The Industrial Revolution

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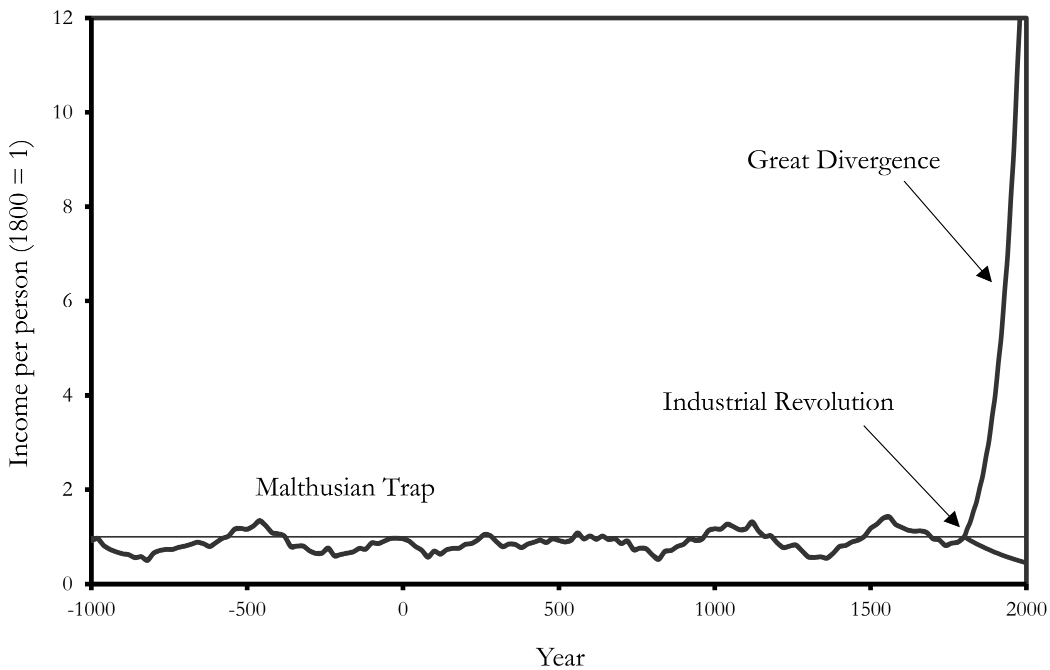
The Industrial Revolution decisively changed economy wide productivity growth rates. For successful economies, measured efficiency growth rates increased from close to zero to close to 1% per year in the blink of an eye, in terms of the long history of humanity, seemingly within 50 years of 1800 in England. Yet the Industrial Revolution has defied simple economic explanations or modeling. This paper seeks to set out the empirical parameters of the Industrial Revolution that any economic theory must encompass, and illustrate why this makes explaining the Industrial Revolution so difficult within the context of standard economic models and narratives.

Introduction

The economic history of the world is surprisingly simple. It can be presented in one diagram, as in figure 1 below. Before 1800 income per capita for all the societies we observe fluctuated. There were good and bad periods. But there was no upward trend. The great span of human history - from the arrival of anatomically modern man to Confucius, Plato, Aristotle, Michelangelo, Shakespeare, Beethoven, and all the way to Jane Austen indeed - was lived in societies caught in the Malthusian trap. Jane Austen may write about refined conversation over tea served in China cups, but for the mass of people as late as 1813 material conditions were no better than their ancestors of the African savannah. The Darcys were few, the poor plentiful.[1]

[1] Clark, 2007 extensively reviews the evidence for this assertion.

Figure 1: A Schematic History of World Economic Growth



Source: Clark, 2007, figure 1.1, 2.

Around 1780 came the Industrial Revolution in England. Incomes per capita began a sustained growth in a favored group of countries around 1820. In the last two hundred years in the most fortunate countries real incomes per capita rose 10-15 fold. The modern world was born. The Industrial Revolution thus represents the single great event of world economic history, the change between two fundamentally different economic systems. The puzzle is why it occurred only around 1780, and why it occurred in a modest island nation on the northwest shores of the European continent.

At one level the transformation the Industrial Revolution represents is very simple. Beginning with the Industrial Revolution, successful modern economies experience steady rates of efficiency advance. Every year more output is produced per unit of input. At a proximate level the growth of income per work-hour in modern societies can be represented as

$$g_y = ag_k + g_A \tag{1}$$

where g_k is the rate of growth of capital per worker hour, a is the share of capital payments in national income, and g_A is the growth rate of efficiency. Since the Industrial Revolution the capital stock has grown about as rapidly as output. Also the share of capital in all earnings is about a quarter. Thus only about a quarter of all modern growth in income per person comes directly from physical capital. The rest is an unattributed rise in the measured efficiency of the economy, year by year.

But while equation (1) suggests that efficiency growth and physical capital accumulation are independent sources of growth, in practice in market economies there has been a strong correlation between the two sources of growth. Economies with significant efficiency growth are also those with substantial growth rates of physical capital. Something links these two sources of growth.

Some economists, most notably Paul Romer, have theorized that this correlation stems from external benefits associated with physical capital accumulation (Romer, 1986, 1987, 1990). For this explanation to work, there would have to be \$3 of external benefit accruing to physical capital investments for every \$1 of private benefit. Most of the modern physical capital stock, however, is still such mundane things as houses, buildings, roads, water and sewer systems, and bridges. These types of investment do not seem to be associated with substantial external benefits. So if productivity advance is systematically associated also with the growth of the stock of such physical capital there must be another mechanism.

The most plausible one is that the association of physical capital accumulation with efficiency advance stems just from the effects of efficiency advance on increasing the marginal product of capital. In a world a relatively constant real interest rates since the Industrial Revolution, such a rising marginal product will induce more investment. And indeed if the economy is roughly Cobb-Douglass in its production structure, efficiency advances will induce a growth of the physical capital stock per person at a rate equal to the growth of output per person, so that the capital-output ratio is constant. This is roughly what we observe.

Thus at a deeper level all modern growth seemingly stems from this unexplained rise in economic efficiency, as a product of a rise in knowledge about production processes. Somehow after 1780 investment in such knowledge increased, or enquiry became much more effective in creating innovation.

Before the Industrial Revolution we find no sign of any equivalent efficiency advances. This is true globally all the way from 10,000 BC to 1800, where we can measure the implied rate of productivity advance just from the rate of growth of population. In this long interval average estimated rates of efficiency advance are 0.01% per year or less. We know this because we can assume before the Industrial Revolution, because of the Malthusian Trap, that output per person and capital per person was, in the long run, constant. In that case any gains in efficiency will be absorbed by population growth according to the formula

$$g_A = cg_N \qquad (2)$$ [2]

We can thus approximate efficiency growth rates from population growth rates if we look at sufficiently long intervals. Table 1 shows these calculations at a world level. Implied rates of technological advance are always extremely slow.

But it is also true that implied rates of technological advance are also slow for those economies where we can measure actual efficiency levels before 1800 through measurements of the real payments to factors. Figure 2 shows the implied efficiency in England 1250-2000. As can be seen there is, surprisingly, in England no sign of any significant improvement in the efficiency of the economy all the way from 1250 to 1800. Only around 1800 does the modern age of steady efficiency advance appear. Before that the measured efficiency of the economy fluctuated, peaking around 1450, but with almost no upwards trend.

The Industrial Revolution thus seems to represent a singularity. A unique break in world history. But also an event where we know clearly what we have to explain. Why did the rate of expansion of knowledge about production efficiency increase so dramatically in England around 1800. Figure 3 shows that the upturn in productivity growth rates can be located to the 1780s/1790s. That upturn us preceded by seven decades in which the average annual productivity growth rate was a mere 0.14% per year. Fast by the standards of the pre-industrial world, but glacially slow in modern terms. Overall productivity growth rates 1780-9 to 1860-9 averaged 0.58% per year, about half way to fully modern levels.

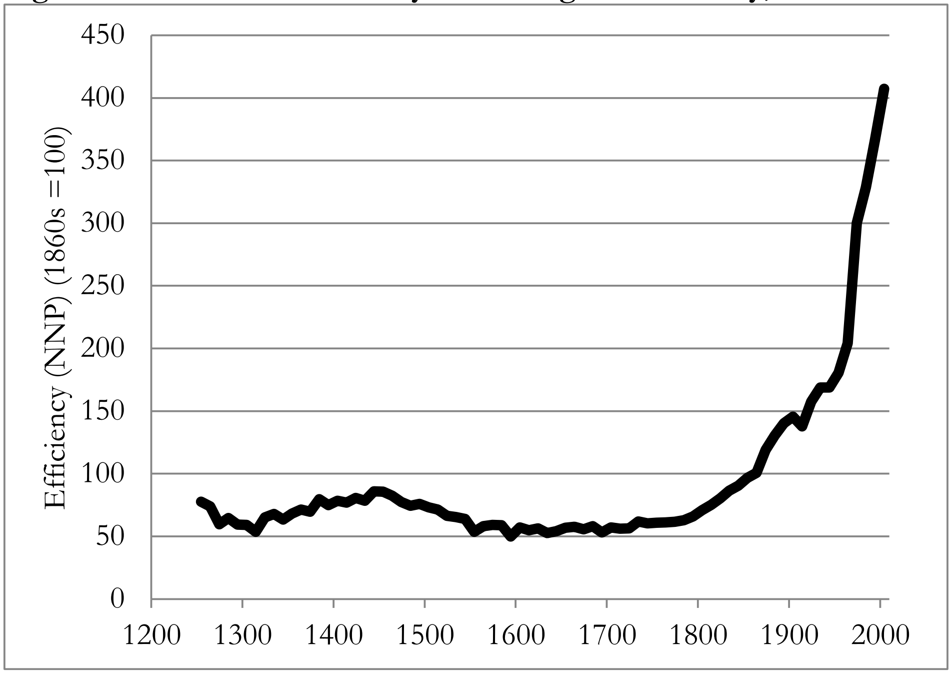
[2] For a more detailed explanation see Clark, 2007, 379-82.

Table 1: Population and Technological Advance at the World Level, 130,000 B.C. to 1800

Year	Population (millions)	Population Growth Rate (%)	Technology Growth Rate (%)
130,000 BC	0.1	-	-
10,000 BC	7	0.004	0.001
1 AD	300	0.038	0.009
1000 AD	310	0.003	0.001
1250 AD	400	0.102	0.025
1500 AD	490	0.081	0.020
1750 AD	770	0.181	0.045

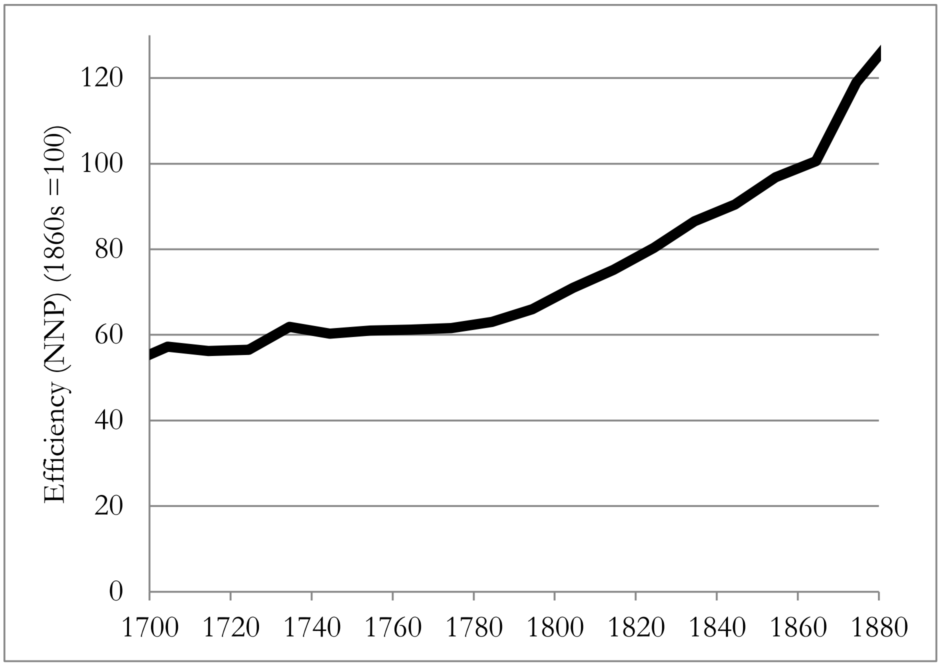
Source: Clark, 2007, table 7.1.

Figure 2: Estimated Efficiency of the English Economy, 1250-2000



Source: Clark, 2010.

Figure 3: Efficiency Levels, England, 1700-1880



Source: Clark, 2010.

We also know what sectors contributed most of the productivity advance 1780-9 to 1860-9. National productivity growth will be related to productivity advance in individual sectors through the equation

$$g_A = \sum \theta_j g_{Aj} \quad (3)$$

where g_{Aj} is the growth rate of productivity by sector, and θ_j is the share of j in total value added in the economy. These results are shown in table 2.

Textiles contributed nearly half, 43%, of all measured productivity advance. Improvements in transport, mainly the introduction of the railway, was the next biggest source of advance, contributing 20%. Agriculture, ironically, contributed almost 20% also. Coal and iron and steel were in themselves minor contributions despite the fame of these sectors and their innovations in this period. Productivity growth in the half of the economy not covered in table 2 was modest, less than 0.20% per year.

Table 2: Sources of Industrial Revolution Efficiency Advance, 1780s-1860s

Sector	Efficiency Growth Rate (%)	Share of value added	Contribution to National Efficiency Growth Rate (% per year)
All Textiles	2.3	0.11	0.25
Iron and Steel	1.8	0.01	0.02
Coal Mining	0.2	0.02	0.00
Transport	1.5	0.08	0.12
Agriculture	0.4	0.30	0.11
Identified Advance	-	0.51	0.49
Whole Economy	-	1.00	0.58

Source: Clark, 2007, table 12.1.

The decomposition in table 2 established some things already. The Industrial Revolution has been thought of by some as essentially consisting of the arrival of the first of what have been called *General Purpose Technologies*, the steam engine. *General Purpose Technologies*, a rather nebulous concept, have been variously defined. They can be loosely thought of as innovations that have pervasive application throughout the economy, that go through a prolonged period of improvement, and that spawn further innovation in the sectors they are employed in.[3] Various GPTs have been identified, such as the introduction of steam power in the Industrial Revolution, and the introduction of electricity, and the recent IT revolution.

Steam power in England certainly touched a number of areas in the Industrial Revolution. It was important in coal mining, on the railroads, and in powering the new textile factories. The steam engine itself underwent a long process of

[3] Bresnahan and Trajtenberg, 1996.

improvement in thermal efficiency, and in the ratio of power to weight, from its first introduction by Thomas Newcomen in 1707-1712, to the 1880s. The earliest engines had a thermal efficiency as low as 0.5%, while those of the 1880s could achieve thermal efficiencies of 25%. The steam engine was associated also with the widespread use of fossil energy in the economy to replace wind, water and animal power sources in transport, home heating, and manufacturing.

Table 2 suggests, however, that whatever role steam power played in economy wide productivity advance after the 1860s, its role up to then in the new productivity advance of the Industrial Revolution was minor. Coal mining and iron and steel production contributed very little to Industrial Revolution productivity advance, and most of their productivity advance did not stem from the introduction of steam power.[4] Even in transport a substantial part of the productivity advance is attributable to the improvement of the traditional road transport system, the introduction of canals, and improvements in sailing ships. The textile factories of the Industrial Revolution could, if necessary, have still been powered by water wheels even as late as the 1860s. Advances in textiles and agriculture explain the majority of the Industrial Revolution.

