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ENDOGENOUS GROWTH AND

THE MANUFACTURING REVOLUTION*

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Abstract

Manufacturing is undergoing a revolution. Teamwork, job-rotation, multitasking are superseding the Taylorist mode of organization. The skilled workforce, armed with automated machines, is gradually substituting and replacing the unskilled. At the same time the U.S. economy is experiencing record breaking growth. Is faster growth a consequence of this manufacturing revolution? We study this by inserting dynamic career choice into endogenous growth by human capital accumulation. The answer is affirmative: The gradual substitution of the unskilled by the skilled boosts the long-term growth trend. The model also explains worsening wage inequality between as well as within the skilled groups.

Key words*:* human capital growth, manufacturing revolution, wage inequality

JEL Classification: 040

1. Introduction

We are living in an exciting period of our time. After a century of economic development built on division of labor, specialization and the exploitation of scale economies, the mode of operation in manufacturing is "undergoing a revolution".[1] Recently Lindbeck and Snower (1996) write, "Charlie Chaplin at the conveyor belt, in the movie *Modern Times*, is no longer the prototypical worker" (p.315). Likewise, the meaning of 'scientific management' has been completely revolutionized since the days of Frederick Taylor (1911). The Taylorist method of timing work efficiency by stopwatches, providing incentives by piece-rate pay, separating planning from operations, and delineating authority rigidly are now grossly obsolete. Modern industrial catchwords are teamwork, multitasking, job rotation, 'just-in-time' and 'total quality' management.

The obvious question is this: If the modus operandi in manufacturing and scientific management is being revolutionized, what happens to the engine of growth? Such 'holistic' organizations, to borrow Lindbeck and Snower's term, are thought to have spread in the United States in the 1980's.[2] By 2000 all US growth records were broken since records began in 1850, with the economy forging ahead at a prolonged 3-4 percents growth instead of the 1-2 percent earlier.[3] Is this all a coincidence? Are the growth miracle and the manufacturing revolution connected? Are we seeing a glimpse of at least some tendency of higher sustainable growth in the long run?

To reexamine the growth engines we could look into human capital accumulation (Lucas, 1988), horizontal innovation (Romer, 1990), or vertical innovation (Aghion and Howitt, 1992) for evidence and clues. In this paper I restrict my attention to the first of these three channels.[4] Our question may be rephrased as follows. What are the impacts of modern manufacturing and management on the mechanics of human capital accumulation, and in turn on the speed of endogenous long-term growth? An immediate task, which will occupy the remainder of this brief introductory section, is to contrast the old manufacturing mode with the new, with a view to identify useful building blocks to modify the growth mechanics of Lucas (ibid.).

In the traditional Taylorist factory each worker performs a relatively simple task, supposedly driven to his/her maximum productivity via specialization and scale economies. This had two effects on workers and their skills. On the one hand it 'degrades' and thus reduces the demand for skills.[5] On the other hand, it makes the unskilled worker an indispensable part of the production process. Everyone in the vertical organizational structure is assigned a specific and specialized task. Each task may be repetitive and meaningless, but production could not have carried on without this army of the unskilled. By substituting and thus supplanting the craftsman's skill as an essential part of manufacturing, the mass production machine in the Taylorist factories have also made the unskilled a *complementary* and indispensable part of the production process.

The modern manufacturing unit differs from the Taylorist one in two important respects. First, the relentless progress of automation has superseded much of the single-purpose operation that once so degraded the work and the dignity of the unskilled. Second, the horizontal 'holistic' structure, the emphasis on decentralized decision-making and information sharing have greatly reduced the hierarchical distance between job-designations. The demand for skills has increased. By the same token the unskilled are in ever-decreasing demand. Gradually they are substituted out of production by automation, teamwork and multitasking. It is almost ironic that the Taylorist organization degraded yet preserved the indispensability of the unskilled. By contrast the modern organization has lifted the demand for skills, and yet it begins to squeeze the unskilled out of the production equation.

Thus the relationships between capital, skilled and unskilled labors have clearly been transformed from the days of Taylor. It is this shift in factor relations that I want to incorporate into and modify Lucas's growth engine. There has been considerable evidence, both theoretical and empirical, pointing to the fact that capital is complementary to skills.[6] But Goldin and Katz (1998) point out that this capital-skill complementarity is a relatively recent phenomenon. In the early history of automobile production, technological advances together with physical capital substituted for skilled labor, only later advances such as automation complemented it.

