The Great Escape: The Industrial Revolution in Theory and in History

Gregory Clark,
University of California, Davis, CA 95616
gclark@ucdavis.edu
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The Industrial Revolution decisively changed productivity growth rates. For successful economies, measured efficiency growth rates increased from close to zero to more than 1% in the blink of an eye in terms of the long history of human societies: seemingly within 50 years of 1800. Yet we lack any good account of what led to this epochal change. The paper reviews recent theories of the Industrial Revolution. Can the empirical implications of these theories can be reconciled with the historical facts? I find that most, but not all, of the models reviewed are inconsistent with the basic facts of the history of the Industrial Revolution. But one class of models, emphasizing endogenous growth, seems to offer some prospects.

Introduction

World economic history is surprisingly simple, and can be presented in one diagram as in figure 1 below. Before 1800 income per capita for all societies we observe fluctuated, 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] This article is not the place to prove this assertion, but Clark (2003a) shows that measured by calorie and protein consumption, work hours, heights, and life expectancy the average person in England in 1800, when England was probably the richest country in the world, was little better

Then came the Industrial Revolution. 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.[2] But prosperity has not come to all societies. Living standards in some countries are as low as they were for the mass of humanity before 1800. Indeed there is good argument that living conditions for the poorest countries in the world are lower now than for the average person before 1800. This divergence in fortunes since the Industrial Revolution has recently been labeled "the Great Divergence."[3]

Thus world economic history poses three interconnected problems: the long persistence of the Malthusian trap, the escape from that trap in the Industrial Revolution, and the consequent Great Divergence. Explaining the Industrial Revolution also implicitly requires explaining the Malthusian Trap, and the Great Divergence.

Recently a distinguished group of economists - Gary Becker, Oded Galor, Gary Hanson, Chad Jones, Michael Kremer, Robert Lucas, Omar Moav, Douglass North, Edward Prescott, Nancy Stokey, David Weil - have turned once more to the eternal question of the Industrial Revolution. They have sought to build formal models that would explain the long delay in escaping from the Malthusian trap, and sustained growth once the escape occurred. Implicitly they also answer the question "Was the Industrial Revolution inevitable?" This article summarizes and reviews these theories, and asks whether the growth of knowledge about pre-

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off than modern foragers and subsistence agriculture societies such as the Ache of Paraguay, the Hiwi of Venezuela, or !Kung of Botswana, or the Shipobo of Peru.

[2] Incomes per person only rose 8 fold in England, but as mentioned England was rich in 1800, and now is somewhat poorer than countries like the US.

[3] Again the reader will have to take this assertion on trust. Income per capita in England in 1450 was about one seventh of its level in the 1990s. That means that living standards in England in the 15th century (think Agincourt), based on the Penn world tables, exceeded those of countries such as India, Bolivia, and most of Sub-Saharan Africa in 1992. See Clark (2003a).

industrial societies, which has been considerable in the last twenty years, offers any further constraints or suggestions for a theory of the Industrial Revolution.

What is to be explained?

The switch between the two regimes, Hanson and Prescott (2002) cleverly label it "Malthus to Solow," appears in the first instance as a change in the measured rate of Total Factor Productivity (TFP) growth. Denote the quantity of output, capital, labor and land in any economy by *Q, K, N,* and *Z*. Assume also that the efficiency of the economy can be measured by a single index number *A*. In this case we can write

$$Q = AF(K, N, Z) \tag{1}$$

and the growth rate of income per capita will be

$$g_{Q/N} = a.g_{K/N} + c.g_{Z/N} + g_A \tag{2}$$

where *a* is the share of capital in factor costs, and *c* is the share of land, and $g_{..}$ denotes a growth rate. This is the "fundamental equation" of economic growth. This is stated for an economy with only type of output, labor, land, and capital (which is the same as the output). But it generalizes easily into an analogous expression for an economy with many types of output, labor, capital and land. Thus the growth of output, labor and capital become

$$g_Q = \sum \theta_i g_{Q_i} \quad , \; g_L = \sum \frac{b_j}{b} g_{L_j} \;\; g_K = \sum \frac{a_j}{a} g_{K_j} \tag{3}$$

where θ_i is the share in the value of output of the commodity or service *i*, b_j is the share in the total payments to the factors of production paid to workers of type *j,* and a_j is the share in the total payments to the factors of production paid to capital of type *j*

Thus despite the enormous complexity of modern economies, the growth of income per person since the Industrial Revolution reduces to just two possible sources. The first is more capital per person. The second is improved efficiency in the use of capital, labor and land in producing output.

But despite the theoretical possibility in equation (2) of two sources of growth, economists have concluded that two sources of growth is one too many, and that there can be only one source of the great boom in income per person, capital. If capital is measured correctly than g_A should be close to 0.[4] Advances in the measured efficiency of economies don't just drop out of the sky, but result from search for better techniques. Thus the same measured amount of capital, labor and land may now produce more output than before. But that is because of time invested in learning more effective ways to build machines, and better ways to utilize machinery and workers. This search for improvement, involving resources, is just another form of investment.

This presumption of the centrality of capital accumulation in economic growth was not put to serious empirical test until the 1940s. But by the 1950s a number of economists, most famously Robert Solow, had conducted studies that showed at the industry and national levels the residual, g_A, explained almost all growth of output per person.[5] This result has been confirmed in numerous studies since, including studies on the English Industrial Revolution itself.[6] Physical capital accumulation explains only about one third of the growth of income per person over time, and about one third of the differences in income per person across countries. Economic growth since the Industrial Revolution thus seems to mock one of the truisms of

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[4] Changes in the efficiency of the allocation of resources can occur, and would show up as efficiency gains, as would increasing returns to scale external to production enterprises. But I am assuming these forces are small relative to the 10-15 fold gains in income per person we are trying to explain. I return to the issue of returns to scale below.

[5] Griliches (1996) notes that Tinbergen in 1942 carried out the first growth accounting exercise, with the same results as those conducted by Abramovitz and Solow in the 1950s.

[6] See Crafts (1985), Crafts and Harley (1992).

elementary economics "No free lunch." For the last 200 years the people of the advanced economies have fed on a rich diet of free lunches, and the affluence of modern life is founded on this manna from heaven. Further, we shall see below that the most plausible explanation of the growth of physical capital per person since the Industrial Revolution is the existence of the large efficiency residual.

The oddity of the substantial residual is a recent occurrence. As noted, there is no evidence of any long run gains in income per capita before 1800. In the Malthusian economy that preceded 1800 all productivity growth is absorbed by population increases. In this case we can use fundamental growth equation (2) to give a rough estimate of TFP growth rates from when people first evolved up until 1800. Constant output per person implies[7]

$$g_{Q/N} = 0, \quad g_{K/N} = 0,$$

$$\Rightarrow \qquad g_A = c g_N \tag{3}$$

We know that typically in pre-industrial societies the share of land in national income is much larger than since the Industrial Revolution. In England it was about 20-25% from 1300 to 1750 (Clark (2001)). Thus we can calculate long run technological advance at a world scale before 1800 just by looking at long run population growth, as Kremer (1993) pointed out. Table 1 shows this calculation. As can be seen, for the world as a whole there is no period before 1700 when the calculated world rate of efficiency advance exceeds 0.1% per year. Yet as the table also shows, the conventional figures for income growth in England after 1800 suggest that by the nineteenth century the measured productivity growth rate was about 0.8%, close to modern

[7] Here I am assuming that the rate of return on capital did not change over time. In fact rates of return have fallen consistently in the 3,000 or so years that we get observations on them. This observation implies that even with constant income per person, capital per person should have been increasing in the Malthusian era, with correspondingly lower rates of efficiency advance than are estimated in table 1 (Clark(2003a)).

levels for advanced economies. Figure 2 shows TFP growth rates as estimated by Nick Crafts and Knick Harley and others for England since the Industrial Revolution (Crafts and Harley (1992)). Their estimates suggest a relatively abrupt transition to modern levels of productivity growth circa 1800-1830. In a matter of less than 50 years the English economy seemingly underwent a fundamental shift from pre-industrial productivity growth rates to those of the modern epoch. This focuses attention on the Industrial Revolution in 1770 in England as the epochal event of world history.

Explaining Modern Productivity Growth

How do we explain the appearance of an important residual in growth since the Industrial Revolution? If we look at the fundamental equation (2) we see that there are only two ways this can happen. Either the capital stock grew much more rapidly than has been measured, and/or the weight accorded to capital in the equation, *a*, has to be larger.

The capital stock has three important components: tangible capital – buildings, machinery, inventories, intangible capital – research and development expenditures, and human capital – educational investments that increase labor productivity. Until the 1950s measures of the capital stock focused on tangible physical capital. Dennison and Kendrick noted that the labor supply in modern economies incorporates important human capital. Adding human capital to measures of the capital stock reduces the troublesome residual mainly by increasing the share of income, *a*, attributed to capital, since some wage income is a return on capital. If we denote the stock of human capital by H, the fundamental equation of growth (2) should be rewritten as

$$g_{Q/L} = a_K.g_{K/L} + a_H.g_{H/L} - c.g_L + g_A \qquad (4)$$

where a_H is the share of income which is payment for investments in human capital and a_K is the share of physical capital.

But adding human capital did not eliminate the residual, or even reduce it radically. The size of the human capital stock, even in as highly educated a place as the modern USA, makes it still somewhat less than the physical capital stock. And the private rate of return to human capital, which probably exceeds the social return, is about the same as for physical capital. Thus in the USA in 2000 the capital cost of all schooling per member of the active labor force can be estimated, as in table 2, as $182,700, based on the average years of education per worker and the cost of schooling per year (including foregone wages). But the stock of physical capital per worker in the US in 2000 was still greater at $210,500. The share of income derived from this human capital investment per worker, assuming a 10% return on the investment in line with the estimates of George Psacharopoulos, was 26%, compared to 28% for physical capital.[8]

But if we look at economic growth in the US from 1990 to 2000, the growth rate of physical capital at 1.27% per year was twice as fast as the growth of the human capital stock per worker at 0.67%. Thus of the overall growth rate of income per labor hour of 1.89% in this decade, physical capital accumulation per worker explained 0.36%, leaving a residual productivity growth of 1.53%. But including human capital accumulation only explained another 0.18% of the growth, leaving the residual at 1.36% per year, which was 72% of the growth of output per worker hour. And as noted education in modern economies is likely not capital formation but consumption, and costly signaling to employers of individuals likely workplace productivity.

[8] George Psacharopoulos calculated the social rate of return to education in the richer economies in 1993 as being 14.4% per year for primary education, 10.2% for secondary education and 8.7% for Higher education (Psacharopoulos (1993)).

In earlier decades the growth of human capital per worker was much faster (thus in the years 1940-1963 the growth rate estimated in the same way is 2.20% per year). But correspondingly the share of income attributed to human capital was smaller. Thus though including consideration of human capital always reduces the size of the residual attributed to productivity gains in the modern era, these effects were never strong enough to explain more than 30% of the residual.[9]

Equally simply adding in human capital to growth accounting exercises in Industrial Revolution England will not explain the apparent sudden rise of the residual. Figure 3 shows estimated literacy rates in England from the 1580s to the 1920s. There was in fact little change in literacy rates for men, the bulk of the labor force in the Industrial Revolution period. The human capital stock grew little (and was still very small relative to the physical capital stock).

By the 1970s it was clear that while better measurement of capital might reduce the apparent contribution of the residual somewhat, the residual was still the major element in the story of modern growth of income per person. Robert Lucas argued for a larger weight for human capital in equation (4) than estimated from earnings by positing a large human capital externality (Lucas (1988)). But empirical investigations have not revealed any effect powerful enough to resolve the growth conundrum.[10] And as figure 3 shows, such a human capital externality will do little to provide an account of the Industrial Revolution.

Other economists, such as Zvi Griliches, have argued more persuasively the major source of the residual was that the contribution of capital to the growth of output was being under-measured when weighted by the share of output paid to capital owners, a, in the fundamental

[9] See Jorgenson and Griliches (1967).

[10] The external benefits from more human capital would have to occur outside the environment of the firm, or more educated workers would capture the benefits in their earnings. In that case they would most plausibly be knowledge externalities that I will discuss below.

equation of growth. Capital invested in producing knowledge generated large social returns additional to the private returns to investors.[11] For while most modern societies instituted patent systems granting innovators property in the knowledge they created, these systems still give less reward to investment in knowledge than its social benefits. First new techniques generate some consumer surplus which the producers cannot appropriate even if they had absolute control of the knowledge they create. In the absence of perfect price discrimination, consumers will derive some surplus from the knowledge (see Jones (2002)). Also intellectual property rights last only for a few years under most patent systems, even though the knowledge produced may increase in value steadily over time. In addition other producers often circumvent patents by mimicking the original innovation to produce similar competing products. Finally some learning of better techniques, through carrying out production activities, is so basic and diffuse in nature that it is not patentable. Yet this information is transmitted from one firm to another by the movement of workers.

