A general purpose technology explains the Solow paradox and wage inequality

Jacobs, B.; Nahuis, R.

Publication date
2000

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Bas Jacobs[a],*, Richard Nahuis[b]

[a]*University of Amsterdam, Faculty of Economics and Econometrics, Roetersstraat 11, 1018 WB, Amsterdam, The Netherlands*
[b]*CPB Netherlands Bureau for Economic Policy Analysis and KUN, Nijmegen, The Netherlands*

Abstract

We analyze the consequences of a general purpose technology (GPT) on output, productivity, and wages of skilled and unskilled workers. Our endogenous growth model matches three key empirical facts during the 1980s and 1990s: an increasing skill premium, a fall in the real wages of unskilled workers and a slowing down of economic growth after the introduction of a GPT. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: GPT; Wage inequality; Economic growth

JEL classification: O15; O31; O33; O40

1. Introduction

Davis (1992) shows that wage inequality increased in many OECD countries in the 1980s. We think that biased technological change is the major reason for increased wage inequality.[1] A number of stylized facts suggest that today's general purpose technology (GPT), the 'computer revolution', is the obvious candidate for explaining the rise in inequality. First, the introduction of information and communication technology is associated directly with a rising skill premium, see e.g. Krueger (1993).

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*Corresponding author. Tel.: +31-20-525-5088; fax: +31-20-525-4310.

E-mail addresses: jacobs@fee.uva.nl (B. Jacobs), r.nahuis@cpb.nl (R. Nahuis).

[1]Two other reasons are often given. First, trade with low-wage countries could cause downward pressure on wages of unskilled workers, thereby increasing inequality. However, trade with low-wage countries is too small relative to total trade in the industrialized world to explain increased inequality. Second, institutional changes (for example minimum wage laws) might have played a role.

Second, Feenstra and Hanson (1996) show that wage inequality increased sharply in 1979–1983 and this increased inequality parallels a significant increase in ICT investments (Allen, 1997).

Critical in the technology explanation is that the 'computer revolution' accelerates the rate of technological change, or at least, the rate of skill-biased technological change. However, as Aghion et al. point out: ''The main argument put forward against the skill-biased technical change hypothesis is that we have not observed an increase in the rate of productivity growth since the early 1980s'' (Aghion et al., 1999, p. 1644).[2]

The simple point of this paper is that, opposite to the common sense argument, a computer-related bias in technological change is likely to cause a slowdown in output growth. The reason is that high-skilled workers have become more productive in learning and temporarily reallocate their time from production to knowledge accumulation. Therefore, resources are withdrawn from production because high-skilled workers spend less time producing. Further, the computer related GPT increases wage inequality upon arrival, because the increased value of time devoted to knowledge accumulation increases the skill premium.

The seminal paper in this line of research is Greenwood and Yorukoglu (1997) where an economic slowdown occurs because the ICT revolution induces renewal of plants, with plants that are initially less productive. As the adoption of new plants (or technology) involves learning, and skill facilitates learning, wage inequality goes up. Closely related to our analysis is Caselli (1999). In a model with workers differing in learning costs, a technological revolution induces low-cost learners to adopt the new technology. Capital follows the newly skilled workers and thereby leaves the unskilled with less capital and lower real wages.

The rest of this paper is organized as follows. In Section 2 we develop an endogenous growth model of wage inequality and technological change to explore the relationship between output growth and wage inequality. In Section 3 we analyze the equilibrium and transition effects of the model. In Section 4 we show the consequences of the computer revolution on wage inequality, growth, and technological change.

2. The model

We consider a closed economy. There is a continuum of final goods producers, with mass 1 and index j, engaged in monopolistic competition. Every firm produces one product variety j facing a downward sloping demand function for that variety. The profits due to mark-up pricing allow firms to develop firm-specific (knowledge) capital F_j. Firm-specific capital F_j is a necessary input in production of final goods X_j, besides unskilled labor L_j, skilled labor H_j, and capital goods K_j. Unskilled workers are employed in production only. High-skilled workers spend a fraction u_j of their time in production. The remainder of the time endowment, normalized at unity, $1 - u_j$, is devoted to research (or learning). Skilled workers differ from unskilled workers because unskilled workers are not substitutes for skilled workers in research and imperfect substitutes in production. Therefore, wages per efficiency unit of labor differ for skilled and unskilled workers.

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[2]Solow's (1987) quip on this puzzling observation has become famous: ''You can see the computer age everywhere but in the productivity statistics''.

