D support certainly was important. But military demands and money were going into an R&D system that was well endowed with trained scientists and engineers, had a strong university research base, and was populated with companies that were technically capable.

During the 1930s those concerned with the capabilities of the armed forces, both in Europe and the United States, were sharply aware of the advantages that could be gained by enhanced ability to solve complex equation systems rapidly. Ballistics calculations were perhaps the dominant concern, but there were others as well (Kenneth Flamm 1987; Barbara Katz and Almarin Phillips in Nelson 1982). Prior to and during World War II the German and British as well as the

U.S. funded research aimed at developing a rapid computer. It is clear enough that during and shortly after the war, by which time the feasability of electronic computers had been established, the United States vastly outspent other governments in bringing this embryonic technology into a form that was operational in terms of military needs. Several major research universities were involved in the effort, notably MIT. IBM and AT&T participated actively. Early assessments were that the nonmilitary demand for computers would be small. It was apparent by 1960, however, that nonmilitary demand would be large, and it also turned out that the design experience that the major U.S. companies had had in their work on military systems was directly relevant to civilian systems.

The story regarding semiconductors is somewhat different (Franco Malerba 1985; Richard Levin in Nelson 1982). Although military funds had gone into semiconductor devices during World War II, it was the Bell Telephone Laboratories that came up with the critical discoveries and inventions, using their own money, and motivated by the perceived technological needs of the telephone system. Once the potential had been demonstrated, however, the armed services, and later NASA, quickly recognized the relevance of the technology to their needs. Significant government R&D went into supporting technical advance in semiconductors and, perhaps more important as it turned out, the DoD and NASA signaled themselves as large potential purchasers of transistors. The evidence is clear that major amounts of private R&D money went into trying to advance semiconductor technology, in anticipation of a large government market. And in the field of semiconductor technology, as well as computer technology, design experiences with the transistors and later the integrated circuits that were of high value to the military set companies up to produce items for civilian products.

By the mid 1960s the American lead in the new high technology industries, like the old lead in mass production industries, was widely taken as a fact of life, a source of pride for Americans, and of concern to Europeans, but not readily subject to change. Jean Jacques Servan Schreiber pointed to the U.S. lead with alarm, arguing that if Europeans did not act quickly to catch up, they would be permanently subservient to the Americans. His diagnosis of the sources of American strength was rich and complex, if in places ironically amusing in the face of subsequent developments. He pointed not only to American investments in R&D and in science and engineering education, but to the overall quality of the American workforce, its willingness to cooperate with management, and the skill, energy, and willingness to take risks that he believed characterized American management.

In its famous "technology gap" studies, the OECD provided a more systematic, nuanced, and variegated diagnosis. The OECD argued that there was little that American scientists and engineers knew that good Europeans ones did not know also. The "gaps" stemmed mainly from management and organization, and experience, just as we have stressed. Technology is partly in books and mind, partly in the fingers and organization. The information part is largely a public good for those with the requisite training and experience. But the latter part involves significant firm specific investment and learning. Ironically, just at the time when American dominance was most visible, conditions were changing to undermine its sources. By the 1960s the U.S. lead was shrinking, both in the areas of longstanding strength, and in the new high technology fields.

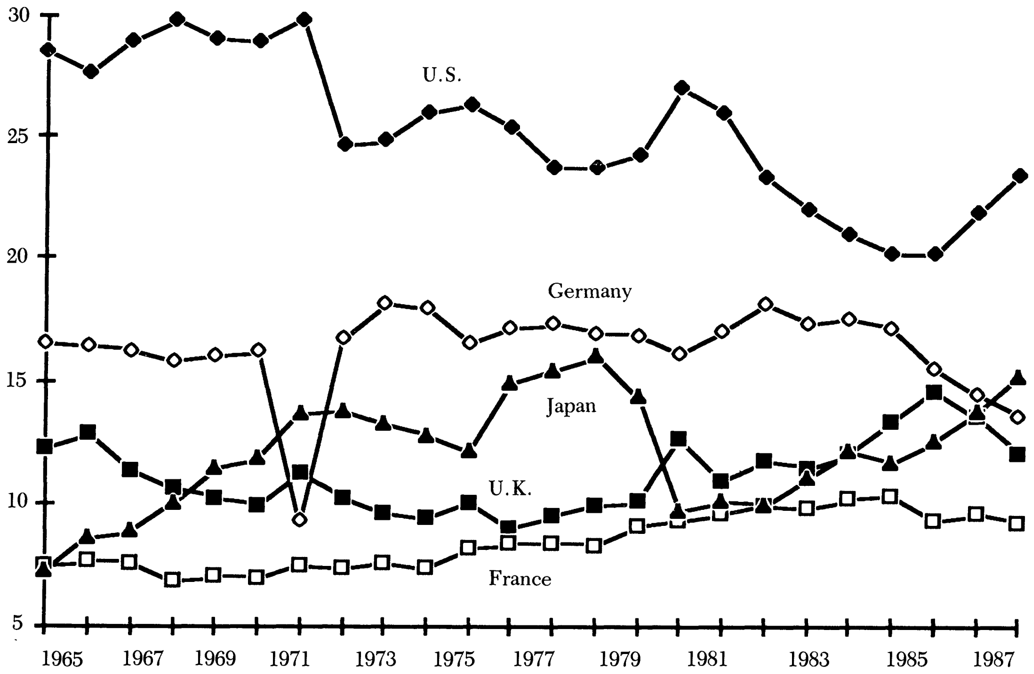

Figure 10. Country Shares of World High-Technology Exports, 1965–1988

Source: U.S. National Science Board (1987, Appendix Table 7–10; 1989, Appendix Table 7–10; 1991, Appendix Table 6–7). Note that decline for Japan in 1980 corresponds to shift in basis of calculation.

V. *The Closing Gaps*

The period since the middle 1950s has seen a dramatic narrowing of the economic and technological gaps among the major industrial powers, largely ending a leadership position nearly a century old. The U.S lead in high technology industries was a more recent phenomenon. Interestingly, it appears to have held up better than the general U.S. economic lead. Figure 10 shows the share of the major industrial nations in exports of high technology products over the period since 1965. Contrary to popular belief the U.S. share has diminished only slightly. The major change has been in the position of Japan relative to Europe, although the latest revised figures soften the picture. Figure 11 shows U.S. exports and imports of high technology products since 1970. It has been the growth of U.S. imports, particularly since 1983, not a decline of export performance, that has been the principal source of the erosion of the U.S. high technology trade balance.

The data on patents reflect the same pattern. Since 1970 there has been a significant decline in the share of patents taken out in the U.S. assigned to Americans. However, a large part of this decline reflects a rise in the fraction of inventions originating in other countries that are patented in the United States. From the middle 1960s to the middle 1980s the share of all world patents given to Americans has been relatively constant. Japan's share has risen dramatically, mainly at the expense of Europe. Many analysts have noted that U.S. patenting has shown an absolute decline

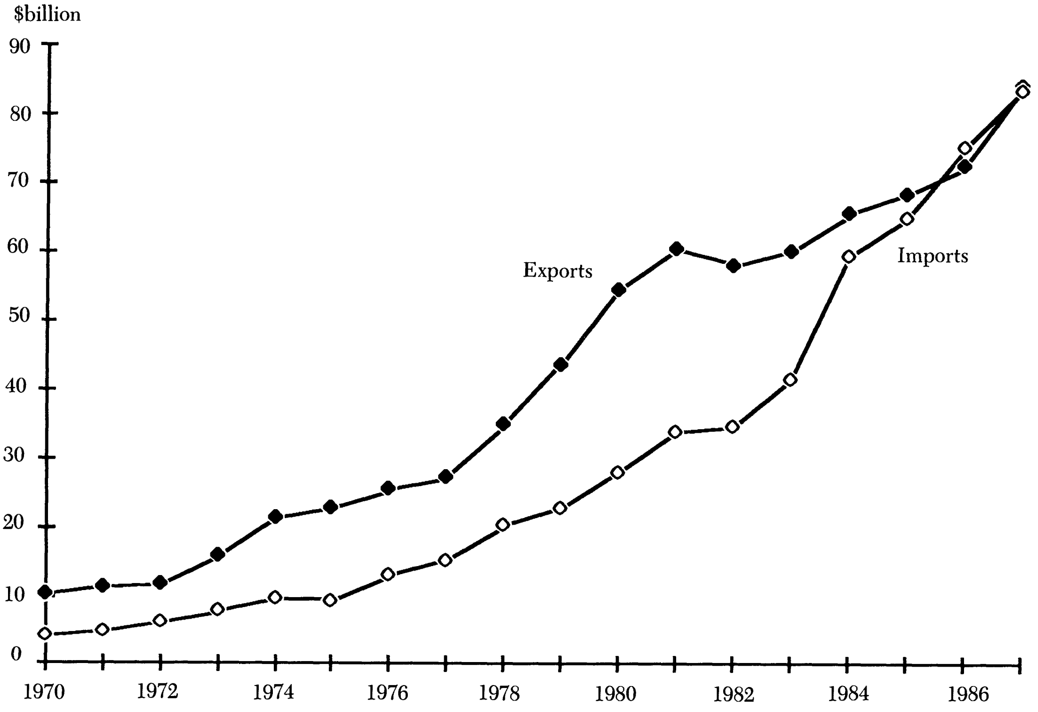

Figure 11. U.S. Trade in High-Technology Products, 1970–1987

Source: U.S. National Science Board (1989, Appendix Table 7–14)

since the late 1960s. That is so, but it is also true of the major European countries and the U.S. rate has partially recovered since 1980. We do not know what forces may account for these trends, but of the major industrial nations only Japan has experienced an increase in patenting (U.S. National Science Board 1991).

Within the group of industries in question, more fine-grained analysis displays a more variegated picture regarding U.S. performance. Between the middle 1960s and the middle 1980s, the U.S. export share held up well in aircraft, aircraft engines and turbines, computing and other office machinery, and in several classes of chemical products. The U.S. export share declined significantly in professional and scientific instruments, and in telecommunications. U.S. firms were routed in consumer electronics. The data on national patenting show a similar pattern. By and large U.S. export shares have persisted in industries where U.S. patenting has held up, and declined where patents by nationals elsewhere have risen relative to American patenting.

The definition of high technology industries is somewhat arbitrary in that it is tied to R&D intensity exceeding a particular level. A number of industries are excluded from the definition, whose product and process technologies are complex and sophisticated, and where technical advance has been significant. Automobiles, machine tools, and other kinds of machinery are examples. By and large U.S. export share and patenting have fallen significantly in these industries. Europe has done rather well. In contrast, the U.S. continues to be the export and patenting leader in many industries connected with agricultural products and others based on natural resources.

Thus beneath the surface of general productivity convergence, there is a much more variegated picture. U.S. performance continues to be strong in several of the most R&D intensive industries, and those connected to natural resources. It has declined in many of the industries—like automobiles, consumer electrical products, and steel making—where the U.S. had a dominant world position since the late nineteenth century. The interesting question, of course, is how this broad convergence came about. What were the forces behind it?

We would highlight four different developments. First, the decline in transportation costs and trade barriers has greatly expanded the flow of world trade, eroding the advantages in market size and raw material costs that U.S.-based firms used to have. Second, technology has become much more generally accessible to those with the requisite skills and willing to make the required investments, and hence much less respecting of firm and national boundaries than had been the case earlier. Third, the other major industrial powers significantly increased the fraction of their work forces trained in science and engineering, and the fraction of their GNP allocated to research and development, thus establishing strong indigenous competence to exploit technologies from abroad, as well as to create new technology. Indeed, by 1980 a number of countries were outspending the United States in nonmilitary R&D as a fraction of GNP. This is important, because the fourth major factor behind convergence was, in our view, a decline in the importance of spillover from military R&D into civilian technology.

The period since 1960 has seen a significant rise in the percentage of manufactured products exported and imported in virtually all major industrial countries. Between 1960 and 1980, U.S. imports roughly doubled as a fraction of GNP. In France, Germany, and the U.K. taken as a group, the ratio of imports to GNP increased by about fifty percent. It grew by a quarter in Japan. All of these ratios were substantially higher for manufacturing alone. Thus, over this period, efficient companies producing attractive products increasingly faced a world rather than a national market. At the same time, trade in natural resources greatly expanded, and countries became less dependent on local materials. Postwar resource discoveries were far more dispersed around the globe than previously. Although the United States continued to be a large contributor to world mineral production, the country became a net importer of most major minerals, implying that the cost to industrial users was essentially the same as that in other countries. Thus the twin advantages long possessed by American mass producers—cheap raw materials and more-or-less exclusive access to the world's largest market, both have dissolved. Despite continuing fears of a return to protectionism, by the 1980s much of the world had largely become a common market.

At the same time, business has become increasingly international. Technologically progressive American companies had established European branches even in the 19th century, but the scale of overseas direct investment surged dramatically during the 1950s and 1960s. In *The American Challenge*, Servan Schreiber expressed concern that American companies were taking over the European economy at least as much by investing there as by exporting. By the late 1960s Europe was beginning to return the favor by establishing branches or buying plants in the United States. Recently Japanese companies have done the same, on a larger scale.

The internationalization of business has greatly complicated the interpretation of international trade statistics. For example, a nontrivial share of the rising U.S. imports in high technology industries mentioned above originate in foreign subsidiaries of U.S.-owned companies (Richard Langlois 1987, ch. 4). While the U.S. share of world manufacturing exports (low and middle tech as well as high tech) fell somewhat from the middle 1960s to the middle 1980s, the export share of U.S.-*owned* firms held up, with gains in exports from foreign branches matching declines in exports from U.S.-based plants (Robert Lipsey and Irving Kravis 1986).

The internationalization of trade and business has been part and parcel of the second postwar development that we want to highlight—the erosion of firm and national borders as barriers obstructing or channeling access to technology. Modern science has, from its beginnings, been an international activity. The ethos of science has for centuries stressed the public and international nature of scientific knowledge. British and French scientists continued to communicate during the Napoleonic wars, and attempts by national governments to define and keep separate a particular national science have often been condemned by the scientific community. Despite this ancient tradition, the real world of practical science has also displayed strong national elements, explicitly so in wartime, implicitly at other times in language, terminology, institutional structures, and objects of study.

In contrast to the universalist ethos of science, the notion that individuals and firms have proprietary rights to their inventions has been accepted for many centuries, and so too the idea that it is appropriate for a nation to gain advantage from the inventive work of its nationals. Nations have often tried to keep national technologies within their borders, however futile these efforts may often have been in many cases. Though technologists from different countries have communicated, and formed something of an international community, until recently the notion that best-practice technology was approachable by any nation with requisite resources was probably not correct. The technological advantage of the American mass market firms in industries like steel and automobiles did not derive from patents or well-protected secrets, but largely from experience gained well ahead of foreigners because of differences in the economic environment. With firms all over the world facing a common market for products and inputs, the forces that used to provide U.S. companies with incentives to get into certain technologies first have been largely eroded.

While the increasing similarity of economic environments may be the immediate reason for the convergence of technological capabilities, another important underlying development in the post World War II era is that many technologies became more like sciences than before. Earlier we described the particular characteristics of science-based industries like chemical products and electronics. It is noteworthy that patents in these industries (and recently in bio technology) have tended to cite scientific literature to a far greater extent than do patents in fields like steel and automobiles. Since 1960, however the number of citations to scientific literature in patents has increased significantly in almost all technological fields, including steel and autos (Narin and Noma 1985). In contrast to an earlier era, a larger proportion of the generic knowledge relevant to a technology now is written down, published in journals, discussed at national and international meetings, taught in schools of engineering and applied science.

Internationalization of business is an important part of this story. It is not just that foreigners can learn what American engineers can learn by going to American universities. European engineers can observe American technology in operation in their home countries, and purchase operating American firms. Companies like IBM have industrial research laboratories in a number of different countries, each employing a mix of nationals. In turn, scientists from IBM and scientists from Phillips, and Fujitsu, meet at conferences and exchange papers. Employees often move across national borders, within a firm or between firms. These are truly international networks, involving highly trained scientists and engineers, employed in universities and in industry, undertaking significant R&D efforts. The technologies emerging from such networks no longer have geographic roots, because horizons have become global, and because material resource inputs more generally have declined in importance, relative to processing.

Generic technological knowledge, of the sort taught in graduate school, written down in books and articles, and exchanged among high-level professionals, does have strong public good attributes. However, access is limited to those with the requisite training, and in many cases only someone who is actually doing research in a particular field can understand the significance of publications in that field. To take industrial advantage of generic knowledge, or technology that is licensed from another company, or more generally to understand what another company has done and how, generally requires significant inputs of trained scientists and engineers, plus research and development expenditure aimed to tailor what has been learned to the specific relevant uses (Pavitt 1987; Nelson and Winter 1982; Nelson 1988).

The other major industrial nations have, with a lag, followed the United States in making those big investments in education and training, and R&D. The convergence in scientists and engineers in R&D as a fraction of the workforce, and in R&D as a fraction of GNP, shown in Figures 8 and 9, is an essential part of, and a complement to, the internationalization of technology. Definitions of these concepts are subject to continuing debate and change, and the most recent revisions by the National Science board put the current U.S. position in a more favorable light. By any definitions, however, the direction of change is clear. The U.S. lead in the early 1960s is striking. Convergence has occurred among those nations with modern educational systems, strong internal scientific and engineering communities, and sophisticated industrial enterprises. Nations without these attributes have tended to fall farther and farther behind the frontiers. There are now few important technological secrets, but it takes major investments of many kinds to command a technology.

Military technology has had a somewhat different history. The major military powers, prominently the U.S., continue to bend strong efforts to prevent military technology from leaking away to potentially hostile nations, or to nations who might serve as a conduit to hostile nations. But just as the political context of world conflict has changed with the end of the cold war, the economic context has altered completely. While American dominance of the frontiers of military technology gave us significant civilian technology advantages during the 1950s and 1960s, today it buys us little outside the military sphere. In terms of access to technology that affects productivity in industry broadly defined, it does not hurt the Europeans or the Japanese that American companies are engaged in military R&D to a much greater extent than they are, and that access to that technology is difficult if not closed.

There are several reasons for the diminished importance of military R&D as a source of technological advantage outside the military field. First, while initially civilian demands for computers, semi-conductors, and jet aircraft had lagged behind military demands, by the mid-1960s the civilian market for these products was as large or larger than the military; and in many dimensions, the performance demanded by the civilian market was actually higher. Companies responded by mounting their own R&D projects to meet these demands. Indeed, a strong case can be made that from the late 1960s the major direction of "spillover" was from the civil to the military. Thus the military bought the KC 10 as its tanker of choice, a plane that grew out of the McDonnel-Douglas DC 10, designed by the company for use by commercial airlines.

At the same time, military R&D increasingly focused on areas where its needs were specialized, engaging in specific product development efforts as contrasted with broadly applicable research. The percentage of military R&D that went into research and experimental development has diminished significantly. With the end of the cold war, the outlook is for further decline in military R&D along with military spending more generally, but at this point we do not foresee dire consequences for American technology as a result.

VI. *Conclusion*

Let us recapitulate. We have argued that the postwar American technological lead had two conceptually distinct components. There was, first of all, the long standing strength in mass production industries that grew out of unique conditions of resource abundance and large market size. There was, second, a lead in "high technology" industries that was new and stemmed from investments in higher education and in research and development, far surpassing the levels of other countries at that time. Several factors lay behind the erosion of these twin leads. The most basic of these is that over the post World War II era, commodity and resource trade, business and finance, and technological communities, have all become increasingly transnational rather than national.

In his now classic 1986 article on convergence, Abramovitz distinguished between two variables influencing the extent to which (firms in) countries that are technologically behind a leader are able to catch up. One of these was "opportunity." The other was "social capabilities." Abramovitz noted that while the U.S. was the clear productivity leader from before World War II, there is little evidence of other countries doing much "catching up" prior to the post World War II era. Our arguments above attempt to flesh out the reasons for this delay. Other countries with the requisite social capabilities, principally then in Europe, lacked the market size and resource availabilities that lay behind the U.S. advantage in mass production industries, and barriers to external trade foreclosed the possibility of replicating the U.S. path on an international basis. Until trade barriers came down after World War II, the "opportunities" really were not there. The reason for persistence of the U.S. lead in "high tech" industry was somewhat different. Until the European nations and Japan made the requisite massive investments in scientific and engineering education, and in R&D, they lacked the "social capability" to catch up in these industries.