The diverse nature of productivity advance in this era makes the Industrial Revolution all the more puzzling. The revolution in textiles came through mechanical innovations that can be traced to a number of heroic individual innovators: John Kay, Richard Arkwright, James Hargreaves, Edmund Cartwright. But the improvements in agriculture stem from the advances of thousands of anonymous farmers in improving yields, mainly involving non-mechanical changes.

Another important element in the Industrial Revolution era is the unimportance of traditional investments in physical capital in explaining the growth of output per worker. Capital per worker rose no faster than output per worker, so that right from the onset of modern growth efficiency growth dominated.

Thus any satisfying account of the Industrial Revolution has to do the following things. First explain why NO society before 1800 - not ancient Babylon, Pharaonic Egypt, China through countless centuries, Classical Greece, Imperial Rome, Renaissance Tuscany, medieval Flanders, the Aztecs, Mogul India, the Dutch

[4] Clark and Jacks, 2007.

Republic – expanded the stock of knowledge by more than 10% a century. Then explain why within 50 years of 1800 the rate of growth of knowledge rose to modern rates in one small country on the margins of Europe, Britain. Then we will understand the history of man.

Theories of the Industrial Revolution

The drama and the centrality of the Industrial Revolution has ensured that there is a steady supply of new or recycled theories of this great transition. These theories mostly fall into a number of discrete categories.

"Bad equilibrium" theories seek to explain the Malthusian stagnation as a productive of a self-reinforcing system of poor economic incentives. The desires and rationalities of people in all human societies are essentially the same. The medieval peasant in Europe, the Indian coolly, the bushman of the veld, share a common set of aspirations, and a common ability to act to achieve those aspirations. What differs across societies, however, are the institutions that govern economic life. Thus

> *The United States inherited a set of institutions – among them common law and property rights – from Great Britain. These institutions made Britain the world's leading nation by the end of the eighteenth century….The result has been two and a half centuries of economic growth* (North, 1994, ---).

Thus there is a caricature of the pre-industrial world that many economists intuitively hold, which is composed of a mixture of all the bad movies ever made about early societies. Vikings pour out of long ships to loot and pillage defenseless peasants and burn the libraries of monasteries. Mongol hordes flow out of the steppe on horseback to sack Chinese cities. Clerical fanatics burn at the stake those who dare to question arcane religious doctrines. Peasants groan under the heel of rapacious lords whose only activity is feasting and fighting. Aztec priest cut out the hearts with obsidian knives from screaming, writhing victims. In this brutal and chaotic world who has the time, the energy, or the incentive to develop new technology?

The advantage of a theory which relies on some exogenous shock to the economic system is that it can hopefully account for the seeming sudden change in the growth rate of measured efficiency around 1800. Institutions can change suddenly and dramatically – witness the French Revolution, the Russian Revolution, and the Iranian Revolution that overthrew the Shah

These theories of an institutional shift in appropriability face two major difficulties, however, one conceptual, one empirical. The conceptual difficulty is that if modern economic growth can be produced by a simple institutional change, then why in all the varied and various societies that the world has seen since 10,000 BC and before was there none which stumbled upon the right set of institutions that made knowledge property? Societies varied markedly in what could be property and how property was transferred between owners. For example, in civil cases over possession of land in the legal system established by the Normans in medieval England after 1066, the party whose right to land was contested could elect to prove his or her title through armed combat with his opponent! This may seem to us a crazy way of settling property disputes to us, but the point is that societies have made all kinds of different choices about institutional forms. Why did some not stumble upon the right set of institutions? It seems that we cannot rely on chance here in institutional choice. There must be something that is keeping the institutions of the pre-industrial world in the "bad" state.

Thus a slightly more sophisticated version of the "bad institutions" theory are those which seek to explain through the Political Economy of Institutions why systematically early societies had institutions that discouraged economic growth (see, for example, North and Thomas, 1973, North and Weingast, 1989, North, 1993, Jones, 2002, Acemoglu, Johnson and Robinson, 2001, 2002, and Acemoglu and Robinson, 2012).

The common feature that Douglass North and other such *institutionalists* point to in early societies is that political power was not achieved by popular elections. In pre-industrial societies, as a generalization, the rulers ultimately rested their political position on the threat of violence. Indeed there is a close empirical association between democracy and economic growth. By the time England achieved its Industrial Revolution it was a constitutional democracy where the king was merely a figurehead. The USA, the leading nation in the world in economic terms since the 1870s, has always been a democracy also.[5]

For economic efficiency in any society property rules have to be chosen to create the maximum value of economic output. In such a case a disjuncture can arise between the property rules in the society that will maximize the total value of output, and the property rules that will maximize the output going to the ruling elite. Indeed North and others have to argue that such a disjuncture systematically arises in all societies before 1800. This idea has been restated recently as the idea that economic growth is the replacement of extractive economic institutions, designed just to secure income for a ruling clique, with inclusive economic institutions, designed to maximize the output of societies as a whole (Acemoglu and Robinson, 2012).

One subset of such theories that has shown amazing persistence, despite its inability to account for the most basic facts of the Industrial Revolution, is that which links the Industrial Revolution to the earlier *Glorious Revolution* of 1688-9. Thus the recent widely read book by Acemoglu and Robinson, *Why Nations Fail*, has a chapter titled "*How a political revolution in 1688 changed institutions in England and led to the Industrial Revolution.*"

The *Glorious Revolution* established the modern political system of the UK, a system that has been continuously modified, but not fundamentally changed since then. The new political system created Parliament, the representative of the propertied classes in England in 1689, as the effective source of power in what is nominally a monarchy.

A basic problem with placing political developments at the heart of the Industrial Revolution is that changes in political regime before 1800 have no discernible impact on the efficiency level of the economy, even 80 years later. The Glorious Revolution had no discernible impact on economic efficiency before 1770, two or three generations after the institutional change, as figure 4 shows. It is also clear in the figure that even the earlier political and military disruptions of the Civil War of 1642-9, and the Interregnum of 1649-1660, were not associated with any decline in the efficiency of operation of the economy.

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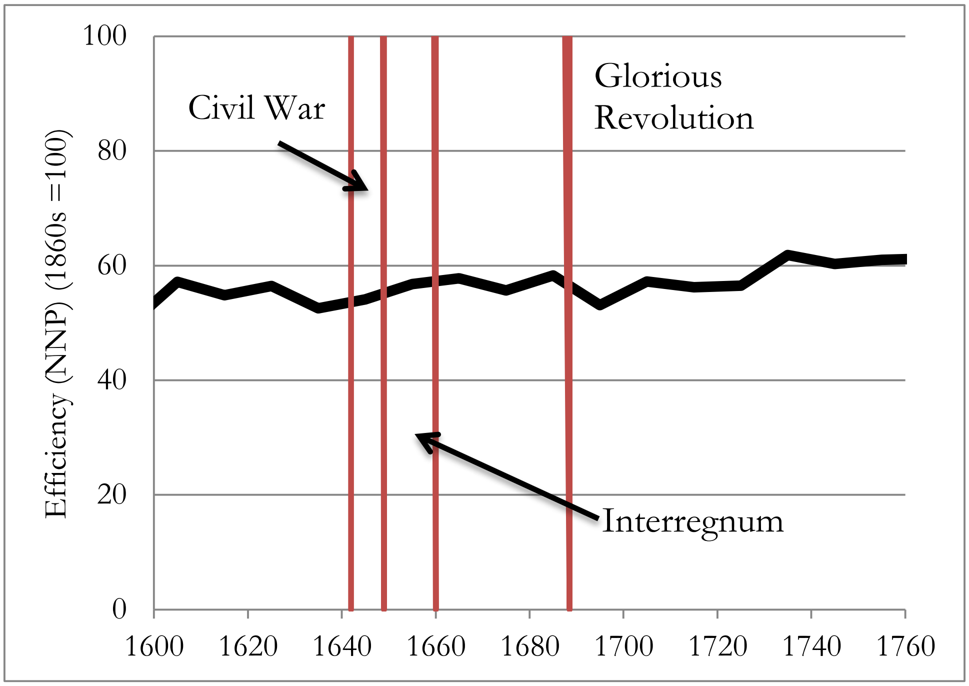
5 The recent rise of China is, however, an exception to the general association of growth and democracy.

Figure 4: Economic Efficiency and Political Changes, England, 1600-1770



Source: Clark, 2010.

Further there is no sign that private investors in England perceived a greater security of property even as a result of the Glorious Revolution. The return to private capital in the economy did not deviate from trend after 1689. Private investors seem to have looked at the political changes with indifference. The return to government debt did eventually decline significantly after 1689, and had fallen to modern levels by the 1750s. This decline was no doubt driven in part by the enhanced taxing power of the government after 1689. But almost all of the money raised from those taxes went to finance the British Navy in the long struggle with France that ended only with the defeat of Napoleon in 1815. Almost none of it went into the subsidization of innovation or education.

And we do see long before the Glorious Revolution or the Industrial Revolution societies that had stable representative political systems, the inclusive institutions of Acemoglu and Robinson, but little or no productivity advance. The Dutch Republic of 1588-1795 was one such regime.[6] Under the political arrangements of the Republic the Netherlands experienced its Golden Age. Despite its modest size and lack of substantial domestic natural resources, it conquered a substantial colonial Empire in the East, possessing for a while the premier Navy in the world, dominating world trade in the seventeenth century. It developed sophisticated systems of banking and public finance, allowing substantial borrowing to develop a modernized transportation system internally, and support the most urbanized society in Europe. But because productivity advance stagnated in the Netherlands 1650-1795, these political and institutional achievements led to no sustained growth, and no break from the pre-industrial world.

From 1223 to 1797 Venice operated as a Republic, with the government under control of a balance of popular and patrician representatives. Policy was geared towards the needs of a trading and commercial empire. Venice again developed an important trading empire in the Eastern Mediterranean, with colonies and dependencies such as Dalmatia, Crete and Cyprus. It also developed important manufacturing activities such as its glass industry. But again none of this was reflected in the kind of sustained productivity advance seen in the Industrial Revolution.

Similarly the free cities of the Hanseatic League were from the middle ages dominated by a politics that emphasized the needs of trade and commerce. Lübeck, for example, became a free city in 1226, and retained city state status till 1937. After gaining its freedom Lübeck developed a system of rule and government, called Lübeck Law, that spread to many other Baltic cities of the Hanseatic League in the middle ages such as Hamburg, Kiel, Danzig, Rostock, and Memel. Under Lübeck Law, the city was governed by a council of 20 that appointed its own members from the merchant guilds and other town notables. It was thus government by the leaders of the commercial interests of the cities. Though not democracy, this was government by interests that should have fostered commerce and manufacturing. Under such rule the Hansa cities became rich and powerful, engaging in substantial manufacturing enterprises, such as shipbuilding and cloth production, as well as trade. But again this was not associated with sustained technological advance.

[6] The Dutch Act of Abjuration of 1581 has been argued by some to be the precursor of the Declaration of Independence of the USA of 1776.

It is true that the early societies we know of in detail seem to have lacked the legal notion that you could own property in ideas or innovations. Thus in both the Roman and Greek worlds when an author published a book there was no legal or practical way to stop the pirating of the text. Copies could be freely made by anyone who acquired a version of the manuscript (on papyrus rolls), and the copier could amend and alter the text at will. It was not uncommon for a text to be reissued under the name of a new "author."[7] It was common to condemn such pirating of works or ideas as immoral. But writings and inventions were just not viewed as *commodities* with a market value.[8]

While the ancients may have lacked them, there were systems of intellectual property rights in place, however, long before the Industrial Revolution. The earliest established foundations of a modern patent system were found in the thirteenth century in Venice. By the 15th century in Venice true patents in the modern sense were regularly being awarded. Thus in 1416 the Council of Venice gave a 50 year patent to Franciscus Petri from Rhodes, who was thus a foreigner, for a new type of fulling mill. By 1474 the Venetian patent law had been codified. There is evidence for Florence also in the fifteenth century of the awarding of patents. The Venetian innovation granting property rights in knowledge, which was very important to the famous Venetian glass industry, spread to Belgium, the Netherlands, England, Germany, France and Austria in the sixteenth century as a consequence of the movement of Italian glass workers to these other countries. Thus by the sixteenth century all the major European countries, at least on an ad hoc basis, granted property rights in knowledge to innovators. They did this in order to attract skilled craftsmen with superior techniques to their lands. The spread of formal patent systems thus predates the Industrial Revolution by at least 350 years.

The claims of North and his associates for the superiority of the property rights protections afforded by the patent system in eighteenth century England thus stem from the way in which the system operated after the Glorious Revolution of 1688-9 established the supremacy of Parliament over the King. Under the patent system introduced in the reign of Elizabeth I (1568-1603) the system was supervised by government ministers. Political interference led to the creation of spurious monopolies for techniques already developed, or the denial of legitimate claims.

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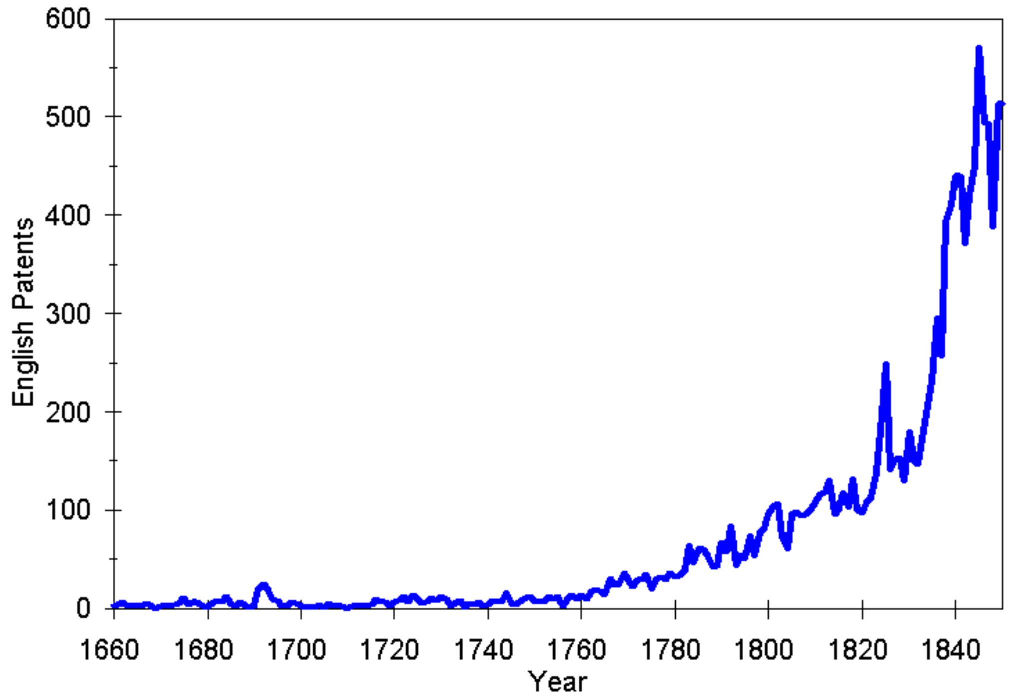
[7] This problem continued into at least the seventeenth century in England, where publishers quite freely pirated the works of authors.

[8] See Long,1991, 853-7.

After the Glorious Revolution Parliament sought to avoid this by devolving the supervision of patents to the courts. Generally the courts would allow any patent to be registered as long a no other party objected. No other major European country had a formal patent system as in England before 1791. But as Figure 5 shows, while the Glorious Revolution produced a brief increase in patent rates, there was no sustained increase in patenting rates until the 1760s, 75 years after the Glorious Revoluton.