Much of the discussions on capital-skill complementarity and skill-biased technological change have concentrated on the skilled. How about the unskilled? Fallon and Layard (1975) show that it is useful to treat capital and skilled labor as a complementary composite unit, which is then taken to be substitutable to the unskilled in a two-level CES production function. To focus on human capital accumulation as much as possible I want largely to abstract from physical capital.[7] It turns out that it suffices to consider the skilled-unskilled relation alone in a production function such as $f(s, n)$, with s and n standing respectively for units of the skilled and the unskilled ('raw' labor). The manufacturing revolution is therefore construed in our simple model as shifts in the relations between s and n. To reiterate, in the Taylorist, mechanical, and vertical structure the skilled are more *complementary* to the unskilled. Substitution for the unskilled was limited until the advent of automation. By contrast, in the modern organization teams of skilled engineers (armed with automated machines) have become increasingly more *substitutable* for the unskilled.

Abstracting from physical capital produces results that are simple and intuitive. It is good to state the intuition of our main conclusions at the outset. We wish to study growth driven by human capital accumulation. But human capital is embodied only in the skilled, who improve over time through education. The unskilled do not train and they stagnate by comparison. Preserving a large unskilled workforce, like in the Taylorist factory, retards growth. Automation and the modern organization release and induce more labor to accumulate human capital, which stimulates growth. The answer to the question posted earlier is a positive one: The manufacturing revolution unambiguously raises the sustainable growth trend.[8] In addition, our model shows that this process worsens not only the wage disparity between the skilled and the unskilled, but also that within the skilled profession itself. The intuition is again simple. The larger between-group disparity is needed to induce more workers to train and to stay longer in schools. But some less intrinsically able individuals will have to be included into the augmented skilled profession. The greater wage disparity within the skilled group is a direct reflection of greater heterogeneity among them.

In terms of modeling, our paper brings together two dynamic mechanisms from the recent theoretical literature. The first one is the Uzawa (1965) and Rosen (1976) model of human capital accumulation, simplified and adopted by Lucas (ibid.) as the centerpiece of the mechanism of endogenous growth. The second is the dynamic mechanism of career choice between the skilled and unskilled, featuring in various ways in recent papers on wage inequality (Galor and Zeira, 1993; Eicher, 1996; Galor, Oded and Tsiddon, 1997;

Acemoglu, 1998; Galor and Moav, 2000; Eicher and Garcia-Penalosa, 2001). Our contribution is to show that inserting endogenous career choice into the Uzawa - Rosen - Lucas framework can shift endogenous growth trend rates, and at the same time explains wage inequality.

The remainder of this paper is organized as follows. The next section connects of human capital accumulation and career choice. Section three establishes the results under two corner solutions of perfect substitutability and complementarity. Section four shows that the result holds in non-corner situations. Section five is concerned with wage disparities. Section six summarizes and concludes.

2. The Dynamics of Growth and Career Choice

Lucas (1988) adopts a simplified linear version of the Uzawa (1965) and Rosen (1976) mechanism linking the rate of human capital accumulation to its level. The Lucas growth engine (in discrete time periods) is

$$h(t+1) - h(t) = h(t)\delta[1 - u(t)], \tag{1}$$

where $h(t)$ is current level human capital, δ is the constant "effectiveness of investment in human capital", and $[1 - u(t)]$ is the proportion of time a *representative individual* spends off work training.

Our first step is to abandon the *representative individual* assumption and to distinguish the skilled from the unskilled. Every citizen is different and would choose to attend school for varying amounts of time. Ignoring population growth we denote the constant population size by *L*. Equation (1) becomes

$$h(t+1) - h(t) = h(t)\delta\int_{i=1}^{L}[1-u_i(t)]di. \tag{2}$$

The size of the integral term $\int_{i=1}^{L}[1-u_i(t)]di$ depends on endogenous career choice in the economy. Since $\int_{i=1}^{L}[1-u_i(t)]di$ increases with (a) the proportion of L who choose to train in order to join the skilled, and (b) the amount of time each individual spends on training, so do the speed of human capital accumulation and the rate of growth.

Each discrete time period have unit length. Suppose in any t the economy has one final perishable product $x(t)$ produced with a constant returns to scale technology using two inputs, namely (*effective* units of) skilled labor $s(t)$, and ('raw' units of) unskilled labor $n(t)$. The particular production technology will be specified later but for the moment we take it in general as

$$x(t) = f[s(t), n(t)]. \tag{3}$$

At the beginning of each period a generation of size L is born. Each individual lives for a single period in which he/she trains, works, consumes and at the end passes away without material bequest. Much of the career choice dynamics hinges on the description and composition of $s(t)$.