It is not our intention here to resolve the full range of issues raised in the convergence literature. We do have two related observations. First, much of the literature treats technology as if it were a "public good," allowing only that there may be some friction in moving it around. Instead, as we have argued, much of what is involved in mastering a technology is organization-specific investment and learning. Hands-on technological capability is more like a private good than a public good. For that reason, if the economic conditions and incentives facing firms in different countries differ significantly, then firms in one country will require technological capabilities very different from those in another country. This argument is far removed from the conventional distinction according to which firms simply "choose" to employ different techniques (e.g., factor mixes) within a common underlying technology. To the extent that our interpretation holds, there is nothing automatic about convergence.

Secondly, however, since the 1950s the world has been changing so that, as a reduced form, the convergence model looks more and more plausible. In our view, it is the internationalization of trade, business, and generic technology and the growing commonality of the economic environments of firms in different nations that have made it so.

We believe that the internationalization of trade, business, and technology is here to stay. This means that national borders mean much less than they used to regarding the flow of technology, at least among the nations that have made the now needed social investments in education and research facilities. National governments have been slow to recognize these new facts of life. Indeed, the last decade has seen a sharp increase in what has been called "techno-nationalism," policies launched by governments with the objective of giving their national firms a particular edge in an area of technology. Our argument is that these policies do not work very well any more. It is increasingly difficult to create new technology that will stay contained within national borders for very long in a world where technological sophistication is widespread and firms of many nationalities are ready to make the investment needed to exploit new generic technology.

A closely related observation is that a well-educated labor force, with a strong cadre of university trained engineers and scientists at the top, is now a requirement for membership in the "convergence club." This is not to denigrate the continued importance of hands-on learning by doing and using, but in modern technologies this is not sufficient. It is no accident that countries like Korea and Taiwan, which have been gaining so rapidly on the world leaders, now have populations where secondary education is close to universal for new entrants to the work force, and where a significant fraction of the secondary school graduates go on to university training (Baumol, Blackman, and Wolff 1989; Barro 1991).

In our introduction we acknowledged another interpretation of convergence—that the trends reflect a growing incapacity of the American economy, and foreshadow the United States falling behind Japan, and perhaps Germany, as Great Britain fell behind the new leading economies at the turn of the last century. While we argue that the principal factor driving convergence over the last quarter century has been internationalization, we do not dismiss the possibility that the United States may be in the process of slipping into second, third, or fifth rank in productivity and per capita income, and in terms of mastering the application of several important technologies. Although the forces that now bind together nations with sufficient "social capabilities" are far stronger than they were in the past, there is certainly room for variance within that group. If the notion of social capability includes, not merely the educational levels at leading universities and research laboratories, but the social and political processes affecting the educational system, transportation and communications networks, and the legal and regulatory apparatus of federal and state governments, then it is entirely possible that a once-dominant nation may slip into social paralysis and decline. The distressing examples of Britain and Argentina are often cited, and Robert Reich (1991) argues that the U.S. is in danger of a similar fate.

To enter this question would require us to survey several additional bodies of literature, and we cannot do that here. There is, first, the puzzle of the extraordinarily slow growth rate of U.S. per worker productivity, per capita income, and total factor productivity, since the early 1970s. There is, second, the question of the national rate of savings and its link to investment: despite the increased flows of financial and direct foreign investment, it is still true to a considerable extent that a nation's volume of investment is closely related to its own flow of savings (George Hatsopoulos, Paul Krugman, and Lawrence Summers 1988), and that the growth of productivity is linked to capital investment (Landau 1990). Third, there is the literature proposing that the U.S. has lagged *because* it was the pioneer of older forms of corporate organization, which have now been made obsolete by radically different ways of organizing companies and political economies (e.g., Freeman 1987; Dertouzos et al. 1989; Lazonick 1990). These and other vital issues are beyond the scope of this article. But none of them impinge upon our basic argument, that the advanced nations of the world have come to share a common technology.

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The Origins of American Industrial Success, 1879–1940

By Gavin Wright*

The United States became the world's preeminent manufacturing nation at the turn of the twentieth century. This study considers the bases for this success by examining the factor content of trade in manufactured goods. Surprisingly, the most distinctive characteristic of U.S. manufacturing exports was intensity in nonreproducible natural resources; furthermore, this relative intensity was increasing between 1880 and 1920. The study then asks whether resource abundance reflected geological endowment or greater exploitation of geological potential. It was mainly the latter. (JEL 042)

Recent thinking about American economic performance has been marked by alarm over the country's loss of its "competitive edge." Most of this discussion is not rooted in an understanding of the historical origins of the economic leadership now thought to be in jeopardy. Modern economists tend to assume that the American advantage has been technological and dates from the remote recesses of history, about as far back as anyone really cares to go. In a volume on U.S. competitiveness, Harvey Brooks writes: "Both our firms and our government, *long accustomed to being the technological leaders in almost every field*, have until recently measured their performance against domestic rather than foreign competitors" (Bruce R. Scott and George C. Lodge, 1985, p. 331; emphasis added). For one country to maintain a technologically based advantage over others for long historical periods is anomalous, and surely calls for explanation. Indeed, it is difficult to see how policies can respond appropriately to "what we have lost" without knowledge of what it was that we had and how we got it. It would be an understatement, however, to say that the subject has been understudied. This paper makes a modest beginning by analyzing American trade in manufactured goods between 1879 and 1940. The competitive success of American manufacturing exports in foreign markets is by no means a comprehensive measure of "success." But because the turn of the century marked the emergence of the United States to a position of world economic preeminence, we may hope to learn something about the broader questions by studying the characteristics of the country's trade with the rest of the world during that key era.

The results are surprising. They suggest that the single most robust characteristic of American manufacturing exports was intensity in nonreproducible natural resources. In fact, their relative resource intensity was *increasing* over the half-century prior to the Great Depression. This does not mean that there was no American technological leadership, in the broad sense of that term. Abundant resources were themselves in many ways a reflection of the advanced state of American technology. But the distinctively American industrial innovations were in many respects specific to the pre-World War II U.S. resource environment and national market, both of which were unique among the countries of the world. Since then, relative American resource abundance has greatly diminished, not primarily

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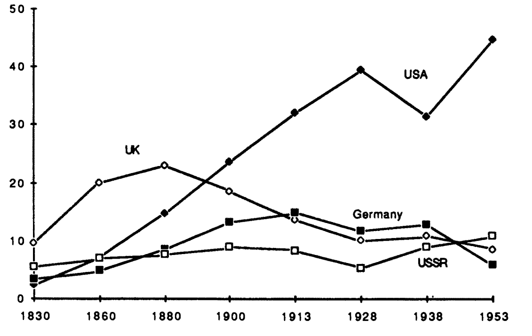
from depletion of national reserves but because of the integration of world markets for minerals and other commodities. Twentieth-century patterns of resource discovery and production suggest that the historic basis for U.S. mineral abundance was much more a matter of early "development" than of geological "endowment."

I. The Ascendance of American Industry on a Global Scale

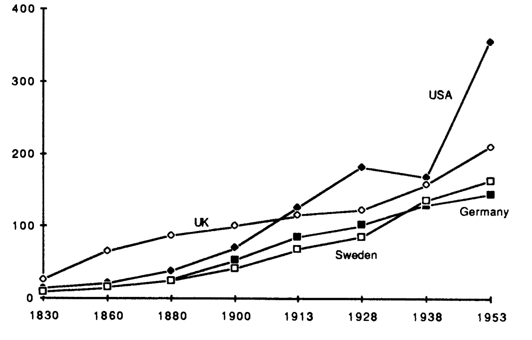
Americans have enjoyed high material living standards since the eighteenth century if not earlier, and the acceleration to modern rates of per capita growth occurred during the first half of the nineteenth century. Broadly based American *industrial* leadership on a worldwide basis, however, can only be dated from the very end of the nineteenth century. According to Paul Bairoch (1982), the U.S. share of total world manufacturing output passed Great Britain's between 1880 and 1900 (Chart 1). In per capita levels of industrial output, the United States was a weak fourth among the nations of the world in 1880, and surpassed Britain only after 1900 (Chart 2). Contemporary testimony suggests that American technology and manufactured goods began to play a qualitatively different role in the world as of the 1890s or shortly thereafter. The first wave of alarmist European books on "Americanization" dates from 1901 and 1902, with titles and themes (*The American Invaders*, 1901; *The Americanization of the World*, 1901; *The American Invasion*, 1902) that would again become familiar in the 1920s and 1960s (William Woodruff, 1975, p. 123). Rapid inflows of standardized, machine-made American shoes after 1894 (said to be more comfortable and more stylish than the traditional types) caused consternation in the British boot-and-shoe industry and forced a drastic technological overhaul (R. A. Church, 1968). Equally dramatic was the burst of American exports of machine tools and other engineering goods after 1895, not only to Britain but to the Continent and other parts of the world (Roderick C. Floud, 1974, pp. 60–62; 1976, pp. 72–82). Though the suddenness of the American

CHART 1. SHARES OF WORLD INDUSTRIAL OUTPUT, 1830–1953



Source: Bairoch (1982, pp. 296, 304).

CHART 2. INDUSTRIAL OUTPUT PER CAPITA



Source: Bairoch (1982, pp. 294, 302).

"invasion" after 1895 may be attributable to temporary factors, it seems clear that a crossover point of some sort was reached at that time.[1]

Industry studies seem to confirm this timing. Robert Allen has shown that prior to the 1890s American blast furnaces had no distinctive world-class status in either labor productivity or fuel efficiency (Allen, 1977, pp. 608–609). By 1900, after key break-

[1]S. J. Nicholas (1980) argues that the apparent decline in the price of American "engineering goods" mainly tracks the prices of iron and steel products, and that the sudden "invasion" of U.S. goods reflected temporary delivery lags by British firms during 1895–1900. As argued below, both of these elements reflected more lasting features of American industrial success.

throughs in adapting the technology to the new Mesabi iron ore, the U.S. industry was the world leader by both of these indicators. Pig iron was an input in the production of steel, which was in turn crucial for railroads, construction, and a wide range of machinery and manufactured goods. According to Allen, before the 1890s American steel rails would not have been competitive in the domestic market without tariff protection (Allen, 1981). Advances in steel were in turn complementary to progress in other industries. U.S. rubber-tire makers, for example, were well behind the French during the bicycle craze of the 1890s, and only gained a productivity advantage in conjunction with mass production of automobiles shortly before World War I (M. J. French, 1987, p. 66). None of this denies that twentieth-century U.S. technology emerged from an evolutionary learning process over a much longer period, as economic historians have long stressed (Paul David, 1975; Nathan Rosenberg, 1976; David Hounshell, 1984). But the qualitative changes in industrial America's place in the world after 1890 justify a closer look at this period.

The timing of U.S. industrial performance corresponds closely to the more comprehensive finding of U.S. world leadership by Angus Maddison, based on estimates of Gross Domestic Product per manhour (Maddison, 1982, p. 212; compare also Moses Abramovitz, 1986). But Maddison seems to assume that U.S. leadership in *productivity* corresponded closely to a position of "world leadership" in *technology*. This is surely not the only possibility. In terms of conventional growth-accounting, the U.S. edge could equally well have been attributable to capital or natural resources. Interestingly, Maddison's figures actually show that the world leader in GDP per man-hour prior to World War I was not the United States but Australia. His explanation is confined to a footnote: "In defining productivity leadership, I have ignored the special case of Australia, whose impressive achievements before the First World War were due largely to natural resource advantages rather than to technical achievements and the stock of man-made capital" (p. 258). Can we be certain that the United States was not also a "special case" whose performance depended on "natural resource advantages"?

Contrary to expectations of increasing resource scarcity, post–Civil War American development featured *declining* relative costs of materials (Louis P. Cain and Donald G. Paterson, 1981, pp. 358–360). Major new metals discoveries continued until World War I, while the rate of discovery of new oil fields accelerated after 1900 (U.S. National Resources Committee, 1937, p. 149). The timing of leadership in industrial production coincides remarkably with American world leadership in coal production (after 1900), and that margin also grew over time. The United States was also the world's leading producer of copper, petroleum, iron ore, zinc, phosphate, molybdenum, lead, tungsten, and many other minerals. At the same time, continuing advances in internal transportation reduced the real costs to manufacturers, creating what historical geographers call the "minerals-dominant economy" of the late nineteenth century (Harvey S. Perloff and Lowden Wingo Jr., 1961, pp. 193–197). The improvements were often qualitative as well as quantitative, most strikingly perhaps in the iron ore from the rich Mesabi range, which began to arrive in the steel mills of the lower Great Lakes in the 1890s. Allen's estimates of total-factor-productivity in iron and steel as of 1907–1909 put the United States at a par with Germany (15 percent ahead of Britain), but the ratio of horsepower to worker was twice as large in America as in either of the other two contenders (Allen, 1979, p. 919). If we were to adopt the conventional view that resource abundance is an *alternative* to technologically based manufacturing, we might well be led to question the authenticity of America's leadership position before World War II. But as argued below, this is not the only choice available to us.

II. Hypotheses from the International Trade Literature

A number of hypotheses bearing on American industrial history emerge from the literature on the bases for international trade. According to the Heckscher-Ohlin model, the composition of a country's trade reflects the relative abundance of factors in that country's endowment. Simple two-factor versions of this theory have frequently been rejected, beginning with the "Leontief Paradox," which revealed that in 1947 U.S. exports were more capital-intensive than were competitive imports (Wassily Leontief, 1953). Attempts to rationalize this result, however, have generated more refined propositions. According to the "neo-factor-proportions" approach, American exports have actually been intensive in skills or human capital. This interpretation was suggested by Leontief himself, and has been supported by an empirical regularity first identified by Irving B. Kravis (1956a), that average wage levels in American export industries have been persistently higher than wage levels in import-competing industries. It has become a standard convention in empirical trade studies to take the relative industry wage as a proxy for skill requirements, and on this basis the skill intensity of American exports has been claimed as a pattern as far back as 1899 if not earlier (Helen Waehrer, 1968). Studies for more recent periods have supported this view with detailed evidence on the occupational structure of the labor force (Donald B. Keesing, 1968).

An alternative "third factor" interpretation for the paradox is that capital is complementary to natural resources, and that the United States had moved into a position of resource scarcity by 1947 (Kravis, 1956b). This possibility is supported by Jaroslav Vanek's important study of the natural resource content of U.S. foreign trade, 1870–1955 (Vanek, 1963), which showed that the country had moved from a net export to a net import position in natural resources over that period. This finding raises the possibility that U.S. comparative advantage may have had a different basis at an earlier time.

A different (though not necessarily mutually exclusive) intellectual strategy is taken by the "neo-technology" approach. The concept of a "technological gap" between the United States and the rest of the world was a commonplace in discussions of trade and direct investment during the 1950s and 1960s (Atlantic Institute, 1970). Though theory makes a sharp distinction between "factor proportions" and "technology" effects, in practice the two ideas are often similar. Employment of skilled professional and scientific personnel is correlated with investment in research, often called "R&D intensity" or simply the "technology factor" (Raymond Vernon, 1970). Similarly, American "technology" has often been linked as much with managerial performance as with science-based production methods. Since the vertically integrated modern business corporation developed earlier and diffused more widely in the United States than elsewhere (Alfred D. Chandler and Herman Daems, 1980), the conceptual correlations among technology, organization, and personnel are likely to be high.

A more difficult conceptual challenge is technological leadership manifest in the form of new products, exported from the United States because they were unavailable elsewhere (Kravis, 1956b). Because exports were small as a percentage of output for almost all American industries, the U.S. case would seem to be a likely example of the historical process described by Staffan Burenstam Linder (1961) whereby new products originally designed for the domestic market begin to enter foreign trade as production expands: "International trade is really nothing but an extension across national frontiers of a country's own web of economic activity" (p. 88). Vernon's "product-cycle" model is perhaps the best-known version: *New products* tended to appear first in the United States because they were responsive to *high-income wants*, and because they were associated with an environment of *high labor costs*. As processes became more mature and routine, trade would be displaced by production abroad, but the volume of U.S. exports was maintained by a continuing flow of new innovations (Vernon, 1966).

There is an ever-present danger of anachronism in applying such concepts historically. The United States did not invent the firearm, the shoe, the bicycle, the camera, or the automobile, and the American versions of these goods were not regarded in European countries as well suited to "high-income wants" (which were better served by the English or French). The size and character of the U.S. domestic market were certainly crucial, but the bulk of the new American exports were producers goods, whose "novelty" lay not so much in consumer taste as in technical specifications or quality. The approach taken here therefore concentrates on the supply side, by analysis of the changing factor content of manufacturing trade over the era of American ascendancy. Though we cannot claim to measure or establish the nature of American "technological leadership" in a rigorous sense, we can illuminate that subject by finding the characteristics of those U.S. products that had the greatest impact on world markets.

This has been the approach of earlier historical work.[2] Using the standard methodology of empirical trade studies, N. F. R. Crafts and Mark Thomas present an analysis of comparative advantage in British manufacturing trade between 1910 and 1935, which they contrast unfavorably with that of the United States (Crafts and Thomas, 1986). They find that Britain continued to export products intensive in capital and unskilled labor and to import goods intensive in human capital (as reflected in the average industry wage). A similar regression for the United States in 1909 shows a reverse result. They conclude: "The U.S. appears already to be following the 'advanced country' pattern of exporting human capital intensive goods and importing unskilled labor-intensive goods in 1909" (p. 637). The next section considers whether this impression should be modified on the basis of a richer data set.

III. New Evidence on American Trade in Manufactures

A. *Average Factor Intensities*

One of the reasons that American manufacturing trade has been understudied is that the Commerce Department trade data are entirely separate from the censuses of manufactures, which have no information about foreign markets. It is not a simple task to match these two sources. Fortunately, a Stanford dissertation by Mary Locke Eysenbach estimated production coefficients for 165 industries according to the system used in Leontief's 1947 interindustry study, and matched these to export and import data for 1879, 1899, and 1914 (Eysenbach, 1976). The present research has replicated her procedures and extended the data set to 1909, 1928, and 1940.[3] For most sample years there are just over 100 usable observations, providing a level of detail roughly comparable to three-digit SITC categories.

To explore the factor intensity of manufacturing trade, I have used Eysenbach's production coefficients to trace relative changes over the entire period of observation. Her capital and labor coefficients are primarily from the census of 1899, while the natural resource coefficients were taken from Vanek (1963) and hence originate in the input-input table for 1947. Thus, this is primarily a study of compositional changes in manufacturing trade over time rather than the actual implicit factor flows in each year. As a sensitivity check, however, estimated coefficients for alternative years have been

[2] An extensive literature on the so-called "labor-scarcity paradox" takes a similar tack, assessing U.S. performance indirectly by measuring the factor-saving bias of U.S. technology relative to British. The suggestion by H. J. Habakkuk (1962) that American technology was capital-intensive and labor-saving has given way to a more complex picture: American methods were more intensive in the use of raw materials and fuel and were characterized by a faster pace and more intensive utilization of capital (David, 1975; Field, 1983). The provocative early successes of the "American system" were limited to a small subset of industries in the 1850s (John James and Jonathan Skinner, 1985). This work concentrates on the mid-nineteenth century, giving little attention to change over time or to the overall scope of U.S. industrial performance.

[3] David Green deserves most of the credit for the detective work that this task entailed.

