7. Explaining Growth since the Industrial Revolution.

Growth Since 1800

Around 1800 the output per person in a small group of advanced economies began to improve at a speed previously unseen. This process is generally called the Industrial Revolution, though as we shall see there is nothing inherently industrial about it. Sometime in the nineteenth century the rate of output growth in a few advanced economies – most notably England and the United States – was rapid enough that the old Malthusian equilibrium that held living standards in its grip for millenia was finally shattered. A new economy emerged, at least in a favored group of countries, where income growth was rapid and persistent. Figure 1 shows the break from the Malthusian past in England. Sometime after 1770 the link between wages and population, where any increase in population caused a decline in wages, changed in Britain. Between 1770 and 1860 English population tripled but real wages also increased.

The emergence of this modern economy led to unprecedented improvements in material well being in the advanced economies of the world. Figure 2 shows, for example, income per capita in England by decade from 1260-9 to 1990-9. As can be seen income per capita increased nearly 10 fold in England since 1800.\footnote{Note, however, that though the conventional date for the onset of the Industrial Revolution in Britain is 1760 or 1770 there is little sign of rapid growth of income per person till the decade of the 1860s.}

As a result of the Industrial Revolution those living in the economically successful countries of the modern world are enormously richer than their Malthusian ancestors. Another
unusual feature of the modern economy, however, is that the gap between the living standards of people in rich and poor economies is seemingly much wider than in the pre-industrial world. In the pre-industrial era the areas with the most favorable demographic factors could attain incomes perhaps four times those with the least favorable demographic regimes. The gap between rich and poor in the modern world is immensely greater than this.

Table 1 shows, for example, the comparative income per capita of a sample of countries since World War II. As can be seen income per capita in modern Western Europe and North America is in the order of 15-20 times that of the world’s poorest economies. Also in the 42 years from 1950 to 1992 this gap shows no sign of any diminution. The gap between the richest and the poorest is indeed wider in 1992 for the countries in the table than for 1950. This implies that even before the Industrial Revolution income per capita in Western Europe was above that of the world’s poorest countries now. Europe started with high incomes per capita relative to much of the world in 1800 because of its fertility pattern. It has since widened its lead on much of the rest of the world. In this second part of the book we explore how this happened.

Most of the change in the structure of economic life in the advanced economies of the world can be traced directly to the unprecedented rise in incomes per person since 1800. For as incomes increase in economies a number of characteristic changes occur simply from the fact of higher incomes. Consumption of most goods and services increases as incomes increase, but as we saw in chapter 3 the increase in demand with income varies sharply across goods. In particular demand for food has a low demand elasticity, particularly at high income levels. For Britain in the nineteenth century the income elasticity seems to have been only about 0.6. For even richer economies, income elasticity is much lower. Thus in Germany real incomes per person rose by 133% from 1910 to 1956, while food consumption per person rose by only 7%,
calorie consumption per person fell by 4% and protein consumption fell by 3%. Indeed the calorie content of the modern European diet is little higher than that of the eighteen century even though people are 10 to 20 times as wealthy, though the character of the diet has switched towards more expensive calorie sources such as meat and dairy products.

This low income elasticity of food demand means that as economies get richer a smaller and smaller proportion of consumption is farm products. In pre-industrial European economies it is estimated that from 50-80% of the population were engaged in agriculture. France is still largely self sufficient in food yet only 6% of the French work force is employed in agriculture, and the proportion is less than 2% in Britain which is a more efficient food producer. The “Industrial Revolution” is so called in part because of the switch of population and production out of agriculture and into industry. But this switch has occurred because of a general rise in the efficiency of the economy, not because of specific advances in the industrial sector alone.

As economies switch labor out of agriculture it has a profound effect on the social character of the economy. In pre-industrial Europe most of the population lived in small rural villages of a few hundred people, because they had to be close to their work in the fields. In the south east of England, for example, villages in the eighteenth century were only about 2 miles apart on average. A typical village would have less than 100 people residing in it. The countryside was densely settled because of the labor required in pre-industrial agriculture. As the proportion of the population engaged in agriculture has fallen, the mass of modern populations is footloose, and has concentrated in urban centers because of the social amenities this offers, and also the employment opportunities there. The urbanization of the advanced economies has produced many associated social changes.