Lucas (ibid.) stresses the point that human capital accumulation is a *social activity*. In the present context the external effect of this activity takes the form of knowledge augmented and passed on one generation to the next. At birth a generation t inherits knowledge level $h(t)$ from their forefathers, augmenting it through training (education) in the form of (2), and passes it on to their offspring in t+1. Let the aggregate effective skilled labor units at period t be

$$s(t) = h(t)\int_{i=1}^{z(t)} u_i(t)\, di \tag{4}$$

where $h(t)$ as specified earlier is inherited human capital level, $z(t)$ is the total 'headcount' of the skilled workforce. The *i*th skilled worker devotes a portion of his/her unit time endowment $0 \le u_i(t) \le 1$ working instead of training, $i \in [1, z(t)]$. In so doing, the *i*th skilled worker offers $s_i(t) = h(t)u_i(t)$ units of effective skilled labor power for productive employment. Without loss of generality the constant population size is henceforth set to unity. It follows that $z(t) + n(t) = L = 1$.

Let $a_i(t)$ denote individual *i*'s intrinsic (cognitive) ability at birth prior to training (if any). Assume further $a_i(t)$ is uniformly and independently (and time-invariantly) distributed along the unit segment, $a_i(t) \in [0, 1]$. Unskilled labors use instead raw physical strength, which is assumed constant across the population. Unskilled wage (equal to earnings per head at *t*), denoted $w^n(t)$, is therefore identical across the unskilled workforce. The earnings of a skilled worker, by contrast, depend on the skilled wage, the time he/she spends at work, and the inherited human capital level. Thus we have

$$w^z(t) = w^s(t)\, u_i(t)\, h(t) \tag{5}$$

where $w^s(t)$ is salary *per effective skilled unit* of labor and is uniform across the skilled workforce.

Cognitive ability $a_i(t)$ reduces the time (denoted $\tau_i(t) \equiv 1 - u_i(t)$) individual *i* needs to train in order to enter the skilled profession. A general representation of the training technology may be $\tau_i(t) = G[a_i(t)],\ dG/da_i < 0$. To simplify the algebra we adopt the following formulation

$$\tau_i(t) = 1 - a_i(t). \tag{6}$$

Since it readily follows that $u_i(t) = a_i(t)$, this formulation has the convenient interpretation that each qualified skilled worker devotes to work strictly according to his/her intrinsic cognitive ability.

Equilibrium career choice is defined by a particular individual with ability $\hat{a}(t)$, devotes a fraction $\hat{u}(t)$ working, a fraction $[1-\hat{u}(t)]$ training, and in so doing earns the same either as skilled or unskilled. Thus we have

$w^s(t)\ \hat{u}(t)\ h(t) = w^s(t)\ \hat{a}(t)\ h(t) = w^n(t)$. Rearranging,

$$\hat{a}(t) = \frac{w^n(t)}{w^s(t)\ h(t)}. \tag{7}$$

The equilibrium value of $\hat{a}(t) \in [0, 1]$ plays a pivotal role in this model and has the following interpretation. First, relative market wages $w^n(t)/w^s(t)$ reflect relative derived demand for factors; it thereby reflects factor-substitutability of a particular production technology. Second, human capital $h(t)$ is inherited from the past and is treated as an exogenous parameter at *t*. Thus the right-hand side of (7) fully reflects relative demand for factors at *t*. Third, from the uniform distribution of ability, the supply (denoted by superscript '*s*') of unskilled labor is $n^s(t) = \hat{a}(t)$, and the supply of skilled *headcounts* is $[1-\hat{a}(t)]$. Given training technology (4), the value of $\hat{a}(t)$ completely determines the supply of effective skilled-labor units since $s^s(t) = \int_{\hat{a}(t)}^{1} u_i(t)\, h(t)\, di$.

Substituting $u_i(t) = a_i(t)$ and evaluating the definite integral, we have

$$s^s(t) = \frac{h(t)\,[1 - \hat{a}(t)^2\,]}{2}. \tag{8}$$

In an equilibrium to be defined shortly, $\hat{a}(t) \in [0, 1]$ captures fully the relative supply of factors at *t*, and via (7) determines equilibrium career choice contingent on factor substitution as well as other characters in the production technology for $x(t)$.