TABLE 1—CAPITAL-LABOR RATIOS FOR MANUFACTURED GOODS, 1879–1940 ($000 PER EMPLOYEE IN 1909 DOLLARS)

	1879	1899	1909	1914	1928	1940
A. 1899 Coefficients						
Exports	4.186	4.059	4.052	3.961	3.946	3.374
Imports	2.608	2.886	2.785	2.850	2.907	3.221
Exports/Imports	1.61	1.41	1.46	1.39	1.36	1.05
B. 1909 Coefficients						
Exports	5.405	4.877	4.967	4.811	4.959	4.193
Imports	2.999	3.079	3.020	3.073	3.486	4.444
Exports/Imports	1.80	1.58	1.64	1.57	1.42	0.94
C. 1947 Coefficients						
Exports	4.725	5.170	6.350	6.790	6.330	5.265
Imports	2.910	3.440	3.420	3.690	4.325	5.850
Exports/Imports	1.62	1.50	1.86	1.84	1.46	0.90

Sources: 1899 coefficients from Mary Locke Eysenbach, *American Manufactured Exports*, 1897–1914, New York: Arno Press, 1976, pp. 302–306; 1909 coefficients from U.S. Census of Manufactures; 1947 coefficients form Wassily Leontief, "Factor Proportions and the Structure of American Trade," *Review of Economics and Statistics*, November 1956, *38*, 403–407.

Trade Figures: for 1879, 1899, 1914 from Eysenbach, pp. 271–275; 1909, 1928, 1940 from U.S. Commerce Department, *Foreign Commerce and Navigation of the United States*. Exact industry groupings available on request.

TABLE 2—MEASURES OF SKILL INTENSITY OF MANUFACTURED GOODS, 1879–1940

	1879	1899	1909	1914	1928	1940
A. Percentage Earning More than $12/Week in 1890						
Exports	52.3	48.7	48.2	45.9	46.6	42.9
Imports	48.5	45.7	47.1	44.1	42.3	41.3
Exports/Imports	1.08	1.07	1.02	1.04	1.10	1.04
B. Average Wage (1909)						
Exports	0.467	0.482	0.487	0.502	0.504	0.541
Imports	0.431	0.433	0.460	0.426	0.463	0.471
Exports/Imports	1.09	1.11	1.06	1.18	1.09	1.15
C. Percentage Women and Child Labor (1909)						
Exports	10.1	10.7	9.9	11.0	11.2	10.4
Imports	30.6	29.0	30.2	27.8	24.2	21.1
Exports/Imports	0.33	0.37	0.33	0.40	0.46	0.49

Sources: Percent $/week from Eysenbach, pp. 307–311; average wage from 1909 Census of Manufactures (wage bill divided by labor force); women and child labor from 1909 Census of Manufactures (females aged 16 and over, under 16, and males under 16, divided by labor force).

used wherever possible. Since all of the coefficients are U.S.-based, the question of whether the factor content of imports accurately corresponds to foreign production techniques is not addressed. Despite these limitations, the procedures follow the spirit of much of the literature on these subjects, and the results (shown in Tables 1 through 3) are suggestive.

Table 1 does confirm that American manufacturing exports were more capital-intensive than American imports from 1879 to 1928. But in terms of contemporary coefficients, the country's surge to world indus-

TABLE 3—NONRENEWABLE NATURAL RESOURCE COEFFICIENTS IN MANUFACTURING GOODS, 1879–1940 (1947 COEFFICIENTS)

	1879	1899	1909	1914	1928	1940
A. Direct Use						
Exports	0.0742	0.0677	0.0918	0.0988	0.09984	0.0564
Imports	0.0131	0.0194	0.0170	0.0133	0.0290	0.0369
Exports/Imports	5.66	3.49	5.40	7.43	3.39	1.53
B. Direct and Indirect Use						
Exports	0.1107	0.1239	0.1647	0.1800	0.1635	0.1240
Imports	0.0565	0.0747	0.0766	0.0749	0.0934	0.1127
Exports/Imports	1.96	1.66	2.15	2.40	1.75	1.10

Sources: Coefficients from Eysenbach, pp. 297–301; trade figures, see Table 1.

trial supremacy was not marked by a shift toward capital-intensive manufacturing exports, nor by an increasing tendency to trade capital-intensive for labor-intensive manufactures with the rest of the world. (It is interesting that the relative capital intensity of exports *in terms of 1947 coefficients* did rise until 1914, after which it declined.) Movement in the direction of the Leontief Paradox within manufacturing is detectable, at least after World War I.

It should be noted that the figures in Table 1 omit refined sugar, an industry that if included would single-handedly generate a Leontief Paradox for manufacturing in every sample year. If classified as a manufactured good (following Eysenbach), refined sugar would account for nearly one-quarter of manufacturing imports before 1900, and sugar refining (in the United States, at any rate) had a capital-labor ratio five times as high as the average for manufacturing. It is open to question whether sugar refining techniques outside the United States were really this capital-intensive. Because the industry is exceptional and because we are not in any case trying to account for all international flows, it seems more informative to leave it out. Though extreme, sugar refining does illustrate one of the compositional reasons for the trend shown in the first two panels of Table 1, namely, the high capital intensity of many agricultural processing industries, which were declining in relative prominence among U.S. exports. Two of the largest contributors to the decline in relative capital intensity of exports were grain mill products, and meat packing and wholesale poultry.

Table 2 displays two indices of skill intensity: (1) following Eysenbach, the percentage of the labor force earning more than $12 per week in 1890, and (2) the average industry wage in 1909.[4] By both measures, there is some tendency for export industries to pay higher wages than import-competing industries. But there is little sign of a trend in the relative skill intensity of exports and imports. As measured by the 1890 "high-wage" index, the skill content of exports went steadily downward. As measured by the 1909 average wage, however, the skill content of exports had an upward trend. There was also an upward trend, however, in the skill content of imports by the same measure (excepting 1914). One of the reasons for this puzzling pattern is suggested by the third panel of Table 2, which reveals a much more dramatic contrast between exports and imports in the percentage of the labor force who are women and children (under the age of 16). It is perhaps not surprising to see that imports are far more women-and-child-intensive than exports, since these workers are associated with "low-wage" and labor-intensive processes (but it is interesting that this direct measure of labor-force composition is a clearer sepa-

[4]Several other skill indices were proposed by Eysenbach, all based on 1890 data. They give results similar to those presented here.

rator than capital-intensity or wage levels, which one might take to be more fundamental). What is striking is the decline over time in this relative intensity, entirely concentrated on the import side. Here we have another likely contributor to the trend toward the Leontief Paradox. Employment of women and child workers in American manufacturing was concentrated in only a handful of industries: canning, preserving, and freezing on the one hand, and textiles and apparel on the other. The first remained a strong net export category, but in the second, the growth of imports was increasingly stifled by tariff barriers, particularly after the 1922 Fordney-McCumber tariff.

Easily the largest factor-intensity differentials were in nonreproducible natural resources, as shown in Table 3. Recall that these are weighted averages for manufactured goods alone and exclude entirely exports of agricultural goods and crude materials. We still find not only that U.S. exports had far higher natural resource content than imports but that this trend was growing both absolutely and relatively over *precisely the historical period when the country was moving into a position of world industrial preeminence*. Using the more inclusive index of direct and indirect use, the resource intensity of manufacturing exports grew by 64 percent to its peak, and even after a slight decline, the 1928 level was still nearly 50 percent higher than that of 1879. The figures confirm a little-noticed analysis by Robert E. Lipsey (1963): "The composition of manufacturing exports has been changing ceaselessly since 1879 in a fairly consistent direction—*away from products of animal or vegetable origin and toward those of mineral origin*" (p. 59; emphasis added).

Table 3 also clearly shows that the resource intensity of imports was growing as well, and that signs of a reversal in the relative balance are detectable even in 1928. By 1940, the historic U.S. specialization had virtually disappeared. This is the modern trend identified first and most clearly by Vanek (1963), of no small importance for interpreting recent American industrial history. But because of his choice of dates and coverage, Vanek missed the fact that the declining phase had been preceded by a long epoch of rising natural resource intensity, of no less importance in interpreting the country's place in the industrial world.

B. *Regression Analysis*

Simple factor-intensity comparison between exports and imports is not conclusive in the presence of more than two factors (Edward Leamer, 1980). An apparent pattern of specialization may merely represent the effect of a third factor, acting as a complement or substitute for one of the other two. This section therefore follows the general format of Crafts and Thomas (1986) and earlier studies in the international trade literature by regressing the net trade balance for each industry against measures of factor intensity. On no account should the coefficients be viewed as structural estimates within a Heckscher-Ohlin framework (compare Leamer and Harry P. Bowen, 1981). They are best considered as descriptive summaries of trade patterns in a multifactor setting, a way of pointing out areas of distinctive strength and tracking changes over time. Because the industry or commodity groupings are inevitably arbitrary, R^2 levels by themselves are not particularly meaningful; but *t*-tests on individual coefficients are a reasonable standard for confidence in that factor's contribution, and R^2 comparisons across years should reflect changes in the tightness-of-fit according to factor content. Following Crafts and Thomas, all reported standard errors were recomputed according to the procedure suggested by Hal White (1980) to adjust for heteroskedasticity in the error structure. The effect generally is to reduce the larger *t*-ratios, so that what is reported here is a conservative version of the account that leaps from the data using ordinary-least-squares. The results are robust to changes in precise variable definitions and to transformations of the coefficients into factor shares at various discount rates. Trade values have been deflated by export and import price indices (Lipsey, 1963, pp. 142–143; 1913 = 100) so that coefficients may be compared across years.

TABLE 4—REGRESSIONS FOR MANUFACTURED NET EXPORTS OF THE UNITED STATES, 1879–1940

	Constant	Capital/ Labor	Natural Resource Coefficient	Average Wage	Percent Women and Children	R^2
1879	-3127	2092**	-10830	-1853		0.079
	(0.68)	(2.24)	(0.74)	(0.27)		
	-228	1725*	-12690		-156	0.103
	(0.06)	(1.77)	(0.83)		(1.53)	
1899	-4068	3729*	-4324	-802		0.075
	(0.66)	(1.73)	(0.11)	(0.07)		
	1735	3140	-8727		-255**	0.093
	(0.28)	(1.46)	(0.21)		(2.02)	
1909	-8965	2648	46950	959		0.146
	(0.92)	(1.17)	(1.17)	(0.06)		
	260	1810	44154		-380**	0.193
	(0.04)	(0.75)	(0.99)		(2.25)	
1914	-21041**	1600	103103*	28468**		0.261
	(2.56)	(0.53)	(1.71)	(2.12)		
	216	1038	98271*		-329*	0.275
	(0.02)	(0.33)	(1.55)		(1.93)	
1928	-21067	5040	112264**	18856		0.143
	(1.20)	(0.83)	(2.19)	(0.52)		
	-4342	4413	107406**		-333	0.149
	(0.17)	(0.67)	(2.01)		(0.87)	
1940	-31898	-1862	126449**	85642		0.085
	(1.13)	(0.42)	(2.22)	(1.38)		
	23714	-2750	117138**		-629*	0.077
	(1.24)	(0.58)	(2.11)		(1.79)	

Notes: Method of estimation is ordinary least-squares, *t*-ratios (in parentheses) adjusted for heteroscedasticity following procedure of White (1980). *Denotes statistical significance at the 5 percent confidence level; **denotes the 1 percent confidence level. There are 64 nonzero observations in 1879, 83 in 1899, and 96 in the remaining years.

The results in Table 4 are broadly consistent with those of the previous section. The capital-labor coefficient is significant in 1879, but it becomes steadily less so in subsequent years and is actually negative by 1940. Thus indications that the Leontief Paradox emerged historically are still present in a multivariate setting. The natural resource coefficient, on the other hand, begins negative and becomes significantly positive after 1909, reaching its peak (in both level and significance) in 1928.

The coefficients of the two labor force variables are also interesting. The coefficient of the average wage is significantly positive in only one year (1914). The coefficient on the percentage of women and child laborers, by contrast, is significantly negative in four of the six years and nearly so in the remaining two. When both variables are included (not shown), the coefficient on the average wage is negative or insignificant in every year. Furthermore, there is an evident inverse relationship between natural resource intensity and the presence of women and children. It appears, therefore, that the concentration of American net exports in "high wage" industries early in the century was attributable to the absence of women and child workers in these "heavy" industries.[5]

An important amendment to this account emerges from Table 5, which uses a new

[5]This does not necessarily mean that the effect is purely compositional, that is, directly explained by the lower wages paid to women and children. Men who worked in these occupational-industrial categories also received lower wages. But these wages did not reflect "skill" levels so much as the ease with which women and children could be substituted for men in these industries.

TABLE 5—REGRESSIONS FOR MANUFACTURED NET EXPORTS OF THE U.S., 1879–1940

	Constant	Capital and Natural Resources/Labor	Average Wage	Percentage Women and Children	R^2
1879	236	2741**	977		0.058
	(0.05)	(2.17)	(0.14)		
	3815	2234		−182*	0.095
	(1.31)	(1.54)		(1.88)	
1899	2495	5650**	4617		0.057
	(0.32)	(2.81)	(0.40)		
	10015*	4677*		−314**	0.088
	(1.98)	(1.95)		(2.58)	
1909	−2974	9312**	6052		0.165
	(0.31)	(3.46)	(0.37)		
	6955*	8045**		−428*	0.229
	(1.93)	(2.68)		(2.67)	
1914	−15799**	13279**	33918**		0.299
	(2.08)	(3.50)	(2.57)		
	7317**	12198**		−386**	0.321
	(2.23)	(3.07)		(2.68)	
1928	−10667	24084**	28310		0.241
	(0.75)	(2.87)	(0.88)		
	9857	22954**		−399	0.252
	(1.09)	(2.61)		(1.40)	
1940	−33084	12118**	86974		0.095
	(1.14)	(2.23)	(1.36)		
	19478**	10590**		−575	0.083
	(2.00)	(1.89)		(1.87)	

Note: See Table 4.

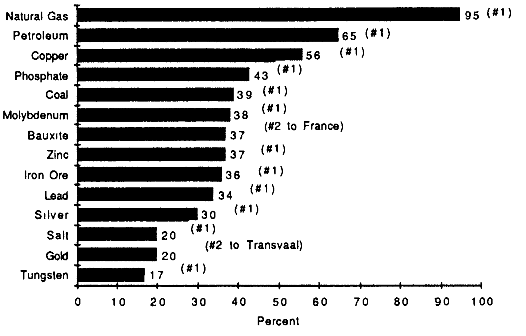
variable created by multiplying the capital-labor ratio and the natural resource coefficient. The results strongly imply that capital and natural resources were complementary factors of production. The coefficient of the new variable is positive through the entire period, growing steadily larger and more significant through 1928. Comparison of R^2 levels between Tables 4 and 5 shows that this new interactive variable is more powerful in accounting for net export performance than the combined effect of its two components, entered separately. The strongest effects are found in 1914 and 1928; in the latter year, for example, the R^2 rises from 0.149 to 0.252 merely by substituting a single variable, the product, for the original two.

This result should caution us against a too-hasty and too-complete rejection of "capital intensity" as a characteristic of American industry. The suggestion is, however, that capital intensity derived not from economy wide abundance of capital per se, but from specialization in an industrial technology in which capital was complementary to natural resources. Strictly speaking, these sorts of tests only describe the direction of trade, not the overall "success" of American industry. But the coincidence of timing between resource intensity and American industrial ascendance obliges us to consider the proposition that the abundance of industrial minerals was a deeper cause of American industry's distinctive strength.

IV. Natural Resources and American Industrial Success

Since industrial success like other historical outcomes requires an uncountable number of mutually interdependent elements, do natural resources really deserve special attention? The scope of America's world leadership in natural resources is displayed in Chart 3, which shows U.S. production of 14 major industrial minerals as a percentage

CHART 3. U.S. MINERAL OUTPUT, 1913: PERCENTAGE OF WORLD TOTAL



Source: Smith (1919), using data from U.S. Geological Survey (1913).

of world totals in 1913. The 95 percent of world natural gas and 65 percent of world petroleum were perhaps of somewhat less economic moment in 1913 than they would be at a later date. But copper, coal, zinc, iron ore, lead, and other minerals were at the core of industrial technology for that era, and in every single case the United States was the world's leading producer by a wide margin. In an era of high transport costs, the country was *uniquely* situated with respect to almost every one of these minerals. Even this understates the matter. Being the number one producer in one or another mineral category is less important than the fact that the *range* of mineral resources abundantly available in the United States was far wider than that in any other country. Surely the link between this geographical status and the world success of American industry is more than incidental. Cain and Paterson (1986) find that between 1850 and 1919, material-using technological biases were significant in nine of twenty American sectors, including those with the strongest export performance, such as petroleum, metals, and machinery.

Resource abundance was a background ingredient in many other distinctively American industrial developments. Continuous-process, mass-production methods, closely associated with modern forms of corporate organization in the analysis of Chandler (1977), were characterized by "high throughput" of fuel and raw materials relative to labor and production facilities (compare Michael Piore and Charles Sabel, 1984). Oliver Williamson (1980) notes that cheap, reliable sources of energy and heat were crucial to this development. Coal was of strategic early importance as a direct source of heat and power, and at a later point as a source of thermal energy for electricity, essential to the efficiency of the moving assembly line and other quasi-flow processes. Alex Field (1987) points out that organizational innovations of this type may be considered "capital-saving" overall, even though firm-level capital requirements were high. In export markets, contemporary comments emphasized non-price competition and particularly the short delivery lags on the part of U.S. suppliers (Nicholas, 1980, pp. 581–587). Quick delivery is a feature one would expect to see where exports have a "vent-for-surplus" quality, because of the length of a production run on a standardized item. In addition, American producer and consumer goods were often specifically designed for a resource-abundant environment. Some of the adjustment problems of U.S. auto companies in recent years stem from their decades of specialization on large, fuel-using cars. There was a parallel problem facing U.S. locomotive manufacturers in the 1920s, who found their foreign sales handicapped by their design for standard-gauge rails, heavy motive power, and heavy train loads (*Markets of the United States*, p. 71).

The emergence of cheap American steel at the end of the nineteenth century was particularly important. Whereas S. J. Nicholas (1980) suggested that the fall in relative U.S. machinery prices was misleadingly proxied by iron and steel prices, it may be that the world success of American engineering goods was buoyed by exactly that development. Table 6 shows the major role played by iron and steel exports over the half-century under discussion. If we aggregate the three headings under which iron and steel products were listed, we find that their share of U.S. manufacturing exports grew steadily, from 5.5 percent in 1879 to 37.5 percent in 1929. If we add in one other

TABLE 6—SHARES OF UNITED STATES MANUFACTURING EXPORTS, 1879–1929 (PERCENT)

	Iron and Steel Products (except Machinery and Vehicles)	Machinery	Automobiles and Parts	SUM (1,2,3)	Petroleum Products	SUM (1,2,3,5)
1879	2.1	3.4	–	5.5	12.1	17.6
1889	2.4	6.1	–	8.5	13.3	21.8
1899	7.6	10.7	–	18.3	9.2	27.5
1913	10.9	14.5	2.3	27.7	10.1	37.8
1923	8.8	12.4	6.4	27.6	13.1	40.7
1926	5.6	12.9	11.5	30.0	16.8	46.8
1927	5.1	13.9	13.3	32.3	14.7	47.0
1928	5.3	16.4	15.7	37.5	13.9	51.4
1929	5.4	16.4	15.7	37.5	13.9	51.4

Source: 1879–1923 (1963), Tables A-8 and A-12; 1926–1929, U.S. Department of Commerce, *Foreign Commerce and Navigation of the United States for the Calendar Year 1929*, Vol. 1, Tables XII and XXIV.

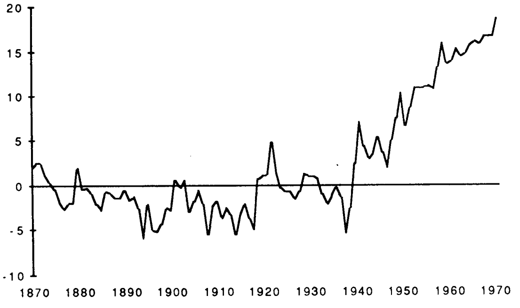
heading in which resource abundance was evidently important, petroleum products, we find that by late 1920s, we have accounted for more than half of all American manufacturing exports. The union of these two sectors is, in essence, the automobile industry. The United States was unquestionably the world's technological leader in automobile production during the 1920s. At the same time, American producers had enormous cost advantages over competitors in raw materials, especially steel. Ford UK faced steel input prices that were higher by 50 percent or more than those paid by the parent company (James Foreman-Peck, 1982, p. 874). It was not accidental that Leontief chose motor vehicles as his most prominently displayed example of the economy as an intricate input-output machine: each million dollars worth of automobiles in 1947 "contained" nearly half that much value in iron and steel, nonferrous metals, and other fabricated metal products (Leontief, 1953, p. 334).