If there is a significant externality associated with investment in knowledge production then the true fundamental equation of economic growth will be

$$g_{Q/L} \quad = \quad a^*_K.g_{K/L} + a_H.g_{H/L} - c.g_L + g_A \tag{5}$$

where a^*, where $a_K^* > a_K$, and hence $a_K^* + a_H + \mathrm{b} + \mathrm{c} > 1$. If most economic growth is going to stem from capital investment, however, then a^* has to be up to three times the payments to capital as a share of national income. Indeed since typically the growth rate of capital per worker hour is not much faster than the growth rate of output per worker-hour, the true coefficient on

[11] There are other models, characteristic of the "New Growth Theory" such as in Romer (1986, 1987, 1990), and DeLong and Summers (1991) which posit a more general externality attached to capital investment, such as from external returns to scale external to the firm. But as we shall see below that this does not provide a very plausible story of growth since the Industrial Revolution.

capital would have to be close to 1.[12] That is the social return from investing $1 in capital, on average, has to be three times as big as the private return.

Most of the investment in capital in modern economies is in houses, buildings and roads – areas where we think there would be no significant external benefit. Table 2, for example, shows measures of both the relative stocks of different types of capital in the UK in 2000, and the relative income flows from each type of capital. Investments in knowledge would show up as "intangible" capital, but this is a small share of the capital stock.

It is hard to imagine any huge external benefit from putting up more sheet rock, or laying more concrete. If we assume that all the externality associated with investment in capital stems from the investments in R&D, then we can calculate for modern economies what the required extra social return on these investments would have to be to eliminate the productivity residual. To do this note that equation (2) above, the fundamental equation of economic growth, can also be written as

$$g_{A_i} = \frac{\Delta Q}{Q} - r\frac{\Delta K}{Q} - w\frac{\Delta L}{Q} - s\frac{\Delta Z}{Q} \tag{6}$$

where *ΔK/Q* is **net** investment as a share of GDP, and *r* is the rental rate per unit of capital (including depreciation). If R&D investment had an extra social rate of return, r_s, then the correct expression for productivity growth would be

$$g_A = \left(\frac{\Delta Q}{Q} - r\frac{\Delta K}{Q} - w\frac{\Delta L}{Q} - s\frac{\Delta Z}{Q}\right) - r_s\frac{\Delta K_{R\&D}}{Q} \tag{7}$$

where $\Delta K_{R\&D}$ is the national investment in each year in R&D. In modern high income market economies, the R&D share in GDP is (excluding defense research) about 2%. Since measured productivity growth rates since the Industrial Revolution have been about 1% per year, this

[12] Romer (1987) makes this point.

implies that the social rate of return on research expenditures must average about 50% of the expenditures per year.

Since different industrial sectors engage in R&D to very different extents, we should empirically be able to at least roughly estimate these spillovers by looking at the connection between industry R&D and the growth rate in measured productivity in an industry, as long as spillovers tend to be localized within an industrial sector. Griliches (1994), for example, looks at the correlation between research intensity of industries, as measured by the ratio of R&D expenditures to sales in the US in 1984 for 143 industries, and measured productivity growth in the years 1978 to 1989. The average ratio of explicit R&D expenditures to sales is about 2%, with many industries spending nothing, but some such as computers spending 10% of annual sales on research and development Griliches estimates the coefficient β in the following regression

$$g_{A_i} = \alpha + \beta \frac{\Delta K_{R\&D\, i}}{Q_i} + \varepsilon_i \,. \tag{8}$$

where $\Delta K_{R\&D}$ is the industry investment in each year in R&D, and Q is the sales of the industry. If the contribution of R&D investment was just the normal rate on return on capital, then the estimate of the coefficient β should be 0. For all the benefits to output growth of greater R&D expenditures would already have been correctly accounted for. If there are spillovers from R&D investment not captured by the investing firms, but showing up instead as falling prices to consumers, then, based on equation (7) above β will measure the extra social rate of return accruing to R&D investments.

Griliches estimates β to be 0.46, though there is so little precision to this estimate that there is one chance in twenty that the true value of β is either less than 0.32 or greater than 0.60.

For the earlier period 1958 to 1973 the estimated value of β is similar at 0.33. These estimates imply very substantial social rates of return from R&D expenditures in modern capitalist economies. Each dollar invested yields an annual rent above what the investors received of between $0.33 and $0.46. These social gains are close to the 50% returns needed to eliminate the residual as an important factor in economic growth. We shall see below that there is ample evidence for very extensive spillovers from knowledge production in Industrial Revolution England.

Thus though the direct evidence is extremely thin, it is at least plausible to argue that modern economic growth has resulted largely from the investment in a particular type of capital, "knowledge capital" devoted to improving the production process. Further since the detailed history of the Industrial Revolution laid out by historians in the past 50 years have emphasized the key role of technological advance (figure 3, for example, shows the upturn in patent grants in England in the 1760s that occurred alongside the Industrial Revolution), the task is seemingly one of showing why either the demand and/or the supply of innovation increased in England in the 1760s.

The Unimportance of Physical Capital

Acknowledging the importance of investment in a particular type of capital, knowledge, would seem to imply, based on equation (2) that there have been two important sources of growth since the Industrial Revolution: efficiency growth fueled by investment in "knowledge capital" which explains 50-70% of growth of income per person, and separately additions to the stock of physical and human capital which explain the other 30-50%. However if investments in "knowledge capital" explain modern efficiency growth, then these knowledge investments also explain the accumulation of physical and human capital. For if efficiency advances (generated by investments in knowledge) and physical and human capital were truly independent sources of income growth then there could be economies with rapid growth of physical capital per person, but no efficiency gains, and economies with rapid efficiency gains but little growth of physical capital per person. In practice both across time and across countries at any given time there is a close association between capital stock growth rates (whether physical or human) and efficiency growth. Figure 4, for example, shows the logarithm of estimated efficiency level of a group of countries compared to the logarithm of capital per worker in 1990. The correlation coefficient between capital per worker and efficiency (in logs) is 0.89 despite the notorious difficulty of accurately measuring physical capital stocks. When two such variables are so closely correlated then either one causes the other, or there is an independent cause of both.

The most plausible account of the linkage of the growth of physical and human capital and efficiency growth is the following. Any gain in measured efficiency for a given stock of capital, labor and land in an economy will increase the marginal product of capital. F_K does not change when the level of efficiency A increases. But the increase in the marginal product of capital means that the rental price of capital, r, is now less than the marginal product of capital. Either the rental on capital must rise to equal the new higher marginal product of capital, or the stock of capital has to increase so that capital is more abundant relative to labor and land and consequently its marginal product lower. In practice the rental rate for capital has not increased since the Industrial Revolution, despite the enormous increase in the measured efficiency of economies. Thus efficiency gains induced more capital investment. The constant rental cost of capital explains the link between efficiency growth and capital stock growth. For example, if the production function was Cobb-Douglas, the marginal product of capital is given by,

$$mp_K = \alpha \frac{Q}{K}$$

$\Rightarrow$

$$K = \frac{\alpha}{r} Q$$

In this case, assuming a roughly Cobb-Douglas technology, output per labor hour will grow at the same rate as the capital stock per worker, and the fundamental equation of growth (2) becomes

$$g_{Q/N} = \left(\frac{1}{1-\alpha} \right) g_A + \left(\frac{\gamma}{1-\alpha} \right) g_{Z/N} \tag{9}$$

Thus investments in knowledge capital that generated efficiency growth not only explain most of modern economic growth at a proximate level, they essentially explain all economic growth.

Thus any satisfying account of the Industrial Revolution has to do just 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 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. And of course explain why economies around the world have benefited from this knowledge expansion to such different degrees. Then we will understand the history of man.

Theories of the Industrial Revolution

Theories of the Industrial Revolution offered by economists fall into three basic types, each of which faces characteristic difficulties. These three types are:-

Exogenous Growth Theories: Some feature outside the economy, such as the institutions of the society, or the relative scarcities of different inputs in production, changed, inducing investment in expanding the production technique by potential innovators within economies. Such a change would include, for example, changes in the institutions governing the appropriability of knowledge, or the security of all property, as posited by Douglass North and others. Thus North and Weingast argue that the arrival of the constitutional monarchy in England in 1689 was the key political innovation that ushered in modern economic growth (North and Weingast (1989)). Joel Mokyr argues that the Enlightenment, an intellectual movement among the elite of Western European society in the eighteenth century, but that had its roots much earlier, was the exogenous shock that changed the fundamental dynamic of the economy (Mokyr (2003)). These theories would predict that we will find in England in 1760, or shortly before then, an institutional or other innovation not seen in ANY earlier society.

Multiple Equilibrium Theories: A shock - disease, war, conquest of new lands - lead the economy to jump from the bad, stagnant equilibrium of the Malthusian embrace to the good, dynamic equilibrium of the modern world. A particular class of theories that has recently attracted adherents in economics is one where families switch from having large numbers of children, each of whom they invest little time in, to one where families have small numbers of children whom they lavish much attention on.

Endogenous Growth Theories: A feature internal to the economic system, some state variable, evolved over time in the long pre-industrial era to eventually create the pre-conditions for modern economic growth. The Industrial Revolution was thus pre-determined from the time the first human appeared on the African Savannah. It was just a matter of time before the economic conditions for rapid technological progress were created. The question then is "what is different about the economy of England in 1760, compared to Florence in 1300, China in 500, Rome at the time of Christ or Athens at the time of Plato?" Posited internal drivers of the economic system that eventually created the Industrial Revolution have included the size of the population itself, and an evolution through natural selection of the characteristics of the population.

Table 4 summarizes the most important features of these various theories.

Exogenous Growth Theories

For economists the great exogenous force that is continually invoked as determining the lives of men and the fates of economies are the institutions that govern societies, determining who owns what, how secure property is, and how property gets transferred (see, for example, North and Thomas (1973), North and Weingast (1989), Jones (2002), Acemoglu, Johnson and Robinson (2001, 2002)). The preferred assumption is that 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. If sustained rapid productivity advance is not observed before 1800 in any society, it must be because all these societies innovation got even less reward than in our own.

> Consider how the model economy would behave in the absence of property rights. In this case, innovators would be unable to earn the profits that encourage them to undertake research in the first place, so that no research would take place. With no research, no new ideas would be created, technology would be constant, and

> there would be no per capita growth in the economy. Broadly speaking, just such a situation prevailed in the world prior to the Industrial Revolution (Jones 2002, p. 121).

> 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 (Douglass North (1993)).

The picture many modern economists thus have of the world before the Industrial Revolution is thus 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 world who has the time, the energy, or the incentive to develop new technology?

This picture of the pre-industrial world is true for some societies, but to explain the long delay in the arrival of the Industrial Revolution it needs to be true for all. And some agrarian societies in the long Malthusian interval turn out to be orderly and peaceable places, even by the standards of the modern USA. Table 5 shows, for example, the percentage of deaths caused by violence and accidents in a variety of pre-industrial societies (with the USA in 2000 given for comparison). While many hunter gatherer and subsistence agriculture societies have extraordinarily high numbers of deaths from violence by the standards of the modern US, others such as England as early as the thirteenth century are peaceable and ordered. Indeed medieval England was a lot more peaceable and ordered, judging by homicide statistics, than many modern societies such as Brazil or Colombia.

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, or the recent 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. But that requires us to switch either to a multiple equilibria theory, or to one of endogenous growth, which we will discuss below.

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."[13] 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.[14]

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

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[13] This problem continued into at least the seventeenth century in England, where publishers quite freely pirated the works of authors.
[14] See Long (1991), pp. 853-7.

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. 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. This still places the key institutional innovation a good 80 years before the Industrial Revolution.

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. Perhaps two thirds of the productivity growth experienced by the English economy from 1760 to 1869 can be attributed directly to the innovations in textiles.

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 6, 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 dieing 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 the majority of 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.

Multiple Equilibrium Theories

The theories discussed above in which a parameter shift external to the economic system provides the Industrial Revolution are clearly unsatisfactory. An alternative class of models posits that the Malthusian state was a low level equilibrium that was replaced, as a result of some exogenous shock, with the modern growth equilibrium.

"Bad" equilibrium theories have come in a number of forms. One set seeks to explain through the Political Economy of institutions why systematically early societies had institutions that discouraged economic growth. The common feature that North and others point to in early societies is that political power was not achieved by popular elections. Indeed there is a close 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.[15] The USA, the leading nation in the world in economic terms since the 1870s, has always been a democracy also.[16] In pre-industrial societies, as a generalization, the rulers ultimately rested their political position on the threat of violence.

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 et al. have to argue that such a disjuncture systematically arises in all societies before 1800.

I will not deal at length with the idea of the bad political equilibrium, despite its continuing popularity, because political changes as occurred in England in 1688-9 so spectacularly fail to explain the Industrial Revolution. They are too early, and economic actors at the time did not regard them as important (Clark (1996)). Also we shall see below another disturbing development for proponents of the Glorious Revolution as the turning point in history – evidence is emerging that output per person and productivity were growing as rapidly in England in the bad old years 1600-88 as in 1689-1860! Modern growth had begun under autocracy.