Furthermore, $\hat{a}(t)$ fully describes the dynamic link via social human capital accumulation activities. We can rewrite equation (2) as

$$h(t+1) - h(t) = h(t)\delta \int_{\hat{a}(t)}^{1} [1 - u_i(t)] di.$$

Substituting $u_i(t) = a_i(t)$ and evaluating the definite integral, the speed of technical progress via social human capital accumulation is expressed only in terms of $\hat{a}(t)$ and δ

$$h(t+1) - h(t) = h(t)\delta\,[\frac{1}{2} - \hat{a}(t) + \frac{\hat{a}(t)^2}{2}]. \tag{9}$$

The intuition of $\hat{a}(t)$ determining the speed of technical progress and human capital accumulation is simple, and is revealed in its starkest form in two limiting cases $\hat{a}(t) = 0$ and $\hat{a}(t) = 1$. If $\hat{a}(t) = 0$ every individual in the society chooses to acquire skill and the unskilled profession is empty. Human capital accumulation proceeds at its maximum speed $(\delta / 2)$. If $\hat{a}(t) = 1$ no one in the society train for skill and the skilled profession is empty. Social human capital accumulation grinds to a complete standstill. The next section shows that these limiting cases correspond to perfect substitutability and perfect complementarity. Section 4 generalizes it to non-corner situations.

3. Two Limiting Cases: Perfect Substitutes and Complements in Production

We will show that the two corner cases of career choice, $\hat{a}(t) = 0$ and $\hat{a}(t) = 1$, correspond to the two corner solutions of perfect substitution and perfect complementarity between the skilled and the unskilled. Recall that Charlie Chaplin in front of the conveyor belt was ridiculed yet indispensable (like a perfect complement) in the production process. In the holistic organization they are gradually substituted by the skilled.

3.1. Perfect Substitutability and Maximum-Speed Growth

Assume for the moment *an effective unit* of skilled labor is a perfect substitute to a unit of unskilled labor. The (constant returns to scale) production function has the form

$$x(t) = f[s(t), n(t)] = \alpha\, s(t) + \beta\, n(t) \tag{10}$$

where α and β are positive constants. The minimized cost function takes the form $c[w^s(t), w^n(t), x(t)] = \min[w^s(t)/\alpha + w^n(t)/\beta]\, x(t)$. The (Kuhn-Tucker) solution for the firm's cost-minimization is

$$\begin{cases} w^s(t) = w^n(t) \Leftrightarrow s(t) > 0, n(t) > 0; \\ w^s(t) > w^n(t) \Leftrightarrow s(t) = 0, n(t) > 0; \\ w^s(t) < w^n(t) \Leftrightarrow s(t) > 0, n(t) = 0. \end{cases} \tag{11}$$

Assume initial human capital stock $h(0) > 1$ at $t = 0$ when we begin our inquiry.[9] We will return to examine this assumption shortly. Since a skilled worker possesses $h(t)\,u_i(t)$ effective units of labor power, at least some able newborn at $t = 0$ would find it worthwhile to train and join the skilled profession provided $h(0)$ is sufficiently large. We will also return to this shortly.

There are three cases from (11) to consider. In the first case, suppose $w^s(0) = w^n(0)$, and $s(t) > 0, n(t) > 0$ hold. From (7) we have $0 < \hat{a}(0) = 1/h(0) < 1$. This confirms the conjecture in the last paragraph, namely that *the skilled profession will be non-empty* for as long as $h(0) > 1$ since the most able individual hardly needs to train to acquire skills. Now $\hat{a}$ links up production substitutability with the dynamic process in the model. For as long as $\hat{a}(t) < 1$, the education process is active, human capital accumulation proceeds by (9) and $h(1) > h(0)$ holds. By similar argument $h(t+1) > h(t)$ for all *t*. Feeding this back into (7), the skilled profession grows $[\hat{a}(t+1) < \hat{a}(t)]$ until $\hat{a}(t) = 0$ for some finite $t > 0$ and the unskilled profession is empty. From then on everyone trains for skill; human capital accumulates at its maximum speed $\frac{h(t+1) - h(t)}{h(t)} = \frac{\delta}{2}$. National output, since (10) takes the form $x(t) = as(t)$ when $n(t) = 0$, grows at the same maximum speed $\delta/2$.

The third case in equation (10) is just a special case of that discussed in the last paragraph. With the unskilled profession already empty from the start, i.e. $\hat{a}(t) = 0$ for $t \geq 0$, both human capital and national incomes grow at a maximum speed $\delta/2$. A low-ability individual chooses the skilled profession by spending a large fraction of his/her time training, even though $w^s(t) < w^n(t)$, since his/her *earning* is greater than remaining unskilled. The spillovers from human capital are at its maximum. Using the skilled earning per head (5), this implies $w^z(t) = w^s(t)\, u_i(t)\, h(t) > w^n(t)$, i.e., $u_i(t)\, h(t) > 1$ which will be true when $h(t)$ is sufficiently large.