Figure 5: Patents per Year, England, 1660-1851



There also existed other institutions in, for example, medieval European society, which we would think would promote innovation better than the modern patent system. Producers in many towns were organized into guilds which represented the interests if the trade. These guilds were in a position to tax members to facilitate lump sum payments to innovators to reveal productive new techniques to the members.

The empirical difficulty with the appropriability argument is the appallingly weak evidence that there was any great gain in the returns to innovators in England in the 1760s and later. The textile industry for example was in the vanguard of technological change in the Industrial Revolution period. Figure 6 shows TFP in the production of cotton cloth, taking cotton as a basic input. From 1770 to 1869 TFP rose about 22 fold.

Figure 6: Cotton Spinning and Weaving Productivity, 1770-1869

Note: The squares show the decadal average productivities. The years 1862-5 were omitted because of the disruption of the cotton famine.
Sources: Cotton cloth prices, Harley, 1998. Labor costs, return on capital, Clark 2010.

Yet the gains of the textile innovators were modest in the extreme. The value of the cotton textile innovations alone by the 1860s, for example, was about £115 million in extra output per year. But a trivially small share of this value of extra output ever flowed to the innovators. Table 3, for example, shows the major innovators in cotton textiles and the gains accruing to the innovators through the patent system or other means. Patents mostly provided poor protection, the major gains to innovators coming through appeals post hoc to public beneficence through Parliament. Also the patent system shows none of the alleged separation from political interference. The reason for this is that Parliament could, on grounds of the public good, extend patents beyond the statutory 17 years to adequately reward those who made significant innovations. James Watt was the beneficiary of such a grant. But such grants depended on social and political protection just as much as in the old days.

The profit rates of major firms in the industry also provide good evidence that most of the innovation in the textile industry was quickly leaking from the innovators to other producers with no rewards to the innovators. Knick Harley has reconstructed the profit rates being made by some of the more successful cotton spinning and weaving firms in the early Industrial Revolution period (Harley (1997)). The cotton spinners *Samuel Greg and Partners* earned an average profit from 1796 to 1819 of 11.7% per year, just the normal commercial return for a risky venture such as manufacturing. Given the rapid improvements in cotton spinning productivity going on in the industry in these years it suggests that whatever innovations were being introduced were spreading from one firm to another very quickly. Otherwise leading firms such as *Samuel Greg* would have made large profits compared to their competitors. Similarly the firm of *William Grey and Partners* made less than 2% per year from 1801 to 1810, a negative economic profit rate. The innovations in the cotton spinning industry seem to have mainly caused prices to fall, leaving little excess profits for the firms that were innovating. Thus a third firm, *Richard Hornby and partners,* in the years 1777 to 1809 was in a sector of the industry, hand loom weaving, which had not yet been transformed by any technological advance. Yet its average profit rate was 11.4%, as high as *Samuel Greg* in the innovating part of the industry. The conclusion is that the host of innovations in cotton textiles do not seem to have particularly rewarded the innovators. Only a few such as Arkwright and the Peels became noticeably wealthy. Of the 379 people probated in 1860-9 in Britain who left estates of £0.5 million or more, only 17 were in the textile industry, even though as noted from 1760-9 to 1860-9 this one sector generated nearly half the productivity growth in the economy (Rubinstein, 1981). The Industrial Revolution economy was spectacularly bad at rewarding innovation. This is why Britain has few foundations to rival the great private philanthropies and universities of the U.S.A. Its innovators captured little of the rewards.

Thus there is no evidence that it was institutional changes providing better rewards for innovators in the Industrial Revolution era that unleashed mankind's creative potential. To explain the Industrial Revolution we need other types of theory.

Table 3: The Gains from Innovation in Textiles in the Industrial Revolution

Innovator	Device	Result
John Kay	Flying Shuttle, 1733	Impoverished by litigation to enforce patent. House destroyed by machine breakers 1753. Died in poverty in France.
James Hargreaves	Spinning Jenny, 1769	Patent denied. Forced to flee by machine breakers in 1768. Died in workhouse in 1777.
Richard Arkwright	Water Frame, 1769	Worth £0.5 m at death in 1792. By 1781 other manufacturers refused to honor patents. Made most of money after 1781.
Samuel Crompton	Mule, 1779	No attempt to patent. Grant of £500 from manufacturers in the 1790s. Granted £5,000 by Parliament in 1811.
Reverend Edmund Cartwright	Power Loom, 1785	Patent worthless. Factory destroyed by machine breakers. Granted £10,000 by Parliament in 1809.
Eli Whitney (USA)	Cotton Gin, 1793	Patent worthless. Later made money as a government arms contractor.
Richard Roberts	Self-Acting Mule, 1830	Patent revenues barely covered development costs. Died in poverty in 1864.

Source: Clark, 2007, table 12.2

Thus the host of innovations in cotton textiles do not seem to have particularly rewarded the originators, famous or obscure. Only a handful, such as Arkwright and the Peels, became wealthy. Of the 379 people probated in the 1860s in Britain who left estates of more than £0.5 million, only 17, or 4 percent, were in textiles.[9] Yet the industry produced 11 percent of national output, and generated the majority of Industrial Revolution efficiency advance. The Industrial Revolution economy was still spectacularly bad at rewarding innovation. Wage earners and foreign customers, not entrepreneurs, were the overwhelming beneficiaries of Industrial Revolution innovation. This is why Britain has few foundations to rival the great private philanthropies and universities of the U.S.A. The Industrial Revolution did not make paupers into princes.

A similar tale can be told for the other great nexus of innovation in Industrial Revolution England: coal mining, iron and steel, and railroads. Coal output, for example, exploded in England in the Industrial Revolution era This coal heated homes, made ore into iron, and powered railway locomotives. Yet there were no equivalents of the great fortunes made in oil, railways and steel in America's late nineteenth century industrialization.

The new industrial priesthood, the engineers who developed the English coalfields, railways and canals, made prosperous but typically moderate livings. Though their names survive to history - Richard Trevithick, George and Robert Stevenson, Humphrey Davy – they again captured very little of the social rewards their enterprise wrought. Richard Trevithick, the pioneer of locomotives, died a pauper in 1833. George Stevenson, whose famous locomotive *The Rocket* in a trial in 1829 ran loaded at 15 miles an hour, an unheard of speed for land travel in this era, did much better. But his country house in Chesterfield was, however, a pitence compared to his substantial contributions to railway engineering. But other locomotives competed in the famous trial, and soon a swarm of locomotive builders were supplying the railway network.

Innovation in the Industrial Revolution era typically benefited mainly consumers in the form of lower prices. As coal output exploded real prices to consumers steadily declined: the real price in the 1700s was 60 percent greater than in the 1860s.

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[9]Rubinstein, 1981, ---.

Coal, iron and steel, and rail carriage all remained highly competitive in England in the Industrial Revolution era. The patent system offered little protection to most of the innovations in these sectors, and innovations quickly leaked from one producer to another.

The rise in innovation rates in Industrial Revolution England was not induced by unusual rewards to innovation, but by a greater supply of innovation at still modest rates of reward. Figure 12.3 illustrated two ways in which innovation rates might increase. The institutionalist perspective is that the rewards offered by the market shifted upwards compared to all previous pre-industrial economies. There is no evidence of any such change. The last significant reform of the patent system was in 1689, more than 100 years before efficiency gains became common. And the patent system itself played little role for most innovation in Industrial Revolution England.

Instead the upsurge in innovation in the Industrial Revolution period, in terms of figure 12.3, reflected a surge in supply. With the benefits to innovation no greater than in earlier economies, the supply still rose substantially. Facing the same challenges and incentives as in other economies British producers were more likely to attempt novel methods of production.

Productivity growth in cotton textiles in England from 1770 to 1870, for example, far exceeded that in any other industry. But the competitive nature of the industry, and the inability of the patent system to protect most technological advances, kept profits low. Cotton goods were homogenous. Yarn and cloth sold in wholesale markets where quality differences were readily perceptible to buyer. The efficient scale of cotton spinning and weaving mills was always small relative to the market. New entrants abounded. By 1900 Britain had about 2,000 firms in the industry. Firms learned improved technique innovating firms through hiring away their skilled workers. The machine designers learned improved techniques from the operating firms. Thus the entire industry – the capital goods makers and the product producers - over time clustered more and more tightly in the Manchester area. By 1900 40 percent of the entire world output of cotton goods was produced within 30 miles of Manchester. The main beneficiaries of this technological advance thus ended up being two parties: consumers of textiles all across the world, and the owners of land in the cluster of textile towns which went from being largely worthless agricultural land to valuable building sites.

The greatest of the Industrial Revolution cotton magnates, Richard Arkwright, is estimated to have left £0.5 m. when he died in 1792.[10] His son, also Richard Arkwright, inherited his father's spinning mills. But though his son had managed his own mills and had much experience in the industry which was still showing rapid productivity growth, he soon sold most of his father's mills, preferring to invest in land and government bonds. By 1814 he owned £0.5 m in government bonds alone. He prospered mainly on government bonds and real estate, leaving £3.25 m when he died in 1843 despite sinking much money into a palatial country house for his family.[11] But Arkwright Senior accumulated less wealth than Josiah Wedgwood, who left £0.6 m in 1795, even though Wedgwood operated in a sector, pottery, which had far less technological progress (potteries were still hand enterprises by and large even in the late 19th c).

Though the first great innovations of the Industrial Revolution era did not offer much in the way of supernormal profits because of the competitive nature of the industry, the second, railroads seemed to offer more possibilities. Railways are a technology with inherent economies of scale. At minimum one line has to be built between two cities, and once it is built a competitor has to enter with a minimum of a complete other line. Since most city pairs could not profitably support multiple links, exclusion, and hence profits, thus seemed possible.

The success of the Liverpool-Manchester line in 1830 – by the 1840s equity shares on this line were selling for twice their par value - inspired a long period of investment in railways. Figure 14.9 shows the rapid growth of the railway network in England from 1825 to 1869, by which time more than 12,000 miles of track had been laid across the tiny area of England. This investment and construction was so frenetic that so called *railway manias* struck in 1839 and 1846.

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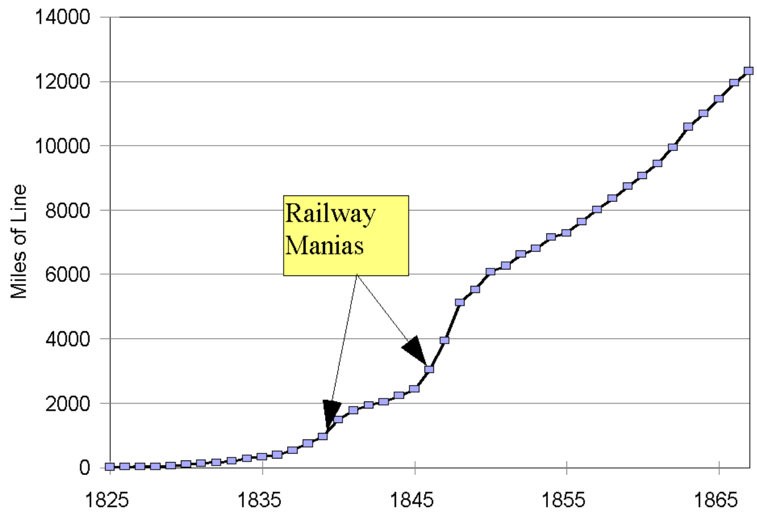
[10] Fitton, 1989, 219.
[11] Ibid., 296.

Figure 7 English Railroad Construction, 1825-1869



Source: Mitchell and Deane, 1971, 225.

Table 4 Profit Rates on the Capital Invested in British Owned Railways, 1860-1912

Period	Rate of Return, UK (%)	Rate of Return, British Empire (%)	Rate of Return. Foreign Lines (%)
1860-9	3.8	-	4.7
1870-9	3.2	-	8.0
1880-9	3.3	1.4	7.7
1890-9	3.0	2.5	4.9
1900-9	2.6	1.6	4.4
1910-13	2.6	3.1	6.6

Source: Clark, 2007, table 14.7.

But again the rush to enter quickly drove down profit rates to very modest levels, as table 4 shows. Real returns, the return on the capital actually invested, by the 1860s were no greater than for very safe investments in government bonds or agricultural land. While railway lines had local monopolies, they ended up in constant competition with each other through roundabout routes.

Thus while, for example, the Great Western may have controlled the direct line from London to Manchester, freight and passengers could cross over through other companies to link up with the East Coast route to London. Again profits inspired imitation which could not be excluded and the profit was squeezed out of the system. Consumers were again the main beneficiaries.

It is for this reason that in Britain, unlike in the USA, there are very few universities and major charities funded by private donors.[12] The Industrial Revolution did not result in great individual or family fortunes in England. By the 1860s the rich were still by and large the descendants of the landed aristocracy. Of 379 men dying between 1860 and 1879 in Britain who left at least £0.5 million, 256 (68 percent) owed their wealth to inherited land. Only 17 (4 percent) were textile magnates, despite textiles being the driving industry in Industrial Revolution productivity advance.[13]

The unsatisfactoriness of conventional institutional accounts – which emphasize returns to innovation and to investment in general - has led to exploration of other avenues by which institutions may matter. Avner Greif, Murat Iyigun, and Diego Sasson have a recent paper which argues that the Industrial Revolution was underpinned by English welfare institutions, dating to the early sixteenth century, which insured against failure (Greif, Iyigun, and Sasson, 2012). It was not the size of the rewards on the upside that distinguished England from other societies such as China, but the cushion against failure for those who tried and did not succeed. James Hargreaves, inventor of the Spinning Jenny, may have died in the workhouse in 1777, but at least he did not die in the street. However, this seems a bit like saying that New York has developed a high risk, high rewards financial sector because it allows for financial support for adults without minor dependents in a way not found,

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12 The industrialization of the United States created much greater private and family fortunes.

13 Rubinstein, 1981, 60-7.

for example, in Texas. Presumably the Harvard graduates in the financial sector have backup plans other than general relief if their Hedge Fund fails.

One thing that is striking about institutionalist explanations in general is the absence of any agreed metric for institutional quality. There is a belief in the physical sciences that a basic element in any scientific analysis of any phenomenon is to have a defined, objective and shared system of measurement. Institutionalists on this standard are still in the pre-science world of phlogiston and other early theories.

Changes in People

The modest signs of any increase in returns to innovation at the time of the Industrial Revolution suggests as an alternative that the transition was instead driven by changes in the aspirations and capabilities of economic agents. And this has been the theme of another set of explanations of the Industrial Revolution. In this extensive set of theories a rise in human capital investment, and consequent improvement in the capabilities of economic actors, is key to the transition between the Malthusian regime and the modern (Becker, Tamura and Murphy, 1990, Lucas, 2002, Galor and Weil, 2000, Galor and Moav, 2002, Galor, 2011).

We certainly see that the English population on the eve of the Industrial Revolution had characteristics that differed from most pre-industrial societies. In particular the levels of literacy and numeracy were high by the standards of the pre-industrial world. Even the great civilizations of the past, such as the Roman Empire, or the city states of the Italian Renaissance, had general levels of literacy and numeracy that were surprisingly low by the standards of Industrial Revolution England. And we know as a general feature that modern high income, fast growth economies are distinguished by high levels of human capital. So increases in human capital that created knowledge externalities, at the gross level, would seemingly be a candidate source of the Industrial Revolution.