This argument that pre-industrial society was stuck in a bad equilibrium has taken other, potentially more defensible, forms. The one that has attracted most attention by economic theorists recently is that in the Malthusian world parents were induced to have large numbers of children, each of whom they provided little to in the way of training or education. One of the

[15] It has to be noted, however, that the franchise was very limited. Also since the vote was by a public ballot, vote buying was common. Finally the number of votes it took to elect a member of Parliament varied widely across England. Until the 1830s there were famous "rotten boroughs" that elected a member of Parliament even though they had almost no population. These seats could effectively be bought by buying the land in the district.

[16] Though again a limited one for much of that time.

great social changes in the advanced industrial economies since the Industrial Revolution is a decline in the number of children the average woman gave birth to, from 5-6 to 2 or less. Proponents of this interpretation of the Industrial Revolution such as Gary Becker and Robert Lucas argue that this switch, induced by changing economic circumstances, has been accompanied by a great increase in the time and attention invested in each child. People are not the same in all societies. The continual efficiency growth of the modern world has thus been created by higher quality people. The supply of innovations was increased by more human capital.

And we saw above in figure 5 that, at least loosely, the Industrial Revolution was associated with an increase in the education level. So increases in human capital that created knowledge externalities, at the gross level, would seemingly be a candidate source of the Industrial Revolution. We also know, though only through very indirect methods, that even quite sophisticated earlier societies, such as the Roman Empire or Renaissance Florence, seemed to have much lower levels of general literacy and numeracy.

We certainly can find interesting evidence that the average numeracy and literacy of even rich people in most Malthusian 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), p. 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 $Z = (X-20)*1.25$, 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 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 population had increased markedly, as table 7 shows.

We can also look at the development of age awareness by looking at census of the living, as in table 8. 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.

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. Thus for North African tombstones, 3% of the deceased are recorded as dying at age 100 or more.[17] 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.

While the basic idea seem pregnant with possibilities, the question arises as to what keeps people in the low level many children/little human capital equilibrium for so long? Here the modelers have had a hard time creating a structure that mathematically produces multiple equilibria, but with realistic assumptions. Becker has stressed the idea of a quality/quantity tradeoff in numbers of children as an interpretation of modern fertility behavior. Becker, Tamura and Murphy (1990) applies a variant of this tradeoff to the Industrial Revolution. Parents' utility is described by

$$V_t = u(c_t) + a(n_t) n_t V_{t+1} \tag{11}$$

where $a(n_t)$ declines in n_t, where c_t is their consumption, n_t the numbers of children, and V_{t+1} is the utility of each of their children. Parents choose between their own consumption, the number of children they have, and the amount of human capital they endow children with. The human capital of the children is created in the way described below by the time inputs of the parents. Since potential output per family, in their representative agent economy, measured in consumption units, has the form

$$y_t = \theta_0 + \theta_1 H_t \tag{12}$$

where H_t is the amount of human capital of generation *t*, and the θs are parameters, this creates the possibility of a "corner solution" in which parents choose to invest no time in their childrens education, so $H_{t+1} = 0$, and instead have many children. A Malthusian equilibrium in this model

[17] Hopkins (1966), p. 249.

is a stable solution where $c_t = c_{t+1}$. Since there is no fixed factor such as land the Malthusian equilibrium can have any level of fertility.

But this picture of the Malthusian world bursting with ill-kemp ill-cared for children is based on a premise derived from a cross section of countries in the modern world, which is that the number of surviving children per family declines with income. As figure 7 shows, it is certainly true that the number of children born per family fell sometime after the Industrial Revolution at a time of rising incomes. But mortality rates among children were much higher in the pre-industrial world, with most of the mortality occurring in the first years of life. Thus if we count only children who survived to reproductive age the average completed family size was close to 2 for all societies before 1800. 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 not unlike the families of America in the 1950s and 1960s. Pre-industrial families faced remarkably similar tradeoffs between the number and quality of children as do modern families.

The Industrial Revolution era in England itself saw an increase in completed family sizes, followed in the late nineteenth century by a decline back towards the Malthusian norm by the 1960s. Further we shall see that there is evidence for pre-industrial England that surviving children per family increased with income.

The Becker, Murphy and Tamura model also generates steady state growth in the high level equilibrium by assuming that

$$H_{t+1} = \Lambda h_t(\phi + H_t) \qquad (13)$$

where h is the fraction of time invested in education of each child, and Λ measures the productivity of human capital investment. Human capital in the next generation is a multiple of the time spent in education and current human capital plus some constant. H in this model is essentially A (thus TFP) in equation (2) above. Thus while the puzzle posed above was why did A start growing rapidly only with the Industrial Revolution, the Becker et al. solution consists of attributing the growth of A to investment in people, and assuming this investment is highly productive, with no diminishing returns. This may echo the behavior they are trying to explain, but it offers little insight.

But it is when we consider the switch between regimes that the model is most unsatisfactory. The escape from the Malthusian trap is completely exogenous to the model. "Technological and other shocks" (p. S32) somehow raise the level of human capital far enough above 0 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." (p. S33). But unless these shocks are somehow making human capital more productive in producing income in equation (12) for exogenous reasons, then technological gains that merely raised incomes would if anything reduce the incentive to invest in human capital. Thus the arrival of highly paid unskilled work in textile factories in the Industrial Revolution we would expect in the Becker, Murphy and Tamura model to reduce educational investment.

What would spark a switch of families towards fewer but better educated children? From the point of view of the individual family there must be some signal in the form of higher relative earnings for educated children. But why would such a change appear in the Malthusian economy? Since in this model, and that of Lucas below, there is only one type of agent we would not observe any wage premium associated with human capital. All agents have the same human capital. However, since the model is supposed to represent the essence of a world where families vary in the amount of human capital with which they endow their children, it is interesting to consider the wage differential between skilled and unskilled labor. Here, however, we find absolutely no evidence of any market signal to parents as we approach 1800 that they need to invest more in the education or training of there children. Figure 8, 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 1200-2000 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.

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). In the low level equilibrium there is again no human capital investment. This arises because Lucas incorporates the equivalent of equation (10) above through a land using sector where human capital plays no role, and through a "modern" sector where human capital enters without diminishing returns. Goods production is thus (simplifying slightly)

$$F(x, H, l) = \max_{\theta}\left[x^{\alpha}\theta^{1-\alpha} + BH(l-\theta)\right] \tag{14}$$

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. As before parents' utility depends on goods consumption, the number of children and the utility of the children, but with the slightly different functional form

$$V_t = c_t^{1-\beta} n_t^{\eta} V_{t+1}^{\beta} \tag{15}$$

Human capital evolves according to

$$H_{t+1} = H_t \varphi(h_t) \tag{16}$$

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 of children η, on their utilities β, and on the form of φ(h).

But like Becker et al (1990) Lucas gives no mechanism that gets the economy from the Malthusian trap to the sustained growth regimes. 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. The unsatisfactoriness of exogenous parameter shifts in the political sphere is replaced by an equivalent, but more mysterious, jump between equilibria.

Returning to the problem of what individual price signal encourages parents to increase the human capital of their children, we see the same issue with human capital explanations of the differences in economic performance between rich and poor countries in the modern world. Private returns to education seem to be as high in poor countries as in rich, and as high in poor countries now as they were at the time of the Industrial Revolution in England. Lucas (1988), which proposes human capital as the source of the differences in the modern world between income per capita in rich and poor economies, solves this problem by positing a human capital externality. But this does not explain why human capital would increase in pre-industrial England with a constant wage premium for skills. Even the Lucas (1988) solution of large external benefits is implausible on its face. Indian textile mills in the early twentieth century, for example, employed mainly illiterate workers, and there was little or no wage premium offered for literacy. But employers could easily determine literacy. Had there been any significant positive externality at the level of the workplace then they would have been induced to offer premiums to recruit literate workers. So the Lucas human capital externality has to operate mainly at the level of neighborhoods or cities. But then the process becomes quite mysterious.

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

None of the above theories explain why the Industrial Revolution had to happen, or why it happened in 1760 as opposed to 500 BC in Ancient Greece. Endogenous growth theories attempt to explain not just how the Industrial Revolution took place, but also why it occurred when it did. The problem in any such model is the creation of the "driver" that will change the state of the world in such a way that the Industrial Revolution comes about. Something has to be different about the world in 1770 than at any earlier date, despite the fact that in the static Malthusian economy on average every important economic variable should remain the same: wages, returns on capital, work hours, and capital per person.

The earliest example of such a potential endogenous growth theory is the elegant one of Michael Kremer (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 human 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. That larger population produces 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

[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.

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 9.

(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 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.

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 9. Thus a simple specification for the effect of population on changes in productivity would be

$$\Delta A = \delta N \tag{17}$$

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

$$g_A = \frac{\Delta A}{A} = \delta \frac{N}{A} \tag{18}$$

But we know from in the preindustrial era where income per capita is constant, that technology is itself driving population so that

$$g_A = c.g_N$$

where c is the share of income derived from land rents. This is equivalent to the condition

[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.

$$N = \theta A^{1/c} \tag{19}$$

where θ is just a parameter. That is the population size depends on the existing level of the technology. Substituting from (3) for A in (2) gives

$$g_A = cN\left(\frac{\theta}{N}\right)^c = c\theta N^{1-c} \tag{20}$$

This formula implies that the rate of efficiency growth, g_A, rises less than proportionately with population. Yet what we see in figure 9 is that the rate of technological advance seems to rise faster than population growth. Figure 9 also shows the rate of technological advance predicted by this Kremer argument (the 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 (18) we posit

$$\Delta A = \delta NA \tag{21}$$

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

$$g_A = \frac{\Delta A}{A} = cN \tag{22}$$

This predicted growth rate of technology as a function of population is also shown in figure 8. Now the fit is closer, 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. And as we leave the Malthusian phase where population growth lags behind the growth rate predicted in equation (10) because real incomes start to rise the growth rate of efficiency will be slower than predicted from population by (20) or (22).

This feature of the Kremer model, that it is hard to produce with an endogenous growth model a discontinuity of the required magnitude, is a general problem for endogenous growth models.

For Hanson and Prescott (2002) the driver is just the comparative productivity of a land using of producing a standard output versus a non-land using method. Output is produced using with a land using "Malthusian" sector where TFP growth rates are slow, and a "Solow" sector using only capital and labor where TFP growth rates are faster. Each generation lives for two periods, with a utility function of the form

$$U(c_{1,t}, c_{2,t+1}) = \ln c_{1t} + \beta \ln c_{2,t+1} \quad . \tag{23}$$

Each generation works for one period, using that income to but land and capital, which it sells in the second period. There is no fertility decision so this is a story about production only. The TFP parameters are chosen such that in the initial period only the land using technology is employed. The rate of TFP growth is calibrated so that the model fits the data for wages, rents and population in England from 1260 to 2000. This requires that the productivity of the land employing sector increases at only 3% per generation of 35 years, while the productivity of the Solow sector increases by 52% per generation. The authors show that with this specification the model can reproduce the gross features of the Industrial Revolution in terms of shares of labor devoted to each sector and output growth. Yet this calibration has some distinctly odd features. The implied annual interest rate is 4-4.5% in the modern Solovian era, but a mere 2% in the Malthusian era.[20] A second empirical implication is that the productivity of land using

[20] This is assuming $\beta = 1$, so that there is no pure time preference.

technologies has increased more slowly since the Industrial Revolution than that of "Solow" technologies. And finally, oddly there is the implication that there is no discontinuity in productivity growth rates before and after the Industrial Revolution. Even in the Malthusian phase, before being used, the "industrial" sector is developing and becoming a viable competitor just as rapidly as later. It is all a matter of the shift in the relative size of each sector.

The Industrial Revolution in this model is inevitable. Once God sets the parameter of the initial state of the "Solow" technology it is just a matter of time. As in Jaws, we know from the setup that the "shark" is coming – the only uncertainty is when it will come.

The stark empirical difficulties faced by this model are the following.

(1) Productivity growth rates in the "industrial" sector do seem to have increased at the time of the Industrial Revolution. The Industrial Revolution is not the result of composition effects only.

(2) Productivity growth rates in "land-using" sectors such as agriculture have been as rapid as those in the rest of the economy since the Industrial Revolution, and also have increased markedly since the Industrial Revolution.

Figure 10 shows, for example, the estimated TFP of English agriculture from 1750 to 1970. As can be seen, productivity growth rates increased sharply in the 20th century. Indeed while TFP in agriculture in 1970 was about 4.2 times its level in 1800, TFP for the economy as a whole had increased only slightly faster, being 4.8 times the level in 1800. The reason this empirical problem does not cause problems for the Hansen and Prescott calibration is that by the time rapid productivity growth in agriculture begins in England, the country they model, the agricultural sector had shrunk to be a small share of the economy.

