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Why and How Education Affects Economic Growth

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Abstract

This paper suggests an additional channel through which education affects economic growth. If growth is driven by industrialization of production, where machines replace labor in a growing number of tasks, then operating these machines requires workers who are educated, namely literate and know arithmetic, whose human capital is less specific and more general. As a result, technology adoption depends negatively on wages of educated workers. Hence, economic growth depends negatively on the cost of education or on the barriers to acquire education. The model shows that if the cost of education is high, economic growth might be slow and even stop completely, creating a development trap.

1. Introduction

Many empirical international growth studies have shown that education has a positive effect on economic growth. This has been shown already in the early growth regression studies of Barro (1991), Barro and Sala-i-Martin (1992, 1995), and many others that followed them. The main explanation for this finding has been the human capital theory. Namely, educated workers have higher human capital and thus higher productivity, so if a country has more educated workers, it has higher productivity. Recently researchers have tried to quantify the human capital effect by using the results of many microeconomic studies that have measured the effect of education on workers' productivity across countries and over time.[1] These studies, which are summarized in Caselli (2005), have found that differences in human capital can explain at most 40% of the differences in output per worker across countries. This paper claims that education has a strong indirect effect on economic growth in addition to the direct human capital effect, since educated workers are required for industrialization and mechanization.

The industrial revolution and the educational revolution coincided in the nineteenth century and were probably intimately related. Clearly, the educational revolution had other motives as well, like the religious motive of the Reformation, or the national motive that came with the birth of nation states at that time. But obviously the economic effect played a significant role as well. The industrial revolution created an ever-increasing demand for educated workers. Both the mechanization of production and the increase in the scale of production changed dramatically the whole character of producing and marketing. It now required new skills, of reading, writing, and arithmetic. The need to handle and operate machines and to take care of them required some knowledge in science and engineering and at least some literacy skills, to read manuals, to correspond with producers on problems in machines, etc. The change in scale of

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production also required workers with such skills, since managing and marketing on a much larger scale requires planning, correspondence, more complex calculations, etc.

It is important to stress that the need for education, which emerged with the industrial revolution, should not be confused with demand for skill or for human capital per se. That existed prior to the industrial revolution as well, as we know that there has been significant professional education in that period, mainly through apprenticeships. But industrialization changed the *type of human capital* required for production. While prior to the industrial revolution human capital was mainly specific to the profession, the industrial revolution created demand for more general human capital, which included the ability to read, to write, and to perform calculations. Hence, while the apprenticeship system could provide most of the required human capital prior to the industrial revolution, following it there was increasing demand for people who have a much broader and flexible human capital, which can be acquired only at schools. This paper shows that this need for educated workers created an obstacle to economic growth. This obstacle could be removed only by reducing the barriers to education, which was done mainly by public supply of education. The paper further shows that the barriers to education affect growth mainly through the wage of educated workers. For less developed countries a relatively high wage of educated workers has a negative effect on economic growth. Interestingly, for developed countries this paper finds an opposite effect. The higher the wage of educated workers, the greater is the growth of output per worker.

To analyze the need for education in the process of industrialization the paper uses a model of industrialization, where machines replace labor in a growing amount of tasks. Such models have been initiated by Champernowne (1963) and have been later developed in various directions in Zeira (1998, 2008), and Alesina and Zeira (2007).[2] This paper extends these models in the following way. A new innovation introduces a machine that replaces workers in a specific task, but also affects the type of workers required in another task, from non-educated workers to educated ones. One example could be that once a weaving machine replaces manual weavers, the task of managing production changes and involves taking care of the machines and also handling a much larger quantity of output. Thus it requires educated labor.

If the new technology involves replacing factors of production, where non-educated labor is replaced by capital and by educated labor, then technology adoption depends crucially on the prices of the factors of production. Hence, high wages of non-educated labor promote technology adoption, while high wages of educated labor reduce technology adoption. The paper calculates the equilibrium wages and finds that barriers to education have a negative effect on technology adoption and on economic growth. Note, that if the economy is relatively developed and all the jobs are performed by educated labor, further technology adoptions require replacing educated workers by machines. At this stage, the role of educated wages is reversed and it has a positive effect on technology and growth.