We may also conjecture that there were links between the economy of high throughput and the intensity of the work pace, which also seems to have been a distinctive feature of U.S. industry (Clark, 1987). American firms paid the world's highest real wages and apparently extracted greater effort from the labor force in return. But it is an anachronism to associate "high wages" with "high skill" technologies for the era in which the United States surged to world industrial preeminence. The United States was a well-educated country, but most of the workers in the fast-paced, heavy-industry, mass-production manufacturing in which the country led the world were not well-educated native-born Americans. In 1910 the foreign born and sons of foreign born were more than 60 percent of the machine operatives in the country, and more than two-thirds of the laborers in mining and manufacturing (U.S. Senate, 1911, pp. 332, 334). There is no reason to believe that this labor force was particularly well educated by world standards. Key industries like iron and steel and motor vehicles paid high wages to unskilled workers (who were nonetheless much cheaper than the skilled craft workers used with older technologies), presumably because it was rough, disagreeable, dangerous, demanding work, and because it was vital to have an ample excess labor supply available (compare Daniel Raff, 1988). In the 1930s these industries were central to the movement for industrial unionism, which subsequently provided an alternative mechanism for the continued association between high-wage industries and American industrial success.

V. What Became of American Resource Abundance?

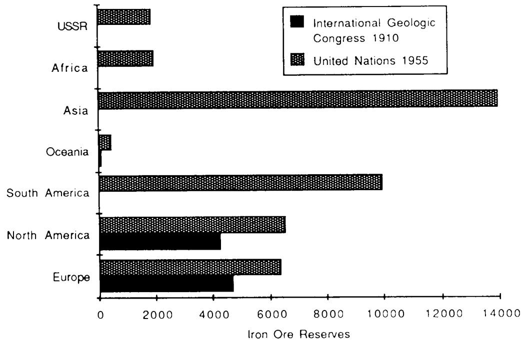
The marked changes in coefficients for 1940 seem to portend the post–World War II pattern, when the United States moved

CHART 4. U. S. NET MINERAL IMPORTS AS A PERCENTAGE OF CONSUMPTION



Source: Manthy (1978, Tables MC1 and MC2).

CHART 5. WORLD IRON ORE RESERVES, 1910 AND 1955



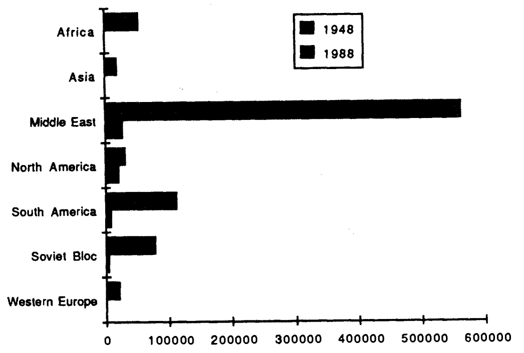
Sources: International Geologic Congress (1910, pp. 1–56): "Actual Reserves" in millions of tons of metallic iron; United Nations (1955, pp. 19–34): "Reserves" in millions of tons of iron content.

steadily and increasingly into a position of net mineral imports (Chart 4). Beginning mainly in the 1920s, one important mineral after another began to enter the net import column: nonferrous metals, bauxite, lead, zinc, copper, iron ore, and petroleum among others. Without conducting extensive global cost comparisons, it is evident that a country for whom resource prices are determined at the margin by imports is not going to have a major locational advantage in resource costs over its industrial rivals. But what exactly was the process of change in America's resource position? A popular conception is that the country has largely exhausted its resource endowment and has had to import so as to avert domestic shortages. Kindleberger has proposed a weaker version of this scenario within the Heckscher-Ohlin framework, in which the more rapid growth of labor and capital relative to resources has turned the country from a net-export to a net-import position with respect to resources (Charles P. Kindleberger 1960, pp. 347–348). It is doubtful that this account is generally valid. Indeed, a closer look at the trend in world mineral supplies casts a different light on the character of the original position.

In 1919 it could confidently be written that "the United States is more richly endowed with mineral wealth than any other country" (George Otis Smith, 1919, p. 282), and such a statement was consistent with the best geological and industrial knowledge of the day. But the clear pattern of discoveries since that time indicates that there was a systematic historical bias in these perceptions, in that American resources had been much more thoroughly explored and exploited than those of other parts of the world. Chart 5 illustrates this process, by comparing world iron ore "reserves", as indicated by a 1910 survey by the International Geologic Congress, with those reported in a United Nations survey in 1955. Granted that quality differences and extraction and transport costs are neglected in a simple chart, nonetheless the pattern is so clear as to be beyond dispute. Europe and North America had by far the largest reserves in 1910, but their "endowments" (which, to be sure, had increased and not decreased) had grown only slightly in the intervening 45 years. What had been a dominating advantage in 1910 was no more than a respectable presence in 1955.

The case of petroleum is even more extreme (Chart 6). Recall that the United States in 1913 (and for a half-century before) had been the world's largest petroleum producer and exporter, by a wide margin. As Chart 6 shows, as late as 1948, North American reserves were nearly equal to those of the Middle East. In 1988, though again reserves of all areas had increased, North America was a minor part of the world petroleum picture. It is difficult to

CHART 6. WORLD CRUDE OIL RESERVES, 1948 AND 1988



Source: American Petroleum Institute (1988, Section II, Table 1): "Estimated Proved Reserves of Crude Oil Annually as of January 1 (millions of barrels)."

avoid the inference that mineral supplies were more a matter of "development" than "endowment."

Where world geological surveys are not available, similar conclusions can be reached by other routes. In the case of bauxite, which takes its name from the French village where it was first developed, the United States and France alternated as first and second in the world until the 1950s. With discoveries in the West Indies in the 1950s, Jamaica quickly moved into first place, at annual production levels larger than those ever achieved in either France or the United States, despite the fact that production levels in those two countries did not decline but continued to grow to levels higher than they themselves had ever achieved. In the late 1960s, Australia replaced Jamaica as number one, again setting new production records without causing an absolute decline in any of the older countries. In both Jamaica and Australia, bauxite production was negligible before World War II. Since the real price of bauxite has declined, it is not the case that domestic reserves have been "exhausted" or that distant supplies have simply been coaxed out along a world supply curve. Rather, early discoveries and mining took place in areas proximate to the early centers of industrial and technological development and within the boundaries of their national jurisdiction.

The last phrase points toward another sense in which resource abundance was historically rather than geologically determined. The United States was the world's largest mineral producing nation, but it was also one of the world's largest countries! Even without Alaska, at 3.5 million square miles, the United States is twice the size of all the countries of eastern and western Europe and Scandinavia combined (excluding Russia). Yet coal and iron ore production in Europe was 30 to 50 percent higher than the U.S. total in the 1910–1913 era. If coal and iron were the imperatives of industrial location ca. 1900, a hypothetical United States of Europe would have rivaled America.

More important than sheer geographic size is economic distance. The United States was a vast free trade area for internal commerce, and the opportunities created by this status provided the incentive for massive investment in transportation infrastructure, including the highly efficient lake transport system that linked Mesabi ore to Pennsylvania coal. In the case of copper, only the combination of national size and efficient internal transportation allow use to say that the "same" economy retained world leadership across the period of American industrial ascendancy, since the early production center in Michigan gave way to remote but larger and richer locations in the Mountain and Southwest regions between 1870 and 1930.

The argument does not stop with national size and efficient transportation. The process of mineral discovery and development was also a prime outlet for creative energies and innovations, often at high levels of technical and organizational sophistication. The United States Geological Survey, formed in 1879 by consolidation of several existing federal surveys, had intimate links with the mining industry. Reports by government geologists in Colorado in the 1880s were crucial in encouraging mining activity and adapting metallurgical knowledge to local requirements (Rodman Wilson Paul, 1960). The American Institute of Mining Engineers became the first speciality group to break away from the American Society of

Civil Engineers. Scientifically trained personnel were also important in expanding the range of *uses* for available minerals. An early report by Yale geologist Benjamin Silliman, Jr., foresaw the commercial possibilities of "cracking" petroleum into various compounds, opening up arrays of new uses for what had been considered a useless waste material (Robert V. Bruce, 1987, pp. 140–142). But as Nathan Rosenberg (1985) points out, much of the early use of science by American industry did not deploy new knowledge at the scientific "frontier," but involved repetitive procedures (such as grading and testing materials) for which scientific training was needed but where the learning was specific to the materials at hand. The abundance of mineral resources, in other words, was itself an outgrowth of America's technological progress.

This view of the matter suggests the answer to the question posed above. The country has not become "resource poor" relative to others, but the unification of world commodity markets (through transport cost reductions and elimination of trade barriers) has largely cut the link between domestic resources and domestic industries. American corporations and engineers have been in the forefront of the globalization of the mineral economy. In essence, the process by which the United States became a unified "economy" in the nineteenth century has been extended to the world as a whole. To a degree, natural resources have become commodities rather than part of the "factor endowment" of individual countries.[6] Presumably this is why international economists now distinguish resource-based "Ricardo goods" from others and treat them separately (for example, Robert Stern and Keith E. Maskus, 1981). This procedure may be appropriate for the contemporary world, but it would be hard to do justice to the historic success of American industry within this conception.

[6]Wilfred J. Ethier and Lars E. O. Svensson (1986) show that in a Heckscher-Ohlin framework with mobility of some factors a country's trade pattern in goods is affected only by its endowment of *nontraded* factors.

VI. Conclusion

Why has the importance of mineral resources in American industrial history been underappreciated? Concern for the future of natural resources is an ancient theme in economics, but most of the attention has been channeled into two rather different issues: fear of rising costs from increased resource scarcity and fear of national strategic inadequacy in the event of war. Refuting the first fear has long been the economist's favorite pastime, as it has been easy to show that producers substitute away from relatively scarce resources and that the real prices of "nonrenewable" resources have historically declined. The second fear has always seemed noneconomic in character, if not indeed a cooked-up rationalization for subsidy or protection. Having thus dealt with the "problem" of resource exhaustion, it was easy to overlook a logically distinct aspect of the matter: the contribution of resource location to the competitive potential of a country's industries. Some economic historians, to be sure, have long analyzed national economic histories in terms of world geographical patterns (William N. Parker, 1984). But it is perhaps understandable that Americans have not been inclined to attribute their country's industrial success to what appear to be accidental or fortuitous geographic circumstances. Another reason is that American industrial leadership took on a rather different shape after World War II. Over the course of the twentieth century, the country was able to parley its resource-based industrial prosperity into a well-educated labor force, an increasingly sophisticated science-based technology, and world leadership in scientific research itself. In the wake of World War II, there were no serious international rivals in such a wide range of industries that it was easy to lose sight of the resource dimension of industrial performance. After the war, there was a brief period of concern that the nation's resource position had been eroded, culminating in the Paley Commission Report of 1952. But such doubts and fears were largely swept away in the American-led world prosperity of the next 25 years.

To be clear about the argument, there is no iron law associating natural resource abundance with national industrial strength. But the distinctive *American* technologies have, as a matter of history, been relatively resource-using. We have now moved from an era in which the rest of the world adapted to an American technology, with varying degrees of difficulty, to an era in which U.S. firms have had to do the adjusting. The adjustment is not made much easier by the consideration developed in this paper, that historical resource abundance was itself largely an outgrowth of American industrial success.

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The British Industrial Revolution in Global Perspective:

How Commerce Created
The Industrial Revolution and Modern Economic Growth

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The Industrial Revolution is one of the most celebrated watersheds in human history. It is no longer regarded as the abrupt discontinuity that its name suggests, for it was the result of an economic expansion that started in the sixteenth century. Nevertheless, the eighteenth century does represent a decisive break in the history of technology and the economy. The famous inventions–the spinning jenny, the steam engine, coke smelting, and so forth–deserve their renown[1], for they mark the start of a process that has carried the West, at least, to the mass prosperity of the twenty-first century. The purpose of this essay is to explain why they occurred in the eighteenth century, in Britain, and how the process of their invention has transformed the world.

The last sentence introduces an important theme of this essay, which is the Britishness of the industrial revolution. Until recent decades, this was axiomatic: The industrial revolution started in Britain with the inventions that created factory textile production, the shift to coal and coke in the iron industry, and the perfection of the steam engine. Economic growth on the continent occurred when these innovations were adopted there. This schema was first called into question by national income studies which indicated that the pace of economic growth in France was not very different from that in England despite the differences in economic structure–hence, the thesis of O'Brien and Keyder (1978) that there were "two paths to the twentieth century." This critique has gathered force with the recent emphasis on the Scientific Revolution, a pan European phenomenon, as the cause of the Industrial. While these contributions broaden our understanding of the industrial revolution, it is our contention that it really was fundamentally British.

Explaining the industrial revolution is a long standing problem in social science, and all manner of prior events have been adduced as causes (Hartwell 1967, Mokyr 1999). The role of political structure–parliamentary checks on the executive, the security of property rights, the flexibility of the legal system–is at the centre of much current discussion. According to this view, the dramatic changes of the late eighteenth century can be traced back to the Glorious Revolution of 1688 that consolidated parliamentary ascendancy, minimal government, and secure property rights. Supposedly, these legal changes created a favourable climate for investment that made the industrial revolution possible (North and Weingast 1989, De Long and Schleifer 1993, LaPorta, Lopez-de-Silanes, Schleifer, Vishny 1998, Acemoglu, Johnson, and Robinson 2005). This interpretation, however, has some weaknesses: Studies of banking and interest rates fail to detect any structural break after 1688, so the improved investment climate is not manifest in anything financial (Clark 1996, Epstein 2000, Quinn 2001). Property rights were at least as secure in France–possibly, in China for that matter–as in England (Hoffman, Postel-Vinay, Rosenthal 2000, Pomeranz 2000). Indeed, one could argue that France suffered because property was too secure: Profitable irrigation projects were not undertaken in Provence because France had no counterpart to the private acts of the British parliament that overrode property owners opposed to the enclosure of their land or the construction of canals or turnpikes across it

[1]There has been a debate about the breadth of technological progress during the industrial revolution with Crafts (1985), Harley (1999), Crafts and Harley (1992, 2000) arguing that productivity growth was confined to the famous, revolutionized industries in the period 1801-31, while Temin (1997) has argued that many more industries experienced productivity growth. Whatever one believes about 1801-31, it is clear that many non-revolutionized industries experienced productivity growth between 1500 and 1850. The incentives to invent discussed in this paper applied to all industries, not just the famous ones I discuss here.

(Rosenthal 1990, Innes 1992, 1998, Hoppit, Innes, Styles 1994). The Glorious Revolution meant that "despotic power was only available intermittently before 1688, but was always available thereafter" (Hoppit 1996, p. 126). Finally, taxes were higher in Britain than across the Channel (Mathias and O'Brien 1976, 1978, Hoffman and Norberg 1994, Bonney 1999). In any event, it was a long stretch from the excise tax on beer or the cost of foreclosing on a defaulting mortgagor (not actually a cheap process in eighteenth century England) to Watt's invention of the separate condenser. An explanation of the technological breakthroughs has to be more focussed on technology than is usual in constitutional discussions.

The industrial revolution was fundamentally a technological revolution, and progress in understanding it can be made by focussing on the sources of invention. This subject has been opened up for economists by the researches of Joel Mokyr (1990, 2002) , and I will examine his views on macroinventions, the scientific revolution, and the industrial enlightenment. While Mokyr takes us forward by emphasizing the social context in which invention occurred and the importance of information flows, we can sharpen our understanding by concentrating on the incentives faced by inventors and the context in which they worked. This approach indicates that the reason the industrial revolution happened in Britain, in the eighteenth and nineteenth centuries, was not because of luck (Crafts 1977) or British genius or culture or the rise of science. Rather it was Britain's success in the international economy that set in train economic developments that presented Britain's inventors with unique and highly remunerative possibilities. The industrial revolution was a response to the opportunity.

What commercial success did for Britain was to create a structure of wages and prices that differentiated Britain from the continent and, indeed, Asia: In Britain, wages were remarkably high and energy cheap. This wage and price history was a fundamental reason for the technological breakthroughs of the eighteenth century whose object was to substitute capital and energy for labour. Scientific discoveries and scientific culture do not explain why Britain differed from the rest of Europe. They may have been necessary conditions for the industrial revolution, but they were not sufficient: Without Britain's distinctive wage and price environment, Newton would have produced as little economic progress in England as Galileo produced in Italy.

There were, however, important features of British popular culture that distinguished the country from much of the continent, and those features–greater literacy and numeracy–underpinned the technological achievements of the eighteenth century. They were not autonomous movers, however, but were themselves consequences of the economic development that preceded the industrial revolution and that produced the high wage, cheap energy economy. Underlying the technological breakthroughs of the industrial revolution was Britain's commercial and imperial expansion of the seventeenth and eighteenth centuries, which was the cause of the peculiar wage and price pattern. The state policies that mattered most were Mercantilism and Imperialism.

The working assumption of this paper is that technology was invented by people in order to make money. This idea has important implications. First, inventions were investments where future profits had to offset current costs. The technical discoveries were either new products or reductions in the cost of making existing products. In either case, the profitability calculation governing invention depended on the prices of the products and the prices of the various inputs. As we will see, labour was particularly expensive and energy particularly cheap in Britain, so inventors in Britain were led to invent machines that substituted energy and capital for labour. Second, the balance between the profits and the costs of an invention depended on the size of its market. The scale of the mining industry in eighteenth century Britain was much greater than anywhere else, so the return to inventing improved drainage machinery (a.k.a. the steam engine) was greater in Britain than in France or China. Third, patents that allow the inventor to capture all of the gains created by his invention raise the rate of return and encourage invention. Indeed, North and Thomas (1973) have argued that it was better property rights for knowledge that explain the inventions of the industrial revolution. However, the English patent law was enacted in 1624 and attracted little interest for much of the seventeenth century, so the explanation of the inventions of the eighteenth turns on the greater incentive to invent rather than on a change in law that met an existing, latent demand for patenting.[2] Fourth, in the absence of patents, the incentive to invent was limited to the gains the inventor could realize in his own firm, and these were likely to have been small. Firms could increase the return to inventing by learning from each other. In that case, they divided the costs and pooled the gains. Indeed, collective invention was important before private invention took off in the eighteenth century and has remained a complement to the present day (Allen 1983, Epstein 1998, 2004, Nuvolari 2004a, 2004b).

Britain–a high wage, cheap energy economy

Since invention was an economic activity, its pace and character depended on factors that affected business profits including, in particular, input prices. Why the industrial revolution happened in eighteenth century Britain is easier to understand if we compare wage rates and energy prices in the leading economies of the day. In these comparisons, Britain stands out as a high wage, cheap energy economy.

Our views of British wages are dominated by standard of living debate. Even optimists who believe the real wage rose in the Industrial Revolution accept that wages were low in the eighteenth century. They were certainly lower than they are today, but recent research in wage and price history shows that Britain was a high wage economy in four senses:

1. At the exchange rate, British wages were higher than those of its competitors.
2. High silver wages translated into higher living standards than elsewhere.
3. British wages were high relative to capital prices.
4. Wages in northern and western Britain were exceptionally high relative to energy prices.