The only remaining case is the second in equation (11), namely $w^s(0) > w^n(0)$, and $s(0) = 0, n(0) > 0$. This implies $\hat{a}(0) = 1$. Since the skilled profession is empty, no one gets trained and the social human capital accumulation process is at a standstill. Reflecting on the skilled earning per head (5), we know $w^z(0) = w^s(0)\, u_i(0)\, h(0) < w^n(0)$. But this inequality must be true even for the most able individual who has $a_i(0) = u_i(0) = 1$. We infer therefore $h(0) < 1$ holds *strictly* under $w^s(0) > w^n(0)$. We dismiss this case as intuitively meaningless using the argument in footnote 9.[10]

A quick intuitive summary of our argument is in order. The definition of skill restricts our attention to $h(t) \geq 1$. Perfect substitutability implies $0 < \hat{a}(t) \leq 1$ at some arbitrary initial time *t*. What we have shown is that the process of human capital accumulation once started will not stop until we reach the corner solution $\hat{a}(t) = 1$ in finite time. Everyone trains; both human capital and national income grow at its maximum speed $\delta / 2$.

3.2. Perfect Complementarity and Growth Stagnation

Assume *an effective unit* of skilled labor is a perfect complement to a unit of unskilled labor. The production function has the form

$$x(t) = f[s(t), n(t)] = \min\{\alpha s(t), \beta n(t)\} \tag{12}$$

where α and β are positive constants. Production must use $s(t)/\alpha$ units of skilled labor *and* $n(t)/\beta$ units of unskilled labor whatever are $w^s(t)$ and $w^n(t)$. The derived relative demand between effective skilled labor units and unskilled labor is $\dfrac{s(t)}{n(t)} = \dfrac{\beta}{\alpha}$.

Again let $h(0) > 1$ at initial time period $t = 0$. The supply for skilled units is given by (8) and the supply for unskilled labor is simply $\hat{a}(0)$. Equating relative demand and supply yields the equilibrium condition $\frac{h(0)\,[1-\hat{a}(0)^2]}{2\,\hat{a}(0)} = \frac{\beta}{\alpha}$. This quadratic equation in $\hat{a}(0)$ has two solutions $\hat{a}(0) = [-\beta \pm \sqrt{h(0)^2\alpha^2 + \beta^2}\,]/\alpha$. Only the positive solution is economically meaningful, thus

$$\hat{a}(0) = \frac{-\beta + \sqrt{h(0)^2\alpha^2 + \beta^2}}{\alpha} > 0\,. \qquad (13)$$

The inequality follows from the intuitive restriction $h(t) \geq 1$.

Now invoke the human capital accumulation process (9). Equation (13) feeding into (9) implies $h(t+1) > h(t)$ if $\hat{a}(t) < 1$. Using this in (7) implies $d\hat{a}(t)/dt > 0$. Long-term equilibrium has $\hat{a}(t)$ approaching unity. More precisely, the skilled profession eventually shrinks to a single most able individual, who devotes his/her entire time-endowment working. Human capital accumulation and national income growth grind to a complete standstill.

The two limiting cases together show that growth rate achieve its maximum under perfect substitution, but there is no growth at all under perfect complementarity. To complete our inquiry we have to examine interior solutions.

4. Substitutability and Growth: Interior Solutions

This section has two simple objectives. First we prove the existence of interior-solution equilibrium where the skilled and unskilled professions are non-empty. Second we show that the manufacturing revolution, via gradual substitution of the unskilled by the skilled, hastens long-term growth.

4.1. Existence of Interior-Solution Equilibrium

There are different ways to depict degrees of substitutability in the constant returns to scale production function $x(t) = f[s(t), n(t)]$. Let $f[s(t), n(t)] = \text{constant}$ define the system of the constant product curve (isoquant) on the *0ns* plane. For our purpose it suffices to work with the curvature ($d^2 s(t)/dn(t)^2 > 0$) of the isoquant.[11] A production function exhibiting easier substitution between *s* and *n* would be less curved, becoming a straight line with constant slope in the limiting case of perfect substitutes. The intuition of easy substitution is that when a factor's supply (in effective skilled units) increases, it is more easily absorbed into the production process, thus necessitating a relatively small perturbation in the marginal rate of substitution and relative wage rates.