This paper shows that education in a country has not only a positive effect on the rate of growth of individual economies, but barriers to education can hold an economy in a stagnant equilibrium without growth. Namely, high cost to education can even cause development traps. This paper therefore contributes to the explanation of the large international divergence of economic growth, which intensified significantly from the industrial revolution until nowadays.[3] The paper also shows that the large international differences in output, which can be caused by differences in education, are much larger than the differences in directly measured human capital. Namely this model offers a partial solution to the puzzle raised by Caselli (2005) and by other development accounting studies. According to this model, although differences in human capital account for only 40% of the differences in output across countries, differences in education explain a much larger part of international output differentials. Hence, education accounts for much more than 40% of output differentials.[4]

The paper is organized as follows. Section 2 presents the model, while section 3 solves the equilibrium. Section 4 analyzes technology adoption and section 5 discusses the patterns of economic growth. Section 6 shows that international output differences caused by education are much larger than differences in human capital and section 7 summarizes.

2. The Model

Consider a small open economy, where a single physical good is produced, which is used both for consumption and for investment. The good is produced by a continuum of tasks, which are ordered on [0, 1]. In the pre-industrial mode of production all tasks are produced by non-educated labor and the production function is Cobb–Douglas in the various tasks:[5]

$$\ln Y = \ln a + \int_0^1 \ln L_N(j)\,dj, \tag{1}$$

where Y is output, $L_N(j)$ is the amount of uneducated labor in task j, and a is a productivity parameter of the country, which is constant over time. Assume also that time is discrete.

Technical progress comes in the form of machines that replace labor in specific tasks or jobs. Thus, a machine invented in period $t-1$ for task j can replace labor in task j from period t on. A machine that replaces a single unit of labor in this task consists of $k(j)$ units of capital, namely of the final good, and the function k is assumed to be increasing. This means that tasks are ordered by increasing complexity. Also assume that capital has to be invested one period before production and the time period is sufficiently long so that all capital depreciates in one period. Hence, the rate of depreciation is 1. It is further assumed that invention of such machines is costless, namely that the cost of a machine embodies only its physical costs, but not the return to innovator. This assumption is made for simplification only.[6]

Let us next assume that industrialization of task j changes an additional task as well, as the need to operate a machine is different than working with a manual technology, as explained in the introduction. The additional task, denoted by s_j, now requires an educated worker instead of uneducated worker. For simplicity, we do not specify s_j but just assume that it is in the upper half of tasks, namely: $s_j \in [0, \frac{1}{2}]$. Clearly the mapping s must be one-to-one, namely if $j > i$ then $s_j \neq s_i$, since each new mechanized task requires education in a different job. It is further assumed that once all labor tasks are performed by educated workers, an industrialization of any additional task does not involve turning another task to educated labor.

Let f_t denote the global technology frontier, where it is assumed that machines are invented by order of complexity, namely by order of j. Since investment in machines must be taken one period ahead of time, it means that machines for all tasks in $[0, f_t]$ that can be used in production from period t on, have been invented already in period $t-1$ and before. It is further assumed that invention is not immediate for all machines. Knowledge progresses gradually, and some machines can be invented only after previous ones were invented and experienced for some time. Hence it is assumed that the global technology frontier progresses in the following way:

$$f_t - f_{t-1} = d(1 - f_{t-1}). \tag{2}$$

Namely, in each period the number of machines invented declines, as they become more and more complicated, and the rate of invention depends on the amount of remaining manual tasks.[7]