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2 Britain does, however, import about half its food requirements since it is very densely populated.
The Economic Theory of Growth

As with the Malthusian theory of pre-industrial income determination, economists have a simple and powerful way of analyzing economic growth. To strip the problem of growth down to its essence let us think initially of an economy which produces only one type of output (wheat, for example). Let $Q$ be the wheat output in the initial year, and $\Delta Q$ the change in output between years. (I use $\Delta$ before a variable to indicate the change in the amount of any quantity or price in a year). Where does this change in output, $\Delta Q$, come from?

There are many elements which help determine output, but they can be divided into four simple ones for our model. The quantity of the inputs of labor, land and capital employed, and the efficiency with which they are combined in production. The first of the inputs is labor, $L$, the number of worker hours devoted to production. In the real world there are many different types of labor but here again, for expositional simplicity, consider an economy in which all labor is the same. An increase in worker hours, $\Delta L$, all other things held constant, will increase the output of the economy. In a competitive economy, one where outputs are sold and inputs purchased in competitive markets, the amount extra work hours contribute to extra output is very simple to calculate. It is just the wage workers are paid per hour. For in a competitive economy each worker is paid the marginal product of their labor. Thus if $w$ is the hourly wage in the initial year, the increase in output explained directly by extra labor inputs is just $w\Delta L$.

Another type of input in production is land (let $Z$ be the number of acres of land). If the land area of the economy increases by $\Delta Z$ this again would increase output. In a competitive economy the amount an extra acre of land contributes is just its marginal product, the rental of the land. Thus in our simple wheat producing economy, if an acre of land rents for 5 bushels of

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3 By having only one type of output we do not have to worry about changes in the price level. Everything, output, wages, rents can be measured in terms of bushels of wheat.
wheat per year, then each additional acre employed in the economy, all other inputs held constant, will add 5 bushels of wheat to output. Thus if $s$ is the annual land rent in the initial year, the increase in output explained directly by extra land inputs is just $s \Delta Z$. Since the land area is fixed this implied that in most modern economies, increases in land inputs will not help explain the growth of output.

The third and last type of input is the capital goods used in production (denoted by $K$). In actual economies this is houses, structures, roads, machines, inventories of goods in process. In our simple economy, however, with only wheat as an output, the only capital good would be stored up wheat. Again for simplicity assume that there is no depreciation of capital. It stays intact while used as an aid to production. If the capital stock changes by an amount $\Delta K$, output will increase by an amount $r \Delta K$, where $r$ is the annual rental paid to owners for use of each unit of capital. In our simple economy where capital and output are both wheat, $r$ will be just the real interest rate (thus if the rental of a bushel of wheat for a year is 0.05 bushels of wheat, the real interest rate is 5%).

If the inputs were the only thing that mattered in the production of output, then by now we would have completely described the sources of changes in output, and thus we would have,

$$\Delta Q = w \Delta L + r \Delta K + s \Delta Z$$

But since a change in output could also come from an increase in the efficiency with which the inputs of capital, labor and land are combined in production, we have to allow this in the equation above. Thus the full expression for changes in output is

$$\Delta Q = w \Delta L + r \Delta K + s \Delta Z + \text{residual} \quad (1)$$

where the “residual” is just any change in output that is not accounted for by changes in the inputs. The residual in our wheat economy, for example, could be the results of good or bad
weather. If we let \( A \) index the level of efficiency of the economy, caused by shocks such as weather, and \( \Delta A \) the change in efficiency, then we can rewrite the above expression as

\[
\Delta Q = w\Delta L + r\Delta K + s\Delta Z + \left( \frac{\Delta A}{A} \right) Q
\]  

(2)

where \((\Delta A/A)\) is now the percentage change in the efficiency of the economy, and \( Q \) is output in the initial year. With some simple algebraic manipulation, detailed in the appendix, we can rewrite this expression as

\[
\frac{\Delta Q}{Q} = a \frac{\Delta K}{K} + b \frac{\Delta L}{L} + c \frac{\Delta Z}{Z} + \frac{\Delta A}{A}
\]