Following the last section our focus remains firmly on $\hat{a}(t)$, which links endogenous career choice to human capital accumulation. Long-term interior-solution equilibrium is defined by $\hat{a}(t) = \bar{a} = \text{constant}$ for all $t = 0, 1, 2, \ldots,\ 0 < \bar{a} < 1$ strictly. It is "interior" in the sense that the two professions are strictly non-empty. From equation (9) the long-term rate of human capital accumulation is $[h(t+1) - h(t)]/h(t) = \delta\,(\frac{1}{2} - \bar{a} + \frac{\bar{a}^2}{2}) = g > 0$.

Writing $x(t) = f[s(t), n(t)] = s(t)\phi[n(t)/s(t)]$, since $s(t) = \int_{\bar{a}}^{1} h(t) a_i di = h(t)(1 - \bar{a}^2)/2$, it is easily seen that in the long-term equilibrium (if one exists) the following relation holds $[s(t+1) - s(t)]/s(t) = [h(t+1) - h(t)]/h(t) > 0$.

Consider a system of isoquants having a finite curvature $\infty > d^2 s(t) / dn(t)^2 > 0$, but we are allowed to compare 'neighboring' systems with different curvatures.[12] Suppose at time τ human capital accumulation has reached an arbitrary level $h(\tau)$ and endogenous career choice is $\hat{a}(\tau) = \overline{a}$. This configuration would be a long-term equilibrium if $\hat{a}(\tau) = \overline{a}$ for all $t > \tau$. If it exists, in this equilibrium $n(t) = \overline{a}$, $z(t) = 1 - \overline{a}$ and $s(t) = h(t)(1 - \overline{a}^2)/2$ for all $t > \tau$. Although *s* grows at a constant rate *g*, they are absorbed completely into the skilled profession. The increasing supply of *s* continuously reduces wage w^s per effective unit of *s*, yet no skilled worker finds it worthwhile to shift to the unskilled profession since the fall in w^s is exactly offset by the rise in *h*.

To prove the existence of such an equilibrium, suppose in the system just described $\hat{a}(\tau + 1) = \overline{a} + \varepsilon$ where ε is an arbitrarily small constant. The growth of efficient units of skilled labors during τ must have so depressed relative wages w^s / w^n in $\tau + 1$ that a larger number of citizens than in τ find it worthwhile to remain unskilled. Now if we allow the system to be replaced by ones with continuously reducing curvatures, the fall in w^s / w^n between τ and $\tau + 1$ approaches zero as $d^2 s(t) / dn(t)^2$ approaches zero. The existence result follows from the finiteness of ε and the fact that the curvature asymptotically approaches zero (linear isoquants when *s* and *n* are perfectly substitutes).

4.2. Characterization of The Interior-Solution Equilibrium

If the production systems are sufficiently compact such that curvature c_i is continuous and differentiable, it follows from the argument just presented that there exists a continuum of such equilibria each identified by its degree of substitutability between *s* and *n* (the curvature of its isoquants). Each of these equilibria will be characterized by a different career configuration $\bar{a}$. Human capital and income will grow at a different rate according to $\bar{a}$.

Again we rank such equilibria in terms of the curvature of their isoquants c_i such that $c_i < c_j$ for $i < j$. Consider two neighboring equilibria *i* and *j* where $c_i < c_j$. The greater substitutability of c_i allows a larger fraction of the population as skilled labor (by analogous reasoning presented in subsection 4.1). In other words $\bar{a}_i > \bar{a}_j$ holds. It follows immediately from (9) that human capital grows faster under equilibrium *i* compared to *j*. This argument is readily extended to all equilibria, and it allows us to conclude that long-term human capital and income grow at a higher rate when the skilled become more substitutable for the unskilled.

5. Between- and Within-Group Inequality

Several papers have recently offered alternative ways to understand the relations between technological change, growth and wage inequality (Acemoglu (1998), Eicher (1996), Eicher et.al. (2001), Galor and Tsiddon (1997), and Galor and Moav (2000)). Our model presented above shares several characteristics in common with these papers, in particular differential innate ability and the convexity arising from human capital accumulation. None of these papers examine the manufacturing revolution and the shift from the Taylorist to the modern organization. Our model is simpler than those just cited. It suffices however to bring out the links between human capital accumulations, within- and between-group wage disparities in a stark and intuitive manner.