These trends are illustrated in Figures 1-4. These figures were constructed from databases of wages and prices assembled from price histories written since the middle of the nineteenth century. The typical price history is based on the archives of an institution that lasted for hundres of years–colleges and hospitals are favourites. The historian works through their accounts recording the quantity and price of everything bought or sold and draws up tables of the annual averages. Usually prices are found for a range of agricultural and food stuffs as well as cloth, fuel, candles, building materials, implements, and a miscellany of other items. Wages and salaries are often also recorded. The commodities are measured in local weights and measures, and prices are stated in local units of account, and these must be converted to international standards. Prices histories have been written for

[2]On the operation of the English patent system, recent research includes: Dutton (1984), MacLeod (1986, 1988), Nuvolari (2004a), Khan (2005), Khan and Sokoloff (2006).

many European cities, and the research is being extended to Asia. By putting all of this material in the computer, international comparisons are becoming possible for the first time, and they are redefining our understanding of economic history. In particular, they throw new light on the origins of the Industrial Revolution, as we shall show.

Figure 1 shows the history of nominal wages of building labourers in leading European and Asian cities from the middle ages to the industrial revolution. The various units of account in which the data were recorded have been converted to grams of silver since silver coins were the principal medium of exchange. The figure shows that the divergence in nominal wages was minimal in Europe at the end of the late middle wages. There was little wage inflation subsequently in eastern Europe. Wages in western Europe rose during the price revolution (1550-1620). Thereafter, there was a three way split with silver wages falling in southern Europe, levelling out in the Low Countries, and continuing to rise in London. From the late seventeenth century onwards, London wages were the highest recorded.

Figure 1

London wages rose above those elsewhere in Britain in the sixteenth century. By the late seventeenth, however, wages in southern English towns like Oxford were rising to close the gap. Wage movements in northern England were more erratic: In the late seventeenth century builder's wages in cities like York were as high was those in Oxford. Wage growth ceased in the north in the early eighteenth century, however, so the region fell behind the south in nominal wages although the level was still higher than in most parts of the European continent. Fast wage growth towards the end of the eighteenth century brought the north to the same level as the south, however, and all parts of England had exceptionally high silver wages (Gilboy 1934, Allen 2001, 2003).

Comparisons with Asia further emphasize the high wages in eighteenth century Britain. In Beijing, Canton, Japan, and Bengal, labourers earned between one and two grams of silver per day–less than half the wage in central or eastern Europe and a smaller fraction of earnings in the advanced economies of the northwest of the continent (Özmucur and Pamuk 2002, Allen 2005, Allen, Bassino, Ma, Moll-Murata, van Zanden 2005, cf. Allen, Bengtsson, Dribe 2005).

Did Britain's high nominal wages translate into high living standards or were they offset by high prices in Britain? To explore this issue, welfare ratios have been computed for leading cities. Welfare ratios are defined to be full time annual earnings[3] divided by the cost

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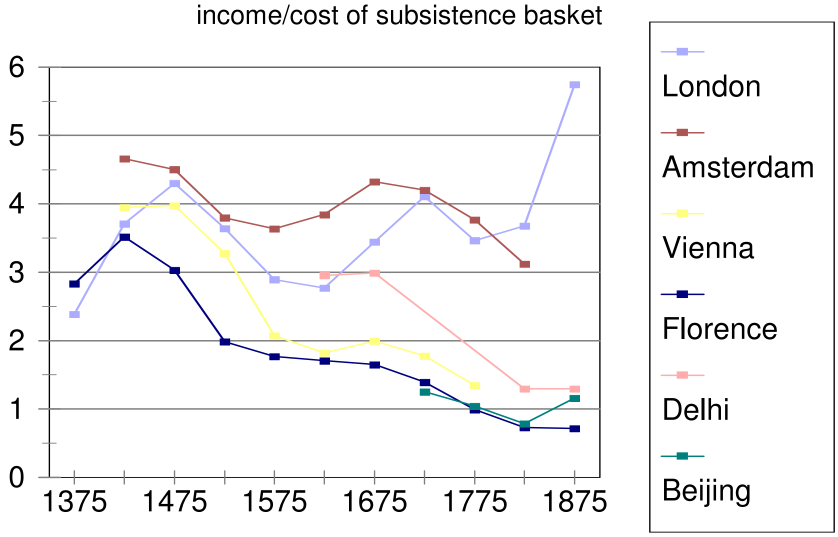
[3]European building workers were paid by the day, and I assume that 250 days was a full year's work, making allowance for Sundays, religious holidays, and erratic employment.

of a basket of consumer goods sufficient to keep a family at a specified standard of comfort–in this case at minimal subsistence. Baskets are constructed with most spending on the grain that was cheapest in each locality (e.g. oats in northern Europe, polenta in Florence, sorghum in Beijing, millet in Delhi). Very small portions of meat, peas or beans, butter or oil, cloth, fuel, and housing are also included. Consumption is set at the low level of 1920 kilocalories per day for an adult male with other family members proportioned accordingly. Calculations with baskets corresponding to a more affluent lifestyle have also been undertaken, and the relative rankings are unchanged.

Figure 2 plots the welfare ratios for the cities in Figure 1. The population decline caused by the Black Death meant that real incomes were high everywhere in the fifteenth century. Welfare ratios in London and the Low Countries were trendless across the early modern period, although there were oscillations in the series. Moreover, fully employed workers in these regions earned three to five times the cost of the subsistence lifestyle. They spent their extra income on a superior diet (with bread, beer, and much more meat) and more non-food consumer goods including some of the luxuries of the 'consumer revolution' of the eighteenth century (Shammas 1990, McKendrick, Brewer, and Plumb 1982, de Vries 1993, Fairchilds 1993, Weatherill 1996, Berg and Clifford 1999, Berg 2005). In contrast, real living standards fell dramatically across the continent, reaching a level of about one. In eighteenth century Florence and Vienna, fully employed building workers earned only enough to maintain their families at rock bottom subsistence. There was no surplus for bread, meat, beer, or wine let along imported luxuries. Real wages also fell sharply in provincial England in the sixteenth century, but even at the trough labourers in Oxford earned at least 50% more than bare bones subsistence. The nominal wage inflation of the late seventeenth century meant that welfare ratios in Oxford were between 2.5 and 3.0 in the eighteenth century.

Figure 2

Subsistence Ratio for Labourers
income/cost of subsistence basket



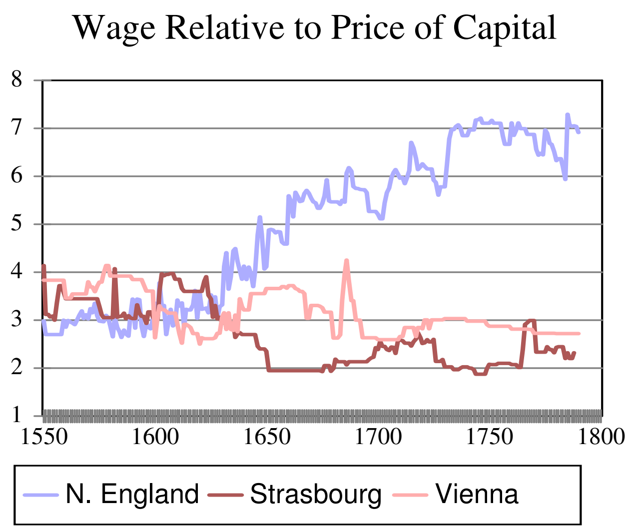
If we extend the comparisons of living standards to Asia, English performance looks even more impressive. Low silver wages in the East were not counterbalanced by even lower food prices. Welfare ratios for labourers in Canton, Beijing, and Japan were about one in the eighteenth and nineteenth centuries–as low as those in the backward parts of Europe. Mass demand for manufactures was very limited across Asia, since most consumer spend was directed towards basic necessities.

Many Asian wages are based on monthly earnings, and I assume employment for twelve months.

The earnings of craftsmen (carpenters, masons, and so forth) followed the same trends as labourers in all countries. Skilled workers, however, earned more than the unskilled, so their welfare ratios were higher everywhere. Craftsmen in London or Amsterdam earned six times what was required to purchase the subsistence basket, while their counterparts in Germany or Italy only 50% more than that standard. Craftsmen in northwestern Europe spent much of their surplus income on more food and better quality food. Nonetheless, the mass market for consumer goods was much larger in Britain and the Low Countries than in most of Europe.

A third sense in which Britain was a high wage economy was in terms of the wage rate relative to the price of capital. Figure 3 plots the ratio of a building labourer's daily wage relative to an index of the rental price of capital in northern England, Strasbourg, and Vienna. The rental price of capital is an average of price indices for iron, nonferrous metals, wood, and brick multiplied by an interest rate plus a depreciation rate. Strasbourg and Vienna were chosen since there are long series of wages and prices for those cities, and their data look comparable to those of most of Europe apart from the Low Countries. The series are 'PPP adjusted' so that we can compare across space as well as over time.

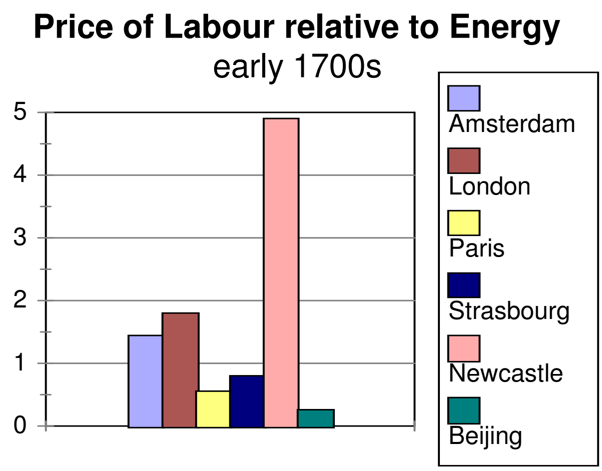
Figure 3



The ratio of the wage relative to the price of capital was trendless and similar in all cities from 1550 to 1650. Then the series diverged. In England, labour became increasingly expensive relative to capital from 1650 onwards. This rise reflects the inflation of nominal British wages at the time. In contrast, the ratio of the wage to the price of capital declined gradually in Strasbourg and Vienna across the seventeenth and eighteenth centuries.

The different trajectories of the wage-rental ratio created different incentives to mechanize production in the two parts of Europe. In England, the continuous rise in the cost of labour relative to capital led to an increasingly greater incentive to invent ways of substituting capital for labour in production. On the continent, the reverse was true: Factor price movements led businesses to search for ways of substituting increasingly cheap labour for capital. It was not Newtonian science that inclined British inventors and entrepreneurs to seek machines that raised labour productivity but the rising cost of labour.

Figure 4



Finally, there is a fourth sense in which labour was costly in industrializing Britain. That involves a comparison of wages to the price of fuel. Figure 4 is bar graph of the ratio of the building wage rate to the price of energy in the early eighteenth century in important cities in Europe and Asia. In this ratio, the price of a kilogram of fuel was divided by its energy content, so energy prices are expressed as grams of silver per million BTUs. The ratio is calculated for the cheapest fuel available in each city–coal in London and Newcastle, peat in Amsterdam, charcoal or fire wood in the other cities.

Newcastle stands out as having the highest ratio of labour costs to energy costs in the world. To a degree the high ratio reflects high British wages, but the low cost of coal was the decisive factor. Indeed, a similar ratio characterized the situation on all of the British coal fields and in the industrial cities (Sheffield, Birmingham, and so forth) built on them. The only place outside of Britain with a similarly high ratio of labour to energy costs was probably the coal mining district around Liège and Mons in present day Belgium. The high cost of labour relative to fuel created a particularly intense incentive to substitute fuel for labour in Britain. The situation was the reverse in China were fuel was dear compared to labour. The Chinese invented very large kilns for firing their pottery because such kilns had a high ratio of volume to surface area and so conserved heat. The reverse was true in Britain where kilns were small and thermally inefficient.

Why were British wages and prices unique?

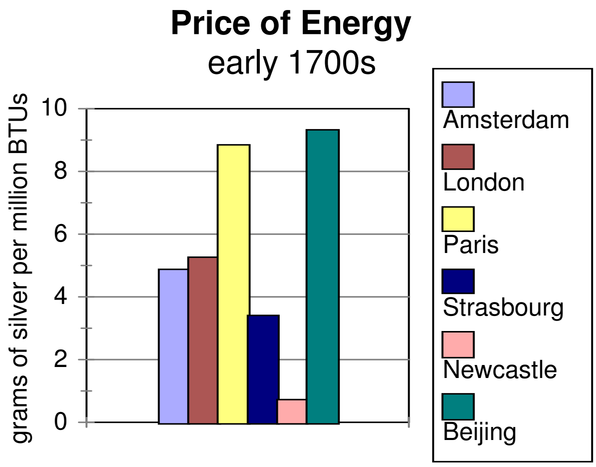
Britain's unusual wages and prices were due to two factors. The first was Britain's success in the global economy, which was in part the result of state policy. The second was geographical–Britain had vast and readily worked coal deposits.

In pre-industrial Europe, real wages moved inversely to the population. As Figure 2 indicates, the real wage rose in Britain and Italy after the Black Death of 1348/9, which cut the population by about one third. As population growth resumed, the real wage fell in most of Europe between the fifteenth century and the eighteenth. The Low Countries were an important exception to this trend. Real wages fell in rural England in the sixteenth century, but London bucked the trend in the same way as Antwerp and Amsterdam, and, indeed, as we have seen, living standards rose generally in southern England from 1650 onwards. Why were England and the Low Countries successful?

The superior real wage performance of northwestern Europe was due to a boom in international trade. The English boom began with the export of 'new draperies' in the late sixteenth century. These were light woolen clothes made in East Anglia and exported to the Mediterranean through London. Between 1500 and 1600, the population of London grew from about 50,000 to 200,000 in response to the trade-induced growth in labour demand. During the Commonwealth, Cromwell initiated an active imperial policy, and it was continued through the eighteenth century (O'Brien 2006). In a mercantilist age, imperialism was necessary to expand trade, and greater trade led to urbanization. Between 1600 and 1700, London's population doubled again, and by 1800 it approached one million. In the eighteenth century, urbanization picked up throughout England as colonial trade increased and manufacturing oriented to colonial markets expanded. Between 1500 and 1800, the fraction of the English population living in settlements of more than 10,000 people increased from 7% to 29%. The share of the workforce in agriculture dropped from about 75% to 35%. Only the Low Countries, whose economies were also oriented to international trade, experienced similarly sweeping structural transformations. In the eighteenth century, the Dutch and the English had much more trade per capita than other countries in Europe. Econometric analysis shows that the greater volume of trade explains why their wages were maintained (or increased) even as their populations grew (Acemoglu, Johnson, Robinson 2005, Wrigley 1987, O'Brien 1999, Ormrod 2003, Allen 2000, 2003).

Coal deposits were a second factor contributing to England's unusual wage and price structure. Coal has a long pedigree as an explanation for Britain's industrial success (Jevons 1865, Neff 1932, Hatcher 1993, Smil 1994, Pomeranz 2000, Sieferle 2001), and Wrigley (1988) put it on the modern research agenda. I add two points to the discussion.

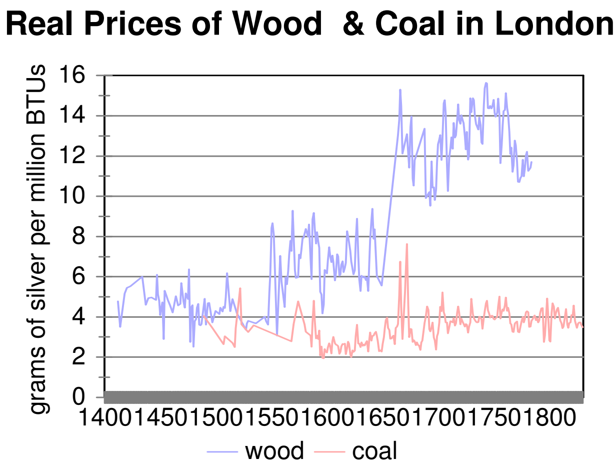
Figure 5



First, coal was not just abundant in Britain–it was cheap, at least in northern and western Britain on or near the coal fields. Figure 5 shows the price of energy in leading cities in the early eighteenth century. London did not have particularly cheap fuel at that time; Newcastle, however, did. The difference in the energy price between the two cities equals the cost of shipping the coal from the Tyne to the Thames. Despite an ocean route, transportation accounted for most of the price of coal in London. Coal prices at other cities in northern and western Britain were similar to those in Newcastle–at least once canal improvements brought down internal shipping costs. Except perhaps for southern Belgium, no region anywhere in the world had the same combination of large population and cheap energy. Belgian coal output, however, was only 3% of Britain's in 1800, and the return from inventing coal using technology was correspondingly reduced.

Cheap fuel was important for two reasons. First, inexpensive coal raised the ratio of the price of labour to the price of energy (Figure 4), and, thereby, contributed to the demand for energy-using technology. In addition, energy was an important input in the production of metals and bricks, which dominated the index of the price of capital services. Cheap energy contributed to the fall in capital prices relative to wages and, thus, contributed to the incentive to substitute capital for labour.

Figure 6



Second, coal is a 'natural' resource, but the coal industry was not a natural phenomenon. Some coal was mined in the middle ages (Hatcher 1993). It was the growth of London in the late sixteenth century, however, that caused the coal industry to take off. As London grew, the demand for fuel expanded, and the cost of fire wood and charcoal increased sharply as fuel was brought from greater distances. Coal, on the other hand, was available in unlimited supply at constant real cost from the fifteenth to the nineteenth century. In the late middle ages, coal and charcoal sold at about the same price per BTU in London. The market for coal was limited to blacksmithing and lime burning. In all other uses, sulfur made coal an inferior fuel. As London's population exploded in the late sixteenth century, the demand for fuel rose, as did the prices of charcoal and firewood. By 1585, wood fuel was selling for twice the price per BTU as coal (Figure 6). That differential made it worthwhile for buyers to figure out how to substitute coal for wood–in fact, a difficult problem (Nef

1932)–and shipments of coal from Newcastle to London began their rapid growth. The take-off of the coal industry was, thus, due to the growth of London. Since this was due to the growth of international trade, the exploitation of Britain's coal resources were the result of the country's success in the global economy as well as the presence of coal in the ground.

The Dutch cities provide a contrast that reinforces the point (Pounds and Parker 1957, de Vries and van der Woude 1997, Unger 1984). The coal deposits that stretched from northeastern France across Belgium and into Germany were as useful and accessible as Britain's. With the exception of the mines near Mons and Liège, they were largely ignored before the nineteenth century. The pivotal question is why city growth in the Netherlands did not precipitate the exploitation of Ruhr coal in a process parallel to the exploitation of Northern English coal. Urbanization in the Low Countries also led to a rise in the demand for fuel. In the first instance, however, it was met by exploiting Dutch peat. This checked the rise in fuel prices, so that there was no economic return to improving transport on the Ruhr or resolving the political-taxation issues related to shipping coal down the Rhine. Once the Newcastle industry was established, coal could be delivered as cheaply to the Low Countries as it could be to London, and that trade put a ceiling on the price of energy in the Dutch Republic that forestalled the development of German coal. This was portentous: Had German coal been developed in the sixteenth century rather than the nineteenth, the industrial revolution might have been a Dutch-German breakthrough rather than a British achievement.

Why Britain's unique wages and prices mattered: Substituting Capital for Labour

Britain's high wage, cheap energy economy was an important determinant of the pace and character of technical change. There were both demand and supply links, and I begin with the former. In analyzing these, it is useful to distinguish between product and process innovations, for they were influenced by different features of the price structure.

Historians of consumption have emphasized product innovations as a cause of the industrial revolution (Berg 2005). Trade with Asia brought new products to Britain–cotton fabrics, Chinese porcelain, coffee and tea. Britain's high wages meant that the demand for these goods was not confined to the middle classes but included skilled workers and even labourers, so the market was far broader than in much of Europe. British manufacturers attempted to make these goods or imitations of them in order to meet that demand. Cotton textiles is a famous example we will consider later. There was also much product innovation in porcelain as English manufacturers (Wedgewood is the most famous) developed materials and designs that could compete with the Chinese (Young 1999). To an important extent, the industrial revolution was an exercise in import substitution.