Not all innovations are necessarily adopted in each country, as shown below. Denote the set of innovations adopted for production in period t by M_t, $M_t \subseteq [0, f_t]$, denote the set of tasks performed by non-educated labor by N_t and the set of tasks performed by educated labor by E_t. Also denote the amount of capital used in task j by $K_t(j)$, and the amount of educated labor used in task j by $L_{E,t}(j)$. Then from equation (1) it follows that output in period t is equal to:

$$\ln Y_t = \ln a + \int_{M_t} \ln\left[\frac{K_t(j)}{k(j)}\right] dj + \int_{N_t} \ln L_{N,t}(j)\, dj + \int_{E_t} \ln L_{E,t}(j)\, dj. \tag{3}$$

Note that if the measure of M_t is m_t, then this is also the measure of the educated jobs E_t, since the mapping s is one-to-one and each such job is created by a new innovation. Hence, the measure of jobs that do not require education N_t is equal to $1 - 2m_t$. If all non-educated jobs have been replaced by machines, equation (1) implies that output is equal to:

$$\ln Y_t = \ln a + \int_{M_t} \ln\left[\frac{K_t(j)}{k(j)}\right] dj + \int_{E_t = M_t^c} \ln L_{E,t}(j)\, dj. \tag{4}$$

Individuals in this economy live for two periods each in overlapping generations. The choice of such a modeling assumption is obvious, since education bears fruit only while an individual is alive, and is not transferred to offspring. Thus it should better be analyzed in a finite lifetime model rather than in an infinite lifetime framework. There is no population growth and a generation is a continuum of size 1. Each person supplies one unit of labor when young and retires in the second period of life. An individual can choose between acquiring education or not, but education requires effort, which is costly in terms of utility. The utility function of an individual born in period t is assumed to be:

$$U = (1-\beta)\ln c_1 + \beta \ln c_2 - I_E \ln e, \tag{5}$$

where c_1 is consumption in the first period of life, c_2 is consumption in the second period of life, and I_E is the indicator function for acquiring education. The term $\ln e$ is the disutility from education, and it is assumed that $e > 1$, and that e is country specific and is negatively related to access to education in the country. We call e the cost of education or the barrier to education. It reflects many realistic factors that affect access to education, like social and ethnic barriers to education, imperfections in credit markets, and also insufficient public education.

As mentioned above, this is a small open economy. Assume that there is full capital mobility and that the world's interest rate is fixed and equal to r. Denote the gross interest rate, or the sum of the interest rate and the rate of depreciation, by $R = 1 + r$.

3. Equilibrium

Since the economy is fully integrated with the world's capital markets, the domestic interest rate is equal to r. Denote the wage of non-educated workers in period t by $w_{N,t}$ and wage of educated workers by $w_{E,t}$. Hence, firm's profits in period t are:

$$Y_t - R\int_{M_t} K_t(j)\,dj - w_{N,t}\int_{N_t} L_{N,t}(j)\,dj - w_{E,t}\int_{E_t} L_{E,t}(j). \tag{6}$$

Using the production function (3) we get the following first-order conditions with respect to the quantities used in production:[8]

$$\frac{Y}{K(j)} = R \tag{7}$$

for capital, and

$$\frac{Y}{L_N(j)} = w_N \tag{8}$$

for non-educated workers, and

$$\frac{Y}{L_E(j)} = w_E \tag{9}$$

for educated workers. If there are no longer manual jobs and all workers are educated, production is described by equation (4) and the relevant first-order conditions are only equations (7) and (9).

To calculate equilibrium wages note that if the factor inputs, as derived from the first-order conditions, are substituted in the production function (3), we get the following equilibrium condition:

$$\ln a - m\ln R - m\ln w_E - (1-2m)\ln w_N - \int_M \ln k(j)\,dj = 0. \tag{10}$$