We find interesting evidence that the average numeracy and literacy of even rich people in most earlier economies was surprisingly poor. A prosperous land owner in Roman Egypt, Isidorus Aurelius, for example, variously declared his age in legal documents in a less than two year span in 308-9 AD as 37, 40, 45 and 40. Clearly

Isidorus had no clear idea of his age. Other sources show he was illiterate (Duncan-Jones, 1990, 80). A lack of knowledge of their true age was widespread among the Roman upper classes as evidenced by age declarations made by their survivors on tombstones. In populations where ages are recorded accurately, 20% of the recorded ages will end in 5 or 10. We can thus construct a score variable Z, which measures the degree of "age heaping," where $Z = \frac{5}{4}(X - 20)$, and X is the percentage of age declarations ending in 5 or 10 to measure the percentage of the population whose real age is unknown. This measure of the percentage of people who did not know their true age correlates moderately well in modern societies also with the degree of literacy.

Among those wealthy enough to be commemorated by an inscribed tombstone in the Roman Empire, typically half had unknown ages. Age awareness did correlate with social class within the Roman Empire. More than 80% of office holder's ages seem to have been known by their relatives. When we compare this with death records for modern Europe we find that by the eve of the Industrial Revolution age awareness in the general European population had increased markedly, as table 5 shows.

We can also look at the development of age awareness by looking at census of the living, as in table 6. Some of the earliest of these are for medieval Italy, including the famous Florentine *Catasto* of 1427. Even though Florence was then one of the richest cities of the world, and the center of the Renaissance, 32% of the city population did not know their age. In comparison a census of 1790 of the small English borough of Corfe Castle in Dorset, with a mere 1,239 inhabitants, most of them laborers, shows that all but 8% knew their age. In 1790 again awareness correlates with measures of social class, with universal knowledge among the higher status families, and lower age awareness among the poor. But the poor of Corfe Castle or Terling in Essex had as much age awareness as office holders in the Roman Empire.

Table 5: Age-Heaping, Rome versus later Europe

	Social Group	Sample Size	Innumeracy rate
Imperial Rome			
Rome	All	3,708	48
Italy outside Rome	All	1,395	43
Italy outside Rome	Town Councilors	75	15
Modern Europe, death records			
Geneva, 1560-1600	All	-	54
Geneva, 1601-1700	All	-	44
Geneva, 1701-1800	All	-	23
Liege, 1740	All	-	26
Paris, c. 1750	All	-	15

Source: Duncan-Jones, 1990, 84-90.

Table 6: Age Heaping Among Living Populations (23-62)

Place	Date	Type of Community	Sample Size	Z
Town of Florence	1427	Urban	-	32
Florentine Territory	1427	Rural	-	53
Pistoia	1427	Urban	-	42
Pozzuoli	1489	Urban	-	72
Sorrento	1561	Urban	-	67
Corfe Castle, England	1790	Urban	352	8
Ardleigh, England	1796	Rural	433	30
Terling, England – Poor relief recipients	1801	Rural	79	19

Notes: The total population of Corfe Castle was 1,239, and of Ardleigh 1,145.
Sources: Duncan-Jones, 1990. Terling, Essex Record Office D/P 299/12/3. Ardleigh, Essex Record Office, D/P 263/1/5.

Another feature of the Roman tombstone age declarations is that ages seem to be greatly overstated for many adults. Thus while we know that life expectancy in ancient Rome was probably in the order of 20-25 at birth, tombstones record people as dying at ages as high as 120. For North African tombstones, for example, 3% of the deceased are recorded as dying at age 100 or more.[14] Almost all of these 3% must have been 20-50 years younger than was recorded. Yet their descendants did not detect any implausibility in recording these fabulous ages. In contrast the Corfe Castle census records a highest age of 90, well within the range of possibilities given life expectancy in rural England in these years.

[14] Hopkins, 1966, 249.

Thus another explanation for the Industrial Revolution is that while the incentives to innovate were not greater, the capabilities and aspirations of economic agents had improved. This raises two important issues. First why did history move in a general direction towards increasing levels of literacy and numeracy? What internal dynamic drove this move? Second, was England sufficiently distinct from earlier societies in terms of the abilities of its economic agents to account for the transition to modern growth?

Figure 8, shows, for example, literacy rates, measured by the ability to sign your name, for England 1580-1920. Two things stand out. The first is that literacy rates for men rose substantially long before the Industrial Revolution. If mass literacy was the key to growth then seemingly the Industrial Revolution would have again appeared 100 years before the 1780s. The second is that dramatic increases in literacy rates are a phenomenon only of the late Industrial Revolution period, the years 1850-1900. Literacy in the Industrial Revolution period itself rose by modest amounts.

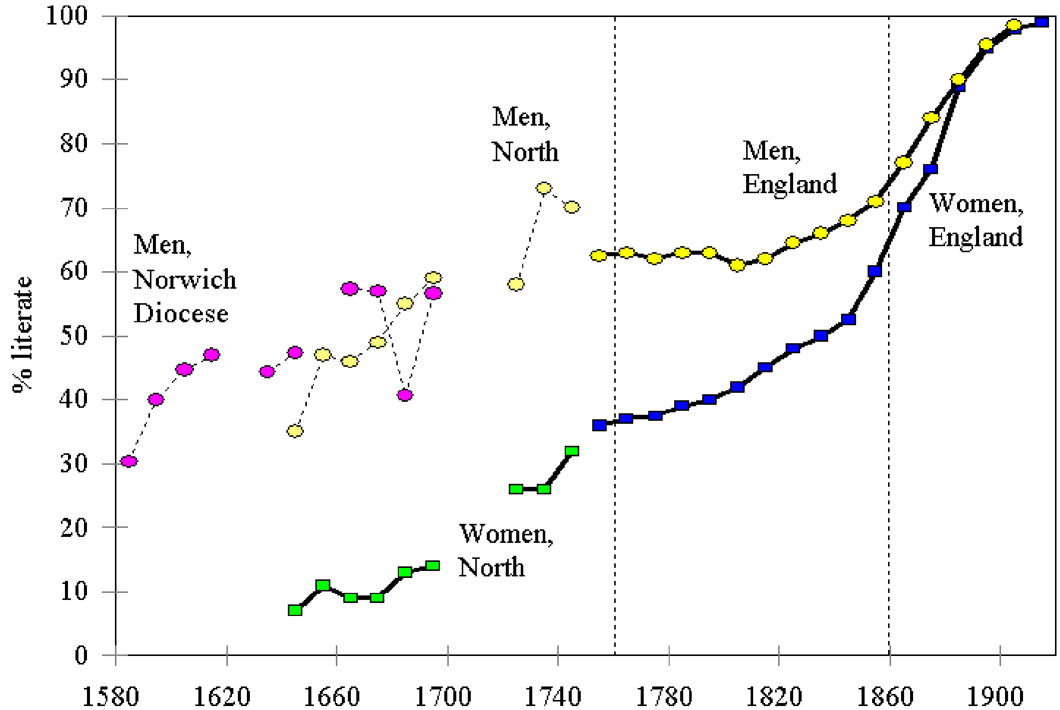
Also literacy rates in England in 1780 were not high by the standards of many other parts of northwest Europe. Literacy rates then exceeded those of England in Scotland, the Netherlands, much of Germany and in Scandinavia. But with those caveats we can ask what might have driven the trend all across northern Europe to greater levels of numeracy and literacy by the eve of the Industrial Revolution.

Another caveat about the role of numeracy and literacy is that given the observed rates of return to schooling, the increased investment in countries like England in the Industrial Revolution period can account little for faster productivity growth rates. Thus we can modify equation (1) to allow for investment in human capital to

$$g_y = a_k g_k + a_h g_h + g_A \qquad (4)$$

where a_h is the share of income attributable to human capital investments and g_h is the growth rate of the stock of human capital. But the growth rate of the human capital stock in England 1760-1860 implied by figure 8 is very modest: less than 0.4% per year. And even if we allowed one third of all the 60% share of wage

Figure 8: Literacy in England, 1580-1920



Sources: 1750s-1920s, Schofield (1973), men and women who can sign marriage resisters. The north, 1630s-1740s, Houston (1982), witnesses who can sign court depositions. Norwich Diocese, 1580s-1690s, Cressy (1977), witnesses who can sign ecclesiastical court declarations.

Source: Clark, 2007, figure 9.3, 179.

payments in income in Industrial Revolution England to be attributed to human capital, this would entail human capital investments increased income growth rates by a mere 0.08% per year. If human capital lies at the heart of the Industrial Revolution it must be because there are significant external benefits associated with human capital investments, as Lucas, 1988, hypothesized.

Why, then, did education levels rise in the centuries leading up to the Industrial Revolution? A theme of many economic models of the transition from Malthusian stagnation to modern growth listed above is that there was a switch from quantity, or at least desired quantity, to quality in families as we moved to the modern world. This theme has been driven by the observation in modern cross sections, looking across countries, that high income, high education societies are those with few children per woman. Also within high income societies there was a period between 1890 and 1980 where again lower income families were those with more children.

Such theories face a number of challenges in modeling the actual world of Industrial Revolution England. The first challenge is that these theories are expressed always in terms of children surviving to adulthood. In the modern world in most societies child survival rates are high, and so in practice births and surviving children are closely equivalent. But in all known pre-industrial societies, including pre-industrial England, large numbers of children did not survive even to their first year. In these cases the distinction between births and surviving children becomes important. Measured in terms of births, Malthusian societies witnessed high fertility, with the average woman surviving to age 50 giving birth to 5 children. But in such societies the average number of children surviving to adulthood could only be 2.

Further since children who died in the pre-industrial world tended to do so fairly early, the numbers of children in any household at any time in the pre-industrial world would typically be 3 or less. For example, of 1,000 children born in England in 1700-24, nearly 200 would be dead within 6 months (Wrigley et al., 1997). Pre-industrial families would look similar to the families of America in the high growth 1950s and 1960s. Pre-industrial families thus faced remarkably similar tradeoffs between the number and quality of children as do modern families. In some sense there has been no change in fertility from the pre-industrial to the modern world, measured in net as opposed to gross terms.

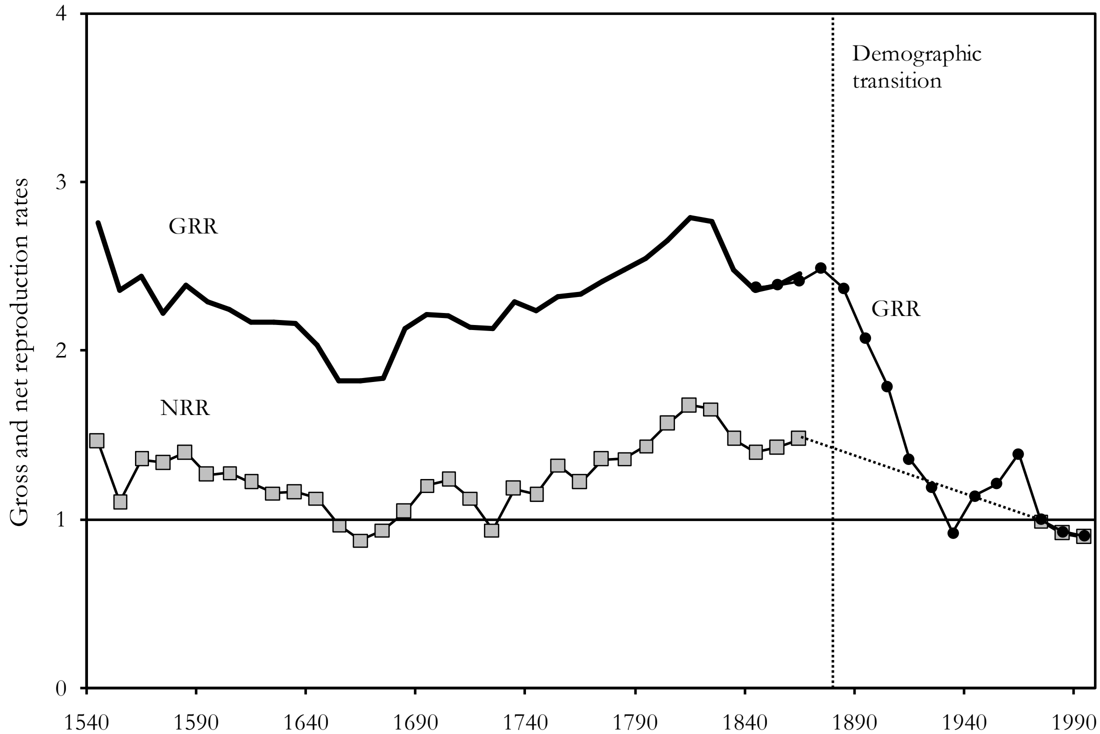
The second challenge these theories face is that in England the transition from high births per woman to lower levels of births per woman did not occur at the onset of the Industrial Revolution, but only one hundred years later in the 1880s.[15] Fertility in England did not show any decline at the aggregate level prior to 1880. Indeed the opposite occurred, as figure 9 illustrates. Births per woman, and also net fertility, rose precisely in the period of the Industrial Revolution in England.

The third challenge is that in cross-section in pre-industrial England there was a strong positive association between net fertility and the wealth or occupational status of families. Figure 10, for example, shows by twenty year periods the numbers of children alive at the time wills were made for married men in England marrying 1520-1879, where those leaving wills are divided into wealth terciles defined across the whole sample. The lowest tercile in wealth would still be men of above median wealth at death. Their implied net fertility is similar to that for men as a whole in England, as revealed by figure 9. But the men of the top wealth tercile marrying before 1780 were leaving on average 3.5-4 surviving children. The most educated and economically successful men in pre-industrial England were those with the largest numbers of surviving offspring. Matching these men to parish records of births shows that this advantage in numbers of surviving children stems largely from the greater fertility of the wives of richer men. Their gross fertility was equivalently higher. This positive association of economic status and fertility pre 1780 has been confirmed in an independent study of gross fertility in parish records in England 1538-1837 by Boberg-Fazlic, Sharp, and Weisdorf, 2011.

For marriages 1780-1879 this pattern of high fertility by the rich and educated disappears. Instead we have for most of the Industrial Revolution period an interval where fertility is unlinked to education, status or wealth. Figure 11 shows the dramatic shift in pattern this represents, grouping married men by wealth deciles. Another feature revealed in figure 11 is that the pattern of higher net fertility with wealth before 1780 continues all through the wealth spectrum. There is no wealth level at which we observe any decline in net fertility.

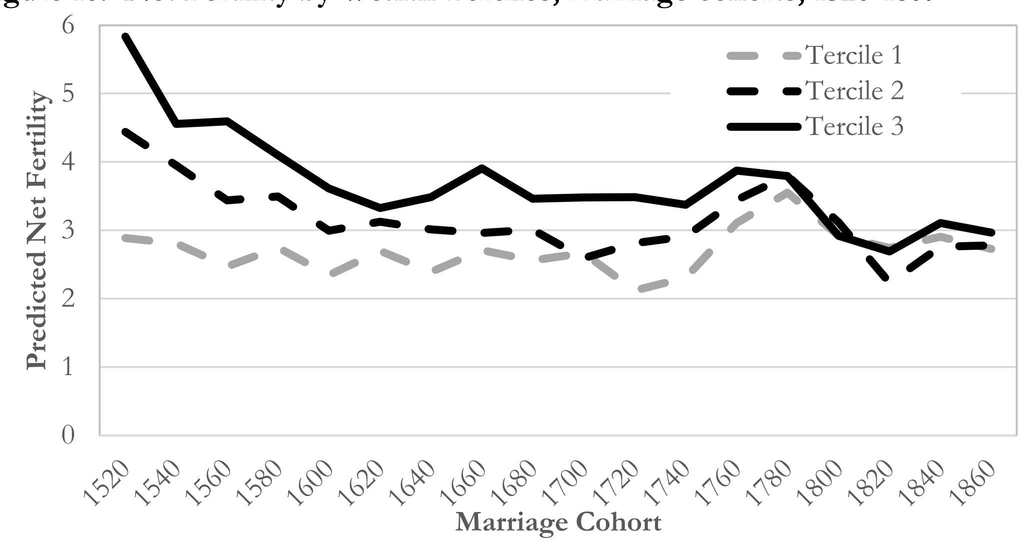
[15] France was the only country to experience a decline in fertility starting in the late eighteenth century, and France of course lagged Britain in terms of the onset of modern growth.