It is important to recognize that the *i*th skilled worker's income is $w^s(t)\,a_i(t)\,h(t)$, not $w^s(t)$. Owing to the uniform distribution of $a_i \in [\overline{a}, 1]$, we measure inequality (denoted λ_{sn}) by the ratio of the mean skilled earning to the unskilled wage $w^n(t)$. Equilibrium mean skilled earning is $(w^s h - w^s h\overline{a})/\overline{a}$. The between-group inequality measure is therefore. Using (7) we have

$$\lambda_{sn} = h \cdot \frac{w^s}{w^n} \cdot \frac{(1-\overline{a})}{\overline{a}} = \frac{(1-\overline{a})}{\overline{a}^2}\,. \tag{14}$$

It is immediate that between-group earnings inequality is positively related to long-term growth rate. Two intuitive reasons emerge clearly from the first equality of (14). First, a higher relative wage is exactly what is needed to attract more individuals to train for skill. Second, as more get enroll for training, this in itself hastens the social process of capital accumulation (*h* is higher). The first reason is well known. The second however is less obvious and seldom mentioned.

The positive association between growth rate and between-group inequality is consistent with the empirical finding of Forbes (1998), although it differs from that of Aghion et. al. (1999). Our result arises however from an entirely different economic process than Aghion et. al. (ibid). They argue that inequality is bad for growth when there are imperfections in the capital market. Our point is that in the absence of such imperfections growth and inequality would be positively related. The final direction of association depends on the relative strength of these opposing pulls.

Now we turn to within-group inequality. Only that within the skilled group needs investigating, as unskilled wage and earning are uniform. Owing to the uniform distribution of $a_i \in [\overline{a}, 1]$, within-skilled inequality (denoted λ_s) can be represented by the earnings gap between the top and the bottom skilled earners

$$\lambda_s = w^s h - w^s h\overline{a} = w^s h(1-\overline{a}) . \quad (15)$$

The conclusion is immediate that within-group inequality is also positively related to long-term growth rate. This arises clearly from the fact that a greater mass of less able individuals is drawn into the skilled profession. The variance of intrinsic ability, in others words, must have risen.

6. Summary and Conclusions

This paper is motivated by the simple question: Could the manufacturing revolution that we see sweeping across American organizations be raising the long-term growth trend? To study this we inserted a career choice mechanism into the Uzawa-Rosen-Lucas model of human-capital accumulation. The result turns out to be affirmative: Even abstracting from physical capital, the gradual substitution of the unskilled by the skilled suffices unambiguously to raise long-term growth rate. The virtue of our model lies with its simple intuition. The Taylorist, vertical organization structure preserves and maintains a sizeable army of the unskilled as an indispensable and complementary part of the manufacturing process. But the unskilled do not train. Its mass and its perpetuation negatively affect growth. In modern manufacturing, automated machines combine and complement with skilled labor, together and gradually they are substituting and replacing the unskilled. This emancipates as well as forces the unskilled to train and to accumulate human capital, which boosts growth. As the growth trend is raised, between-group wage inequality worsens as a necessary inducement to education. Within-group wage inequality also worsens owing to greater heterogeneity among the skilled.

Two caveats of our model are mentioned below. Both point to promising avenues for extension and future work, neither is likely to reverse the direction of our findings. First, our economic agent makes one single career choice as his/her life begins, by observing two simple signals - the prevailing relative wage and his/her ability to train. A richer model would allow him to maximize lifetime expected utility over a schooling period and a working period say, by forming some anticipated wage or even taking some spillover effects of human capital accumulation into account. Provided that wages do not shift wildly, and that the country is large enough for each to take spillovers as given, our simple framework should capture the main direction of the forces involved. The second caveat is the abstraction from physical capital. Automation as argued earlier is an important forces that substitute and shifts workers from unskilled into human capital accumulation. Since capital and skilled are known to be complementary, we simply take the skilled to 'stands in' for the process of automation. While we argue this approach is justified as a first attempt at the question at hand, it remains to study the full picture where human capital is accumulated in tandem with physical-capital. Such a task, however, is left for future research.

So the record-breaking run of US growth experience may be expected to last for a while yet, and the higher speed limit recently observed might indeed be 'safe'. This finding should be exciting to many of us, not only in the United States but in other countries as well. Prevailing views have typically attributed this new growth experience to information technology (IT). We have offered a different perspective in this paper by emphasizing the substitution of the unskilled. IT has had tremendous impacts on skills and on human capital. It also has many unique characteristics of its own (e.g. network externality and switching costs). Combining IT with the manufacturing revolution is another rewarding avenue for furthering our understanding on growth.

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Notes

[1] Milgrom and Roberts (1990) begin their article by proclaiming, "Manufacturing is undergoing a revolution." They document many anecdotal evidence of this revolution. Two recent papers by Lindbeck and Snower (1996, 2000) study the origins of this organizational shift and its effects on wage inequality.

[2] Aoki (1986) compares the Japanese, horizontal organizational structure with the American, vertical one. Lindbeck and Snower (2000) note that "This [Western] structure is increasing giving way to flatter organization" (p.375).