We next turn to individual utility maximization in order to derive an additional relation between the wages of educated and non-educated labor. Maximizing utility (5) we get that a person who earns w in the first period of life, consumes $(1 - \beta)w$ in the first period and βwR in the second period of life. Hence the difference in utility between acquiring education and not acquiring education is equal to:

$$\ln w_E - \ln w_N - \ln e.$$

It therefore follows that the ratio between equilibrium wages of educated labor and non-educated labor must be e:

$$\frac{w_E}{w_N} = e. \tag{11}$$

Substituting (11) in equation (10) leads to the following equilibrium condition that determines the equilibrium wage of non-educated workers w_N:

$$\ln w_N = \frac{\ln a - m\ln R - m\ln e - \int_M \ln k(j)\,dj}{1-m}. \tag{12}$$

If all jobs are for educated labor, namely if more than half of the tasks have already been industrialized, the wage of educated workers w_E can be calculated in a similar way and is equal to:

$$\ln w_E = \frac{\ln a - m\ln R - \int_M \ln k(j)\,dj}{1-m}. \tag{13}$$

4. Technology Adoption

As mentioned above, not all available technologies are everywhere adopted. The reason for that is that although the new technology reduces labor and saves labor costs, it requires purchasing a machine, which is costly. It also requires hiring educated workers for some job instead of non-educated workers that did this job before and that is costly as well. Hence the technology is adopted only if it increases overall profits. Thus, we next examine the marginal profit of technology adoption. In equilibrium this marginal profit will be equalized to zero, or it might be positive if firms have reached the global technology frontier f and cannot adopt more technologies at the time. The marginal profit of adopting technology j is the derivative of the profit function (6) with respect to j. This marginal profit is equal to:

$$Y\left[\ln\frac{K(j)}{k(j)}-\ln L_N(j)-\ln L_N(s_j)+\ln L_E(s_j)\right] \\ -RK(j)+w_N L_N(j)+w_N L_N(s_j)-w_E L_E(s_j). \quad (14)$$

Substituting the first-order conditions (7)–(9) in (14) we get that the marginal profit is:

$$Y[\ln Y-\ln R-\ln k(j)-\ln Y+\ln w_N-\ln Y+\ln w_N+\ln Y-\ln w_E] \\ =Y[2\ln w_N-\ln w_E-\ln R-\ln k(j)]. \quad (15)$$

An innovation is adopted as long as profits increase, namely as long as (15) is non-negative. Hence the condition for adoption of a machine for task j, namely the condition for industrialization of j, is:

$$2\ln w_N-\ln w_E-\ln R\geq \ln k(j). \quad (16)$$

Condition (16) for technology adoption yields a number of results. First note that since k is increasing, and since technologies are ordered by complexity, if technology j is adopted all technologies $h<j$ are adopted as well. Hence, there exists a country frontier at each period t, m_t, such that $m_t \leq f_t$ and such that all the technologies $h \leq m_t$ are adopted, namely $M_t=[0, m_t]$. The variable m_t measures the degree of industrialization in the country at time t. Clearly, m_t is the maximum m in $[0, f_t]$ that satisfies the condition of industrialization:

$$2\ln w_N-\ln w_E-\ln R\geq \ln k(m). \quad (17)$$

From this condition we also learn that high wages for non-educated workers stimulate technology adoption, while high wages for educated workers have an opposite effect. The cost of machinery also has an effect on technology adoption. The higher the function k of the cost of machinery is, the smaller technology adoption is. Finally, note that if all tasks are performed by educated workers, a similar calculation shows that the equilibrium condition for industrialization is:

$$\ln w_E-\ln R\geq \ln k(m). \quad (18)$$

We can now substitute the equilibrium wage equations in conditions (17) and (18). First note that since the ratio between educated and non-educated wages is e, according to (11), then condition (17) for industrialization becomes:

$$\ln w_N-\ln e-\ln R\geq \ln k(m). \quad (19)$$

Hence, the cost of education has a negative effect on technology adoption. This is actually the main result of this paper. But we need to study the effect of e more carefully, since w_N itself depends on the cost of education e. Hence, substitute the equilibrium wage equation (12) in condition (19) and get the following condition for technology adoption:

$$\ln a - \ln R - \ln e \geq \int_0^m \ln k(j)\,dj + (1-m)\ln k(m). \tag{20}$$

This is the condition for $m < \frac{1}{2}$, as long as there are jobs for non-educated labor. In a similar way, substituting (13) in (18) shows that the condition for technology adoption when all jobs are filled by educated labor, namely when $m \geq \frac{1}{2}$, is:

$$\ln a - \ln R \geq \int_0^m \ln k(j)\,dj + (1-m)\ln k(m). \tag{21}$$

Note that the right-hand side of equations (20) and (21) is increasing with m, since:

$$\frac{d}{dm}\left[\int_0^m \ln k(j)\,dj + (1-m)\ln k(m)\right] = (1-m)\frac{k'(m)}{k(m)} > 0.$$

Denote this increasing function by $q(m)$. We can now define formally the level of equilibrium industrialization in the economy. Industrialization m_t is defined by:

$$\begin{cases} q(m_t) = \ln a - \ln R - \ln e, & \text{if } q(f_t) > \ln a - \ln R - \ln e, \\ m_t = f_t, & \text{if } q(f_t) \leq \ln a - \ln R - \ln e, \end{cases} \tag{22}$$

if $m_t \leq \frac{1}{2}$. If the solution to (22) is greater than $\frac{1}{2}$, the equilibrium industrialization m_t is defined by:

$$\begin{cases} q(m_t) = \ln a - \ln R, & \text{if } q(f_t) > \ln a - \ln R, \\ m_t = f_t, & \text{if } q(f_t) \leq \ln a - \ln R. \end{cases} \tag{23}$$

The dynamics of technology adoption can be summarized by the diagram in Figure 1. While q is the right-hand side of (20) and (21), the left-hand side of the two equations is the horizontal broken line I, which is equal to $\ln a - \ln R - \ln e$ below $\frac{1}{2}$ and to $\ln a - \ln R$ above $\frac{1}{2}$. Technology adoption follows the world technology frontier f, namely $m = f$, as long as $I(m) \geq q(m)$. In the case described in Figure 1, education costs are too high and the economy stops adopting technologies at $m^* < \frac{1}{2}$. If the curve I is everywhere above q, namely if $\ln a - \ln R - \ln e \geq q(1/2)$, then the economy experiences sustained technical change.

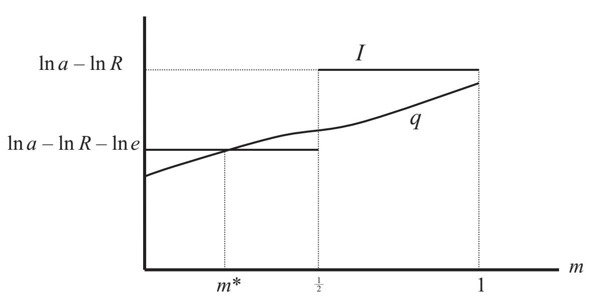

Figure 1. Technology Adoption

5. Economic Growth

In this section we analyze the patterns of economic growth in the economy, taking into consideration both situations where the economy adopts technologies and is therefore at the global technological frontier and situations where the economy is trapped and stops adopting technologies, as described in Figure 1. First, note that using the production function (3) and the first-order conditions (7), (8), and (9), we get that aggregate output as long as $m \le \frac{1}{2}$ is described by:

$$Y = a(1-2m)^{1-2m} m^{2m} K^m L_E^m L_N^{1-2m}. \tag{24}$$

Hence, output is described by a Cobb–Douglas production function in capital, educated and non-educated labor, but the shares of the factors of production are not fixed, but change with technology.