Figure 9: The Fertility History of England, 1540-2000



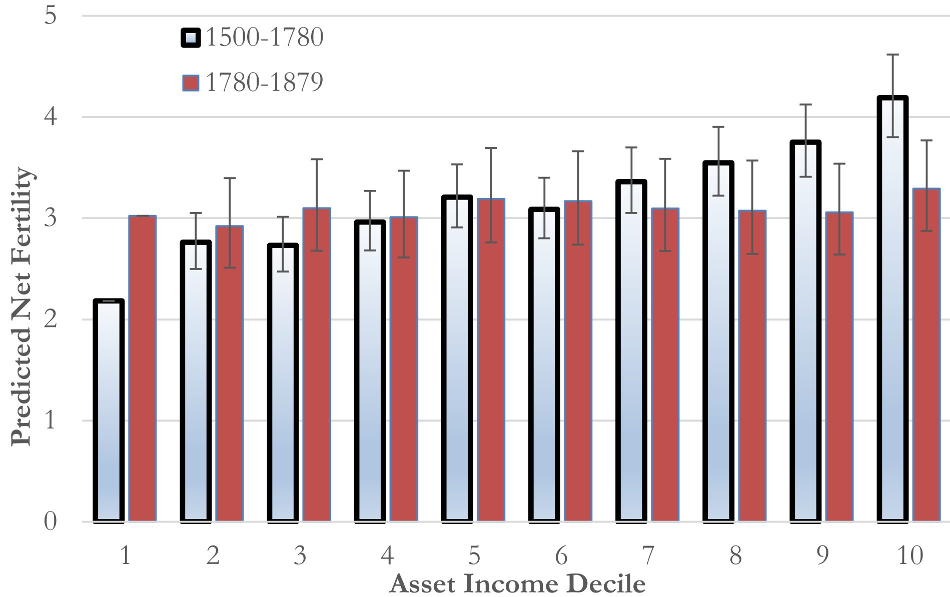
Source: Clark, 2007, figure 14.6, p. 290.

Figure 10: Net Fertility by Wealth Terciles, marriage cohorts, 1520-1879



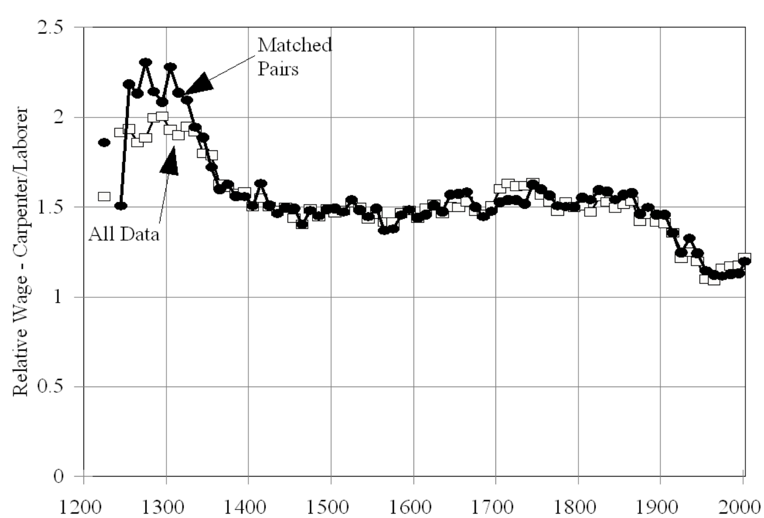
Source: Clark and Cummins, 2013a.

Figure 11: Net Marital Fertility by Wealth Decile, Marriages 1500-1779 and 1780-1879



Note: The lines at the top of the columns indicate the 95% confidence interval for the net fertility of these groups relative to the decile of lowest asset income. All assets normalized by the average wage in the year of death from Clark, 2010.
Source: Clark and Cummins, 2013a.

Figure 12: The Skill Premium, Building Workers, England, 1220-2000



Source: Clark, 2005.

The delay in the decline in aggregate fertility levels in England till after the Industrial Revolution represents a formidable challenge for theories that seek to explain the Industrial Revolution through a quality-quantity tradeoff, and rising levels of human capital. However, these recent findings that richer families did indeed reduce their fertility just at the time of the onset of the Industrial Revolution offers some hope for models based on heterogenous agents as opposed to a single representative agent. But if richer families were changing their behaviors in response to economic signals, we would expect to find in this period sign of greater returns to human capital investments. Another problem for quality-quantity models of the Industrial Revolution is that such evidence is lacking. Figure 12, for example, shows the earnings of building craftsmen – carpenters, masons, bricklayers, plasterers, painters, plumbers, pavers, tilers and thatchers – relative to unskilled building laborers and assistants. The skill premium is actually at its highest in the interval 1220-2000 in the earliest years, before the onset of the Black Death in 1348, when a craftsman earned nearly double the wage of a laborer. If there was ever an incentive to accumulate skills it was in the early economy. Thereafter it declines to a lower but relatively stable level from about 1370 until 1900, a period of over 400 years, before declining further in the twentieth century. Thus the time of the greatest market reward for skills and training was long before the Industrial Revolution. And the period of the Demographic Transition in England, the switch towards smaller family sizes circa 1880, is not associated with any rise in the skill premium.

The information on the skill premium in building may be criticized as showing only the returns to a very limited form of human capital. What about wider measures of the impact of quantity of children before and after the Industrial Revolution on child outcomes? Do we find that for marriages prior to 1780 there is little or no cost in terms of child outcomes where richer families have more children, but that after 1780 a quality-quantity tradeoff becomes evident?

The same source that was used above to measure net fertility as a function of wealth and socio-economic status, men's wills, can also be employed to measure the effects of the number of children on the outcomes for children before and during the Industrial Revolution (Clark and Cummins, 2013b).

In measuring the quality-quantity tradeoff in the modern world the problem has been that "high quality" families tend to have fewer children. The observed relationship between quality and quantity may thus reveal no underlying causal relationship. In capturing the true quality-quantity trade-off, researchers have had to control for the inherent endogeneity of family size. We can thus portray parent influences on child "quality" as following two potential routes, as in figure 13. Since in the modern world high 'quality' parents also tend to have smaller numbers of children, the observed negative correlation between n and child quality may stem just from the positive correlation of parent and child quality. As figure 14 shows the estimate of the tradeoff between quantity and quality will be too steep using just the observed relationship. Estimates $\hat{\beta}$ of β in the regression

$$q = \beta n + u, \tag{5}$$

where q is child quality, n child numbers, and u the error term are biased towards the negative, because of the correlation between n and u.

To uncover the true relationship investigators have followed a number of strategies. The first is to look at exogenous variation in family size caused by the accident of twin births (e.g. Rosenzweig and Wolpin, 1980, Angrist, Lavy, and Schlosser, 2010, Li, Zhang, and Zhu, 2008). In a world where the modal family size is 2, there are a number of families who accidentally end up with 3 children because their second birth is of twins. What happens to the quality of these children compared to the quality of the children of such families compared to those of two child families? These studies find the uncontrolled relationship between quantity and quality decreases. Indeed it is often insignificant and sometimes positive (Schultz, 2007, 20). For instance; Angrist, et al., 2010, find "no evidence of a quality-quantity trade-off" for Israel using census data. Li, Zhang, and Zhu, 2008, however, do report the expected relationship instrumenting using twins in China, but only in the Chinese countryside. But in China there are government policies designed to penalize couples who have more than the approved number of children, so we may not be observing anything about the free market quality/quantity tradeoff.

In summary, there is a clear raw negative correlation in modern populations between child numbers and various measures of child quality. However, once instruments and other controls to deal with the endogeneity of child quality and quantity are included, the quality-quantity relationship becomes unclear. The quality-quantity tradeoff so vital to most theoretical accounts of modern economic growth is, at best, unproven.

Figure 13: Parent influences on child quality

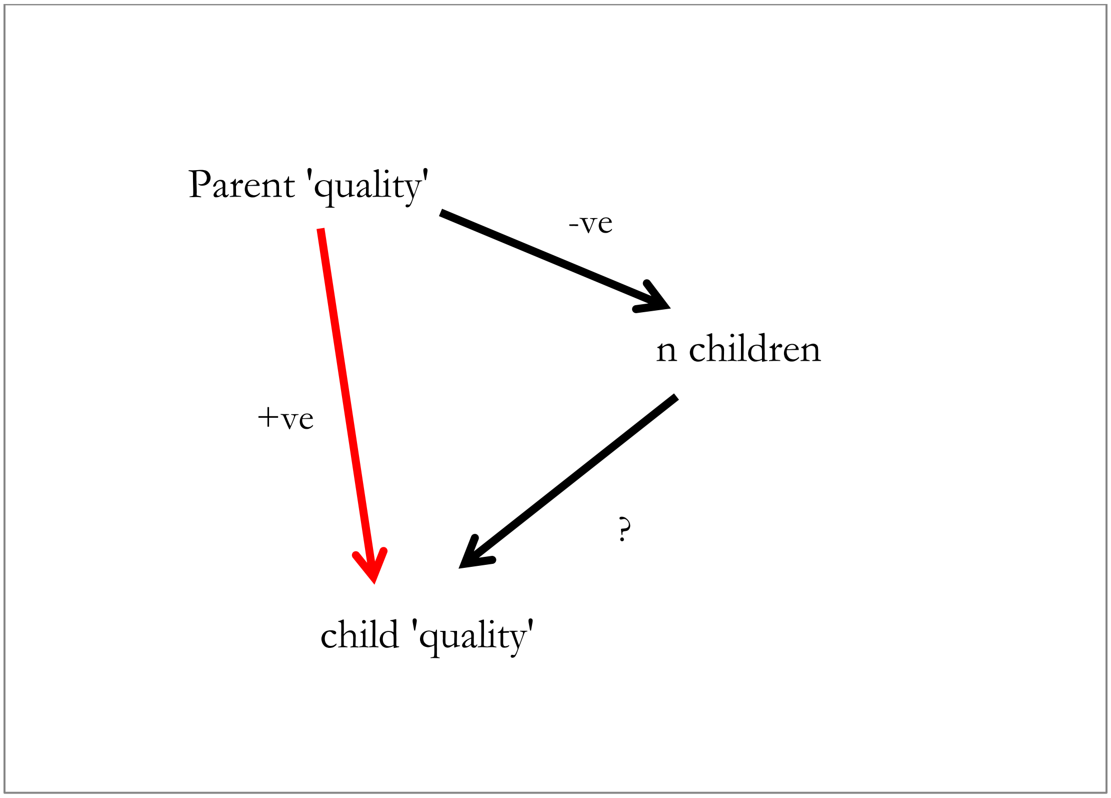
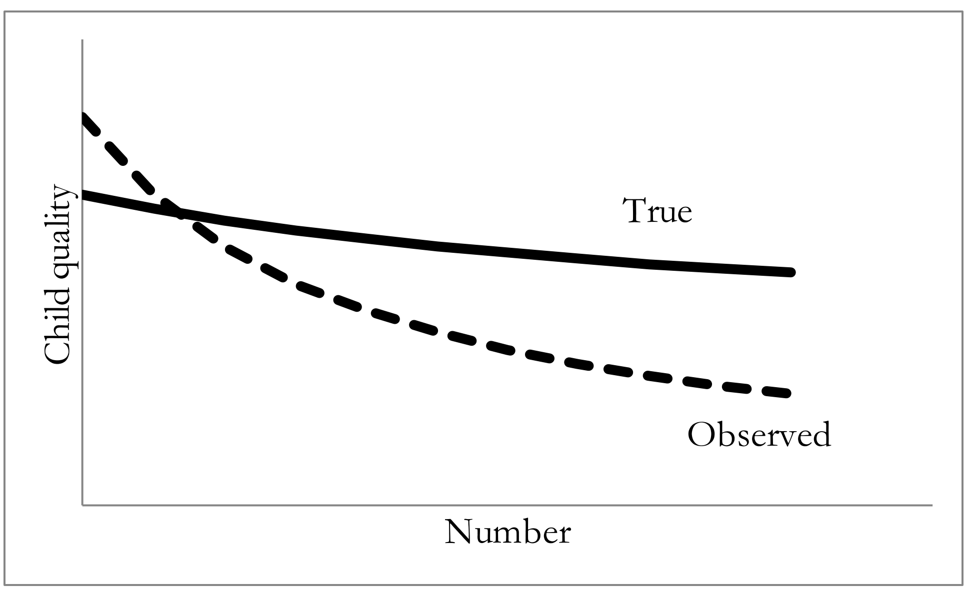


Figure 14: The True and Observed Quality-Quantity Tradeoff



However, we see above that in the period 1540-1780 in England the modern negative relationship between child numbers and parent quality is reversed and is instead positive. Thus in this period in estimating β in equation (5) we will find that $\hat{\beta}$ is in this case biased instead towards 0. Figure 15 shows this effect. Any negative effects of quantity on quality found will be underestimated, as opposed to the bias in estimating β in modern studies. Then there is the intermediate fertility regime in England, marriages formed 1780-1880, where parent quality and numbers of children are uncorrelated, so that $\hat{\beta}$ will be unbiased.

The second advantage of the pre-industrial data from England for observing the quality-quantity tradeoff is the much greater variation in family sizes before 1870 than in the modern world, and the evidence that this variance was largely the product of chance, like modern twin births. Figure 16 shows the distribution of the number of surviving children per father, at the time of the father's will, for fathers marrying 1500-1799, and 1800-1869. This number will include children from more than one wife, where a first wife died and the husband remarried.

As noted above we can measure family size in two ways. A second is the number of births per family, gross fertility. This is shown in figure 17, giving the distribution of births per mother for the wives of men marrying in England 1500-1799, where the husband had only one wife. Thus despite the average of 5 births per wife, in 10% of all marriages there was only one child born, in about 20% only two. The number of baptisms is the overwhelming explanator of the number of surviving children per man. The R^2 of the regression predicting numbers of surviving children from the number baptized is 0.73. On average 0.62 of each child born would be alive at the time of the will. If we include in this regression indicators for location, social status, wealth, and time period then the R^2 increases only marginally to 0.75. At the individual family level both gross fertility, births, and net fertility, the number of surviving children, were largely random variables. Only a tiny fraction of the variation in each is explained by correlates such as wealth, occupation, literacy and location.