Process innovations were important in their own right, and much of the product innovation also involved redesigning production processes to suit British conditions. What mattered was the wage of labour relative to the prices of capital and energy. Britain's high–and rising wage–induced a demand for technology that substituted capital and energy for labour. At the end of the middle ages, there was little variation across Europe in capital-labour ratios. As the wage rose relative to the price of capital in Britain, it was increasingly desirable to substitute capital for labour and that is what happened. Sir John Hicks (1932, pp. 124-5) had the essential insight: "The real reason for the predominance of labour saving inventions is surely that...a change in the relative prices of the factors of production is itself a spur to innovation and to inventions of a particular kind–directed at economizing the use of a factor which has become relatively expensive." Habakkuk (1962) used this insight to argue that high wages led Americans to invent labour saving technology in the nineteenth century, and a similar situation obtained in eighteenth century Britain.[4] Economists have since debated how to formalize these ideas (David 1975, pp. 19-91, Temin 1971, Ruttan 2001, Ruttan and Thirtle 2001, Acemoglu 2003). One problem is that businesses are only concerned about costs in toto–and not about labour costs or energy costs in particular–so all cost reductions are equally welcome. I will not review the debate here. Instead, I will show that invention in the British Industrial Revolution was consistent with Hick's observation, while the subsequent perfection of technology looks more like a neutral process. The following generalizations apply to many inventions including the most famous:

1. The British inventions were biased. They were labour saving and energy and capital using.

Thanks to Adam Smith, the pin factory is the most famous production process of the eighteenth century. Smith argued that high productivity was achieved through a division of labour among hand workers. It is very likely that he derived his knowledge from Diderot and d'Alembert's *Encyclopédie* (1765, Vol. V, pp. 804-7, Vol. XXI, 'épinglier') since both texts divide the production process into eighteen stages, and that cannot be a coincidence.[5] Indeed, Smith seems to have used the *Encyclopédie* for the exact purpose that Mokyr suggests–to find out about the latest technology.

There is a difficulty, however. The *Encyclopédie*'s account is based on the production methods at l'Aigle in Normandy. This was not the state-of-the-art practise as carried on in Britain. The first high tech pin factory in England was built by the Dockwra Copper Company in 1692, and it was followed by the Warmley works near Bristol in midcentury. (Hamilton 1926, pp. 103, 255-7). The latter was a well-known tourist destination (Russell 1769), and Arthur Young visited it. Both mills were known for their high degree of mechanization, and they differed most strikingly from Normandy in the provision of power. In L'Aigle, machines were powered by people turning fly wheels that looked like spinning wheels. In contrast, the Warmley mill was driven by water power. Since the natural flow of the stream could not be relied on, a Newcomen steam engine was used to pump water from the outflow of the water wheel back into the reservoir that supplied it. "All the machines and wheels are set in motions by water; for raising which, there is a prodigious fire engine, which raises, as it is said, 3000 hogsheads every minute." (Young 1771, p. 138.) Powering the mill in this way immediately eliminated the jobs of the wheel turners (their wages amounted to one sixth of the cost of fabricating copper rod into pins) and probably other jobs as well. Many French workers, for instance, were employed scouring pins. This activity was done with large machines driven by water power at English needle factories at the time.[6] Arthur Young observed that the Warmley works "are very well worth seeing." It is a pity that Adam

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[4]Fremdling (2004, pp. 168-9) entertains this possibility, as does Mokyr (1993, pp. 87-89), who also raises many objections to it.

[5]Peaucelle (1999, 2005, 2006) has examined Smith's sources very carefully and identified several additional French publications that he argues Smith relied on. All of these sources describe production in Normandy.

[6]Early eighteenth century water-driven scouring machinery is still in operation and can be seen at the Forge Mill Needle Museum, Redditch.

Smith relied on the French *Encyclopédie* to learn about the latest in technology rather than travelling with Arthur Young.

Why did the English operate with a more capital and energy intensive technology than the French? L'Aigle was on a river, and water power drove a forge in the town, so geography was not a bar (indeed, the steam engine at Warmley shows that water power was possible almost anywhere if you were willing to bear the cost of a steam engine). The Swedish engineer R.R. Angerstein (1753-5, p. 138) visited Warmley in the 1750s and noted that "the works uses 5000 bushels of coal every week, which, because they have their own coal mines, only costs three Swedish 'styfwer' per bushel," which was about half the Newcastle price.[7] In addition, English wages were considerably higher than French wages. Innovation in pin making is an example of factor prices guiding the evolution of technology.

2. As a result of 1, cost reductions were greatest at British factor prices, so the new technologies were adopted in Britain and not on the continent.

One of the big themes in the history of the industrial revolution is the lag in adopting British technology on the continent. There has been a tendency to regard the inventions of the industrial revolution as such marvellous improvements that only a fool would ignore them. Coke smelting is an important example, and Landes (1969, pp. 216, 528) attributed its slow diffusion on the continent to entrepreneurial failure. However, a close study of the economics shows that coke smelting was not profitable in France or Germany before the mid-nineteenth century (Fremdling 2000). Continuing with charcoal was rational behaviour in view of continental factor prices. This result looks general; in which case, adoption lags mean that British technology was not cost-effective at continental input prices.

3. The famous inventions of the industrial revolution were made in Britain rather than elsewhere in the world because the necessary R&D was profitable in Britain (under British conditions) but unprofitable elsewhere.

Research and development was expensive, and it was fundamental to inventing in the eighteenth century. Consequently, inventions were undertaken only when the R&D benefits exceeded the costs. If the French or Germans did not adopted an invention when it was freely available, then it brought them no benefit, and there would have been no point in expending resources to have invented it. If we ask why coke smelting, or the spinning jenny, or the steam engine were invented in Britain rather than in China or France, the adoption lags imply that the rates of return to these R&D projects were zero outside Britain. To understand invention, we do not have to entertain the arcane questions that arise in cultural discussions of the topic: Did Chinese science have a sufficiently developed concept of the vacuum to allow the conceptualization of the low pressure steam engine? Was French engineering theoretically inclined while British was empirical? The answer lies in different economic conditions that led different countries to invent different kinds of technology.

4. Once British technology was put into use, engineers continued to improved it, often by economizing on the inputs that were cheap in Britain. This made British technology cost-

[7] I am thank Martin Dribe for help in deciphering the Swedish stwyfer.

effective in more places and led to its spread across the continent later in the nineteenth century.

As British technology evolved, capital and energy intensities declined. Chapman (1970, p. 253) observed that "the mechanical genius of Lancashire was directed towards a reduction of plant costs, which fell from £2 per spindle at the height of the Arkwright era to less than £1 a spindle by 1836." It was the same story with steam power: The first Newcomen engines were profligate in their use of fuel. Smeaton improved them in the mid-eighteenth century cutting the use of coal. Watt's separate condenser saved more fuel. The high pressure steam engine, and the Cornish engine reduced energy use much further (Nuvolari 2004a). By the mid-nineteenth century, steam engines could be used in France even though coal was expensive since they did not use much of it. The culmination of this process was compound condensing marine engines that finally made steam ships cheaper than clipper ships on the very long routes from the Pacific to Britain (Harley 1971).

Three idealist explanations

The theory advanced here explains the technological breakthroughs of the industrial revolution in terms of the economic base of society–natural resources, international trade, profit opportunities. Through their impact on wages and prices, these prime movers affected both the demand for technology and its supply. An alternative approach traces the inventions of the industrial background back to the realm of ideas and culture. This view is advanced by cultural historians like Margaret Jacob (1988, 1997) and Larry Stewart (2004) and by economists like Joe Mokyr (2002). His writings have been highly influential in putting technological history at the centre of debate and in emphasizing the importance of networks and communication channels for understanding invention. However, the history of wages and prices as well as the detailed investigation of famous inventions (to be considered shortly) both suggest that economic evolution exerted a stronger influence on invention than autonomous changes in culture or ideas.

There are three distinct idealist explanations of the industrial revolution that need to be considered:

1. The technological breakthroughs were 'macro-inventions,' i.e. acts of genius or serendipity rather than responses to economic incentives.
2. The technological breakthroughs were applications of scientific discoveries that were made for scientific rather than economic reasons.
3. The industrial revolution was the result of the spread of scientific culture that made people more experimental, more numerate, and more systematic in their study of technology. This cultural change was due to the success and example of Newtonian science.

These possibilities affected the supply of technology rather than its demand. The first two increased the supply of technology by providing engineers with Big Ideas to develop. The third improved the ability of engineers to turn ideas into commercial applications.

Consider macro-inventions first. These differ from micro-inventions, which are "the small incremental steps that improve, adapt, and streamline existing techniques already in use, reducing costs, improving form and function, increasing durability, and reducing energy and raw material requirements." Microinventions are "more or less understandable with the help of standard economic concepts. They result from search and inventive effort, and respond to prices and incentives." In contrast, macroinventions embody "a radical new idea, without clear precedent" and emerge "more or less ab nihilo." They "do not seem to obey obvious laws, do not necessarily respond to incentives, and defy most attempts to relate them to exogenous economic variables. Many of them resulted from strokes of genius, luck or serendipity" (Mokyr 1990, p. 13.) Mechanical spinning is a pre-eminent example. (Mokyr 1993, p. 20).

Stress on pure genius is hard to square with my discussion of wages, prices, and the incentives they created for inventing technology, for that analysis treats all of the inventions of the industrial revolution as micro-inventions. Which were they: micro or macro? The tests are: (a) to see whether mechanical spinning, for instance, emerged 'ab nihilo' or whether it was a development of existing ideas and (2) to see whether its 'invention' involved a development program that made sense in terms of economic opportunities. When we perform these tests, we see that the famous inventions of the industrial revolution look more like micro-inventions than macro-inventions.

How about scientific discovery as a source of eighteenth century technology? This is a favourite theme of university presidents and vice chancellors, and, indeed, has been argued by proponents of scientific research since the seventeenth century. In 1671, Robert Boyle developed the argument. "Inventions of ingenious heads doe, when once grown into request, set many Mechanical hands a worke, and supply Tradesmen with new meanes of getting a liveleyhood or even inriching themselves." There were three ways by which "naturalists" could improve technology. "The first [was] by increasing the number of Trades, by the addition of new ones." The pendulum clock and scientific instruments were Boyle's examples. "The second [was] by uniteing the Observations and Practices of differing Trades into one Body of Collections," so that techniques used in one trade could be transferred to another. "And the third [was] by suggesting improvements in some kind or other of the Particular Trades." Cornelius Drebbel's invention of turkey red dye was an example, but what particularly excited Boyle were the possibilities of inventing "engines" to mechanize production. "When we see that Timber is sawd by Wind-mills and Files cut by slight Instruments; and even Silk-stockings woven by an Engine...we may be tempted to ask, what handy work it is, that Mechanicall contrivances may not enable men to performe by Engines." Boyle thought that there were more possiblities here "than either Shopmen or Book men seem to have imagined" and experimental scientists would discover them. (Boyle 1671, Essay 4, pp. 10, 20.)

Was Boyle right? The impact of scientific discovery on technology was explored thoroughly in the 1960s (Musson and Robinson 1969, Mathias 1972). The search turned up only one important application of scientific knowledge to industry–the steam engine, which was based on the discovery that the atmosphere has weight. It is a big leap, however, from that connection to the conclusion that the discovery of the weight of the atmosphere *caused* the invention of the steam engine. I will examine its history and argue that it was only in Britain that the economic benefits were great enough to justify the expense of perfecting the steam engine. No one would have found it worthwhile anywhere else in the world. Its invention was as much a response to economic opportunities as to scientific advance. And apart from the steam engine, there's not many applications that can be linked to science.

The third idealist explanation is the most amorphous. The basic idea is that the scientific revolution created a 'culture of science' that led to the inventions of the industrial revolution. The explanation is usually developed in two stages. The first stage explains why the industrial revolution happened in Europe at the end of the eighteenth century (rather than in China or in the middle ages); the second explains why it happened in Britain rather than France.

Mokyr (2002, p. 29) gives a succinct statement of the first stage claim.

> I submit that the Industrial Revolution's timing was determined by intellectual developments, and the true key to the timing of the Industrial Revolution has to be sought in the scientific revolution of the seventeenth century and the Enlightenment movement of the eighteenth century. The key to the Industrial Revolution was technology, and technology is knowledge.

Mokyr coined the term Industrial Enlightenment to describe the features of the Enlightenment that linked the Scientific Revolution of the seventeenth century to the Industrial Revolution of the eighteenth and nineteenth. The Industrial Enlightenment emphasized the application of the scientific and experimental methods to the study of technology, the belief in an orderly universe governed by natural laws that could be apprehended by the scientific method, and the expectation that the scientific study of natural world and technology would improve human life. These ideas were popularized until they eventually permeated the culture. The channels through which this was done included professional scientific societies like the Royal Society, and the publication of books like the *Encyclopédie* that described manufacturing processes (although the tale of pin-making gives us pause). Popular scientific societies and lectures also played a role in disseminating the new approach to technology and nature.

According to Mokyr (2002, p. 29), the industrial enlightenment explains "why the Industrial Revolution took place in western Europe (although not why it took place in Britain and not in France or the Netherlands.)" This must be so when the pre-eminent example of knowledge diffusion is Diderot and d'Alembert's *Encyclopédie*. Britain's lead over France is attributed to a difference in the engineering cultures of the two countries: The French were supposedly theoretical, while the British were practical. This is the second stage claim.

With a theory so multi-faceted, it is hard to reach a definitive judgement: The theory stimulates, but there are many grounds for reservation. The theory posits European and national cultures that make little allowance for class or social status differences in attitudes. What exactly were the links between Cambridge dons like Newton and artisan inventors like Abraham Darby or James Hargreaves? This problem was apparent to eighteenth century writers. In <u>The Fable of the Bees</u>, Mandeville (1724) remarked:

> They are very seldom the same Sort of People, those that invent Arts, and Improvements in them, and those that enquire into the Reason of Things: this latter is most commonly practis'd by such, as are idle and indolent, that are fond of Retirement, hate Business, and take delight in Speculation: whereas none succeed oftener in the first, than active, stirring, and laborious Men, such as will put their Hand to the Plough, try Experiments, and give all their Attention to what they are about.

To close the gap between high science and artisan technology, the culturalists propose coffee houses giving popular science lectures. Who attended these events and what they heard are less than clear. The minutes of the Chapter Coffee House society, which met between 1780 and 1787, have been published (Levere and Turner 2002), and they provide a rare peek inside. They warrant attention since the history of the society provides "hard evidence of the interplay between science and technology, and industrial revolution." But does it? 60% of the 55 members were Fellows of the Royal Society and only five had a connection to manufacturing. Of those five, only one ever attended a meeting. The Chapter Coffee House was not science communicating with industry. It was science talking to itself. There probably were some occasions when high science addressed the hoi polloi, but the suspicion must be that Mandeville was right: these were separate spheres.

More suspicion that the Industrial Enlightenment was mainly an upper class cultural phenomenon with little relation to production comes from the study of its twin–the Agrarian Enlightenment. This involved many of the same themes as the Industrial Enlightenment–except applied to farming rather than manufacturing–and, indeed, many of the same people, once returned to their country houses at the close of the London season. These were the celebrated improving landlords of England, who enclosed their estates, turned their home farms into experimental stations, patronized Arthur Young (a great collector of farming data), published reports of new crops and cultivation methods, and promoted improved farming among their tenants. This was the enlightenment project applied to agriculture, but, unfortunately for the cultural theory, it had little effect on agricultural productivity (Wilmot 1990). The impact of the Agrarian Enlightenment was inherently limited because it was a movement among the gentry and aristocracy, not among the farmers who actually tilled the land. The books were written by landlords, for landlords. The King could play at being Farmer George, but there was little connection with real production. Was the Industrial Enlightenment as ineffective?

It is important to distinguish between popular culture and elite culture and ask how they were related. Cultural historians see popular culture changing in response to high science, an elite cultural activity. In contrast, I contend that popular culture evolved in response to changes in the economy. The growth of international trade led to much greater urbanization in northwestern Europe. Jobs in trade, manufacturing, and commerce required skills that agriculture had not demanded. Literacy rates in medieval Europe were much higher in cities than in the countryside for this reason, so literacy rose with urbanization. The high wage economy of the commercial centres also aided the accumulation of human capital by making it easier for people to pay for education and knowledge. Beyond that, the invention of printing sharply reduced the price of books leading to much greater effective demand for both useful knowledge and pleasure (van Zanden 2004a, 2004b, Reis 2005). The same factors probably boosted numeracy (Thomas 1987). Knowledge of arithmetic and geometry was important to keep accounts and navigate ships. In his path breaking epidemiological study of London, Graunt (1662, p. 7) attributed his calculations not to science but to trade: "It depends upon the Mathematiques of my Shop-Arithmetic." The much greater level of human capital in the eighteenth century than in the middle ages is an important reason why the industrial revolution did not happen earlier.

Do differences in human capital explain why the industrial revolution occurred in Britain rather than France? Literacy in France as a whole was lower than in Britain, but France was a bigger country with a larger population and considerable diversity. Literacy in northern France was about as common as in Britain, and so human capital differences may not have been important. Indeed, it is not clear that there was much difference in inventiveness between eighteenth century Britain and France. There are certainly many examples of the French inventing. Why do we think the British had a more pragmatic engineering culture than the French? Because it was Brits who first smelted iron with coke, invented the steam engine, and discovered how to spin with machines. In the rest of this essay, I will show that these differences in behaviour were due to differences between the countries in the profitability of doing R&D. If that argument is accepted, then cultural explanations become superfluous.

Some famous inventions

The only way to adjudicate between the cultural and economic explanations of technical change is to test them against the history of invention. I will examine three famous inventions–coke smelting, mechanical spinning, and the steam engine. I explore four themes:

- What was the origin of the idea embodied in the invention? Was it an inspired act of genius or a scientific discovery? With the exception of the steam engine, which was based on science, the fundamental insight was copied from other activities. Boyle proposed the publication of craft knowledge to promote invention-by-copying, and Mokyr has made it part of his Industrial Enlightenment. Indeed, copying was the general pattern and shows that the Industrial Revolution was based on little ideas–not big ideas as often assumed.
- What technical problems had to be solved in order to put the idea into practice? How much R&D was involved in making the idea work? R&D was the crux of invention in the eighteenth century, and all of the famous inventions including Newcomen's steam engine, required substantial development programs to perfect them. These R&D projects exhibited the modern trilogy of development costs, external finance, and patenting. The expense of R&D turned invention from a scientific into an economic activity.
- How were these inventions related to Britain's unique wages and prices? Were the inventions biased in the sense that they cut costs more at British prices than at foreign prices? All of these inventions make sense in terms of the high wages and cheap coal of the British economy. Despite being known, they were not adopted in other countries where wages were low and energy expensive.
- Why were they invented in Britain rather than elsewhere in Europe? The bias of the technical change implies that R&D was a profitable investment in Britain but would not have been in other countries.

The invention of coke smelting

Coke smelting is one of the famous inventions of the industrial revolution and had an enormous long run impact, for it was essential for the production of cheap iron, which, in turn, was required for the railroad, metal steam ships, and the general mechanization of industry. The invention of coke smelting clearly illustrates the themes of this essay: It was a little idea, not a big idea. Initially, coke iron was more expensive than charcoal iron, and the first problem was to develop a market for the new product. This was accomplished through an R&D program to make thin-walled castings. The second problem was to cut production costs, so coke iron was competitive with charcoal iron for refining into wrought iron. This problem was solved inadvertently as problems of irregular water supply were addressed. Coke smelting was a biased technical improvement, which was not profitable to use in most of Europe, and would not have been profitable to invent outside of Britain. That is why the discovery was made in Britain rather than France.

How much creativity did coke smelting require? What engineering problems did it pose?

Coke smelting did not depend on any scientific discovery nor did it require an act of genius. In fact, it required almost no thought at all. Coal was a much cheaper source of energy than wood, and attempts were made to substitute the cheaper fuel in most applications during the seventeenth century. If coal was being burnt to heat the house, why not chuck it into the blast furnace instead of expensive charcoal? And, indeed, there are many examples of people doing just that in the seventeenth century. Dud Dudley was an early pioneer who claimed in his book *Metallum Martis* (1665) to have successfully smelted iron with coke, and he had the iron goods around his house to prove it. Others followed, and there is no reason to believe that they failed. The problem was that the process was not economic. Most iron in the seventeenth century was refined into wrought iron, and pig iron smelted with coal contained too much sulfur for this to be successful. This was a typical problem in substituting coal for wood: the coal introduced impurities, so new technology had to be invented to eliminate them. Wrought iron was not successfully made from mineral fuel pig iron until the middle of the eighteenth century.