Production is designated by a Cobb–Douglas production function:[3]

$$X_j = A F_j^{1-\alpha} K_j^{\alpha} \left((u_j H_j)^{\beta} L_j^{1-\beta} \right)^{1-\alpha} \tag{1}$$

where $0 < \alpha < 1$, $0 < \beta < 1$ and A is an exogenously given Hicks-neutral technology parameter. We interpret $A F_j^{1-\alpha}$ as a measure for factor productivity. Production features constant returns to scale in physical inputs K, uH, and L. The production function is homogeneous of degree 1 in K and F so as to get a steady state in which K and F grow at the same rate. Note that technology F itself is not skill biased but neutral in both types of labor.

Each firm faces a downward sloping demand function for its variety: $X_j = (p_j / p_X)^{-\varepsilon} X$ where $\varepsilon > 1$ is the constant elasticity of demand. p_X is the aggregate ideal price index and X is aggregate output. We focus on symmetric equilibria, hence prices and levels of production reduce to: $p = p_X = p_j$ and $X_j = X$ for all j.

In order to expand production, the firm devotes some, $(1 - u_j)$, of its high-skilled workers to the production of knowledge F:

$$\dot{F}_j = B(1 - u_j) H_j F_j \tag{2}$$

where a dot denotes a time derivative and B denotes the productivity of research. Research is firm-specific. Productivity of a firm's research depends on the accumulated stock of firm-specific knowledge. The knowledge production function features constant returns to scale in F. Therefore, knowledge production is the growth engine of the model.

Firms maximize the net present value of profits subject to their demand function and the accumulation constraint on firm-specific capital. First-order conditions are as follows. First, the wage rate of an unskilled worker, w_L, equals the marginal productivity of an unskilled worker in production:

$$w_L = \xi A K^{\alpha} F^{1-\alpha} (uH)^{\theta} L^{\xi-1} \tag{3}$$

where we normalized prices: $p \equiv \varepsilon / (\varepsilon - 1)$ and defined $\theta \equiv (1 - \alpha)\beta$ and $\xi \equiv (1 - \alpha)(1 - \beta)$. Second, the skilled workers' wage, w_H, obeys:

$$w_H = \theta K^{\alpha} F^{1-\alpha} (uH)^{\theta-1} L^{\xi} = qBF \tag{4}$$

The wage of a skilled worker equals the marginal product of a skilled worker in production. Arbitrage between production and learning ensures that the high skilled wage must also equal the marginal value of time devoted to research — the last term. q is the relative price of firm-specific capital (knowledge) in terms of final output, i.e. 'Tobin's q' for firm-specific capital. The wage differential between unskilled and skilled workers, expressed as the ratio of the wages, is $\omega(u) \equiv w_H / w_L = \theta L / (\xi u H)$. The wage differential increases as high-skilled workers spend more time learning (u lower): $\omega' < 0$. Third, the marginal product of capital equals the rental rate (r):

$$r = \alpha K^{\alpha-1} F^{1-\alpha} (uH)^{\theta} L^{\xi} \tag{5}$$

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[3]Time subscripts are omitted so as to avoid unnecessary notation.

Fourth, the optimal time path of firm-specific capital is governed by an option arbitrage equation:

$$rq = (1 - \alpha)K^{\alpha}F^{-\alpha}(uH)^{\theta-1}L^{\xi} + qB(1 - u)H + \dot{q} \tag{6}$$

The marginal value of a unit of F equals the value of investing the same amount in the capital market (rq). The former equals the marginal product of F in production (first term), the marginal product of F in research (second term), and a capital gain (last term).

A representative household supplies skilled and unskilled labor inelastically. We assume that households have a constant propensity to consume out of real income pX:[4]

$$C = (1 - s)pX \tag{7}$$

s is the savings rate. Consumption is a CES aggregate of all existing varieties:

$$C \equiv \left(\int_0^1 C_j^{(\varepsilon-1)/\varepsilon} \, dj \right)^{\varepsilon/(\varepsilon-1)}.$$

Capital is costlessly assembled by competitive capital-assembly firms by a production function that is identical to the consumers' CES aggregate above, i.e.

$$I \equiv \left(\int_0^1 I_j^{(\varepsilon-1)/\varepsilon} \, dj \right)^{\varepsilon/(\varepsilon-1)},$$

where investment demand for each variety is denoted I_j. Demand curves from the capital-assembly firms and consumers are identical and are represented by a single downward-sloping demand curve for each variety. Goods-market equilibrium gives the resource constraint of the economy: $X = C + I$.