(3)

where \( a \) is the share of total output paid to capital, \( b \) the share paid to labor, and \( c \) the share paid to land. The expressions of the form \((\Delta x/x)\) are just the annual growth rates of the relevant variables, given our definitions above, and I use the notation \( g_x \) for \((\Delta x/x)\). That means I can rewrite the above expression as,

\[
g_Q = a.g_K + b.g_L + c.g_Z + g_A
\]

(4)

This implies that the rate of growth of output is the rate of growth of capital, labor and land, each weighted by their share in national income, plus any growth rate in efficiency the economy experiences. Suppose, for example, that efficiency growth was 0% per year, and capital, land and labor all grew by 3% per year. Then total output would grow at a rate of 3% per year (since \( a + b + c = 1 \)).

In some cases we are interested in the growth of total output (such as if we are considering the likely military power of a state). But more often we are interested in the rate of
growth of output per worker, $Q/L$. For the material living standard of a society depends on output per worker. The rate of growth of $Q/L$, $g_{QL}$ is

$$\frac{\Delta \left( \frac{Q}{L} \right)}{\left( \frac{Q}{L} \right)}$$

For the small changes in $Q$ and in $L$ economies experience year by year this is approximately equivalent to,

$$\frac{\Delta Q}{Q} - \frac{\Delta L}{L}$$

Thus

$$g_{QL} \approx g_Q - g_L$$

Similarly the rate of growth of capital per worker, $g_{KL}$ is $g_K - g_L$, and the rate of growth (or more often of decline) of land per worker, $g_{Z/L}$ is $g_Z - g_L$. If we subtract $g_L$, the rate of growth of the labor supply from each side of the equation giving $g_Q$ above we get

$$g_{QL} = g_Q - g_L = a.g_K + b.g_L + c.g_Z + g_A - g_L$$

$$= a(g_K - g_L) + c(g_Z - g_L) + g_A$$

$$\Rightarrow g_{QL} = a(g_{K/L}) + c(g_{Z/L}) + g_A \quad (6)$$

Since $g_Z$ is typically 0, since the land area is fixed, we can further simplify this expression to
\[ g_{Q/L} = a.g_{K/L} - c.g_L + g_A \]  \hspace{1cm} (7)

This is the “fundamental equation” of economic growth, and it reduces the possible sources of growth to only two. This fundamental expression for the sources of growth in income per capita has been derived for an economy with only one output, one type of labor, one type of land, and one type of capital (which is just stored up output). But it generalizes easily into an analogous expression for an economy with many types of output, labor, capital and land, as the appendix shows. Thus the growth of output becomes

\[ g_Q = \sum \theta_i g_{Q_i} \]  \hspace{1cm} (8)

where \( \theta_i \) is the share in the value of output of the commodity or service \( i \). The growth of the labor input becomes

\[ g_L = \sum \frac{b_j}{b} g_{L_j} \]  \hspace{1cm} (9)

where \( b_j \) is the share in the total payments to the factors of production paid to workers of type \( j \). And the growth of the capital stock is similarly

\[ g_K = \sum \frac{a_j}{a} g_{K_j} \]  \hspace{1cm} (10)

Thus despite the enormous complexity of modern economies, the growth income per person since the Industrial Revolution can be reduced to just two possible sources. The first is the accumulation of more capital per person, called “capital deepening.” The second is an improvement in the efficiency of the use of capital, labor and land in producing output.

Notice that population growth acts as a drag on the economy’s growth rate, assuming that the labor supply \( L \) is proportionate to the population. This drag, \(-cg_L\), in the equation above, has been very modest however, since the nineteenth century as a result of the decline in the share of
national incomes that goes to land rents. Figure 3, for example, shows the share of national income in England estimated paid to the owners of agricultural land from 1200 to 2000. While in the years before 1800 land rents were typically one quarter of all incomes, since then they have dropped to a mere --%. Thus while before 1800 population was a major determinant of income, since 1800 population has become less and less important. Interestingly Ricardo and the other Classical economists writing in the early nineteenth century foresaw a very different world in which land would earn a higher and higher share of income as population grew. This did not happen because demand for the products of land – food and other raw materials – had an income elasticity of less than one, so that as incomes rose demand for manufactures and services increased much more.