Figure 15: The True and Observed Quality-Quantity Tradeoff, marriages pre 1780

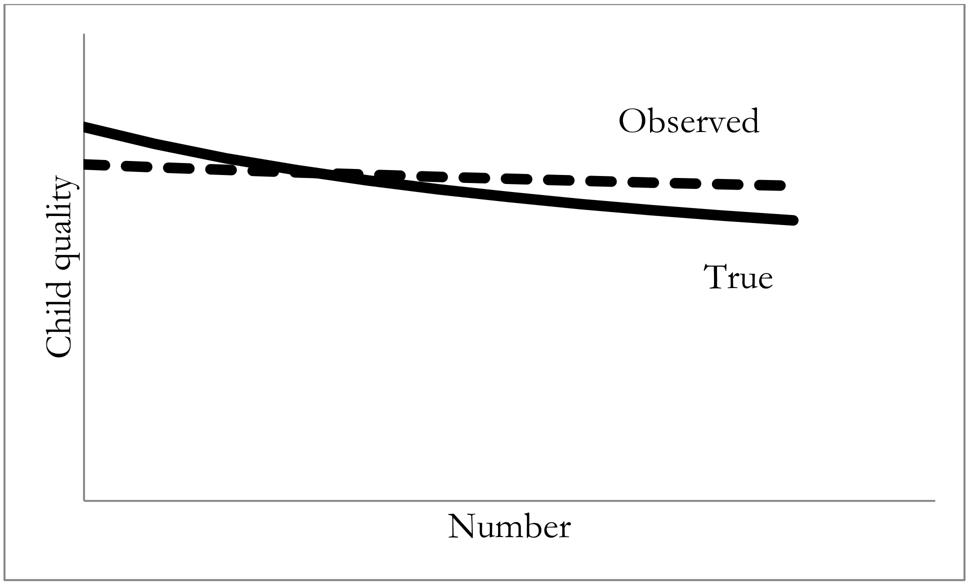
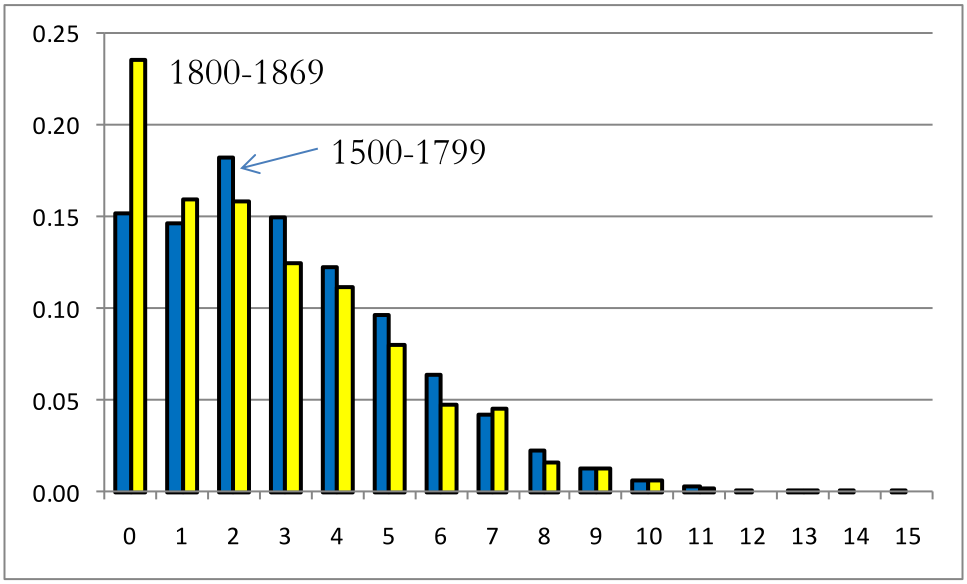


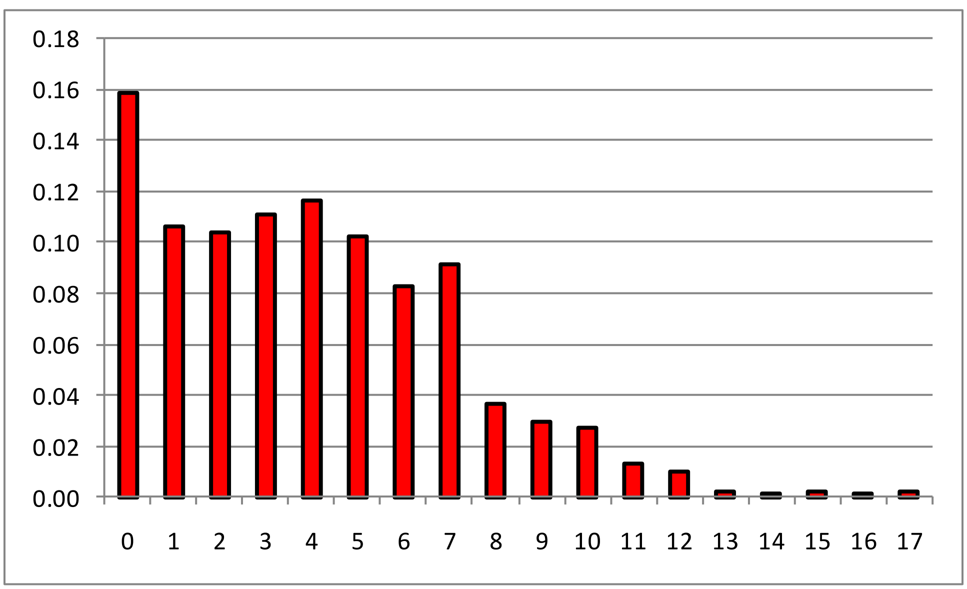
Figure 16: The distribution of net family sizes in pre-industrial England



Note: Number of observations before 1800, 6,940, after 1800, 1,418.

Source: Clark and Cummins, 2013b.

Figure 17: The Distribution of number of baptisms per wife, 1500-1799



Note: Number of observations before 1800, 818.

Source: Clark and Cummins, 2013b.

When the coefficient β in the equation

$$q = \beta n + u$$

is estimated by OLS estimate of β will be, in the limit,

$$\hat{\beta} = \beta + \frac{cov(n,u)}{var(n)}$$

But in pre-industrial England the degree of bias this will impart will be small because n was largely a random variable, so the bias in estimating β will be correspondingly very slight.

Thus suppose $n = \theta u + e$. Then

$$\frac{cov(n,u)}{var(n)} = \frac{\theta var(u)}{\theta^2 var(u) + var(e)}$$

The greater is var(e), the random component in n, then the less the bias in the estimate of β. We show below that for marriages formed before 1870 var(e) was enormous relative to θ^2var(u). We can thus use the observed correlation between quality and quantity in this period as a measure of the true underlying causal connection between quantity and quality in the years before and during the Industrial Revolution.

We have three measures of child quality for sons born over the years 1500-1879: the wealth of those probated, the socio-economic status of those probated, and the probate rates of all sons. The likelihood of a man being probated was strongly linked to their wealth and social status. Probate was only required if the estate of the deceased exceed a certain limit. In 1862 65% of men of high socio-economic status (professionals and gentlemen) were probated, compared to 2% of laborers (Clark and Cummins, 2013a).

The sample of father-son pairings is very much biased towards the rich. As table 6 shows, will makers in the years 1500-1920 were disproportionately from the upper social groups. In 1862 the bottom two social groups in the table were 40 percent of men dying, but they represent only 8 percent of fathers and sons where both were probated (Clark and Cummins, 2013a, table A.12). In contrast the top 3 social groups represented 13 percent of men dying in 1862, but a full 67 percent of those where both father and son were probated. Thus what we are principally looking at here is the effects of family size on the outcomes for children of the upper third of the population in pre-industrial England. But this is the group whose behavior was changing first around 1780, then around 1880, in the two stage demographic transition observed in Industrial Revolution England.

The effect of family size on wealth is estimated from the size of the coefficient b_2 in the expression

$$lnW_s = b_0 + b_1 lnW_f + b_2 lnN + b_3 DFALIVE + e \qquad (6)$$

Where N is the number of surviving children, lnW_s the average log wealth of sons of a given father, and DFALIVE the fraction of sons for whom the father was alive at the time of son's probate. DFALIVE is a control for the effects of sons who die before fathers, and thus likely receive smaller transfers of wealth from fathers. Such sons will also tend to be younger. And in this data wealth rises monotonically with age until men are well past 60. Since some fathers had more than one probated son, we averaged wealth across the probated sons and treated each family as the unit of observation.

With this formulation, b_3 is the elasticity of son's asset income as a function of the number of surviving children the father left. N varies in the sub-sample of fathers and sons from 1 to 13. The coefficient b_2 shows the direct link between fathers' and sons' wealth, independent of the size of the fathers' family.

Table 7 shows the estimated coefficients from equation (6) for father's dying 1500-1920. The results are reported for the data pooled across all years, and for fathers dying 1500-1819 (who would have sons born up until 1800 typically), those dying 1820-1880 and post-1880. The link between father's and son's wealth as revealed by the estimate of b_1 is highly significant and stable across the sub-periods.

Table 6: Social Distribution among Will Makers, and Father-Son Pairs

Social group	N all wills	% all wills	N father-son	% father -son
Gentry/Independent	405	7	220	15
Merchants/ Professionals	506	9	167	11
Farmers	1,906	33	605	41
Traders	883	15	152	10
Craftsmen	1,132	19	217	15
Husbandmen	708	12	99	7
Laborers/Servants	268	5	16	1

Source: Clark and Cummins, 2013b.

The estimated coefficient on the log of surviving children is negative in all three periods, as would be implied by a quality-quantity tradeoff. So this study is unusual in finding for the early period a quantitatively and statistically significant effect of family size on son outcomes. However, even though it will be potentially biased towards zero for fathers dying before 1820, the value in these earlier years is estimated as being similar to that in 1820-80.[16] There is no indication in this data of a substantially more adverse quality-quantity tradeoff with the arrival of the Industrial Revolution. There is nothing in the estimates of table 7 to suggest that changing family sizes among the wealthy and educated in Industrial Revolution England were driven by a changing quality-quantity tradeoff. Again the economic environment seems stable as the dramatic changes of the Industrial Revolution were occurring.

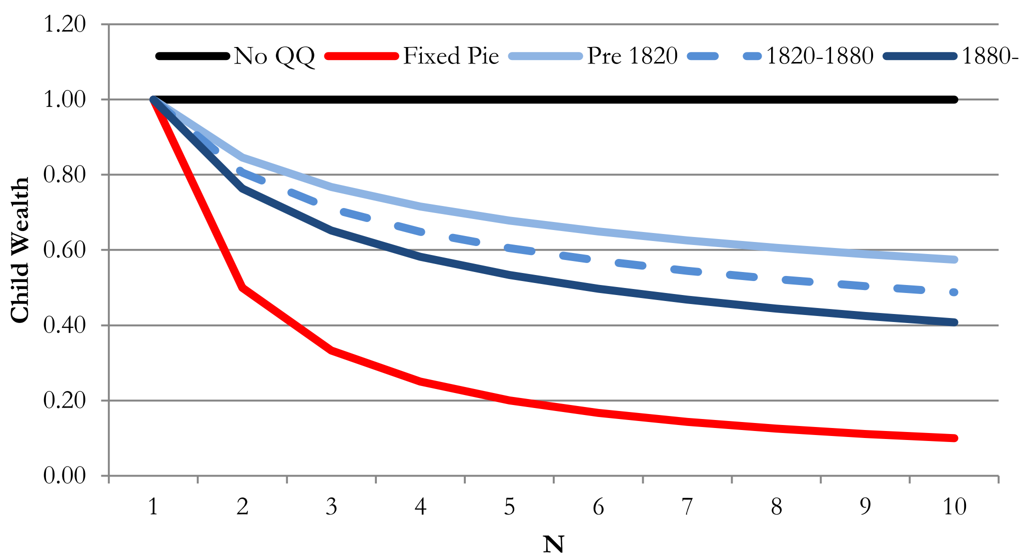
[16] The bias, as argued above, will be small before 1880 because of the randomness of family sizes.

Table 7: Son's Wealth and Family Size

	All	Pre 1820	1820-1880	1880-
LnWf	.502***	.560***	.527***	.457***
	(.030)	(.051)	(.073)	(.046)
LnN	-.311***	-.241***	-.312	-.390**
	(.082)	(.090)	(.227)	(.176)
Dfalive	-.868***	-.710**	-.611	-.866*
	(.258)	(.314)	(.643)	(.448)
Constant	2.032***	1.929***	2.024***	1.696***
	(.158)	(.210)	(.502)	(.341)
Obs	1,029	610	175	244
R-squared	.292	.306	.281	.302

Robust standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$
Source: Clark and Cummins, 2013b.

Figure 18: The Empirical QQ Effect, 1500-1920



Source: Clark and Cummins, 2013b.

The predicted quantitative effects of sibling size on wealth at death are shown in figure 18, where wealth at a family size of 1 fixed at 1. Pooling all the data, the effects of family size on the outcomes for children measured in terms of wealth are actually reasonably modest. Moving from a family of one child (with our data by definition a boy), to one of 10 children, reduces the average wealth of sons by only 51 percent. This is demonstrated visually in figure 18.

This is not a very strong effect if the main transmission of wealth was through division of a fixed pie of wealth among children (the red line in figure 18). For in that case the expected coefficient on *lnN* should be -1. The average wealth of the children of a family of 10 would be only 10% of that of a family with only one sibling. We can derive similar estimates of the effect of family size by period on the chances of being probated, and on occupational status. In each case the effects are in the right direction, but even more modest than for wealth (Clark and Cummins, 2013).

The facts above about the transition from pre-industrial to modern fertility in England in the Industrial Revolution era represent a formidable challenge to those trying to model the Industrial Revolution in a child quality-quantity framework. Since some of these patterns were discovered only in the last few years, such as the strong positive association of wealth and fertility in pre-industrial England, many of these models fail to capture essential features of the fertility transitions (Clark and Hamilton, 2006, Clark and Cummins, 2013a, Boberg-Fazlic, Sharp, and Weisdorf, 2011).

Some of the theory papers mentioned above, such as that of Becker, Tamura and Murphy, 1990, fail at the first challenge. They posit a pre-industrial world world that never existed of high net fertility and rapid population growth. And while they model a world with two equilibria – in one of which parents invest nothing in the human capital of their children, and in the other considerable human capital – the escape from the zero human capital Malthusian trap is exogenous to the model. "Technological and other shocks" (Becker, Tamura and Murphy, 1990, S32) somehow raise the level of human capital far enough above zero to lead to a convergence to the high growth equilibrium. These shocks are conceived to be "improved methods to use coal, better rail and ocean transports, and decreased regulation of prices and foreign trade." (Becker, Tamura and Murphy, 1990, S33). But how such shocks get translated into human capital is never specified. The arrival of highly paid unskilled work in textile factories in the Industrial Revolution, for example, we would expect in the Becker, Murphy and Tamura model to reduce educational investment.

Robert Lucas creates a Malthusian trap with many of the same characteristics of Becker, Murphy and Tamura (Lucas, 2002), but which tries to model better pre-industrial fertility, measured as surviving children, so that it increases in income. In the low level equilibrium there is again no human capital investment. This arises because Lucas specifies a land using sector where human capital plays no role, and a "modern" sector where human capital enters with constant returns. Goods production is thus (simplifying slightly)

$$F(x, H, l) = \max_{\theta}\left[x^{\alpha}\theta^{1-\alpha} + BH(l-\theta)\right] \qquad (4)$$

where x is land per person, H is human capital per person, l is the labor devoted to production, and θ is the labor devoted to the land using sector. However, the assumption that there is a crucial difference in character between the farm sector and other areas of the economy is unsupportable both for the pre-industrial and for the modern eras. We see above in table 2 that agriculture in England in the Industrial Revolution era experienced unusually fast productivity growth rates also. And agriculture had as much demand for skills and human capital as other sectors of the economy.[17]

In Lucas, 2002, parents' utility depends on goods consumption, the number of children and the utility of the children, but with the slightly different functional form

[17] Hanson and Prescott, 2002, is another model which produces an Industrial Revolution by positing a difference between the farm and non-farm sectors. The inherent rate of productivity growth in the non-farm sector is assumed to be higher. This means that wherever the economy starts there will eventually be an Industrial Revolution. Why that Industrial Revolution does not occur in 1800 BC as opposed to 1800 AD is not explained. Also productivity growth rates in the "industrial" sector in England in reality increased at the time of the Industrial Revolution. The Industrial Revolution was not the result of composition effects only. And, as noted, productivity growth rates in the farm sector also increased in the Industrial Revolution era, and since then have been as rapid as those in the rest of the economy.

$$V_t = c_t^{1-\beta} n_t^{\eta} V_{t+1}^{\beta} \tag{5}$$

Human capital evolves according to

$$H_{t+1} = H_t \varphi(h_t) \tag{6}$$

where h is the labor invested in education. This means that in the Malthusian equilibrium there is no investment in human capital since H starts as 0. Thus all production is conducted using the land using technology. Since there is a land constraint, now there will only be a constant output Malthusian equilibrium if n = 1, so that the population stabilizes. To ensure this Lucas assumes that each child requires a fixed investment of *goods*, *k*. As population increases, so that output per person declines, the relative cost of children thus rises. Eventually *n* will be driven to 1.