Galor and Weil (2002) 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

$$V_t = c_t^{1-\gamma}(y_{t+1}n_t)^{\gamma} \tag{24}$$

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). This should make clear that the preferences specified over goods and children in all these models have no function other than making a bow towards the form of maximizing over preferences in economic models. They do not somehow better explain the world – they are just ways of reproducing, mathematically, observed behavior.

Potential income per worker is of the form

$$y_t = A_t x_t^{1-\alpha} H_t^{\alpha} \tag{25}$$

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

$$H_{t+1} = H(h_t, (g_A)_t), \tag{26}$$

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

$$g_{At} = g(h_t, N_t) \tag{27}$$

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 thus at least try 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 (as opposed to educational inputs) 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. They also potentially face the same problem as the Kremer model that they will not be able to reproduce the seeming suddenness of the Industrial Revolution.

Galor and Moav (2002) employ 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

$$V_t^{\,i} = (c_t^{\,i})^{1-\gamma}(n_t^{\,i}(H_{t+1}^{\;\;i})^{\beta^i})^{\gamma} \tag{28}$$

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

$$y_t^i = A_t x_t^{1-\alpha} (H_t^i)^\alpha \tag{29}$$

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.

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 descendents 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.[21] 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.

Surprisingly to this author, the key assumption of Galor and Moav that high income families have more surviving children in the pre-industrial world is true, even for England in the

[21] 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.

years leading up to the Industrial Revolution. This was surprising (at least to the author) since the cities, where the educated and the skilled were disproportionately located in the pre-industrial era, were notoriously unhealthy places until well into the nineteenth century, and demographic historians assume that cities in pre-industrial Europe would have died out was it not for continual migration from the countryside. London, for example, with nearly 10% of the population of England by 1700, was the center of government, commerce, and the law. Yet in each decade from the 1570s to the 1800s burials in London exceeded baptisms, often by a considerable margin.

But there are other sources that point very clearly, despite this, to income having a strong effect on the numbers of surviving g children in pre-industrial England. Figure 11, for example, shows the infant mortality rates of eight London parishes in the years 1538-1653 compared with the percentage of the households in each parish which were 'substantial' in the tax listings of 1638. There is a clear association between household income and a child's chance of surviving the first year of life, with the richer parishes having less than half the infant mortality of the poorer ones. Indeed the crude measure of household income used here explains 62% of the variation in infant mortality rates.

Another source of data is the number of children listed in the wills of the rich and the poor. In seventeenth century England wills were made by people in a wide range of economic circumstances, and seemed to typically mention all surviving children. Wills were also generally made within days of death. Examining a sample of wills from Suffolk and London in the years 1620-35 we find that in both town and countryside, as table 9 shows, literate testators left more surviving children than the illiterate. Given the huge range in numbers of surviving children per testator, from 0 to 13, the sample sizes are too small for London and for the towns to find statistically significant differences in numbers of survivors with literacy. But for the sample of testators whose residence was the countryside the difference is statistically significant. The literate were leaving more survivors (Clark and Hamilton (2003)).

This raises the question of what features exactly of families were responsible for higher reproductive success? Is it occupation, literacy, or wealth? To investigate this further we considered a sample of wills where we can also calculate some approximation to the total value of the estate. For male testators in Suffolk where we have enough information to do regression analysis on the numbers of survivors, estimated assets averaged £284 (about 16 times the yearly wages of a carpenter). Of these estimated assets £82 was cash or bonds, £86 housing, and £116 farmland.

To measure the influence of assets on numbers of surviving children we regressed the numbers of children specified in the will on the following variables: an indicator variable for whether the testator was literate (DLIT), an indicator variable for whether the testator lived in a town (DTOWN), indicator variables for 5 types of occupation (DOCC1, DOCC2, DOCC3, DOCC4, DOCC5), an indicator variable for whether the testator had been a widower (DWID), and indicator variables for the assets in the range £50-100, £100-200, £200-500, £500+ (DASS1, DASS2, DASS3, DASS4). The indicator variable for widowers was used as a partial measure of the likely age of the testator. The resulting estimates were as shown in table 10. What shows up very clearly is that other things equal town residence correlates with fewer surviving children, but the other major correlate is the assets bequeathed by the testator. Testators with £500 or more in assets would leave, other things equal, about 1.24 more surviving children than those with no assets.

The reproductive advantage of those bequeathing larger stocks of assets is not mainly because they are more likely to get married, or again because those with larger stocks of assets are just being observed later in the life cycle. The last three columns show the estimated coefficients when we regress reproductive success on the same measures, using only those who were, or had been, married by time of death. Even looking just at the married assets matter almost as much, and now literacy is a statistically significant predictor of reproductive success.

This strong association of assets and reproductive success is surprising since we have such a weak measure of the assets bequeathed. The implication would be that the real effects of wealth on reproductive success must be even stronger than the ones observed here.

Unfortunately we do not have information on the wills of the children to check to what extent parental characteristics were passed on to children. We do know that the greater the assets of parents at death, the greater the average bequest per child, despite there being more surviving children in these families. Thus at least at some point in their lives such children are well endowed with material assets relative to the average person.

Thus the conditions may well have existed in pre-industrial England for a selection towards certain cultural types in the population. Exactly what is being selected for is hard to tell since literacy and assets are highly correlated. Interestingly an examination of the numbers of surviving children in the frontier conditions of New France in the seventeenth century shows that there if there was any survival advantage it was to the illiterate and low status individuals. And in the same community there was no gain in literacy rates between 1630 and 1730.

Material living conditions did not improve over the eons-long Malthusian era. Yet while the material conditions people were living in did not change, the suggestion of Galor and Moav that people themselves were changed by their long exposure to the Malthusian economy in settled agrarian societies finds support for pre-industrial England at least. We saw in table 5 that there are indications that England was an extraordinarily stable society for 500 years before the Industrial Revolution, where the overwhelming source of deaths was from sicknesses that could be avoided through economic success. In this case institutional stability could have helped launch an Industrial Revolution, but through a very indirect effect on the prevailing cultural norms.

While this approach suggested by Galor and Moav seems promising, it like any endogenous growth theory is going to predict a relatively slow transition between pre-industrial stagnation and modern growth. However this apparent failing may not be as damaging as it would appear.

The Timing and Pace of the Industrial Revolution

We have been following the traditional assumption, so far, represented by figure 2, that the Industrial Revolution was a relatively abrupt transition to modern productivity growth rates. For recent empirical work suggests that the Industrial Revolution may be a much less abrupt transition than figure 5 implies. Thus figure 11 shows an estimate of GDP per person by decade from 1600-9 to 1860-9. What we see is that output per person was rising already in the years 1600-1689, before any institutional changes of the Glorious Revolution of 1688-9. And indeed if we project forwards this growth rate we would not be far off in estimating GDP per capita in the 1860s. Thus there are clear signs of growth beginning before the traditional date of the Industrial Revolution. TFP in the economy is harder to estimate. In the earlier years land was an important component of income, and population grew rapidly in the years after 1760. But at the same time there was a switch to massive imports of food, raw materials and energy by the 1860s, so that the total land input into the economy was growing more rapidly than would appear from looking just at domestic land inputs. But, these caveats notwithstanding, figure 12 shows a rough estimate of productivity levels in England from 1600-9 on. The raw productivity series does show a change in trend around 1780. But there is significant productivity growth from 1600 on at a relatively constant pace.

Even that modest upward move in productivity growth rates after 1780 in England may just be the result of chance factors. The simple equation we have been assuming above is that

$$\Delta\text{TFP} = \text{technological innovation} = \text{change in the stock of ideas.}$$

While this is probably true on average, the link between the stock of knowledge and the level of TFP is mediated by entirely accidental factors about the price and income elasticities of demand, and the relative prices of inputs in production. Thus the assumption that TFP growth before 1800 indexes knowledge growth before 1800 is probably incorrect. Historians of art, architecture, music, mathematics, astronomy, and physics, for example, would all point to much earlier epochs as representing the turning point between a world of slow expansion of knowledge and the modern world. Aggregate TFP growth rate is just the sum of the productivity growth rates of individual sectors weighted by their share in national outputs. Thus

$$g_A = \sum_j \theta_j g_{Aj}$$

where θj is the share of national income derived from sector j, and g_{Aj} is the productivity growth rate in sector j. Thus since productivity growth in production of good X generally reduces the price of good X relative to other goods, if productivity growth in producing a particular good is to have a large measured effect on national TFP either the good must represent a large share of expenditure initially, or the (uncompensated) price elasticity of demand must be close to or above 1, or there must exist substantial export markets for the good. Even fairly broad categories of goods vary dramatically in their price elasticities. Thus for the modern USA we get:

Metals	1.52
Furniture	1.26
Motor Vehicles	1.14
Oil	0.91
Clothing	0.64
Housing	0.55
Food	0.12

The Industrial Revolution in 1760-1860 in Britain was not a very widely based expansion of TFP based on a whole series of innovations across subsectors of the economy. Most of the economy saw no TFP growth, and the national TFP gains mostly came from one industry, textiles. Thus figure 12 shows as well as estimated TFP levels in England by decade, TFP absent all textile innovations, or just absent all textile exports. Textiles contributed a large amount of national TFP growth because it met all three conditions above: it began as a substantial industry, its share of consumption did not decline with price declines, and there grew up a huge external market which eventually absorbed more than half of output. Absent textiles there would have been no change in the trend in TFP growth all the way from 1600-1869.

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 and/or low price elasticities of demand. Then the technological dynamism of the economy would not show up in terms of output per capita or in measured productivity. Figure 13, for example, shows estimated output per worker in book production (including paper) from the middle ages on in England. There were productivity gains here almost as dramatic as those in textiles in the Industrial Revolution through the development of the printing press. Yet the contribution of all this productivity advance to nation TFP was to a first approximation 0, given the tiny share of expenditures on books in the period of rapid productivity advance before 1650. Printing was not the only area of productivity gain before 1700. Window glass, nails, gunpowder, nails and pepper all were products whose price fell significantly relative to wages in the years 1250 to 1700. All saw significant productivity growth (in the case of pepper from the reduced cost of getting it from south Asia), yet all contributed little or no measurable TFP growth given the nature of demand.

Thus the dating of the Industrial Revolution is not so clear as has traditionally been assumed. The true break from the Malthusian embrace will be difficult to date, and the changes may be much more gradual than traditionally assumed. This as noted bodes well for endogenous growth approaches, and badly for models based on a move between equilibria, or for models based on exogenous changes in property rights.

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 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 equilibria again fails because there is little sign of any major changes in the underlying parameters of the economy 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 productivity growth rates. 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 TFP growth 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.

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Figure 1: World Economic History in One Picture