3. General equilibrium and dynamics

We can derive the steady-state share of time spent producing (u^*):

$$u^* = \frac{\alpha - sp}{\alpha - (1 - 1/\beta)sp} \tag{8}$$

where $\alpha > sp$ is assumed in order to arrive at a feasible steady-state allocation ($0 < u < 1$).[5] Note that the steady-state value of u depends only on the production technology parameters α and β, the saving rate s and the inverse of the monopoly mark-up p. Recall that $\omega(u) = \theta L/(\xi uH)$, hence the technology/saving parameters and the relative supplies of high- and low-skilled workers determine long-run wage inequality. The steady state technology-capital-stock ratio ($R \equiv F/K$) is:

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[4]We abstract from an inter-temporal utility maximizing framework to reduce the complexity of the model.

[5]This condition is a modified version of the transversality condition known from the Ramsey model that the saving rate must be less than the share of capital or: $\alpha > s$, see e.g. Barro and Sala-i-Martin (1995) p. 89.
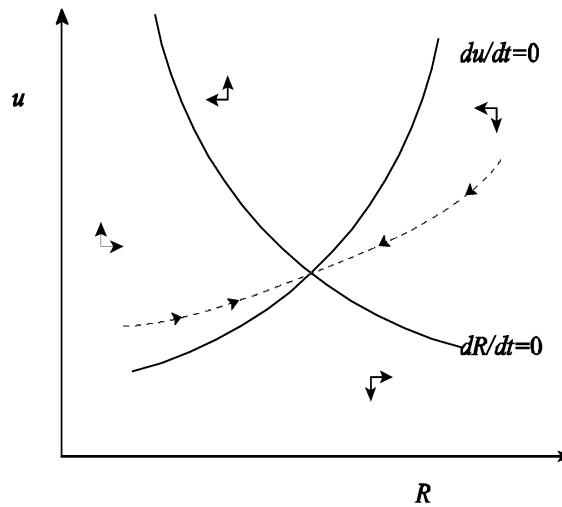
Fig. 1. Phase diagram. Key: R is the ratio of capital-technology, u is the fraction of time skilled workers devote to production.

$$R^* = \left(\frac{B(1 - u^*)H}{spA(u^*H)^\beta L^{1-\beta}} \right)^{1/(1-\alpha)} \tag{9}$$

The steady-state growth rate of the stocks (K and F), output (Y), and wages of skilled and unskilled workers (w_H, w_L) will be equal to $g = B(1 - u^*)H$.

The transitional dynamics are simple as u is the 'jump' variable and R is the 'predetermined' variable. Fig. 1 gives the phase portrait in (R, u)-space. The $\dot{R} = 0$ ($\dot{u} = 0$) locus gives all combinations (R, u) where $R(u)$ is not changing. The equilibrium can be found where the two phase lines intersect.[6] Starting from an initial ratio of capital and firm-specific knowledge $R(0)$, u jumps to the stable branch, and the economy converges along the stable branch towards the equilibrium.

4. A computer revolution ...

A GPT as the computer revolution affects the marginal productivity of research as it opens new opportunities for knowledge-creating activities throughout the economy. The essential characteristic of a GPT is that it does not directly increase productivity, because it is a *general purpose* technology. Productivity only increases as a consequence of efforts to develop new firm-specific technology with the GPT. Therefore, this paper mimics the computer revolution by an increase in the research productivity. Accordingly, B increases to B'. Graphically, this can be represented by a rightward shift of both the $\dot{u} = 0$ and the $\dot{R} = 0$ loci, see Fig. 2.

On impact, time in production u falls to equate the marginal productivity of high-skilled workers in

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[6] In order to guarantee saddle-point stability we assume that $u^* > (\theta/(1 - \theta))^2$. Then, it is easily verified that the phase line $\dot{R} = 0$ is downward sloping and $\dot{u} = 0$ is upward sloping.
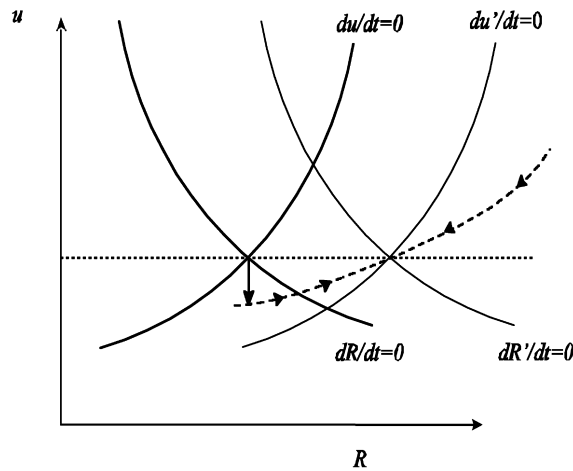
Fig. 2. Adjustment to the new steady state. Key: An increase in research productivity shifts both phaselines out. The jump variable u falls on impact. Both u and R increase along the transition to the new steady state.