But equation (24) does not inform us much about the equilibrium level of output, since the quantities of all factors of production are endogenous. We therefore next use the information on the three factor prices. Taking the first-order conditions (8) and (9), using equation (11) on the ratio of the two wages and adding them we get:

$$Y_t = \frac{w_{N,t}}{1-2m_t + \dfrac{m_t}{e}}. \tag{25}$$

Note that the direct positive effect of the barrier to education e on output reflects the positive effect of the wage of educated workers on income. Substituting the equilibrium value of the non-educated wage (12) into equation (25) yields the following equilibrium amount of output, which is of course also output per worker:

$$\ln Y_t = \frac{\ln a - m_t \ln R - m_t \ln e - \int_0^{m_t} \ln k(j)\,dj}{1-m_t} - \ln\left(1-2m_t + \frac{m_t}{e}\right). \tag{26}$$

Note that according to equation (26) the cost of education e has two effects on output. One is the positive effect through wages of educated labor, mentioned above, and the other is the negative effect through the wage of non-educated workers. Of course, there is an additional indirect effect through the level of technology m. If m exceeds $\frac{1}{2}$ it can be shown by use of equations (9) and (13) that output is given by:

$$\ln Y_t = \frac{\ln a - m_t \ln R - \int_0^{m_t} \ln k(j)\,dj}{1-m_t} - \ln(1-m_t). \tag{27}$$

We can now calculate the rate of economic growth in the country. First, as long as line I in Figure 1 is above line q, all new technologies are adopted and $m_t = f_t$. In that case the rate of growth is (approximately) equal to the derivative of ln Y_t, in (26) or (27), with respect to the level of technology, multiplied by the change in the technology frontier (2). Hence, as long as $f_t < \frac{1}{2}$, the rate of economic growth is:

$$\frac{\Delta Y_t}{Y_{t-1}} \cong d\frac{2-e^{-1}}{1-2f_t + f_t e^{-1}} + d\frac{a - \ln R - \ln e - q(f_t)}{1-f_t}. \tag{28}$$

A similar calculation shows that if $f_t \ge \frac{1}{2}$, the rate of economic growth is:

$$\frac{\Delta Y_t}{Y_{t-1}} \cong d + d\frac{a - \ln R - q(f_t)}{1 - f_t}. \tag{29}$$

If the economy is trapped in a situation where the I and q curves intersect, there is no technology adoption and hence the rate of growth is 0. It is easy to see that as long as new technologies are adopted the rates of growth in (28) and (29) are positive and actually are higher than d. It is also easy to see that wages also rise as the economy grows.

From equations (28) and (29) and from Figure 1 it appears that economic growth depends on three main economic factors. One is the basic productivity of country a, which has a positive effect on growth. This variable can be interpreted as representing geography, and indeed empirical studies using international data have shown that geography has a significant effect on economic growth.[9] The second factor is the cost of machinery q, which has a negative effect on growth, and indeed Barro (1991) and many other empirical studies have shown that the cost of investment goods has a negative effect on growth. The third factor is the cost to education e.

As mentioned above, the cost of education e has two opposite effect on the rate of growth. One is positive, shown by the first term in (28), which reflects wages of educated workers. The second is negative, shown by the second term in (28), which reflects the effect of non-educated workers. The total effect of the cost of education is therefore ambiguous. The derivative of (28) with respect to e is:

$$\frac{d}{(e - 2ef + f)^2} - \frac{d}{e(1-f)}.$$

It can be shown that this derivative is negative for low f and positive for high f. Thus the cost of education hurts growth at the early stages of development and increases growth at higher levels. For advanced economies, for which $f_t > \frac{1}{2}$, the rate of growth does not depend on the cost of education at all.

This analysis of course paints only a partial picture of the effect of the cost of education on the rate of growth, since it applies only to growing economies. But if the costs of education are sufficiently high, the economy might find itself in a state of no growth at all. Hence the effect of education costs is not linear, but it can be quite significant, as high costs can lead to development traps. Such a trapped economy, like the one in Figure 1, can gain significantly from investing in public education, which reduces the cost of education. This can lift the curve I upward and enable the economy to grow and even escape the development trap. This effect of the cost of education on growth is due to its effect on the cost of adoption of new technologies, since these technologies, which lead to mechanization, require hiring more educated workers.