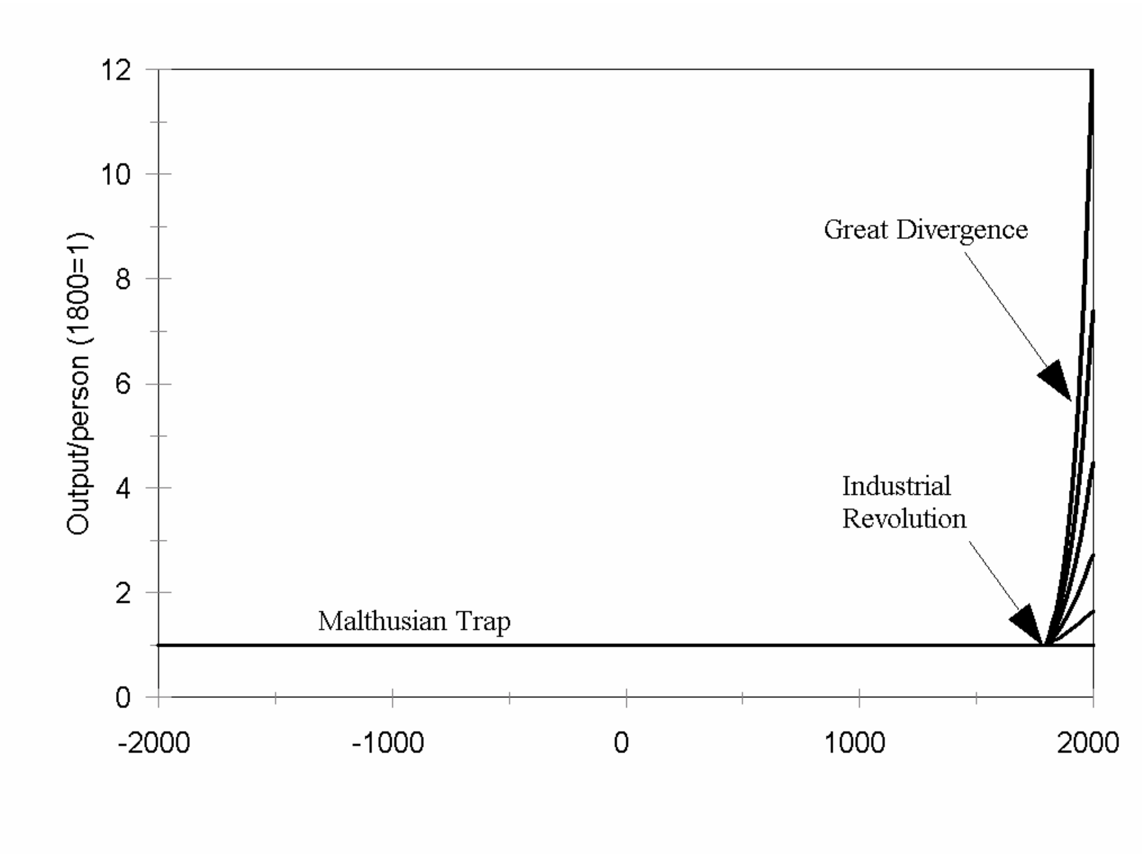
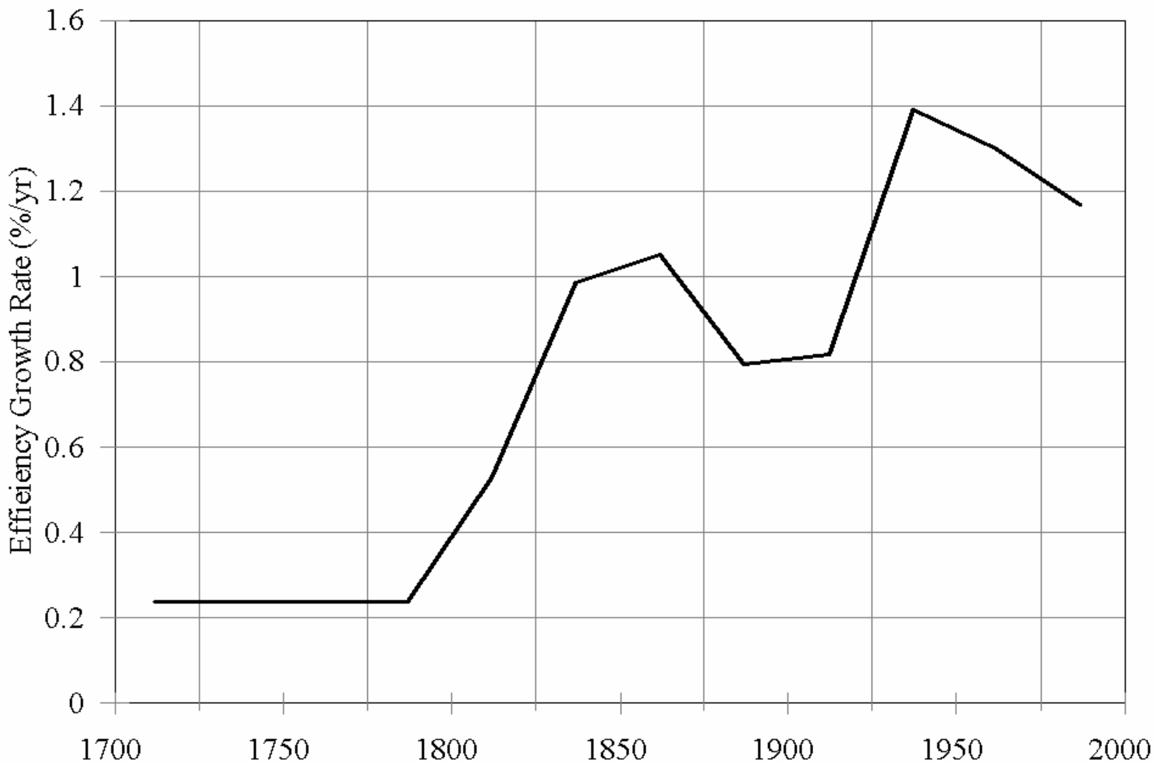
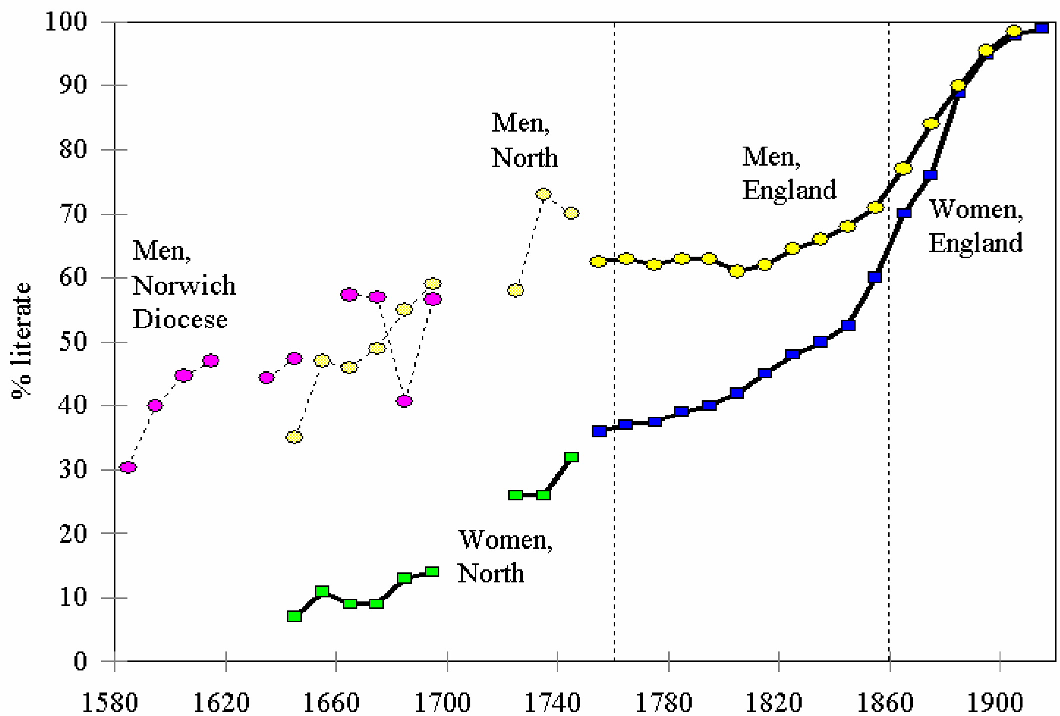


Figure 2: Estimated Efficiency Growth Rates, England 1700-2000



Source: 1700-1831, Crafts and Harley (1992). 1831-1860, Deane and Cole (1967).

Figure 3: 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.

Figure 4: Patents per Year, England, 1660-1851

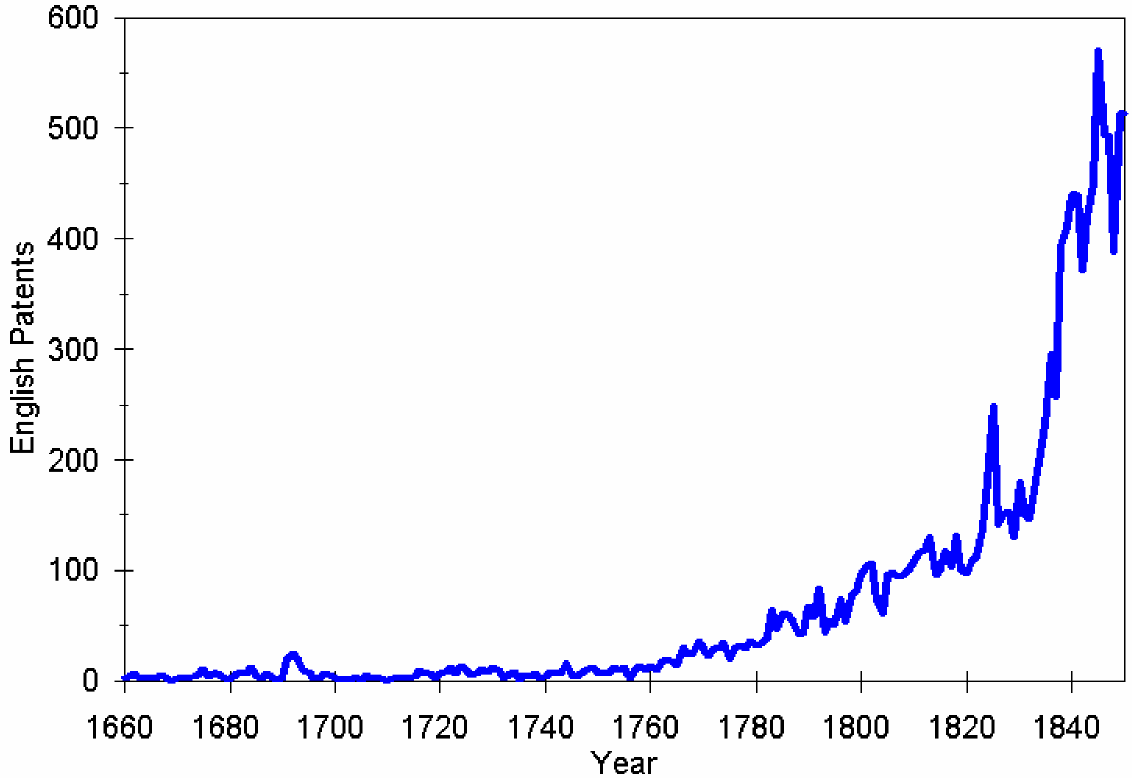
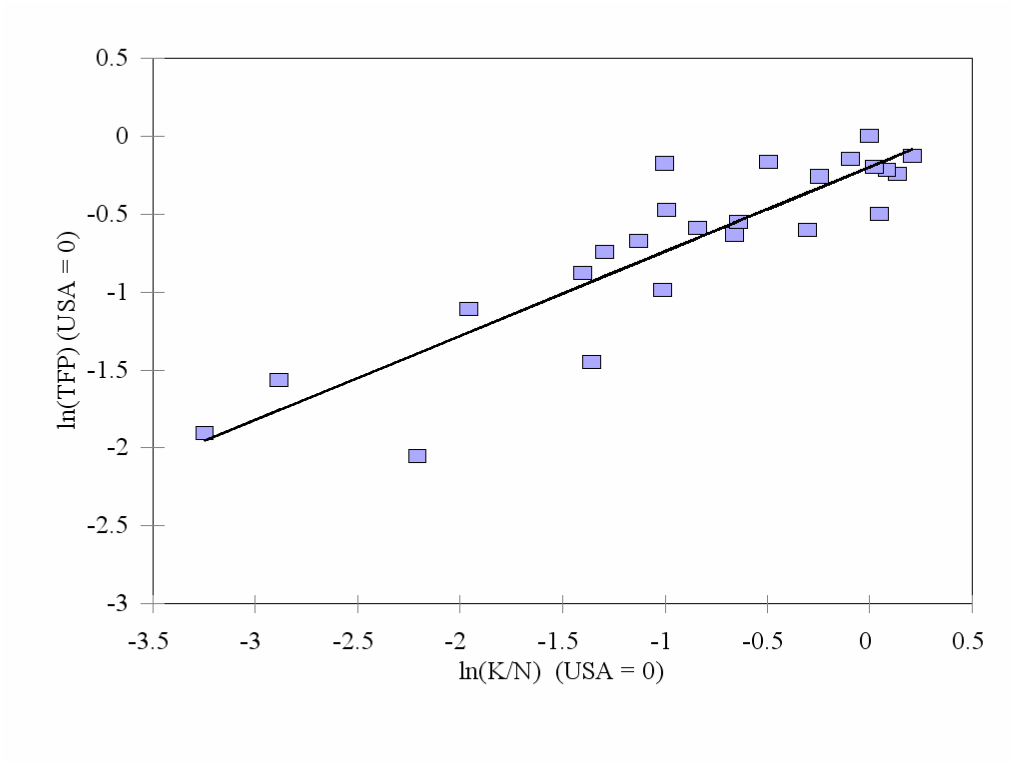
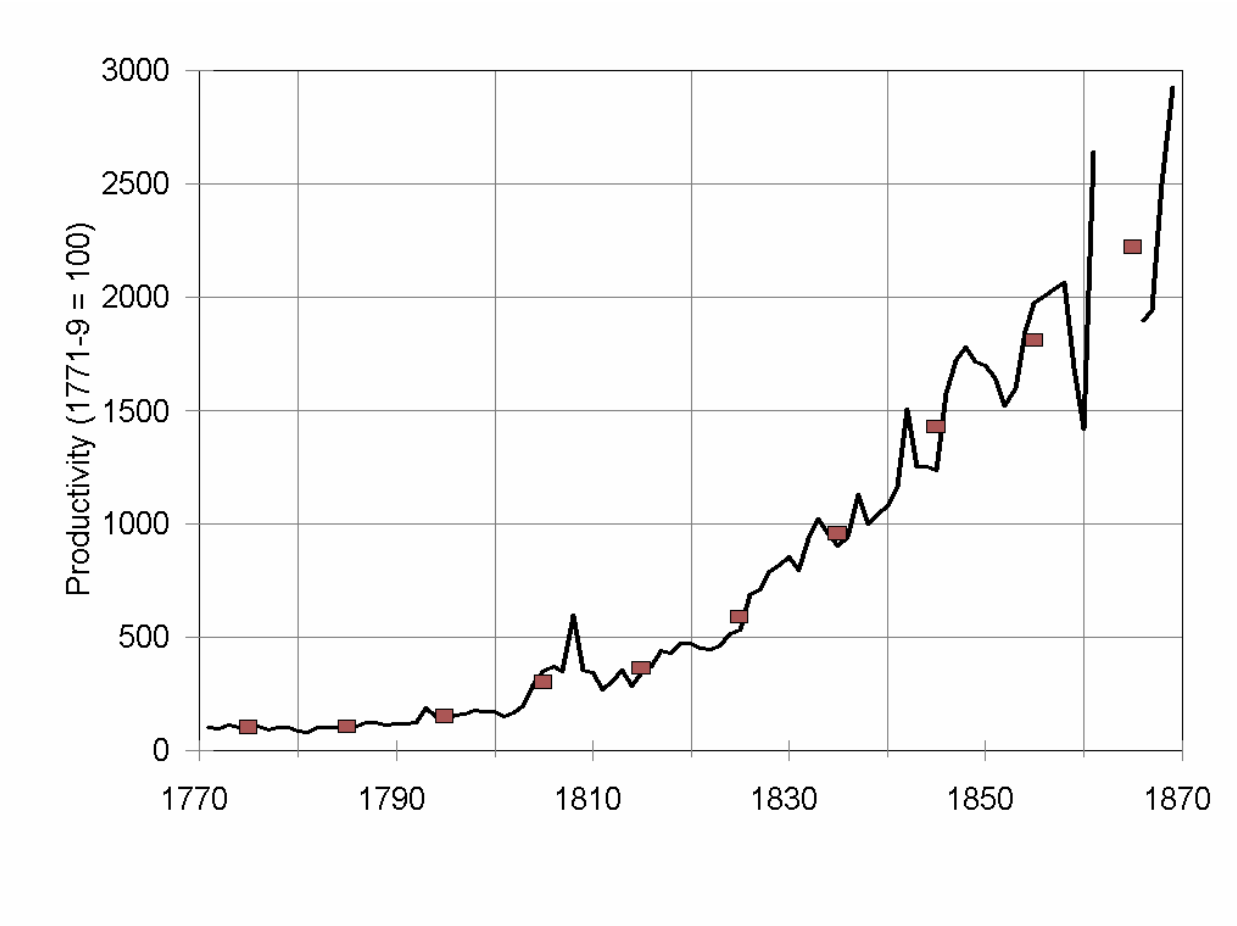