Abraham Darby I is usually credited with the invention of coke smelting, but, as noted, he did not conceive the idea. Darby probably learned about coke smelting from Shadrach Fox, who had a contract to supply the Board of Ordnance with cast iron shot in the 1690s. This iron was probably smelted with coke, and the Fox's furnace was the one at Coalbrookdale that Darby later leased. The furnace blew up in 1701, and Fox smelted some more iron with coal or coke at the Wombridge Furnace. Darby leased the Coalbrookdale from Fox in 1708, rebuilt it, and set off on his career smelting coke iron (King 2003, p. 52).

The link from Fox to Darby solves several puzzles–why Darby never patented coke smelting (although he patented a casting process) and how he had the confidence to use coke from the very inception of his business. He seems to have known the process would work technically, for he did no experimenting with coke nor does he seem to have had a back-up plan to use charcoal if coke smelting failed. Also, Shaddrock Fox's experience showed that coke iron was suitable for castings, which was the application Darby had in mind.

Darby's R&D project

Indeed, Darby's contribution to 'inventing' coke smelting was in finding a commercially viable application for the material. In about 1702, Darby and other Quakers established the Baptist Mills Brass Works near Bristol. Most brass was then fabricated by drawing it into wire or by hammering sheets into pots, kettles, and such like. Casting was traditionally limited to church bells and canon. However, by the late seventeenth century, the Dutch were casting many other products using sand moulds and reusable patterns. In 1703, Darby set up his own foundry and tried to cast iron pots with sand moulds, but he was unsuccessful. In 1704, he went to the Netherlands to study sand casting. He brought back some Dutch workers and got them to try casting iron, but they were also unsuccessful. However, an English apprentice, John Thomas, believed he could do it, and Darby paid him until he was successful in 1707. This was Darby's principal R&D project, and it resulted in a patent for casting iron with sand molds. Darby's partners in Baptist Mills did not want to pay for this research, but he found a new financial backer in Thomas Foudney.

When Darby leased the Coalbrookdale furnace from Shadrach Fox, his plan was to smelt pig iron and cast iron pots with sand moulds. Not only were the castings successful, but the silicon in the coke iron rendered it more fluid than charcoal iron, so it proved possible to make pots with thinner walls that sold at a higher price. This was essential for the success of coke smelting since the iron itself was expensive. This was the process that Darby patented (Mott 1957-9, p. 78, Hyde1977, pp. 40-1).

The smelting process involved two further examples of technological borrowing. The first was in the manufacture of coke. Darby had learned how to make coke when he was apprenticed to a maltster, for coke had been invented for that use (Matt 1957, Raistrick 1989, pp. 23, 25). The second was the use of the reverberatory furnace to remelt the pig iron for casting. Reverberatory furnaces had been used since the middle ages to melt the brass for bell founding, and Dud Dudley may have used such a furnace to cast iron. In the 1670s and 1680s, the reverberatory furnace was used to smelt lead and copper by two chartered companies associated with Sir Clement Clark, who may have experimented with melting iron. Darby was the first to make a commercial success of the reverberatory furnace in the iron foundry (Mott 1957-9, p. 76, King 2003, p. 51). Evidently, Darby's plan to cast pots with coke pig iron did not come out of nowhere. It was the combination of several recent developments in the iron and copper industries.

For the first half of the eighteenth century, coke smelting was limited to only a few furnaces making foundry pig, for the metal was too expensive and impure to refine into wrought iron, the main product of the industry. This problem was overcome through 'learning by doing' or, more exactly, through inadvertent discovery made in the course of solving other problems. The bellows of blast furnaces were run with water power, and a dry summer meant that the water level dropped in the reservoir supplying the wheel resulting in a fall off in blast and reduced iron production. This problem was resolved at Coalbrookdale by installing a Newcomen steam engine to recycle water by pumping it from the outflow of the water wheel back into the supply reservoir. Coalbrookdale was one of the first firms to use this process (Raistrick 1989, pp. 107-115). As was the case with Warmley, coal was mined at Coalbrookdale, and the cheap fuel made the Newcomen engine feasible.

The improved water supply resulted in stronger, more regular blast to the furnace, and that had the unintended consequence of cutting fuel consumption. Lower fuel consumption, which was an *energy-saving* technological improvement, cut costs enough to make coke iron competitive with charcoal. Coke iron production took-off after mid century.

Coke smelting was a biased technical improvement that reduced costs in Britain more than on the continent.

By replacing charcoal with coke, Darby's smelting process cut costs in localities where coal was cheap. Since most coal in Europe in the eighteenth century was mined in Britain, coke technology (once perfected) conferred a great advantage on Britain. Conversely, coke smelting was pointless where coal was as dear as it was in most Europe before the mid-nineteenth century. As late as the 1840s, 80% of French and Prussian iron was charcoal. Belgium is the exception that proves the rule, for it shifted early to coke, and it was also the only part of the continent with large scale coal mining in the eighteenth century and a price structure like Britain's (Landes 1969, p. 217). While Landes has argued that Britain's lead is evidence of superior entrepreneurship, Fremdling (2000) has shown than coke iron did not pay on the continent before the 1850s. Production costs explain the diffusion of the technology–not attitudes to innovation.

Why not France?

It took almost a century from the perfection of coke smelting at Coalbrookdale until its use was widespread on the continent. During that period, the technology was well known and freely available but not adopted. Since it conferred no benefit to French or German producers, there would have been no point in developing it in those countries. It was not the impracticality of the engineering culture that explains the lack of attention to coke smelting. Inventing the process would not have paid.

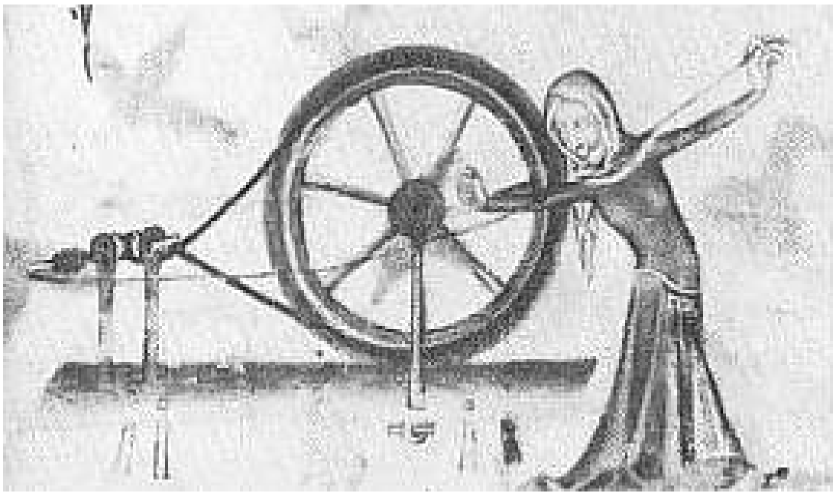
The invention of cotton spinning machinery

How much creativity did mechanical spinning require? What engineering problems did it pose?

The spinning jenny and water frame were not based on scientific discoveries. Were they instead 'macro inventions' that required enormous leaps of the technological imagination? To know, we must see if the spinning machines really did spring ab nihilo or whether they had genealogies that indicate less dramatic departures from previous practice. I begin with hand spinning to highlight the technical problems that Hargreaves and Arkwright faced.

Figure 7 shows a spinning wheel in operation. The raw cotton was first carded to produce a roving, which was a loose length of cotton fibres. The two key operations in spinning were drawing out the roving so it became thinner and then twisting it to impart strength. In the late medieval period, this was done with a 'spinning wheel'. It consisted of three parts–the wheel itself, the spindle, and the string that acted as a belt to connect the wheel to the spindle. Sometimes a treadle was connected to the wheel so that the spinster could turn it with her foot; otherwise she used her right hand. She held the roving in her left hand, and its other end was attached to the horizontal spindle. The wheel was spun, and the spindle rotated. The spinster pulled back the roving so that it thinned out and then moved her hand to the left. This allowed the thread to slip off the end of the spindle each time it rotated. Each time that happened, the thread was twisted once. When enough twist was imparted, the spinster moved her left hand to the right, so it was once again between her and the spindle. In this position, the thread was wound onto the spindle. The process was repeated as the next few inches of roving were pulled away from the spindle to be thin out in turn.

Figure 7



It is hard to see anything that came ab nihilo in Hargreaves' spinning jenny. It was little more than a spinning wheel on its side with several spindles connected by belts to a common wheel. Indeed, the story is that Hargreaves conceived the jenny when he saw a spinning wheel fall over and continue spinning while it was on the ground. A sliding frame replaced the spinster's left hand and drew the rovings away from the spindles. The difficulty, as with most eighteenth century technology, lay in working out of the details of the linkages and rods that drew out the cotton roving. The spinning jenny was an engineering challenge. It did not require a scientific breakthrough or a great leap of imagination.

Figure 8

Arkwright's water frame was another spinning technique that was more portentous in its consequences and arguably more clever in its design. But, again, it was based neither on a scientific breakthrough nor on an original idea. Figure 8 shows a water frame, and Figure 9 is a close-up of the 'clockwork'. The rovings entered at the top. They then passed through three pairs of rollers. The rollers operated like mangels, pulling the cotton between them. The second pair spun at twice the speed of the first, and the third doubled the speed again. For this reason, the first pair of rollers simultaneously pulled the roving into the mechanism and at the same time held it back with respect to the second pair, which was spinning faster and tugging it forward. The cotton was, thus, stretched and thinned out as it went between the two pairs of rollers. The stretching was repeated between the second and third pairs of rollers since the third pair spun faster than the second. In this way, the water frame accomplished the first task in spinning–drawing out the fibre.

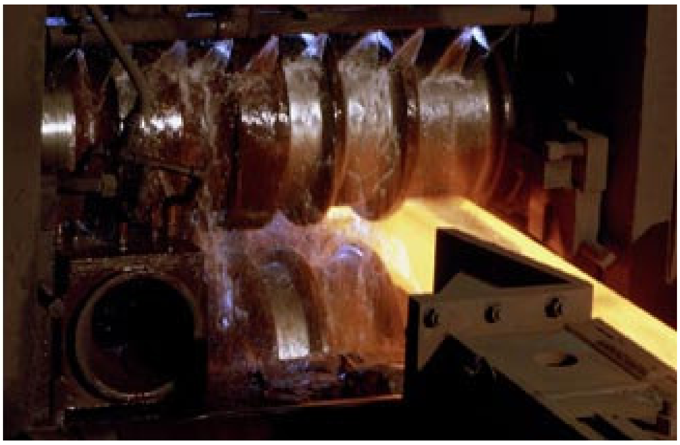
Figure 9

The second task was accomplished by the flyers, which spun around at the bottom of the frame, simultaneously twisting the fibre and coiling it on the bobbin.

Not much of this was original with Arkwright. The flyer, indeed, was an old device and none of the cotton inventors could take credit for it (another example of copying). The novelty of the water frame lay in the trains of rollers that drew out the cotton. This idea, however, was not Arkwright's either: Wyatt and Paul took out patents on the idea in 1738 and 1758. Much effort was put into perfecting the machine, licenses were sold, and they erected their own factory in Birmingham. It was not successful, although Matthew Boulton thought it might have been had it been well managed. The Wyatt and Paul R&D program was a failure.

If there were any macro inventors, they were Wyatt and Paul. But were they? The test of a macro-invention is whether it was conceived ab nihilo or whether it had a pedigree that shows that it involved only a small variation in practice. By that test, roller spinning was a micro-invention. Rollers were a general purpose

Figure 10



technology whose use was spreading in the early eighteenth century.[8] Rollers had a long history in metallurgy where bars, ingots, plates, and nails were shaped (Figure 10). Coin faces were pressed into gold and silver with engraved rollers. Indeed, the similarities between a metal rolling mill and roller spinning were so great that Rees (1819-20, II, p. 173) reports that Arkwright conceived of roller spinning when looking at a rolling mill. There are sixteenth and seventeenth century designs for corn mills using rollers. In the late seventeenth century, cast glass was rolled at Saint-Gobain and polished with a roller. Cloth was pressed by rollers under enormous weight in the calendering process. In 1696, the Paris mint was using rollers. In the late seventeenth century, 'milled' sheet formed by rolling lead replaced cast lead sheet. In 1670, the Dutch developed a roller device with spikes to tear up rags for paper making and in 1720 applied rollers to pressing paper. Rollers were also used to crush rock. Applying rollers to stretching cotton was no doubt clever, but the idea had a history. When he discussed Cort's invention of puddling and rolling, Mokyr (1993, p. 22) discounted it as a macro invention since rolling had a long history in metallurgy. The same argument applies to cotton. Rollers were in the air in the first half of the eighteenth century. Wyatt and Paul did not think them up from nowhere. Roller spinning was not a macro invention.

Hargreaves' and Arkwright's R&D projects

The challenge with roller spinning was making the idea work. Hargreaves faced the easier challenge. His first jenny was reportedly made with a pocket knife, but getting a design that could be operated satisfactorily took from 1764 to 1767 (Aspin and Chapman 1964, p. 13). Hargreaves began trying to realize money from his invention almost immediately by selling jennies. He moved to Nottingham. As he continued to improve the jenny he needed a financial backer. He first went into partnership with a man named Shipley and later with Thomas James (Aspin and Chapman 1964, 19, 22-3, 34-5). They established a spinning factory. In 1770, Hargreaves patented the jenny, but it was too late. His patent was challenged in court and eventually voided on the grounds that he had sold jennies before it was issued. Despite the widespread use of the jenny in the late eighteenth century, Hargreaves realized very little money from the invention.

Arkwright's challenge was far greater. Figure 11 shows Wyatt and Paul's diagram from their second patent, and it can be compared to the Arkwright machine to see the engineering problems involved. Both devices used a flyer to twist and wind the finished thread. Wyatt and Paul's diagram shows one pair of rollers, whereas Arkwright's frame had

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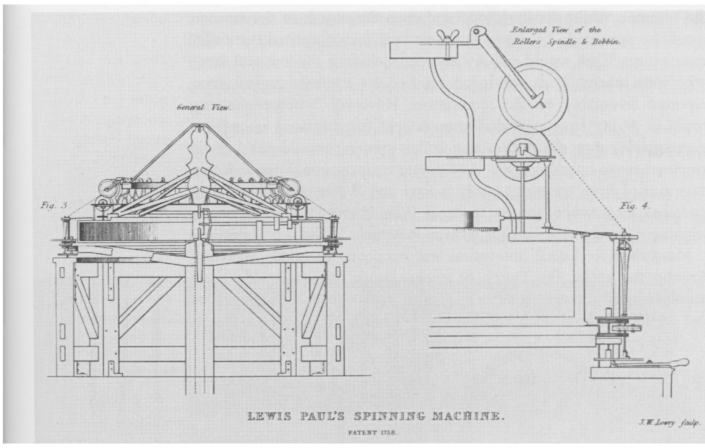
[8]Singer, et al. (1957, Vol. III, pp. 16-7, 32, 45, 47, 177, 238-9, 340-4, 414-5), Raistrick 1972, p. 91), Rowe (1983, pp. 8-10), Beveridge (1939, pp. 191-2, 287-9, 485-9, 652-6) Mokyr (1990, p. 60), Hunter (1930, pp. 170-1).

three. It was essential to have several in a series so that they could pull against each other. Wyatt and Paul did mentioned two pairs in the description of the machine in their first patent: Deciding the number of rollers was a development challenge, and it looks as though Wyatt and Paul went down a wrong alley in their R&D program by trying to develop a machine with only one set of rollers.

Figure 11



They never confronted, therefore, the other development challenges that Arkwright overcame in the 1760s. These included:

- The increase in speed from one set of rollers to the next. In the early water frame displayed in Strutt's North Mill, Belper rotation speed doubles from one train of rolls to the next.
- How to arrange the gears to connect the main power shaft to the rollers and coordinate their movements. The rollers and gears were produced as a module known as the 'clock work' in recognition of the apparatus that inspired it.
- The spacing between the rollers. The distance had to be slightly less than the length of a cotton fibre. That allowed stretching and thinning of the thread since a fibre that was past the grip of the first rollers and caught by the second pair could be pulled ahead of an adjacent fibre that was held by the first rollers but not yet in the grasp of the second. If the rollers were too close, all of the fibres would be gripped by both pairs, so there would be no stretching. If the rollers were too distant, the thread would be pulled apart: Proper operation required some fibres to be gripped by both rollers to prevent breakage, while others were held by one or the other pair for thinning. Thought and experimentation were required to work this out.
- The materials with which to make the rollers. One was grooved metal and the other wood covered with leather. They had to pull the fibre without catching.
- The pressure with which the top roller pressed down on the bottom one. This was regulated by hanging weights from the top ones, as shown in Figure 9. The optimal weight could only be determined by repeated trials.

The point of this discussion is to emphasize the real issues involved in 'inventing' mechanical spinning. The originality was not in thinking up the roller; rather, the challenges were the practical issues of making the roller work in the application. Wyatt and Paul spent some years on this, but did not succeed. Arkwright employed clockmakers over a five year period to perfect the design. We have no record of exactly what they did, but the comparison of the Wyatt and Paul design with Arkwright's frame highlights the problems they faced. These challenges could only be met by constructing models or experimental prototypes. 'Inventing' the water frame involved a significant R&D program.

The R&D program had very modern financial implications that are worth noting. First, the object was to make money for Arkwright, and patenting the invention was the essential step in securing that income. This was done in 1769. Second, there was the formidable problem of financing the R&D. Arkwright did what modern inventors do: he found venture capitalists–'projectors' in the language of the eighteenth century. His patent was jointly held with John Smalley and David Thornley, and each partner was committed to finance one third of the development costs. Quickly they ran out of money, and Samuel Need and Jedediah Strutt were brought in as partners. Strutt was an established 'projector,' who had already made a fortune financing improvements in frame knitting. Development work continued. Strutt himself suggested dusting the rollers with chalk to prevent the cotton from sticking to them. Several cam operated devices were added to wind the thread, raise and lower the bobbins and move the thread back and forth along the rollers to prevent a groove's being worn in the surface. In 1774, Jedediah Strutt claimed that £13,000 had been spent on developing Arkwright's device. This included the construction of buildings, which posed problems of layout and power transmission, and it indicates the scale of the finance required to turn the idea of roller spinning into the reality of a working cotton mill (Hills 1970, pp. 60-71).

Roller spinning was not unusual. If we examine the revolutionary inventions of the eighteenth century, we see that they were not based on revolutionary ideas. They were based on little ideas and often on copying products and practices from other places or industries. Success depended on solving the engineering problems in making the simple idea work. Edison famously remarked that 'invention was 1% inspiration and 99% perspiration.' Sweat was at least as important in the eighteenth century as it was in the late nineteenth. Mokyr (1993, p. 33) correctly observed that Britain 'had a *comparative* advantage in *micro*inventions.' The questions are where that advantage came from, and why it was activated.

What was the motive for mechanizing spinning?

Mechanical spinning was a child of globalization. India was the world's greatest cotton textile producer, and the East India company imported vast amounts of printed cotton cloth. This was important for later developments, for it showed that there was a large British market. So much was imported, that wool and linen manufacturers succeeded in 1701 in having printed cotton fabrics excluded from Britain. The import of white cottons was still permitted, and printing was done in England. A small British production of cotton cloth ensued. In 1721, the ban was extended to all cotton fabrics: the domestic production and consumption of purely cotton fabrics was made illegal. "The Lancashire cotton industry...secured in 1736 a relaxation for goods of flax warp and cotton weft [called fustians], a relaxation which by custom (or subterfuge) came to cover the great bulk of the industry's production and even, it is probable, the growing part of it that used hand-spun cotton twist for warps," i.e. all cotton cloth (Fitton and Wadsworth 1958, p. 68). English cotton producers, thus, received ambiguous protection from Indian imports. Similar restrictions were imposed in other European countries. While offering domestic protection, the laws did permit the importation of Indian cottons for re-export, and that market boomed with the growth of the slave trade in the mid-eighteenth century, for cotton cloth was bartered with African chiefs for slaves. This was another market which British producers could hope to supply–if their costs were competitive.