[3] The title of a *Business Week* article (April 10, 2000, p.242), "The Economy: A Higher Safe Speed Limit," captures the imagination of many. Jogenson and Stiroh (2000) and more recently Gordon (2002) ascribe information technology as the driving force behind the change. Be that as it may, the general sentiment is one of bewilderment, as Lawrence Summers calls it, a "paradigm uncertainty."

[4] The choice of my focus is partly a matter of taste and scope, but there is also the hope that this would lead to new insights on the relations between this manufacturing revolution, growth, and wage inequality. Fortunately this aspiration is positively rewarded, as I will show in Section 5 below.

[5] A wide literature in sociology pertaining to the degradation work and the alienation workers readily attests to this. See for instance Braverman (1974). Such alienation of the working class, documented in detail in Karl Marx's Das Kapital (1867), lies at the heart of his thesis of class struggle and socialism. Such ideas also become obsolete in the face of the manufacturing revolution.

[6] Griliches (1969) formulates and provides initial empirical evidence on capital-skill complementarity. Bound and Johnson (1992) argue that technological change has biased towards the skilled and this is a major cause for the increasing relative demand for skilled labor. A large part of the debate in the literature has concentrated on explaining the widening wage gaps between as well as within skill groups. Levy and Murnane (1992) survey the literature and concluded that shifts in both supply and

demand for factors have contributed for the More recently Krusell, et. al. (2002) provide evidence that changes in input supplies alone can account for most of the observed skill premium.

[7] We could think of automation as taking place exogenously, and in such a way rendering the skilled (armed with automated machines) more substitutable for the unskilled. We know (a) capital and skills are becoming more complementary, and (b) automated machines are increasingly substitutable for the unskilled. Other things being equal, the skilled must be increasingly substitutable for the unskilled.

[8] One would like to seek empirical or historical evidence to verify or refute our finding. The recent record-breaking growth in the U.S. strengthens our position. On the other hand, automation and the horizontal organization form were adopted in Japan somewhat earlier than the U.S., yet Japanese growth has stagnated for almost a decade. Neither anecdote is sufficient proof one way or the other.

[9] The case of $h(t) < 1$ can be dismissed out of hand for it is inconsistent with the definition of a skilled labor. To see this recall from equation (6) that the most able individual joins the skilled profession without training and offers $u(t)\,h(t) = h(t)$ units of effective skilled labor power for employment. $h(t) < 1$ would have implied that even the most able skilled worker is *less* productive as skilled labor than as unskilled.

[10] The text omits the only remaining case concerning initial human capital stock - $h(0) = 1$. The analysis and result are identical to the case of $h(0) > 1$ so we relegate it to a footnote. The skilled earning per head equation becomes $w^z(0) = w^s(0)\,u_i(0)$.

Taking this into account, growth rates for human capital as well as national income in the three cases in equation (10) are

$$\begin{cases} w^s(0) = w^n(0) \Leftrightarrow s(0) > 0,\, n(0) > 0;\, 0 < \hat{a}(0) < 1,\, \hat{a}(t) = 0 \;as\; t \to \infty;\, g = \delta/2 \\ w^s(0) > w^n(0) \Leftrightarrow s(0) = 0,\, n(0) > 0;\, \text{dismissed since it implies } h(0) < 1, \text{ see foot note 10} \\ w^s(0) < w^n(0) \Leftrightarrow s(0) > 0,\, n(0) = 0;\, \hat{a}(t) = 0 \text{ for all } t \geq 0,\, g = \delta/2. \end{cases}$$

This reinforces the result derived in the text.

[11] The elasticity of substitution of the linearly homogenous production function $x = f(s, n)$ can be written as $\sigma = \frac{r}{sn}\frac{nr + s}{c}$ where $r = -\frac{ds}{dn}$ is the marginal rate of substitution, and $c = \frac{d^2 s}{dn^2} = r\frac{dr}{ds} - \frac{dr}{dn}$ is the curvature of the isoquant. The degree of substitutability between *s* and *n* is thus inversely proportional to the curvature of the isoquant (cf. Allen (1938), p.342).

[12] Imagine we denote the *i*th production system in terms of its curvature c_i, where $c_i \in [0, \infty)$, $i = 1, 2, \ldots$. Imagine also technology is sufficiently compact such that c_i is continuously differentiable, and we rank them such that $c_i < c_j$ for $i < j$. The two limiting cases are perfect substitutability - $c_i = 0$, and perfect complements - $c_i = \infty$.