Figure 5: Efficiency versus Capital per Worker



Source: Penn World Tables, Version 5.6.

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 (1997). Labor costs, Clark (2003b). Return on capital, Clark (1998).

Figure 7: The Demographic Transition in Europe

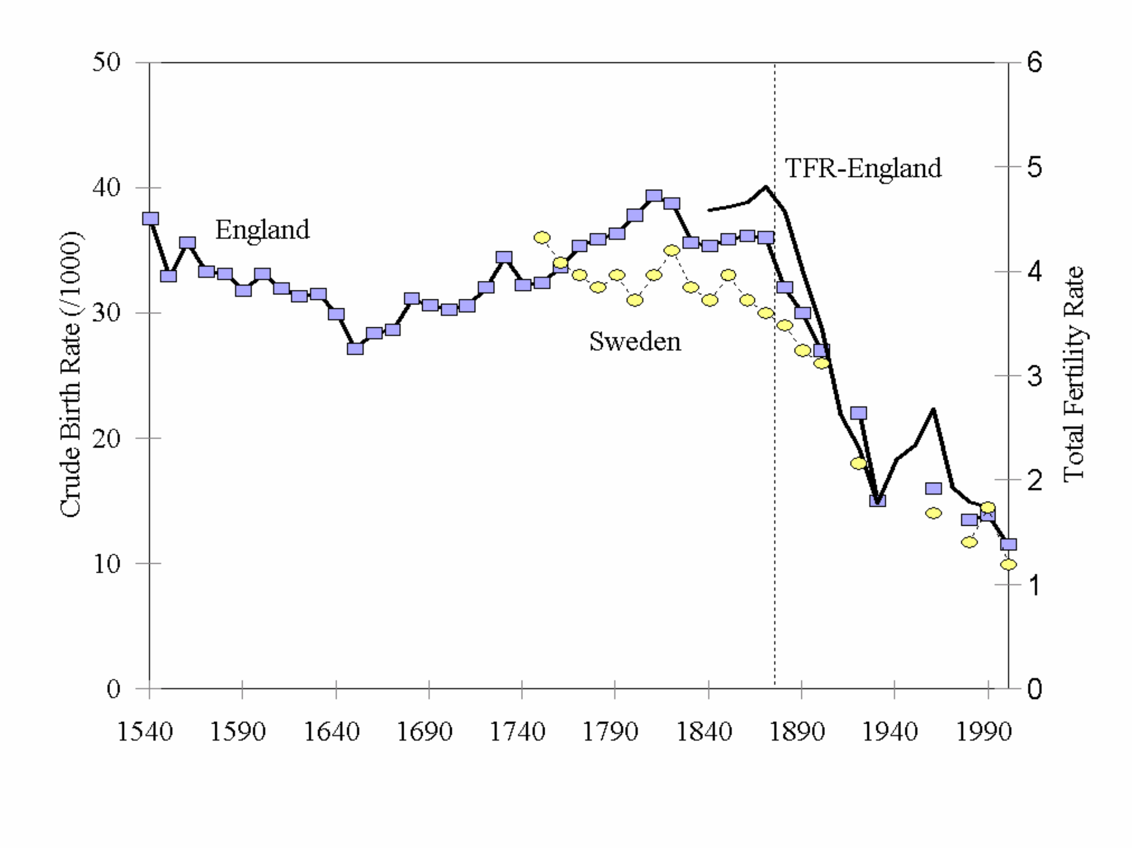
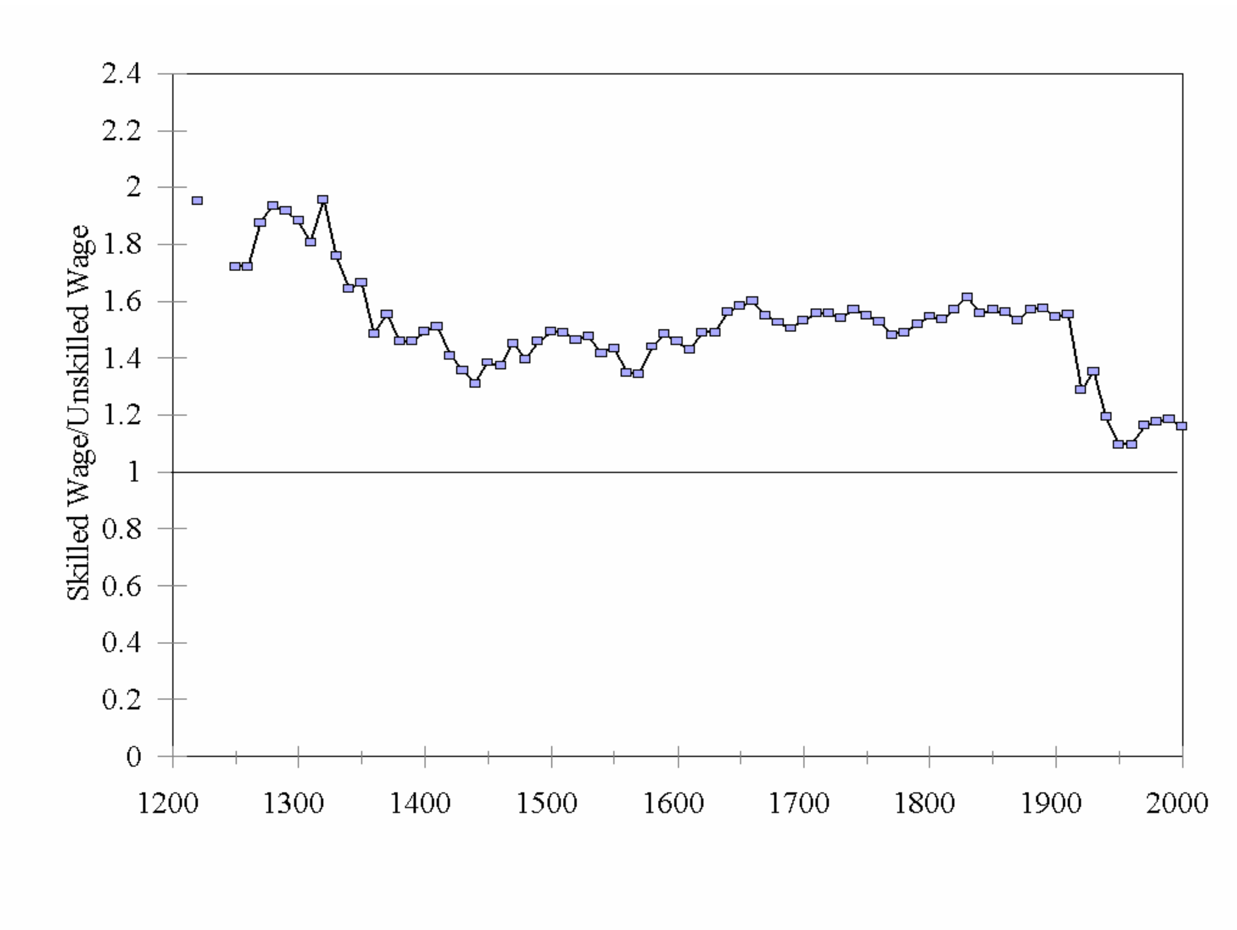


Figure 8: The Wage of Skilled Relative to Unskilled Building Workers, 1220-2000



Source: Clark (2003).

Figure 8: Population and the Rate of Technological Advance – Actual versus predicted