**Interpreting the Fundamental Equation of Growth**

Though the fundamental growth equation developed above suggests two possible independent sources of modern economic growth, economists have to believe, however, that economic growth since the Industrial Revolution has been entirely the result of capital accumulation. If capital is measured correctly than $g_A$ should always be close to 0. The reason economists are forced to this conclusion is our strong belief that advances in the measured efficiency of economies do not just happen. They result from human activity in 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 there was a search undertaken for more effective ways to build machines, and for better ways to utilize machinery and workers. This search for improvement, since it involves resources, is just another form of investment.
This deeply held belief of economists of the importance of capital accumulation in economic growth was not put to serious empirical test until the 1940s and 1950s. In part this was because statistical evidence on the growth of national economies was not assembled on a systematic basis until the 1920s, when first Canada and then the USA embarked on projects to measure national output and its components annually. By the 1950s a number of economists had conducted studies that showed at the industry and the national level the residual explained almost all of the growth of output per person. But in 1956 and 1957 both Moses Abramovitz and Robert Solow, who were independently attempting to account for twentieth century US growth in terms of equation (1), first emphasized the problematic nature of the importance of the efficiency residual for economists (Abramovitz (1956), Solow (1956)). As Abramovitz noted later,

This result….was a surprise to me, and it seems, to most economists. After all, capital accumulation was a great subject in economics. In a vague way we all thought it must play a large part in explaining growth, not just a small and supporting role (Abramovitz 1993, p. 218).

This result, that when actually fitted to data, the residual explains most growth since the Industrial Revolution has been confirmed in numerous studies since the 1950s. Capital accumulation explains typically only about one third of the growth of income per person over time. It also explains only about a third of the differences in income per person across countries now laid out in table 1. Economic growth since the Industrial Revolution thus seems to mock one of the truisms of elementary economics “No free lunch.” For the last 200 years the people of the advanced economies have fed on a rich

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4 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.
diet of free lunches, and the affluence of modern life is founded on this manna from heaven.

When we look across countries and try and explain the differences in income per capita in the modern world at any time, again the residual is the dominant force in explaining the great disparities of income per capita across countries. Thus table – shows an estimate for 199- for a range of countries of the comparative importance of capital versus efficiency differences in accounting for differences in income per capita. Measured efficiency differences again explain about --% of the observed variation.

**Restoring Capital to its Rightful Place**

Following the papers of Ambramovitz and Solow economists set about trying to show that the residual was really just the product of mis-measurement, and that capital was indeed, as it had to be, the fundamental source of growth. The first of these efforts, pioneered by Edward Dennison and John Kendrick, consisted of trying to show that the accumulation of capital had been faster than had been previously measured. If capital was growing faster than Abramowitz and Solow assumed then the troublesome residual would be correspondingly smaller. This project consisted first in recognizing that the capital stock of all economies has three important components:

(1) Tangible capital – buildings, machinery, inventories,

(2) Intangible capital – research and development expenditures aimed at improving the production process,

(3) Human capital – educational investments aimed at improving the effectiveness of workers
Earlier measures of the capital stock focused on the stock of tangible physical capital. The hope was that more comprehensive measures of capital stocks would reveal much more rapid growth of capital. If capital was growing faster than Abramowitz and Solow assumed then the troublesome residual would be correspondingly smaller.

In particular Dennison and Kendrick argued that much of the labor supply in modern economies incorporates human capital, the investment of time and money in improving the skills of the people engaged in production. When human capital was added to the measures of capital stock growth in modern economies it would reduce the size of the troublesome residual in two ways. It would increase the share of income, \( a \), attributed to capital, since some wage income would now be a return on capital. And since over time human capital stocks have grown faster than physical capital stocks it would increase the growth rate of the capital stock.