Britain's high wage economy affected the cotton industry in two respects. First, the high incomes of British workers underpinned the mass market in cloth that was revealed during the period of unrestricted imports (Lemire 1991, p. 55). Second, at the exchange rate, British wages were considerably higher than Indian wages. While distance provided some protection, English spinners could only compete in producing the coarsest yarn, which was the least labour intensive.

Lowering labour costs was the key to competitiveness. There was a large potential domestic market, and a vast foreign market supplied by India and other producers. Cost reductions promised a large increase in market share and immense fortunes for the successful innovators–both of which were realized through mechanization.

Why not France?

Globalization affected other European countries as it affected England. For much of the pre-industrial period, France had possessions in India and was flooded with Indian calicoes in the late seventeenth century. Their importation was banned in 1686. France also had new world colonies and was active in the slave trade where French ships carried about 40% of the volume of English ships (Curtin 1966, pp. 211-2). French producers had an African market, albeit a smaller one than the English. In 1786, when English production was already soaring as mechanized spinning spread, Britain imported 18 million pounds of raw cotton, while France imported 11 million (Crouzet 1985, p. 32). The French cotton market was substantial, and French manufacturers had opportunities to compete against Indian textiles in Africa like their British counterparts, a feature emphasized by Inikori (2002, pp. 427-51).

And yet the French not only failed to invent mechanized spinning, they did not adopt it even when it was freely available. This was not for lack of knowledge. John Holker was an English Jacobite, who fled to France in 1750 where he established himself as a cotton manufacturer. In 1754, he succeeded in being appointed Inspector General of Foreign Manufactures charged with importing successful foreign technology. In 1771 he sent his son to Lancashire to report on the new machines, and his son brought back a jenny. This was copied and made available to French producers; indeed, the state subsidized its use. It was installed in some large scale factories but was otherwise ignored by the cotton trade. In 1790, there were about 900 jennies in France compared to 20,000 in England (Aspin and Chapman 1964, p. 49). The disproportion was at least as great with water frames. About 150 large scale mills were in operation in Britain in the late 1780s. In France, there were only four and several of these were extremely small and not representative of British practice. (Wadsworth and Mann 1931, pp. 193-208, 503-6, Chapman and Butt 1988, pp. 106-11).

Why did the French ignore the new spinning machines? Cost calculations for France are not robust, but the available figures indicate that jennies achieved consistent savings only at high count work, which was not the typical application (Ballot 1923, pp. 48-9). In France, a 60 spindle jenny cost 280 livre tournois in 1790 (Chassagne 1991, p. 191), while a labourer in the provinces earned about three quarters of a livre tournois per day, so the jenny cost 373 days labour. In England, a jenny cost 140 shillings and a labourer earned about one shilling per day, so the jenny was worth 140 days labour (Chapman and Butt 1988, p. 107). In France, the value of the labour saved with the jenny was not worth the extra capital cost, while in England it was. French cost comparisons show that Arkwright's water frame, a much more capital intensive technique, was no more economical than the jenny. The reverse was true in England where water frames were rapidly overtaking jennies. The French lag in mechanization was the result of the low French wage.

Global competition was the impetus to invent mechanical spinning. The result was a biased technical improvement that benefited Britain with its high wage economy much more than continental producers like France.

Why the British rather than the French invented mechanical spinning

As we have indicated, both the jenny and the water frame required considerable expenditures in R&D to make them work. The same would have been true in France. Would these expenditures have been worthwhile in France? No–mechanized spinning brought no economic benefit there in view of the low wage. We need look no further to understand why the spinning jenny and the water frame were invented in England rather than France or, indeed, most other parts of the world.

Steam engine

An idea from science

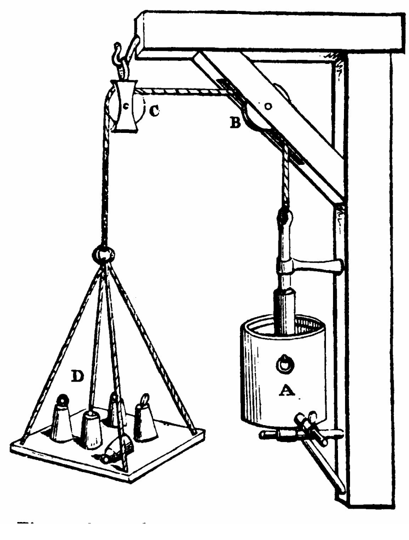
The steam engine presents a variation on the theme. Big Ideas did not have much to do with coke smelting or mechanized spinning, but the low pressure steam engine, developed by Newcomen and improved by Watt, was the best example of a scientific spin-off in the eighteenth century. It was based on the idea that the atmosphere had weight, which was a seventeenth century discovery and a hot topic in experimental physics. Even in this case, however, economic incentives were a key to the application of this new knowledge. Without the British coal industry, the steam engine would not have been developed.

The link from science to the steam engine was direct. The science began with Galileo, who discovered that a suction pump could not raise water more than about 34 feet–despite a vacuum existing above the column of water that had been drawn up to that height. Aristotle had said that nature abhorred a vacuum but only, it seemed, for 34 feet! Galileo suggested to Evangelista Torricelli, his secretary, that he investigate this problem. In 1644 Torricelli inverted a glass tube full of mercury and placed its bottom in a bowl of mercury. The mercury stabilized in the tube forming a column 76 centimeters high with a vacuum above it. This was the world's first barometer, and Toricelli concluded that the atmosphere had weight and pushed the mercury up the column. This was confirmed in 1648 by placing the barometer in a larger container and pumping the air out of it–the column of mercury collapsed and then reappeared as air was readmitted into the larger container.

A particularly important set of experiments was performed in Magdeburg by Otto von Guericke. In 1655, he put two hemispheres together and pumped the air out of the space they enclosed. It took sixteen horses to pull them apart. In another portentous experiment in 1672, von Guericke found that if the air was pumped out of cylinder A (Figure 12), the weights D rose as the atmosphere pushed the piston down into the cylinder. Evidently, the weight of the air could perform work.

This idea had been anticipated by Christian Huygens in 1666 who used exploding gun powder to drive a piston up a cylinder. When it reached the top, the gases from the explosion were released creating a vacuum. Air pushed the piston down and raised the load. This design was not effective. However, his assistant, Denis Papin, realized that filling the cylinder with steam and then condensing it accomplished the same purpose. In 1675, Papin built the first, very crude steam engine.

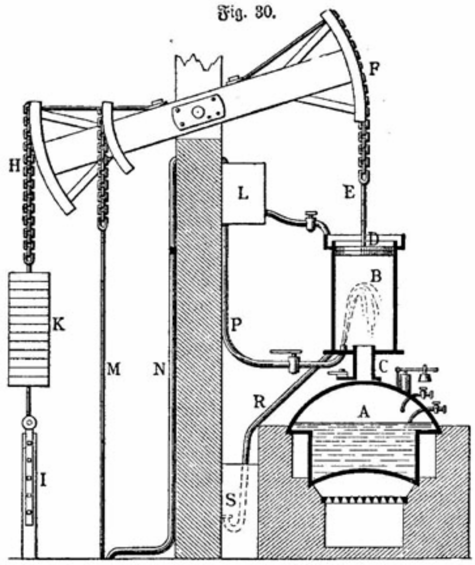
Figure 12



The first practical application of steam technology was Savery's steam vacuum pump patented in 1698. It created a vacuum by condensing steam in a reservoir; the vacuum then sucked up water. The purpose of Savery's devise was draining mines, but it was not widely used, and it was not a steam engine.

Figure 13

Fig. 30.



Newcomens Dampfmaschine.

But still an R&D project

The first successful steam engine was invented by Thomas Newcomen.[9] Like Savery's device, it was intended to drain mines. Newcomen's engine applied the discovery that the atmosphere has weight. That application required a major R&D project, and that project meant that the invention was an economic commitment as well as a scientific spin-off.

Newcomen's design (Figure 13) was suggested by von Gierecke's apparatus: First, replace the weights with a pump (I). Second, construct the 'balance beam' so it is slightly out of balance and rests naturally with the pump-side down (H). Then, if a way were contrived to create a vacuum in the cylinder (B), air pressure would depress the piston (E) and raise the pump. Next, if air were reintroduced into the cylinder, the vacuum would be eliminated and the pump would drop since the beam is slightly out of balance. Finally, recreating the vaccum would raise the pump again since the pressure of the atmosphere would again depress the piston. Thus, creating a vacuum and relieving it raises and lowers the pump. This apparatus becomes a 'steam engine' when steam is made by boiling water (A) and drawing it into the cylinder when the piston is raised, and the vacuum is created when cold water is injected into the cylinder (B) to condense the steam. This is a low pressure engine since it is not steam pressure that pushes the piston up: the point of the steam is simply to provide a gas that fills the cylinder and which is condense to create the vacuum. At the heart of the Newcomen engine was seventeenth century science.

While the Newcomen engine differed from other eighteenth century inventions in its scientific basis, it was similar in the engineering challenges it posed. Twentieth century engineers who have built Newcomen engines have found it to be tricky and difficult to make them actually work (Hills 1989, pp. 20-30). That Newcomen could resolve the engineering problems was a remarkable achievement. He began experimenting around 1700 and apparently built an engine in Cornwall in 1710, two years before his famous engine at Dudley.

In this decade of R&D, Newcomen learned many things. He discovered by accident that the steam could be condensed rapidly if cold water was injected into the cylinder (B). He found that the water supply tank (L) for the injector worked best if it was placed at the top of the engine house, so the injection water entered the cylinder at high pressure and volume. The pipe (R) that drained the condensed water from the cylinder had to run far enough down into a hot well (S), so that atmospheric pressure could not force condensed water back into

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[9]Recent work on the development of the steam engine includes Hills (1989), Nuvolari (2004a), von Tunzelman (1978).

the engine. The top of the cylinder had to be sealed with a layer of water–nothing else worked. The dimensions of the balance and the weights of the engine's piston and the pump (K) had to be coordinated for smooth operation. Linkages between the beam and the valves had to be designed so that they would open and shut automatically at the correct moments in the cycle. No wonder it took Newcomen ten years to create an operating engine. It was a time consuming and expensive undertaking.

Like many practitioners of R&D, Newcomen hoped for a pay-off through patenting his creation. In this he was frustrated because the Savery patent was extended 21 years to 1733 and construed to cover his very different engine! Newcomen was forced to do a deal with the Savery patentees to realize any income at all.

A biased technical improvement that favoured the British

R&D costs mean that the link between Galileo and Newcomen was mediated by economics. Scientific curiosity and court patronage may have been reason enough for Torricelli, Boyle, Huygens and other scientists to devote their time and money to studying air pressure (David 1998), but Newcomen was motivated by prospective commercial gain. What was that gain? The object of the engine was to drain mines, so the demand for the technology was determined by the size of the mining industry. In 1700, England's lead was immense: It produced 81% of the tonnage in Europe and 58% of the value. Germany, which had been Europe's mining centre in the late middle ages, produced only 4% of the tonnage and 9% of the value in 1700. The change was all down to coal. Servicing the drainage needs of England's coal industry is one reason why steam engine research was carried out in England.

Coal mattered for a second reason as well. There were alternative ways of powering pumps–water wheels or horse gigs–so there was effective demand for steam power only if it was cost-effective. The early steam engines were profligate in their consumption of fuel, so they were cheap sources of power only if fuel was remarkably cheap. Desaguliers (1744, II, pp. 464-5), an early enthusiast of steam power, put the matter succinctly:

> But where there is no water [for power] to be had, and coals are cheap, the Engine, now call'd the Fire-Engine, or the Engine to raise Water by Fire, is the best and most effectual. But it is especially of immense Service (so as to be now of general use) in the Coal-Works, where the Power of the Fire is made from the Refuse of the Coals, which would not otherwise be sold.

The Newcomen engine was a biased technological improvement that shifted input demand away from animal feed and towards combustible fuel.

Free fuel overcame high fuel consumption, but, by the same token, the energy-intensity of the Newcomen engine restricted its use to the coal fuels. Since most of the coal mines were in Britain, so were most of the engines. At the expiry of the Savery-Newcomen patent in 1733, there were about 100 atmospheric engines in operation in England. By 1800, the total had grown to 2500 in Britain of which 60 - 70% were Newcomen engines.[10] In

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[10]Kanefsky and Robey (1980, p. 171). The uncertainty depends on how one classifies the engines of unknown type. As the production of Watt engines is reasonably well established, the unknown engines were probably Newcomen, and that choice yields the higher

contrast, Belgium, with the largest coal mining industry on the continent, was second with perhaps 100 engines in 1800.[11] France followed with about 70 engines of which 45 were probably Newcomen (installed mainly at coal mines) and 25 were Watt. The first steam engine was installed in the Netherlands in 1774, in Russia in 1775-7, and in Germany at about the same time. None seem to have been installed in Portugal or Italy (Redlich 1944, p. 122, Tann 1978-9, p. 548, 558). The Newcomen engine "was adopted in numbers only in the coal fields...The machines were, until well into the 19th century, so symbolically linked to the coal-fuel matrix in which they had come to maturity that they could not readily pass beyond its limits" (Hollister-Short 1976-7, p. 22). The diffusion pattern of the Newcomen engine was determined by the location of coal mines, and Britain's lead reflected the size of her coal industry–not superior rationality.

Why the steam engine was invented in Britain rather than France or China

Moreover, the diffusion pattern of the Newcomen engine indicates that it would not have been invented outside of Britain during the eighteenth century. Non-adoption was not due to ignorance: The Newcomen engine was well known as the wonder technology of its day. It was not difficult to acquire components, nor was it difficult to lure English mechanics abroad to install them (Hollister-Short 1976). Despite that, it was little used. A small market for engines implied little potential income for a developer to set against the R&D costs. The benefit-cost ratio was much higher for Newcomen than for any would-be emulator on the continent. Newcomen had to know about the weight of the atmosphere in order to make his engine work, but he also needed a market for the invention in order to make its development a paying proposition. The condition was realized only in Britain, and that is why the steam engine was developed there rather than in France, Germany, or even Belgium.

Why did the industrial revolution lead to modern economic growth?

I have argued that the famous inventions of the British industrial revolution were responses to Britain's unique economic environment and would not have been developed anywhere else. This is one reason that the Industrial Revolution was *British*. But why did those inventions matter? The French were certainly active inventors, and the scientific revolution was a pan-European phenomenon. Wouldn't the French, or the Germans, or the Italians, have produced an industrial revolution by another route? Weren't there alternative paths to the twentieth century?

These questions are closely related to another important question asked by Mokyr: Why didn't the industrial revolution peter out after 1815? He is right that there were previous occasions when important inventions were made. The result, however, was a one-shot rise in productivity that did not translate into sustained economic growth. The nineteenth century

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percentage.

[11]The total is very poorly established and is surmised from an estimate of 200 engines installed in France (then including Belgium) in 1810 made by Perrier, the first important French steam engine manufacturer (Harris 1978-9, p. 178).

was different–the First Industrial Revolution turned into Modern Economic Growth. Why? Mokyr's answer is that scientific knowledge increased enough to allow continuous invention. Technological improvement was certainly at the heart of the matter, but it was not due to discoveries in science–at least not before 1900. The reason that incomes continued to grow in the hundred years after Waterloo was because Britain's pre-1815 inventions were particularly transformative, much more so than continental inventions. That is a second reason that the Industrial Revolution was *British* and also the reason that growth continued throughout the nineteenth century.

Cotton was the wonder industry of the industrial revolution–so much so that Gerschenkron (1962), for instance, claimed that economic growth in advanced countries was based on the growth of consumer goods industries, while growth in backward countries was based on producer goods. This is an unfortunate conclusion, however, for the great achievement of the British industrial revolution was, in fact, the creation of the first large engineering industry that could mass produce productivity-raising machinery. Machinery production was the basis of three developments that were the immediate explanations of the continuation of economic growth until the First World War. Those developments were: (1) the general mechanization of industry, (2) the railroad, (3) steam powered, iron ships (Crafts 2004). The first raised productivity in the British economy itself; the second and third created the global economy and the international division of labour that were responsible for significant rises in living standards across Europe (O'Rourke and Williamson 1999).

The nineteenth century engineering industry was a spin-off of the coal industry. All three of the developments that raised productivity in the nineteenth century depended on two things–the steam engine and cheap iron. Both of these, as we have seen, were closely related to coal. The steam engine was invented to drain coal mines, and it burnt coal. Cheap iron required the substitution of coke for charcoal and was prompted by cheap coal. (A further tie-in with coal was geological–Britain's iron deposits were often found in proximity to coal deposits.) There were more connections: The railroad, in particular, was a spin-off of the coal industry. Railways were invented in the seventeenth century to haul coal in mines and from mines to canals or rivers. Once established, railways invited continuous experimentation to improve road beds and rails. Iron rails were developed in the eighteenth century as a result, and alternative dimensions and profiles were explored. Furthermore, the need for traction provided the first market for locomotives. There was no market for steam-powered land vehicles because roads were unpaved and too uneven to support a steam vehicle (as Cugnot and Trevithick discovered). Railways, however, provided a controlled surface on which steam vehicles could function, and colliery railways were the first purchasers of steam locomotives. When George Stephenson developed the Rocket for the Rainhill trials, he tested his design ideas by incorporating them in locomotives he was building for coal railways. In this way, the commercial operation of primitive versions of technology promoted further development as R&D expenses were absorbed as normal business costs.

Cotton played a supporting role in the growth of the engineering industry for two reasons. The first is that it grew to immense size. This was a consequence of global competition. In the early eighteenth century, Britain produced only a tiny fraction of the world's cotton. The main producers were in Asia. As a result, the price elasticity of demand for English cotton was extremely large. If Britain could become competitive, it could expand production enormously by replacing Indian and Chinese producers. Mechanization led to that outcome. The result was a huge industry, widespread urbanization (with such external benefits as that conveyed), and a boost to the high wage economy. Mechanization in other activities did not have the same potential. The Jacquard loom, a renowned French invention of the period, cut production costs in lace and knitwear and, thereby, induced some increase in output. But knitting was not a global industry, and the price elasticity of demand was only modest, so output expansion was limited. One reason that British cotton technology was so transformative was that cotton was a global industry with more price-responsive demand than other textiles.

The growth and size of the cotton industry in conjunction with its dependence on machinery sustained the engineering industry by providing it with a large and growing market for machinery. The history of the cotton industry was one of relentlessly improving machine design–first with carding and spinning and later with weaving. Improved machines translated into high investment and demand for equipment. By the 1840s, the initial dependence of cotton manufacturers on water power gave way to steam-powered mills (von Tunzelman 1978, pp. 175-225). By the middle of the nineteenth century, Britain had a lopsided industrial structure. Cotton was produced in highly mechanized factories, while much of the rest of manufacturing was relatively untransformed. In the mid-nineteenth century, machines spread across the whole of British manufacturing (one of the causes of the continuing rise in income). Until then, cotton was important as a major market for the engineering industry.

The reason that the British inventions of the eighteenth century–cheap iron and the steam engine, in particular–were so transformative was because of the possibilities they created for the further development of technology. Technologies invented in France–in paper production, glass, knitting–did not lead to general mechanization or globalization. One of the social benefits of an invention is the door it opens to further improvements. British technology in the eighteenth century had much greater possibilities in this regard than French inventions. The British were not more rational or prescient than the French in developing coal-based technologies: The British were simply luckier in their geology. The knock-on effect was large, however: There is no reason to believe that French technology would have led to the engineering industry, the general mechanization of industrial processes, the railway, the steam ship, or the global economy. In other words, there was only one route to the twentieth century–and it went through northern Britain.

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