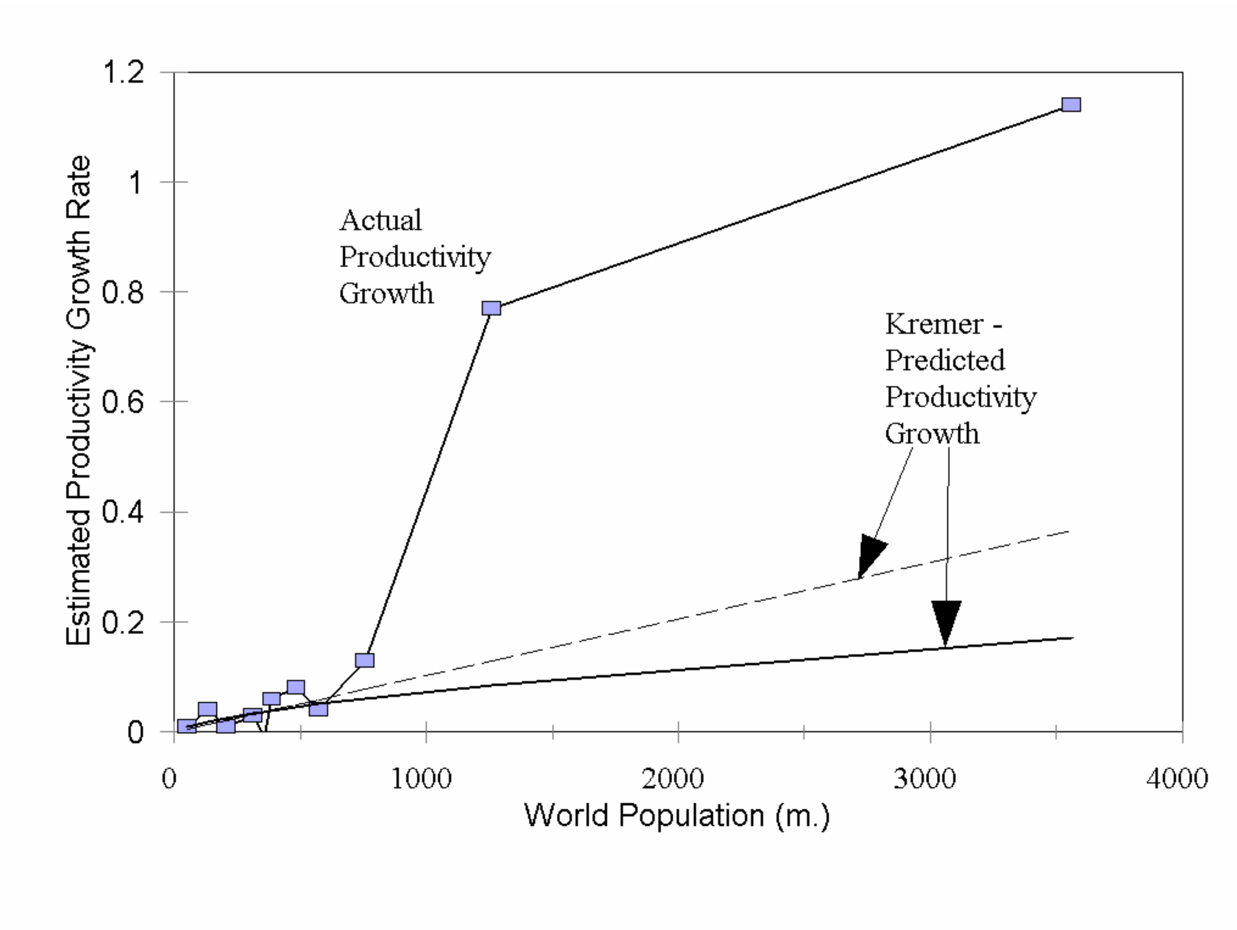


Figure 9: Productivity Growth in English Agriculture, 1750-1970

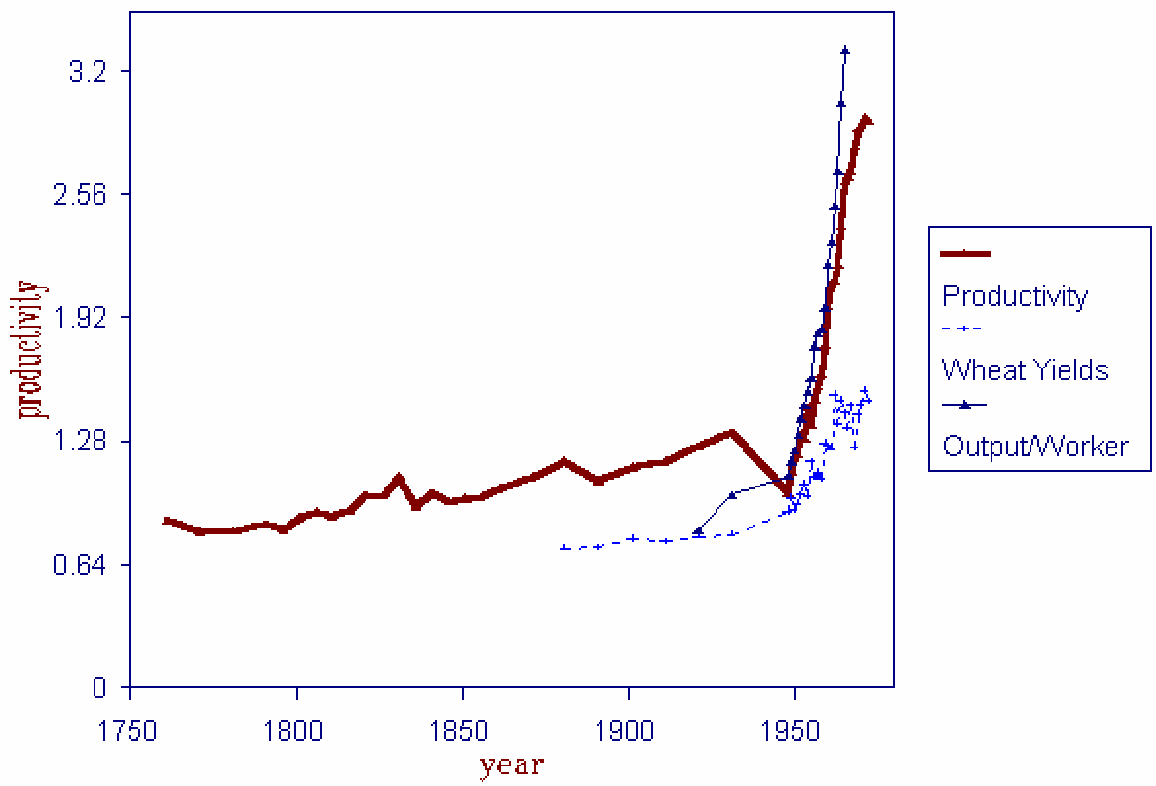
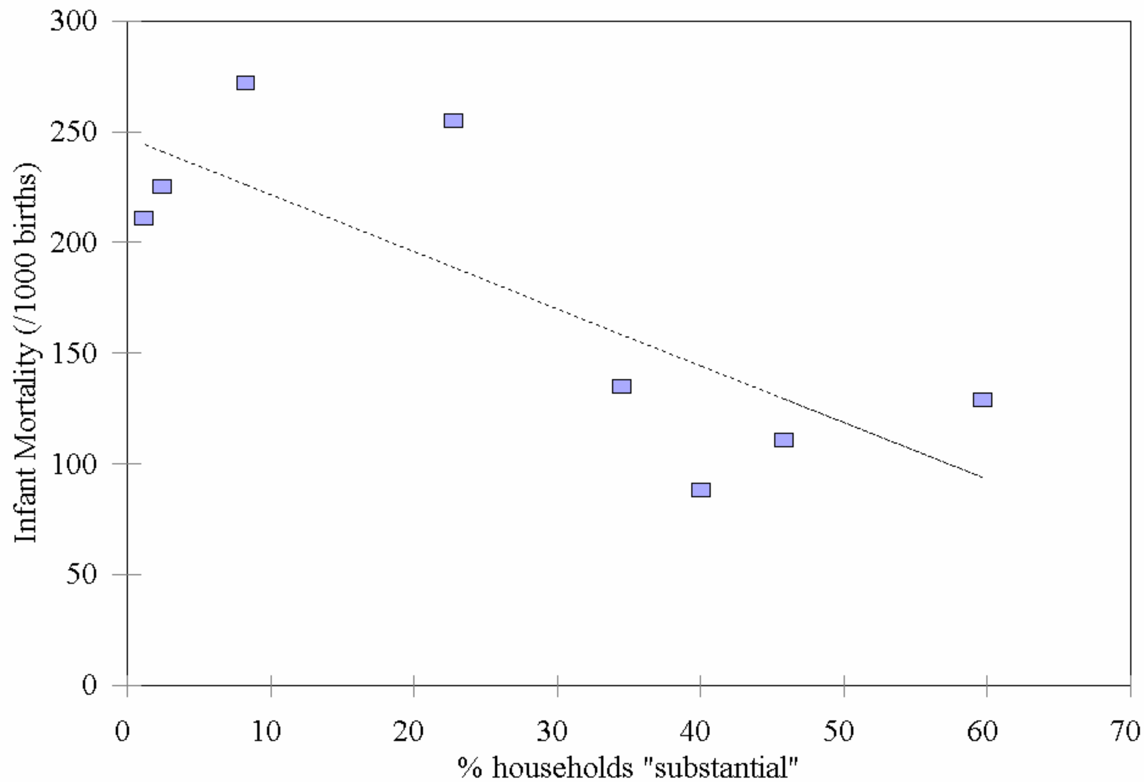


Figure 10: Household Income and Infant Mortality, England, 1538-1653



Source: Landers (1993), pp. 186-188.