learning and producing. Therefore, high-skilled workers spend more time learning in order to accumulate firm-specific capital F. The growth rate of output falls, exactly because u falls, see Fig. 3a. Thus, the introduction of a GPT causes a slowdown in output growth. This explains the empirical puzzle that we cannot see the computer revolution yet.

However, over time output growth recovers as the stock of technology increases. Consequently, high-skilled workers reduce time learning because a higher stock of knowledge increases the value of an hour producing, see also Fig. 3b. Productivity and output growth will recover in the long run as the new technology is implemented and the stock of productive knowledge increases. The increase in B leads to a permanently higher growth rate in the long run because time devoted to knowledge accumulation has become more productive.[7]

Wage inequality rises immediately after the shock, see Fig. 3c. Skilled workers receive a premium as a result of higher productivity in learning (or R&D) in order to cope with the new technology. Unskilled workers will experience an initial decrease in wages because there are fewer, complementary, skilled workers producing. As the new technology is implemented skilled workers gradually reallocate their time and spend more time producing again. Wage inequality decreases as skilled workers cooperate with unskilled workers in production. In the long run, wage inequality will be at the same level as before the computer revolution.

A major puzzling fact is that productivity growth did not accelerate in the ICT using industries for a long time (see Gordon, 2000). The ICT producing industry has driven the macroeconomic acceleration in growth. We stress that the development of (firm-specific) applications takes much time and resources.[8] Our technology explanation does indeed accord with the facts: sluggish growth in the 1980s, a simultaneous increase in wage inequality and a fall in the real wages of unskilled workers. Currently, economic growth is recovering so that one might expect lessened pressures on wage

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[7]A Jones (1995) type of model would overcome this implausible result. It would, however, seriously complicate the dynamic analysis which is crucial for our point, while only altering the conclusions for the long run.

[8]For example, the dynamo's implementation went up from 5% in 1899 to 78% in 1929 (David, 1991). If the ICT revolution is to be placed no later than 1985, it is time for the ICT using sectors to show increasing productivity.
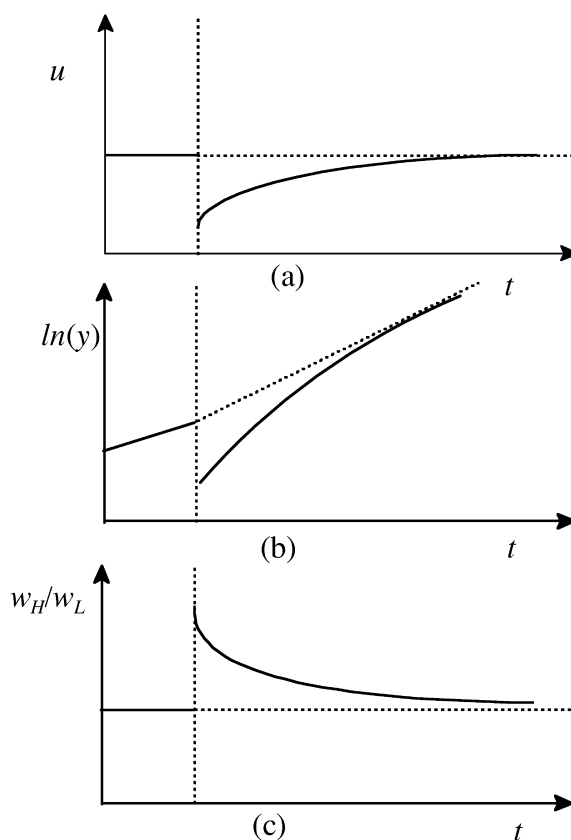
Fig. 3. Effects of a GPT. Key: An increase in *B* increases time learning — panel (a), decreases output in the short run — panel (b), and increases inequality — panel (c).

inequality in years to come. Aghion et al. (1999, p. 1656) suggest that this is indeed the case empirically.

Acknowledgements

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