6. Education and Human Capital

This section shows that the effect of education on output can be much larger than what is implied by the direct effect of human capital. We begin by presenting this effect by application of the theory of human capital to the issue of international output differences, following Caselli (2005) and others. The theory can be described by use of a Cobb–Douglas production function $Y = AK^{\alpha}(hL)^{1-\alpha}$, where h measures human capital in the country, calculated by applying standard coefficients from wage regressions to average years of schooling. Normalizing the labor force L to 1, as in our model, and assuming full capital mobility at the global interest rate r, and that all countries face the same rate of depreciation d, we get that output (per worker) is:

$$Y = hA^{\frac{1}{1-\alpha}}\left(\frac{\alpha}{r+d}\right)^{\frac{\alpha}{1-\alpha}}. \tag{30}$$

Hence, output should be proportional to human capital and vary similarly. In contrast, Caselli (2005) and others have found that output is much more volatile than h.

We next identify in our model the counterpart of human capital h. The measure we construct for human capital in the model is:

$$eL_{E,t} + L_{N,t}. \tag{31}$$

This measure normalizes the productivity of a non-educated worker to 1 and the productivity of an educated worker is e, namely productivities are proportional to the respective wages. Actually, this is similar to the measure used by Caselli (2005), except that he uses the global wage patterns and measures local average years of schooling, while in our model we use the direct local wage ratio, which is of course related to average schooling.

To calculate the above measure of human capital in the economy we calculate the amounts of educated and non-educated workers respectively from the first-order conditions (8) and (9) and get:

$$L_{E,t} = \int_{E_t} L_E(j)\,dj = m_t \frac{Y_t}{w_{E,t}}$$

and

$$L_{N,t} = \int_{N_t} L_N(j)\,dj = (1-2m_t)\frac{Y_t}{w_{N,t}}.$$

Substituting in (31) we get the following relation:

$$\frac{Y_t}{eL_{E,t} + L_{N,t}} = \frac{w_{N,t}}{1-m_t}. \tag{32}$$

Equation (32) proves the main claim of this section, since it shows that the fluctuations in output are much larger than the fluctuations in human capital. The left-hand side of equation (32) is the ratio between output and human capital. If the only effect of education is the direct human capital effect, this ratio should be constant, as implied by (30). But in our model this ratio increases with industrialization significantly, as is shown by the right-hand side of equation (32). An increase in m raises the wage of non-educated workers w_N, and it also reduces the denominator in the right-hand side. Hence, (32) increases significantly with m. As countries differ in their technological level m because of differences in education costs e, these differences cause much larger differences in output than what is implied by the theory of human capital, especially if we compare countries at the technology frontier with countries stuck at a low industrialization level m. Hence this paper finds that the effect of education on economic growth, through the barriers it might create to industrialization, is much greater than what is implied by the direct effect of human capital.

7. Conclusions

This paper attempts to supply an additional explanation to the effect of education on economic growth. It is based on acknowledging that the process of industrialization and mechanization is crucial to economic growth. This process consists of using more and more machines to replace a growing number of tasks, which have been previously produced by labor. This change in the mode of production affects not only the tasks replaced by machines, but also other tasks, which are close to them. In other words, using more machinery changes other jobs: those who operate the machines, those who need to handle larger amounts of output, those who have to keep maintenance of the machines, etc. Thus industrialization not only replaces some jobs by machines, but also changes the type of other jobs. Clearly the main change is the decline of the old type of human capital, which was artisan-specific or profession-specific, to a more general human capital, that can be easily adjusted to a rapidly changing mode of production. This general human capital consists mainly of literacy, basic knowledge of science, and basic knowledge of arithmetic and mathematics. In other words, the process of industrialization requires for more and more tasks workers who have school education.