Figure 11: GDP per person, England, 1600-1869

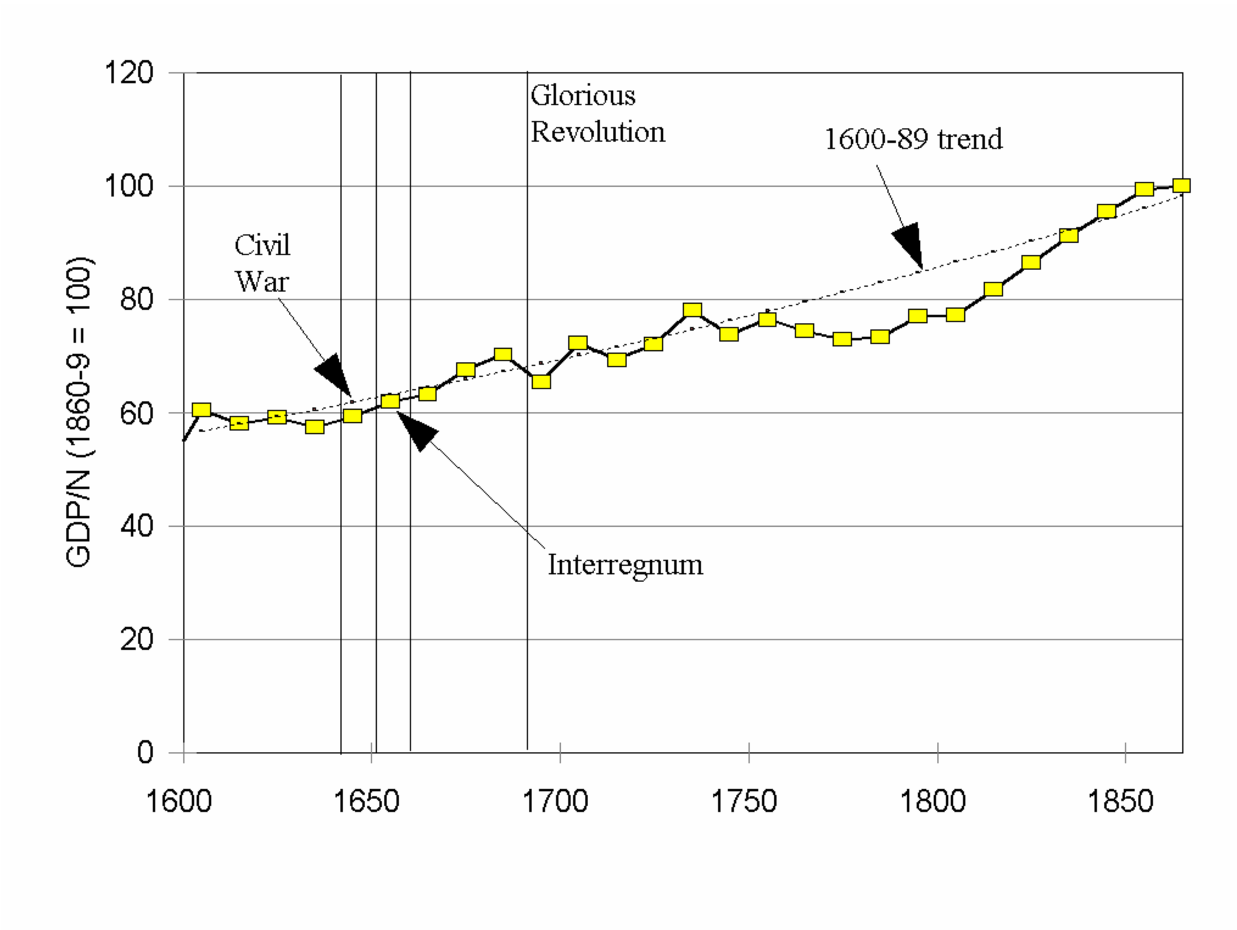


Figure 12: Overall TFP in England, 1610-1869

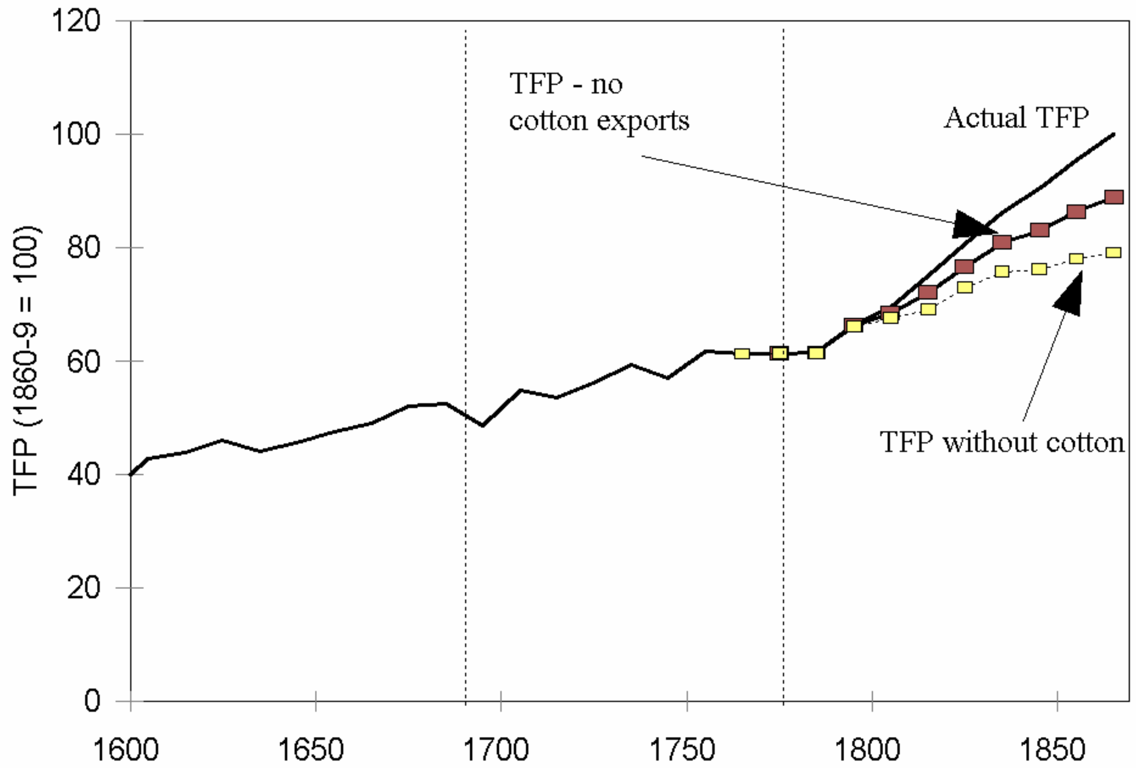
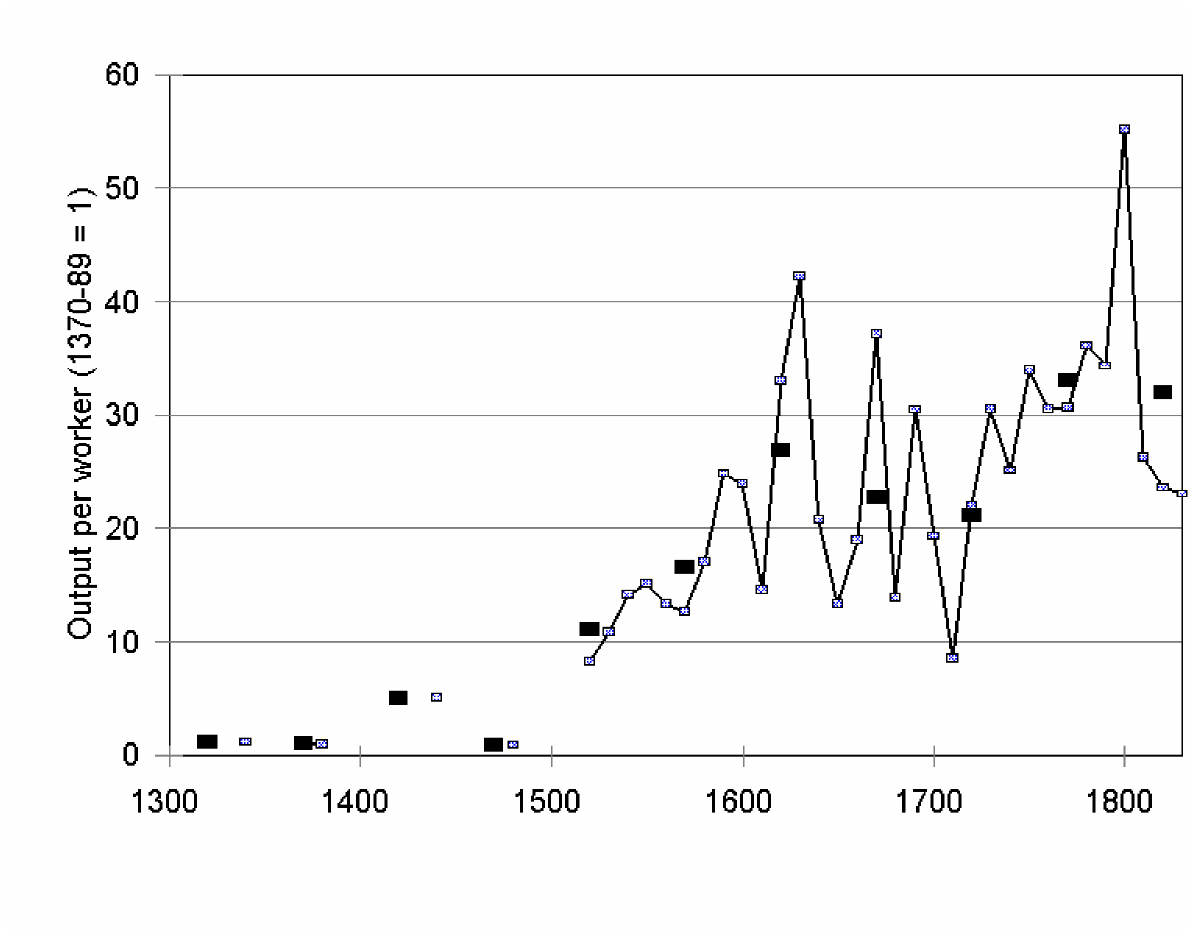


Figure 12: Output per worker in printing, 1340-1839



Notes: The solid squares indicate the 50 year averages of productivity.

Source: Clark and Levin (2001)

Table 1: Growth Rate of World Population and Implied Efficiency Advance

Year	Population (m.)	Growth Rate of Population (% per year) g_N	Growth Rate of Income/Person (% per year) $g_{Q/N}$	Implied Rate of Technological Progress (% per year) g_A
-10,000	4	-	-	-
-500	100	0.03	0	0.01
1	170	0.11	0	0.03
1,000	265	0.04	0	0.01
1,300	360	0.10	0	0.02
1,400	350	-0.03	0	-0.01
1,500	425	0.19	0	0.05
1,600	545	0.25	0	0.06
1,700	610	0.11	0	0.03
1,800	900	0.39	0	0.10
1,900	1,625	0.59	*0.77	*0.77
2,000	5,500	1.22	**1.54	**1.14

Note: *England, **United Kingdom.

Source: Population estimates are summarized in Kremer (1993).

Table 2: The Replacement Cost of the Human Capital Stock in the USA, 2000

Education	Civilian Labor Force (m)	Years of education	Direct Social Cost ($ b.)	Foregone earnings ($ b.)	Cost per person ($)
Less than High School	11.177	10	879.2	0	78,658
High School	63.173	12	5,962.9	1,767.4	122,366
College (less than 4 years)	31.820	14	4,166.8	2,155.4	198,682
College (4 or more years)	34.671	16	7,075.2	3,727.0	311,556
Civilian Labor Force	140.843		18,084.1	7,649.7	182,713

Notes: The foregone earnings per year are assumed for each level of education to be 70% of the average wage and salary compensation a person with education at the category below aged 25-29 earned (this is assuming that students take classes or study for 1,350 hours per school year – undoubtedly an overestimate).

Source:

Table 3: The UK Capital Stock in 1990

Type of capital	Share in stock	Share in rental payments
Buildings	72%	54%
Intangibles	1%	3%
Plant and Machinery (not vehicles)	17%	31%

Source: (Oulton, 2001)

Table 4: Theories of the Industrial Revolution

Author	Key elements in explaining sustained efficiency growth.	Endogenous Growth?	Is the Industrial Revolution inevitable?
North and Thomas (1973), North and Weingast (1989)	Increased appropriability of knowledge.	No.	No.
Becker, Murphy and Tamura (1990)	No diminishing returns to human capital. Switch to higher quality children with higher income.	No.	No.
Kremer (1993)	Knowledge growth rate increases with population.	Yes.	Yes.
Galor and Weil (2000)	Knowledge growth rate increases with population. No diminishing returns to human capital. Switch to higher quality children with higher productivity growth rates.	Yes.	Yes.
Jones (2001)	Knowledge growth rate increases with population. Increased appropriability of knowledge.	No.	No.
Hansen and Prescott (2002)	Slow efficiency growth land-intensive sector. Fast efficiency growth land-free sector.	No.	Yes.
Lucas (2002)	Land using sector where human capital not productive. Industrial sector where human capital productive. No diminishing returns to human capital.	No.	No
Galor and Moav (2002)	Evolution of preferences for human capital. No diminishing returns to human capital. Switch to higher quality children with higher productivity growth rates.	Yes	Yes

Table 5: Causes of Death: Hunter Gatherer versus Agrarian versus Modern Societies

Group	e_0 (assumed)	% deaths illness or degenerative	% deaths Accident	% deaths homicide (excluding executions)
Foragers				
Ache, Forest period	37	31.4	13.1	55.5
Yanomamo, 1970-4	-	80.2	7.2	12.6
!Kung before 1973	35	88.3	11.7	
New Guinea (Hewa, Gebusi, Goilala)	35	-	-	21.7
Agta	21	-	-	6.8
Pre-Industrial England				
Bedford, 1270-76	35	98.2	1.0	0.8
Nottingham, 1530-38	35	98.6	0.7	0.7
London, 1300-49	25	98.5	0.6	0.9
London, 17th c	25	99.0	0.9	0.1
London, 18th c	25	99.2	0.7	0.1
Modern				
USA, 2000[a]	-	95.4	3.9	0.7
Brazil, 1995[b]	-	89.0	6.8	4.2
Colombia, 1998[b]	-	78.4	7.5	14.1

Notes: Assuming the population of Bedford in 1270-6 was 50,000 and the population of London in 1300-49 was also 50,000. The English figures exclude judicial executions, but a relatively small percentage of felonies resulted in executions.

Sources: Hill and Hurtado (1996), p. 174, Hair (1971). Hanawalt (198-). [a]U.S. National Center for Health Statistics, Vital Statistics of the United States. [b]W.H.O.

Table 6: The Rewards to Textile Innovators in the Industrial Revolution

Innovator	Device	Year	Patent?	Result
John Kay	Flying Shuttle	1733	Yes	Impoverished by litigation trying to enforce patent. House destroyed by machine breakers 1753. Died in poverty in France c. 1764
Richard Arkwright	Water Frame Carding Frame	1769	Yes	Patents invalidated by courts 1785. Most of £0.5 m. fortune at death in 1792 made post 1781 when patents in dispute.
James Hargreaves	Spinning Jenny	1769	No – patent denied	Forced to flee by machine breakers in 1768. Died in obscurity in workhouse in 1777.
Samuel Crompton	Mule	1779	No – gave device to Bolton industry for £70.	Given grants of £500 by manufacturers subscription in the 1790s, and in 1811 of £5,000 by Parliament. Died subsisting on an a Parliamentary annuity of £63 in 1827.
Reverend Edmund Cartwright	Power Loom	1785	Yes.	Machine commercial failure during life of patent. Early Manchester factory destroyed by machine breakers. Granted £10,000 by Parliament in 1809.
Eli Whitney (USA)	Cotton Gin	1793	Yes	Forced out of business by infringers by 1797. Congress refused to renew patent in 1807. Made a fortune in the subsidized mass production of muskets, but never again patented his innovations.
Richard Roberts	Self-Acting Mule	1830	Yes.	Patent revenues £7,000 by 1839. Development costs of £12,000. Parliament extended patent by 7 years. Died in poverty in 1864. Daughter granted pension of £300 by Parliament.

TABLE 7: AGE-HEAPING, ROME VERSUS LATER EUROPE

	Social Group	Sample Size	Z - All	Z – Men	Z - Women
Imperial Rome					
Rome	All	3,708	48	47	50
Italy outside Rome	All	1,395	-	43	-
Italy outside Rome	Town Councilors	75	-	15	-
Africa and Numidia	All	5,330	52	52	52
Africa and Numidia	Office Holders	34	-	18	-
Africa and Numidia	City of Carthage	240	38	43	33
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), p. 84-90.

Table 8: Age Heaping Among Living Populations (23-62)

Place	Date	Type of Community	Sample Size	Z – All	Z-Male	Z-female
Town of Florence	1427	Urban		32	25	40
Florentine Territory	1427	Rural		53	49	56
Pistoia	1427	Urban		42	-	-
Pozzuoli	1489	Urban		72	73	71
Sorrento	1561	Urban		67	61	74
Corfe Castle, England	1790	Urban	352	8	5	10
Corfe Castle, Poor	1790	Urban	76	14	-	-
Corfe Castle, Higher Status	1790	Urban	75	-3	-	-
Ardleigh, Essex	1796	Rural	433	30	35	25
Terling, Essex – 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.

Table 9: England, surviving children as a function of literacy

Residence	% literate	Testator signed Number	% married	Testator signed Children	Testator made mark Number	% married	Testator made mark Children
London	82	129	74	2.10	29	62	1.69
Other towns	69	87	87	2.93	39	87	2.15
Countryside	61	223	88	3.26	346	91	2.84

Source: Clark and Hamilton (2003).

Table 10: The Determinants of the Number of Surviving Children, Males

Variable	**Full Sample** Average Value	**Full Sample** Coefficient Estimate	**Full Sample** Standard Error	**Married** Average Value	**Married** Coefficient Estimate	**Married** Standard Error
CONSTANT	-	2.026	0.211	-	2.416	0.224
DWID	0.178	1.238**	0.242	0.175	0.882**	0.241
DLIT	0.442	0.303	0.201	0.439	0.460*	0.209
DTOWN	0.181	-0.699**	0.258	0.148	-0.602*	0.271
DASS1	0.152	0.305	0.309	0.138	0.248	0.327
DASS2	0.136	0.629*	0.320	0.175	0.448	0.332
DASS3	0.251	1.030**	0.274	0.257	0.995**	0.287
DASS4	0.247	1.240**	0.211	0.164	0.970**	0.308
N		692			621	
R^2		.078			.068	

Note: * = statistically significant at the 5% level, ** = statistically significant at the 1% level

Source: Clark and Hamilton (2003).