In the contrasting endogenous growth regime, H is large, so that nearly all output comes from the technology where there are constant returns to H. Consumption and human capital grow at the same rate, and fertility and educational investment per child is constant. The number of children per parent chosen in this steady state growth path will depend on the weights in the utility function for children η versus their utilities β, and on the form of $\varphi(h)$.

But like Becker et al., 1990 Lucas gives no mechanism that gets the economy from the Malthusian trap to the sustained growth regime. Instead he has to assume that somehow enough human capital, H, accumulates for non-economic reasons to push the economy far enough from the Malthusian equilibrium for convergence on the modern growth regime to begin. The Industrial Revolution is again the deus ex machina.

We thus see a very poor match between the elements that would seem to go into a human capital story of the Industrial Revolution – the Industrial Revolution itself, the average size of families, and the premium paid in the labor market for skills. If human capital is the key to the Industrial Revolution, the trigger for its expansion in pre-industrial England remains mysterious if we assume a universal set of preferences for all societies.

Endogenous growth theories such as those of Galor and Weil, 2000, and Galor and Moaz, 2002, seek to avoid the need for some exogenous shock to trigger the switch to higher human capital investment and the consequent Industrial Revolution. This requires that some elements of the economy must be evolving endogenously within the pre-industrial era. Since incomes and consumption are predicted to be static within the Malthusian regime it is not these. Instead Galor and Weil, 2000, rely on the accumulation of population in the pre-industrial era to drive up the rate of innovation and the return to human capital. In this they rely on an interesting paper by Michael Kremer which argues for population size as a driver of rates of productivity advance (Kremer, 1993).

Kremer assumes that the social institutions that provide the incentives to individuals to create knowledge are the same in all societies. Each person has a given probability of producing a new idea. In this case the growth rate of knowledge will be a function of the size of the community. The more people you are in contact with the more you get to benefit from the ideas of others. There was substantial but slow productivity growth in the world economy in the years before 1800, and that all got translated into a huge expansion of the world population, through the effects of equation (2) above. That larger population produced more ideas and more rapid growth. Sheer scale is what produces modern economic growth.[18]

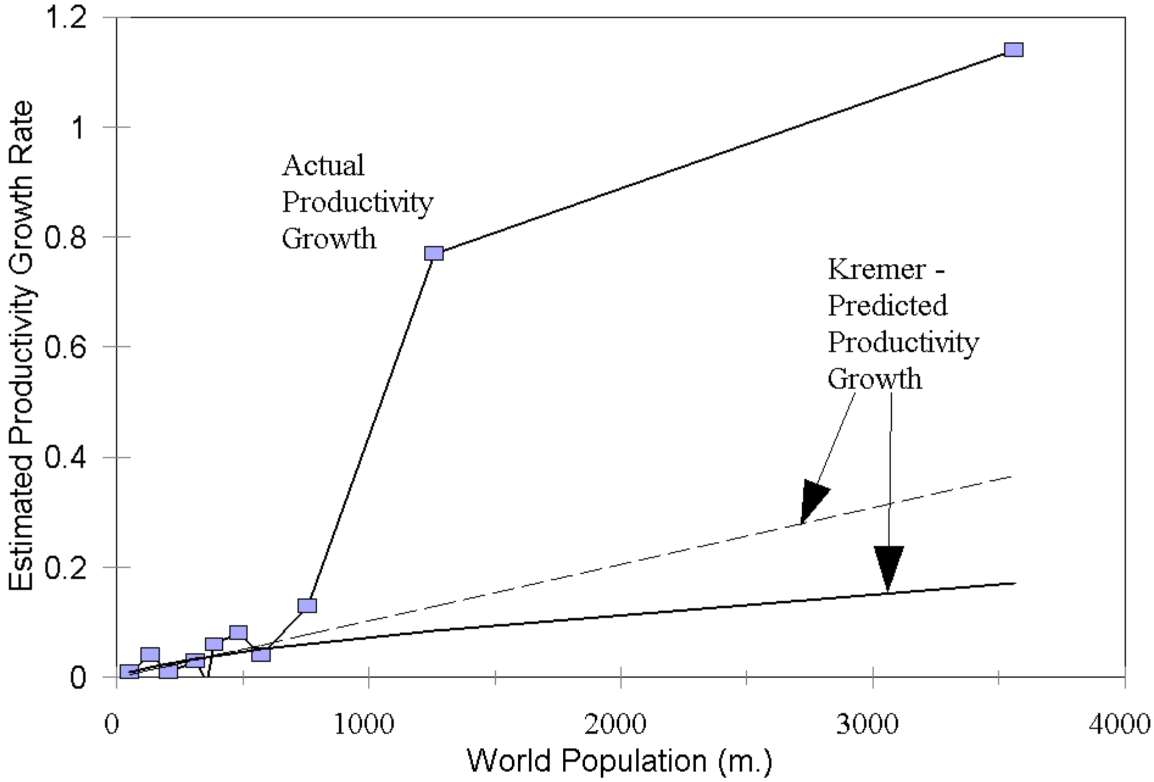
Kremer supports the argument with two sorts of evidence

(a) The first is population growth rates for the world as a whole in the pre-industrial era. World population growth rates are faster the greater the size of populations. That implies, since population growth rates and the rate of technological advance are proportionate, that productivity growth rates were speeding up over time as population grew. This is shown in Figure 19.

(b) The second is population density, as an index of the level of technology in the pre-industrial world, for major isolated geographic areas – Eurasia, the Americas and Australia - as a function of the land area. The prediction is that the smaller the

[18] Diamond, 1997, contains many of the same ideas, merged also with consideration of the role of geography in creating the community that benefits from knowledge expansion.

Figure 19: Population and the Rate of Technological Advance – Actual versus predicted



land area, and hence the potential population, the lower will be the rate of technological advance. In this case at any given time population density will depend on land area. This is found for the three cases examined.

One immediate implication of the Kremer argument, however, would be that ceteris paribus the Industrial Revolution should have occurred in China. Chinese population in the pre-industrial world was large relative to that of Europe. Even as late at 1800 it has been estimated that China contained 260 million people, while Europe outside Russia had only 130 million, half as many as China. Thus Galor and Weil, 2000, has no insight to offer on why the Industrial Revolution was British, as opposed to Chinese. It is a more general theory about the world transition to growth.

Interesting though Kremer's ideas are, no matter how much population is a driver of the rate of technological advance, population alone cannot produce a discontinuity in the rate of technological advance circa 1800 of the magnitude indicated in figure 19. Thus a simple specification for the effect of population on changes in productivity would be

$$\Delta A = \delta N \tag{7}$$

where A is now the stock of knowledge (the number of ideas). If every person has some chance of producing a new idea then the expansion of the idea stock will be at best proportional to the population size.[19] This implies that the rate of growth of ideas (=productivity) will be

$$g_A = \frac{\Delta A}{A} = \delta \frac{N}{A} \tag{8}$$

But integrating equation (2) above this is equivalent to the condition

$$N = \theta A^{1/c} \tag{9}$$

where θ is just a parameter. That is the population size depends on the existing level of the technology. Substituting from (9) for A in (8) gives

$$g_A = cN\left(\frac{\theta}{N}\right)^c = c\theta N^{1-c} \tag{10}$$

This formula implies that the rate of efficiency growth, g_A, rises less than proportionately with population. Yet what we see in figure 19 is that the rate of technological advance seems to rise faster than population growth. Figure 19 also shows the rate of technological advance predicted by this Kremer argument (the

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[19] Assuming that there is no duplication of ideas with a larger population, where the same thing is discovered by multiple people. In actual fact we would expect that the gains in idea production would rise less than proportionately with population.

lowest curve). The increase of the rate of technological advance as we move to modern population sizes is just not fast enough to explain what we observe.

Technology growth rates would be more responsive to population if instead of (8) we posit

$$\Delta A = \delta NA \qquad (11)$$

This says that the stock of ideas grows as a product of the number of people, and the existing stock of ideas (with again no duplication of ideas). This in turn implies that

$$g_A = \frac{\Delta A}{A} = cN \qquad (12)$$

This predicted growth rate of technology as a function of population is also shown in figure 19. Now the fit is closer before 1800, but there is still no close fit with modern productivity growth rates. At best productivity growth rates would be proportionate to population under the Kremer assumptions.

This feature of the Kremer model, that it is hard to produce with an endogenous growth model a discontinuity of the magnitude seemingly observed in the Industrial Revolution, is a general problem for all such endogenous growth models. Thus the Galor and Weil endogenous growth model, which uses the Kremer population size driver as the spark for the Industrial Revolution (and is described further below), has been simulated in Lagerlöf, 2006. Figure 20 shows the outlines of that simulation, where time is measured on the horizontal axes in terms of generations. In the Galor-Weil model there is a transition period between the Malthusian regime and modern growth in which technology advances more quickly, incomes rise above subsistence, and population expands. But this transition period here lasts 20 generations, which would be 500-600 years.[20]

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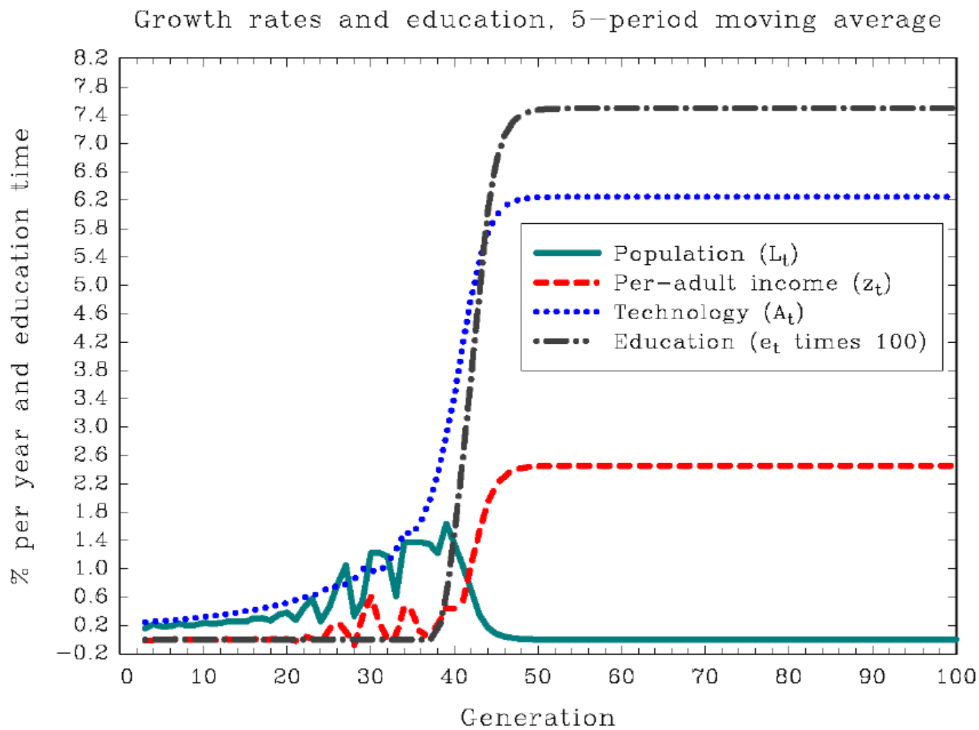
[20] Lagerlöf assumes a generation length of 20 years, but this is too short for any pre-industrial society, where 25-30 years would be more realistic.

Figure 20: Simulated the Galor and Weil, 2000, Endogenous Growth Model



Source: Lagerlöf, 2006, Figure 5, 130.

But we do not see at the world level in 1200-1800 any signs of the income growth rates, or the population growth rates predicted in this simulation of the Galor-Weil model. Table 1, for example, shows that at the world level population growth rates remained in the range on 0.1-0.2% per year, far slower than figure 20 implies. Clark, 2007, shows that there is no sign on a world scale that incomes per person had risen above those of the hunter-gatherer era, despite the prediction of figure 20 that by then incomes per capita in the world would have risen to 3 times their Malthusian level by 1800. Also, at least in England we see no sign of the abrupt rise in human capital coincident with declining fertility portrayed in figure 20. Measurements of human capital as in figure 8 suggest a much more modest transition starting hundreds of years before the Industrial Revolution and continuing through it.

Galor and Weil, 2000, as noted above, marry the key idea of Kremer that the rate of technological progress depends on population size with the Beckerian human capital approach. They posit a utility function of the form

$$V_t = c_t^{1-\gamma}(y_{t+1}n_t)^{\gamma} \tag{13}$$

Utility now is a weighted average of the consumption of the parents and the aggregate potential income of their children, y_{t+1}, in the next period. While in Lucas children have a fixed cost in goods, in Galor and Weil they have a fixed cost only in time. That means that at low incomes, when time is cheap, people would have more children, as in the Becker, Murphy and Tamura (1990), and we would not get a Malthusian steady state. To get a Malthusian equilibrium where income per capita is stable, the authors make an additional assumption that there is a minimum physical consumption level, $\tilde{c}$. This means that as long as potential income is below some level $\tilde{y}$ increases in income are associated with increases in fertility. As income falls low enough we must reach a state where there is surplus enough beyond $\tilde{c}$ to allow for 1 and only one child per family (treating families as having one parent).[21]

Potential income per worker is of the form

$$y_t = A_t x_t^{1-\alpha} H_t^{\alpha} \tag{14}$$

where x is land per person, and A is related to the efficiency of goods production. Now human capital is required even in the Malthusian equilibrium. H evolves according to the time invested in educating each child, h, through a function of the form

$$H_{t+1} = H(h_t, g_{At}), \tag{15}$$

[21] A feature of these theoretical models is that the preferences specified over goods and children in all of them have no function other than allowing the modellers to get the desired outcome in terms of child numbers and human capital in a constrained maximization setting. They do not better explain the world, or offer further insight or predictions about fertility behavior. They are just ways of reproducing, in a desired mathematical format, observed behavior.

where H increases in g_{At}. The TFP variable A evolves according to a function of the form

$$g_{At} = g(h_t, N_t) \quad (16)$$

where N_t is the total population size. Efficiency thus grows more rapidly in large economies with more time resources devoted to each child. And the growth of efficiency increases the human capital per child and the subsequent output per person. Galor and Weil, 2000, thus at least tries to preserve some distinction between human capital and the TFP of the economy. But it is not clear whether there is any real substance to the formal mathematical separation. There is no way observationally to distinguish economies which have high output because TFP is high, or those that have high output because the human capital stock, as opposed to educational input stock, is large.