If we denote the stock of human capital by \( H \), then the argument here is that the fundamental equation of growth (7) should be rewritten as

\[
\frac{gQ}{L} = a_K \cdot \frac{gK}{L} + a_H \cdot \frac{gH}{L} - c \cdot \frac{gL}{L} + g_A
\]

(10)

where \( a_H \) is the share of income which is a payment for investments in human capital and \( a_K \) is the share of income paid to owners of physical capital. This procedure will eliminate the efficiency residual only if the share of income going to human capital, \( a_H \), is large relative to the share going to physical capital, and the rate of growth of human capital stocks are large relative to the growth rate of physical capital.

To estimate the typical share of human capital in income we need to know the value of the stock and the rate of return on human capital. The replacement cost of the stock of human capital, even in the most sophisticated and educated of modern economies, is however still less than the value of physical capital. The USA in 2000, for example, is one of the most highly
educated economies in the world, measured as years of schooling per worker. The capital cost of all this schooling per member of the active labor force can be estimated, as in table 4, 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.\(^5\)

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 explains 0.36%, leaving a residual productivity growth based on equation (7) of 1.53%. But including human capital accumulation only explains 0.18% of the growth, leaving a residual productivity growth of 1.36% per year, which was 72% of the growth of output per worker hour.

In some 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

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\(^5\) 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)). But these estimates are believed to be very much an upper bound, since they assume no difference in the intrinsic abilities of those receiving just primary education compared to those who receive higher education. If those getting more education would have anyway earned more than their confreres with less education then we have overestimated the returns.
productivity gains in the modern era, these effects were never strong enough to explain more than 30% of the residual.⁶

Dale Jorgenson and Zvi Griliches supplemented this correction for human capital for the period 1945 to 1965 in the USA with a major correction to the figures for the physical capital stock. They argued that as with labor, the contribution of capital stocks to output should be measured by the number of capital-hours supplied, and not just by the stock of capital. Using data from the US manufacturing census on electricity usage in manufacturing relative to the rated electricity consumption capacity of electrical machinery Grilices and Jorgenson argued that from the 1945 to 1965 the average electrical machine in manufacturing in the US ran nearly twice as many hours per year. If this increase in capital utilization was applied to the capital stock as a whole then the growth rate of capital would be much greater, and the residual correspondingly smaller. But this seems mainly like a re-labeling of the residual rather than a real solution to the problem of the sources of growth. For the ability to utilize the same stock of capital more intensively is just another example of efficiency increase.

Thus 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.

**Knowledge Capital**

At the same time economists such as Zvi Griliches were exploring another approach to eliminating the troublesome residual. This is 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,

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⁶ See Jorgenson and Griliches (1967).
$a$, in the fundamental equation of growth. Such an under measurement would inflate the size of the measured efficiency residual.

The most important issue here is the imperfect appropriability of knowledge. Capital invested in producing knowledge may generate large social returns additional to the private returns to individual investors. For while modern societies almost all have patent systems that grant innovators property in the knowledge they produce, these systems almost always under-reward investment in knowledge, compared to its social benefits, for a number of reasons.

1. New techniques generate some consumer surplus which the producers cannot appropriate even if they had absolute control of the knowledge their activity resulted in. As long as the patent holder cannot engage in perfect price discrimination, consumers will derive some surplus from the knowledge (see Jones (2002)).

2. 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. Thereafter the knowledge becomes public property, generating no return to the investor.

3. Other producers can often circumvent the patent and still use the knowledge by mimicking the original innovation and produce competing products not covered by my patent.

4. 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 can be carried 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 must be

$$g_{Q/L} = a^* g_{K/L} + a_H g_{H/L} - c g_L + g_A$$

(11)

where $a^*$, where $a_k^* > a_K$, and hence $a_k^* + a_H + b + c > 1$. 

If most economic growth is going to stem from capital investment, however, then the true coefficient on capital, $a^*$, has to be up to three times the payments to capital as a share of national income. Indeed since as we see from table – the growth rate of capital per worker hour is typically just slightly faster than the growth rate of output per worker hour, the true coefficient on capital would have to be close to 1. That is the social return from investing $1 in capital has to be three times as big as the private return, so the external benefits have to be three times as great as the private benefits.