As a result, the adoption of new technologies requires replacing non-educated workers both by machines and by educated workers. Hence, the adoption of technology depends crucially on the prices of these factors of production. High wages of non-educated workers are conducive to growth, while high wages of educated workers deter technology adoption and economic growth. Hence, education has an effect on the equilibrium rate of growth and it can even stop growth altogether if it is too expensive. The way education affects growth is through the relative wage of educated workers, namely through the returns to education. If these are too high, reflecting high barriers to education, growth is reduced and might even come to a stop.

There is vast empirical support to the result that education is important to economic growth, but we should be cautious in interpreting it as empirical support to the main claim of this paper. First, it is hard to show that the causality runs from education to economic growth and not the other way around. Secondly, our main variable e, the barrier to education, is not observable. It reflects many economic factors, like social or ethnic barriers, imperfections in capital markets, difficulty of raising funds by government for investment in public education, and more. We could use proxy variables, like the relative wage of educated to non-educated workers, or the number of educated workers, as done in most growth regressions, but these are to some extent endogenous variables. Another difficulty in measuring the effect of education that is analyzed in this paper is that it is nonlinear. Hence, it might be hard to find such a relation in a standard empirical study.

We next discuss in brief a few policy implications of the theory. One clear implication that holds especially for less developed countries is that public education might supply a trigger for economic growth and can pull a country out from the current state of poverty. But we should be rather careful in subscribing such a recommendation. First, it could be that a country is poor and stuck at a development trap not only due to high e, but also due to low a, which may be a result of tropical location, being landlocked, or suffering from insufficient infrastructure. In such a country building public education might help, but in order to get out of the development trap some additional investments might be necessary. A second problem of this policy implication is of finance, since a government in a poor country cannot raise enough revenue to finance a good system of public education. And the problem is not only financial. In order to build a system of public education there is a need to train a sufficient number of teachers, and in a poor economy, where every hand is needed in the field, this might be a hard policy to implement. Nevertheless, the vast empirical evidence on the importance of education, and the argument that is made in this paper, lead us to believe that any attempt to overcome development traps must include a significant increase and improvement of public education, in order to reduce the existing barriers to education.

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Notes

1. Early examples for such studies are Klenow and Rodríguez-Clare (1997), Hall and Jones (1999), and many others.
2. This approach is indebted also to Habbakuk (1962) and to the literature on induced technical change initiated by Kennedy (1964). Recently there have been more papers that follow this line of research, on capital that replaces labor as crucial to the process of economic growth; see Givon (2006), Peretto and Seater (2006), and Zuleta (2008). See also Beaudry and Collard (2002) and Saint-Paul (2006). Three recent papers that model replacing unskilled by skilled workers as in this paper, but for very different purposes, are Acemoglu and Zilibotti (2001), Caselli and Coleman (2006), and Zeira (2007).
3. This divergence is described in Maddison (1995), Pritchett (1997), and Bourguignon and Morrison (2002).
4. This result has some similarity to the claim of Galor and Moav (2000) that human capital can help speed technical progress, since educated workers cope better with new technologies. This paper differs in stressing a different mechanism. It argues that education is required for industrial production and is thus crucial to the process of industrialization.
5. We can add structures capital to the production, since most capital was structures prior to the industrial revolution, as shown by Maddison (1995, ch. 2). But since it has no effect on the results of the analysis and just makes the presentation more cumbersome, we leave it out. We can also add some educated jobs which existed prior to the industrial revolution, mainly in services, like government, law, religion, etc. Again, it would not change the main results of the analysis.
6. There is a justification for this assumption. First, if machines are used by many producers, each covers a small part of the invention costs, which become negligible relative to the physical costs of building the machine. See Zeira (2008) for elaboration of this argument.
7. See Jones (1995), Kortum (1997), and Segerstrom (1998) for a similar argument in R&D-based growth models.
8. Whenever possible, time subscripts are deleted.
9. See the work of Sachs (2001) and others. Acemoglu et al. (2005) also acknowledge the effect of geography on growth, but attribute it to institutions rather than to direct geographic effects.