The functional form chosen for the utility function is such that the share of time devoted to raising children is always γ once families have achieved the subsistence consumption. Thus there is a built in trade-off between the quality and quantity of children. Any move to more education must be associated with lower fertility. Thus the authors build in an inverse U shape to fertility as potential incomes rise – with an increase caused by the subsistence constraint on the lower end, and then a decline caused by the rising value of investment on education at higher potential incomes. Again the utility function here does no real explanatory work. It captures an observed empirical regularity.

The system is constructed so that the amount of time invested in each child increases with the expected rate of technological progress, and the rate of technological progress increases with the time investment per child. At the Malthusian equilibrium the parents spend the minimum possible amount per child, and the only determinant of technological progress is the population size N. By the assumption that g_A is positive, even without any educational investments, population grows in the Malthusian equilibrium, so that the steady state potential income is maintained by the balance of declining land per person and increasing technological efficiency.

But as population increases so does the base rate of technological progress, leading parents eventually to invest more than the minimum time in educating their children. At moderate population levels this creates a Malthusian regime with still the minimum consumption per person, but more children each getting some education and a faster rate of technological progress. Eventually population is sufficiently large so that education is productive enough that parents choose fewer high quality children, the population growth rates decline, and potential incomes begin a continuous increase.

Galor and Weil, 2000 still faces the fundamental problem of the earlier human capital models, however, in that what drives parents to invest more in education in the Industrial Revolution era is a rising perceived return to education. This, as we noted, we do not observe. Nor do we observe any more adverse tradeoff between quantity and quality as we move from 1500 to 1920.

Galor and Moav, 2002, employs many of the modeling elements of Galor and Weil, 2000, except that the Kremer driver for the Industrial Revolution, technological progress being a positive function of population, is replaced. The new driver is a natural selection, either through genes or cultural transmission, of individuals of a certain type in the Malthusian era. Individuals of type *i* are assumed to choose between consumption, the number of children, and the quality of the children according to a utility function of the form

$$V_t^i = (c_t^i)^{1-\gamma}(n_t^i(H_{t+1}^i)^{\beta^i})^{\gamma} \tag{16}$$

Now individuals care not about the potential income of their children, but the amount of human capital they possess. The weight individuals give the human capital of their children, indexed by β^i, thus varies with their type. High β families thus produce children with more human capital and more earnings potential. There are assumed, for simplicity, to be just two types of individual, high β and low β. The potential earnings of each type, y_t^i, are a function of the land labor ratio, x, the level of technology, A, and human capital, H_t^i, where

$$y_t^i = A_t x_t^{1-\alpha}(H_t^i)^{\alpha} \tag{17}$$

Now some of the return to education becomes externalized. "Low β" types gain from the increases in A generated by the investments of the "high β" types. But the idea is still that once efficiency starts growing more quickly a given amount of time spent on education produces more human capital. You get more for each year of education. Again this would seem to imply that the wage premium of skilled workers would have to rise in the Industrial Revolution era, which as noted above we do not observe.

Again in the Malthusian era a minimum consumption level, $\tilde{c}$, binds and all gains in potential income go to child rearing. The "high quality" types choose to endow their children with more human capital, however, and this means that they have higher potential incomes in the following period, which results in their descendants having not only higher quality children, but also more children. Thus the composition of the population changes in the Malthusian period towards individuals with the "high quality" values.[22] This increase in average education inputs, increases the private return to education by speeding up the rate of technological advance inducing both high β and low β types to invest in more education and fewer children.

The Galor and Moav, 2000, model does have one potentially useful feature, which is that the change in the composition of the population can proceed for generations in a Malthusian state where rates of population growth and levels of income remain low. It would be potentially consistent with the slow rise of education levels in Europe in the 300 years preceding the Industrial Revolution.

The Galor and Moav, 2000, model thus fits the positive association of fertility with wealth and socio-economic status in pre-industrial England detailed above. However, if we were to elaborate the model to a large number of types we would see that English demography before 1800 is inconsistent with this model. For in Galor and Moav, 2000, the positive relation between income and fertility will only be found at lower levels of income close to the consumption constraint, $\tilde{c}$. Once income gets high enough in the pre-industrial period we would see a negative connection between income and fertility, as in the modern era. The highest quality types would die out in the pre-industrial era along with the lowest quality types. Selection in

[22] Interestingly the composition of the population in the post Malthusian period switches back towards the "low quality" types since once potential income for even the low quality types passes a certain boundary they begin to have more children since they spend they invest same time as the high quality families in child rearing but invest less in each child.

Galor and Moav, 2000, is for those whose quality type leads to income just modestly above the subsistence consumption constraint.

Thus while the empirical evidence is clear that for at least 500 years before the Industrial Revolution there was differential fertility in England towards those of higher socio-economic status, there is no evidence that the selection was of the specific type posited in Galor and Moav, 2000. In particular the evidence is that the quality-quantity tradeoff that is central to Galor and Moav, 2000, while present, was relatively weak in all periods in England before 1920.

As with the other endogenous growth models, Galor and Moav, 2000, would also imply a much slower transition between a world of slow technological advance and the modern era than is observed in practice in the total factor productivity data for England.

Technological Change before the Industrial Revolution

We have been following the traditional assumption, so far, represented by figures 2-3, that the Industrial Revolution was a relatively abrupt transition to modern productivity growth rates around 1780. As figure 2 illustrates, for England as a whole the efficiency of the economy showed no expansion 1250-1780. The measured productivity growth rate before the Industrial Revolution is effectively 0. This, as discussed above, makes it seem dauntingly difficult to discern reasons for the transition to rapid economic growth. The underlying institutional, political, and social variables were changing slowly if at all in England in the years 1700-1870 in which this transition was accomplished.

The conclusion, from the aggregate productivity level of the economy, that the transition to modern growth was rapid does, however, seem at variance with the general historical picture of England 1200-1780 as a society that was over time advancing in education, in scientific knowledge, in technical abilities in navigation, warfare, in technical abilities also in music, painting, sculpture, and architecture. England in 1780 was a very different place from England in 1250, even if the standard of living of the average consumer measured mainly in terms of their consumption of food, clothing, housing, heat and lighting changed little.

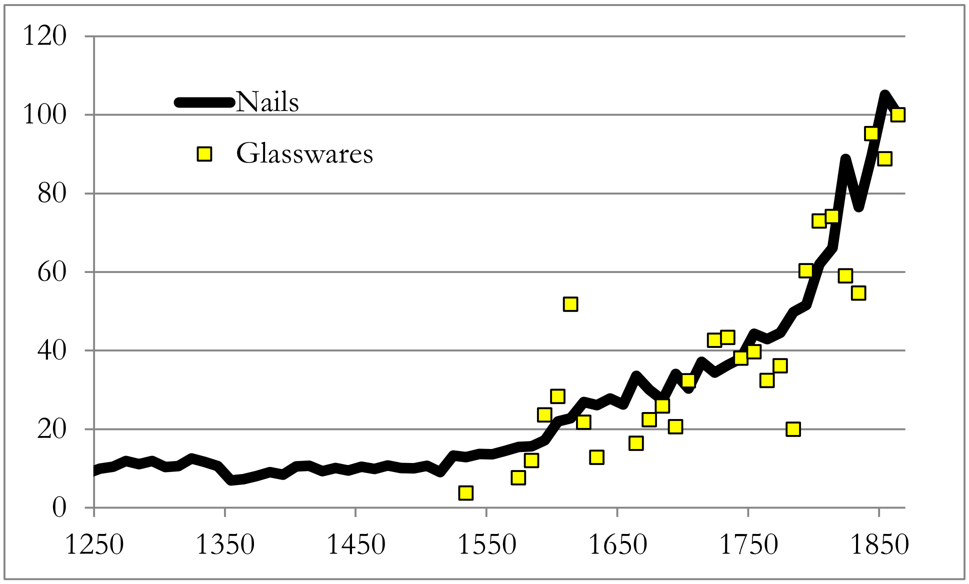
The reason for this mismatch is that, as noted above in equation 3, national productivity growth will be related to productivity advance in individual sectors through

$$g_A = \sum \theta_j g_{Aj} \qquad (3)$$

where g_{Aj} is the growth rate of productivity by sector, and θ_j is the share of j in total value added in the economy. National efficiency advance is measured by weighting gains by sector with the value of output in that sector. The effects of innovation on national productivity measures is thus crucially dependent on the pattern of consumption.

Much of the technological advance of the period 1250-1780 had minimal impact on measured productivity at the national level because the share of expenditure on these goods was so small in the pre-industrial economy. The printing press, for example, led to about a 25 fold increase in the productivity of

Figure 21: Efficiency of Production of Nails and Glassware, by Decade, 1250-1869.



<u>Source</u>: Clark, 2010.

production of written material between 1450 and 1600 in England. But since the share of income spent on printed materials in 1600 was only about 0.0005, the productivity gains from this innovation at the national level were miniscule (Clark and Levin, 2001).

We can see also in figure 21 that the production of such manufactured items as iron nails and glassware saw significant productivity advances before 1780 also. But this efficiency advance would be a negligible contribution to national productivity advance because of the small share of total production value these goods represented in a pre-industrial England where iron nails had limited use, and glasswares were enjoyed only by the richest groups in the society.

Further, for many goods whose production was becoming more efficient through technological advances, no consistent series of prices can be calculated. There was, for example, a great advance in military technologies in European countries such as England over the years 1250-1780. The infantry of 1780, or a naval ship of that period, would have swept from the field the equivalent medieval force. English troops of 1780 would have quickly overwhelmed the fortifications of 1250, but the fortifications of 1780 would have been impregnable even against medieval armies of major size. But none of this would be reflected in conventional productivity measures. There is no allowance in these measures for the delivery of more effective violence by the English Navy over the years.

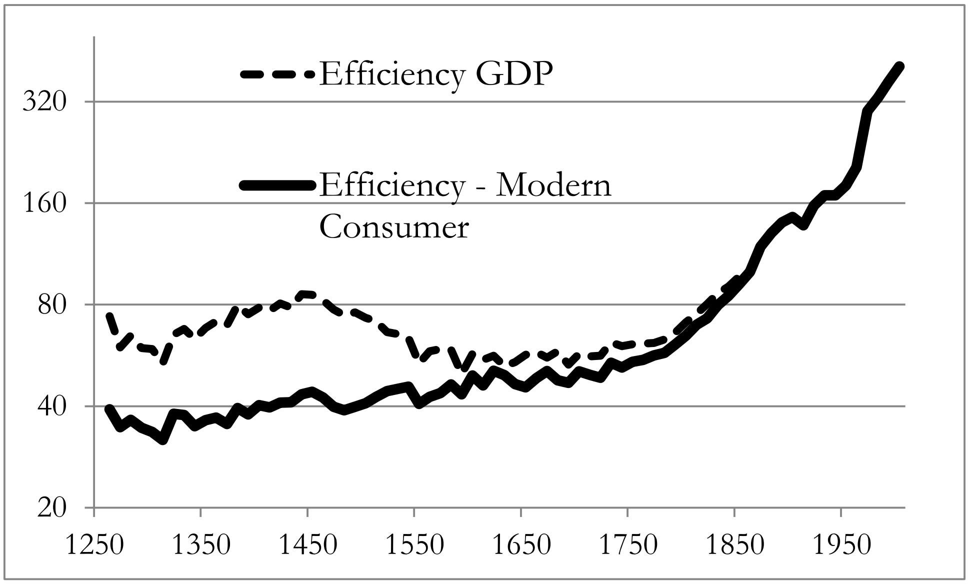
There is no allowance also in the national productivity measure for improvements in the quality of literature, music, painting, and newspapers. These sources also do not reflect medical advances such as the one third reduction in maternal childbirth mortality between 1600 and 1750.[23]

This makes it possible that the rate of technological advance in the economy, measured just as a count of innovations and new ideas, was actually increasing long before the breakthrough of the Industrial Revolution. But accidents of where these technological advances came in relation to mass consumer demand in the pre-industrial economy create the appearance of a technological discontinuity circa 1780. Suppose that prior to the Industrial Revolution innovations were occurring randomly across various sectors of the economy - innovations in areas such as guns, gunpowder, spectacles, window glass, books, clocks, painting, new building techniques, improvements in shipping and navigation – but that just by chance all these innovations occurred in areas of small expenditure. Then the technological dynamism of the economy would not show up in terms of output per capita or in measured productivity in the years leading up to the Industrial Revolution.

To illustrate this, suppose we consider a consumer whose tastes were close to those of the modern university professor. Their consumption is much more heavily geared towards printed material, paper, spices, wine, sugar, manufactured goods, light, soap and clothing than the average consumer in the pre-industrial English economy. Based on their consumption how would the efficiency growth rate of the economy 1250-1769 look compared to 1760-1869 and 1860-2009? Figure 22 shows the results, where efficiency is measured as an index on a log

[23] Wrigley et al., 1997, 313.

Figure 22: Economic Efficiency from the Perspective of a Modern Consumer, England, 1250-2009



Notes: The weights in consumption for the modern consumer are assumed to be half from the consumption basket of the pre-industrial worker. But the other half is composed of books (.1), manufactured goods (.1), clothing (.1), sugar (.03), spices (.03), drink (.05), light (.05), soap (.02), and paper (.02).
Source: Clark, 2010.

scale on the vertical axis. Thus the upwards slope of the line indicates efficiency growth rates. Now in the years 1300-1770 there is an estimated efficiency growth rate of 0.09% per year for the goods consumed by a university professor. This is followed by efficiency growth rates of 0.6% per year 1760-1870, and 0.9% a year for 1860-2010. Estimated efficiency advance is still very slow for the pre-industrial period, but we can think of the economy in this period as going through a more protracted transition between pre-industrial growth rates and modern growth rates.

Framed in this way, the possibility reopens of some variety of endogenous growth explanation of the Industrial Revolution, with a more gradual transition to higher rates of technological advance starting in the medieval period or earlier. However, the existing endogenous growth models such as Galor and Weil, 2000, and Galor and Moav, 2002, bring with them a set of assumptions and implications which are difficult to reconcile with empirical reality, as was discussed above. The key idea in Galor and Moav, 2002, however, that in the Malthusian regime preferences might be changed by differential net fertility, does seem to offer some promise. We do see strong differences in fertility by social class in England all the way from 1250 to 1780. And there is evidence that parental characteristics in terms of wealth, occupation and education were very strongly inherited in pre-industrial England, allowing differential fertility to have significant effects on the characteristics of the population even after relatively few generations.[24] While we do not see sign in the data of the specific selection for a preference for small family sizes and high child quality, there is sign of a more generalized selection for characteristics associated with economic success.

Conclusion

The Industrial Revolution remains one of histories great mysteries. We have seen in this survey that the attempts by economists to model this transition have been so far largely unsuccessful. The first approach emphasizing an exogenous switch in property rights stemming from political changes, despite its continuing popularity, fails in terms of the timing of political changes, and their observed effects on the incentives for innovation. The second approach, which looks for a shift between self-reinforcing equilibria again fails because there is little sign of any major changes in the underlying parameters of the economy circa 1780 which would lead to changed behavior by individuals. The most promising class of models are those based on endogenous growth. The problem here is to find some kind of "driver" that is changing over time that will induce changes in the rate of innovation. Previously these models seemed to face insuperable difficulties in that they find it very hard to model the kind of one time upward shift in productivity growth rates that the Industrial Revolution seemed to involve. But as we gather more information on the empirics of the Industrial Revolution, and the years before, the discontinuity in technological innovation rates seems less than has been imagined, and the transition between the old world of zero productivity growth rates and the new world of rapid productivity growth much more gradual. This bodes well for endogenous growth models.

[24] As evidenced by the persistence of status of surnames in England 1300-2012, the correlation of underlying social status between fathers and sons seems always to have been of the order of 0.75, which is very high. See Clark, 2014.

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