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 5, 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, from which we derived the fundamental equation of economic growth, can also be written as

$$g_A = \frac{\Delta Q}{Q} - r \frac{\Delta K}{Q} - w \frac{\Delta L}{Q} - s \frac{\Delta Z}{Q}$$

(12)

where $\Delta K/Q$ is net investment as a share of GDP, and $r$ is the rental rate per unit of capital (including depreciation allowances). If R&D investment had an extra social rate of return, $r_s$, then the correct expression for productivity growth would be
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 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 $\beta$ in the following regression

$$g_{A_i} = \alpha + \beta \frac{\Delta K_{R&D_i}}{Q_i} + \varepsilon_i.$$  

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 $\beta$ 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 (13) above, $\beta$ will measure the extra social rate of return accruing to R&D investments.

Griliches estimates $\beta$ 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 $\beta$ is either less than 0.32 or greater than 0.60. For the earlier period 1958 to 1973 the estimated value of $\beta$ 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 yielded an annual rent above what the investors received of between $0.33 and $0.46. These social gains that are close to the 50% returns needed to eliminate the residual as an important factor in economic growth.

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. This conclusion has powerful implications for government policy. It suggests that there should be very substantial government subsidies directed towards investments in knowledge. Alternatively there should be measures to make knowledge more appropriable. Though this would have profound consequences for the distribution of income, reducing the earnings of unskilled labor relative to the skilled workers engaged in knowledge production dramatically.

The Role of Physical Capital in Economic Growth

The fundamental equation of economic growth, (7) above, seems to suggest that growth since the Industrial Revolution has had two independent sources. Most important there is
efficiency growth fueled by investment in “knowledge capital” which has large social external
benefits that show up in the residual. But there is also a substantial independent contribution
from investments in physical capital and human capital, which explains 30-50% of the growth in
income per person. However if investments in “knowledge capital” created the measured
efficiency gains, then these knowledge investments also generated the accumulation of physical
and human capital. For if efficiency advances (generated by investments in knowledge) and
physical and human capital are 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. In a more
efficient economy the last unit of capital employed will increase output by more than before.
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, as we shall see, 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 have generally 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,

\[ mp_k = \alpha \frac{Q}{K} \]

⇒

\[ K = \frac{\alpha}{r} Q \]

Because of this the growth rate of capital will also equal the growth rate of output. 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 (7) becomes

\[ g_{QL} = \left( \frac{1}{1 - a} \right) g_A - \left( \frac{c}{1 - a} \right) g_L \]  \hspace{1cm} (16)

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.

**The Agenda**

We see above that the most plausible way to explain economic growth in the advanced economies since the Industrial Revolution is that investments in “knowledge capital” starting
around 1800 generated great social externalities, which increased the measured efficiency of the economy, and with it the stock of physical and human capital. Thus the path to explaining the economic history of the world is clear. All we need explain is why there was in all societies in the millennia before 1800 such a limited investment in the expansion of production knowledge, and why this changed for the first time in Britain some time around 1800. Then we will understand the history of man.
References


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<td><strong>North America</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>USA</td>
<td>10,703</td>
<td>16,351</td>
<td>33,293</td>
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<td>Canada</td>
<td>9,093</td>
<td>14,102</td>
<td>26,904</td>
</tr>
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<td>Mexico</td>
<td>2,990</td>
<td>5,522</td>
<td>8,762</td>
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<td><strong>Europe</strong></td>
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<tr>
<td>France</td>
<td>5,429</td>
<td>12,336</td>
<td>22,358</td>
</tr>
<tr>
<td>Sweden</td>
<td>-</td>
<td>14,828</td>
<td>23,635</td>
</tr>
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<td>Switzerland</td>
<td>10,451</td>
<td>20,611</td>
<td>26,414</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>7,525</td>
<td>12,085</td>
<td>22,190</td>
</tr>
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<td>Germany</td>
<td>-</td>
<td>12,428</td>
<td>22,856</td>
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<tr>
<td><strong>South America</strong></td>
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<td></td>
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<tr>
<td>Argentina</td>
<td>6,430</td>
<td>9,265</td>
<td>11,006</td>
</tr>
<tr>
<td>Brazil</td>
<td>1,655</td>
<td>3,620</td>
<td>7,190</td>
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<tr>
<td><strong>Asia</strong></td>
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<td></td>
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<tr>
<td>Hong Kong</td>
<td>-</td>
<td>6,506</td>
<td>26,699</td>
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<td>India</td>
<td>705</td>
<td>1,073</td>
<td>2,479</td>
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<td>Japan</td>
<td>2,227</td>
<td>11,474</td>
<td>24,675</td>
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<td>Korea</td>
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<td>2,716</td>
<td>15,876</td>
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<td>Taiwan</td>
<td>-</td>
<td>2,790</td>
<td>-</td>
</tr>
<tr>
<td><strong>Africa</strong></td>
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<tr>
<td>Egypt</td>
<td>1,371</td>
<td>1,970</td>
<td>4,184</td>
</tr>
<tr>
<td>Kenya</td>
<td>694</td>
<td>821</td>
<td>1,244</td>
</tr>
<tr>
<td>Nigeria</td>
<td>752</td>
<td>1,113</td>
<td>707</td>
</tr>
<tr>
<td>Uganda</td>
<td>539</td>
<td>608</td>
<td>941</td>
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<tr>
<td><strong>Oceania</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>9,174</td>
<td>14,820</td>
<td>25,559</td>
</tr>
</tbody>
</table>

*Note:* GDP per capita computed using the chain method.

*Source:* Penn World Tables Alan Heston, Robert Summers and Bettina Aten, Penn World Table Version 6.1, Center for International Comparisons at the University of Pennsylvania (CICUP), October 2002.
Figure 1: Real Output per Person and Population, England 1260-9 to 1860-9
Figure 2: Real GDP per person in England, 1260s-1990s
Figure 3: The Share of Farmland Rents in National Income, England 1260-2000
Figure 4: Efficiency versus Capital per Worker

Source: Penn World Tables, Version 5.6.
Table 3: Economic Growth Since the Industrial Revolution

<table>
<thead>
<tr>
<th>Country</th>
<th>Years</th>
<th>Growth rate of Q/L (%)</th>
<th>Growth rate of K/L (%)</th>
<th>Contribution of capital accumulation to growth (%)</th>
<th>Share of output growth explained by capital accumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Britain</td>
<td>1950-80</td>
<td>2.05</td>
<td>3.07</td>
<td>0.74</td>
<td>37</td>
</tr>
<tr>
<td>Germany</td>
<td>1950-80</td>
<td>4.35</td>
<td>5.24</td>
<td>1.31</td>
<td>30</td>
</tr>
<tr>
<td>USA</td>
<td>1950-80</td>
<td>1.92</td>
<td>2.59</td>
<td>0.65</td>
<td>34</td>
</tr>
<tr>
<td>Japan</td>
<td>1950-80</td>
<td>6.67</td>
<td>6.90</td>
<td>1.72</td>
<td>26</td>
</tr>
<tr>
<td>India</td>
<td>1950-80</td>
<td>1.34</td>
<td>2.76</td>
<td>0.69</td>
<td>51</td>
</tr>
</tbody>
</table>

Note: *Capital growth rate not known, set equal to output growth. The share of capital in national income is assumed to be 0.25.*
Table 4: The Replacement Cost of the Human Capital Stock in the USA, 2000

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

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 5: The UK Capital Stock in 1990

<table>
<thead>
<tr>
<th>Type of capital</th>
<th>Share in stock</th>
<th>Share in rental payments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings</td>
<td>72%</td>
<td>54%</td>
</tr>
<tr>
<td>Intangibles</td>
<td>1%</td>
<td>3%</td>
</tr>
<tr>
<td>Plant and Machinery (not vehicles)</td>
<td>17%</td>
<td>31%</td>
</tr>
</tbody>
</table>

Source: (Oulton, 2001)