General Purpose Technology and Wage Inequality

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Abstract

The recent changes in the U.S. wage structure are often linked to the new wave of capital-embodied information technologies. The existing literature has emphasized either the accelerated pace or the skill-bias of embodied technical progress as the driving force behind the rise in wage inequality. A key, neglected, aspect is the "general purpose" nature of the new information technologies. This paper formalizes the idea of generality of technology in two ways, one related to human capital (skill transferability) and one to physical capital (vintage compatibility) and studies the impact of an increase in these two dimensions of technological generality on equilibrium wage inequality.

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1 Introduction

The U.S. wage distribution has undergone remarkable changes during the past three decades. Wage inequality has grown fast over that period, reaching arguably the highest peak in the Post-War era: the ratio between the ninth and first deciles of the weekly wage distribution for males rose by 40% between 1963 and 1995 (Katz and Autor, 1999). Part of this increase in inequality is attributable to wage differentials between educational groups, but a substantial fraction of the increase (from one half to two thirds, according to Juhn, Murphy and Pierce, 1993) took place within groups.

The rise in the educational premium is well understood as the combination of an acceleration in relative labour demand for more educated workers and a contemporaneous slowdown in their relative supply (Katz and Murphy, 1992, Krusell et al., 2000).[1] Perhaps more challenging is to understand the sources of the rise in within-group (or residual) inequality. The common denominator among most of the theoretical papers in the literature is that they identify the recent wave of capital-embodied technological change as the primary source of the increase in the various dimensions of wage inequality.[2]

A first strand of the literature (Katz and Murphy, 1992, Acemoglu 1998, 1999) emphasizes the secular trend in the *skill-bias* of new technologies: the new equipment goods are designed to increase the productivity of workers with certain skills (i.e. more educated, or more "able"), hence the market return for this type of measured and unmeasured skills increases and so does inequality of wages in the workforce. A second strand points to the *acceleration* in the speed of embodied technical change: the rapid rise in capital-embodied productivity induces a surge in the demand for equipment and, when equipment is complementary in production with skilled labour, inequality rises (Krusell et al. 2000). More directly, it can induce an increase in the demand for skilled labour if the latter has a comparative advantage in coping with the uncertainty and the novelties associated with times of rapid technical change (Galor and Tsiddon, 1997, Greenwood and Yorukoglu, 1997, Caselli, 1999, Rubinstein and Tsiddon, 1999, Aghion et al., 2000, Galor and Moav, 2000, Aghion et al., 2000, Gould et al., 2001, and Violante, 2002).

In this paper we focus on yet another important feature of technological change that

[1] See Aghion (2002) for a survey of the competing theories attempting to explain the evolution of the educational premium.

[2] There are notable exceptions. Di Nardo, Fortin and Lemieux (1996) and Lee (1999) emphasize the role of institutional changes, such as deunionization and the decline in the real minimum wage. Wood (1995) argues that trade liberalization is responsible for the rise in inequality. Acemoglu (2002) provides an interesting discussion of how these non-technological factors become much more important when interacted with technical change.

has been neglected by the existing literature on inequality: its *general purpose nature.* Bresnahan and Trajtenberg (1995) coined the term "general purpose technologies" (GPT) to describe certain drastic innovations that have the potential for pervasive use and application in a wide range of sectors of the economy. Lipsey et al. (1998) cite as examples of such innovations, in ancient times, writing and printing, and in more recent times, the steam-engine, the electric dynamo and last, the microchip. A recent report of the Computer Science and Telecommunications Board of the National Academy of Sciences confirms the view of information technologies as GPT's as it states that "*...increased processing power can also often be used to [...] increase flexibility and generality, attributes that are key to much of the ongoing transformation of communication technology*" (page 116). There is a small literature on the relation between GPT and aggregate productivity: the GPT is modelled as a technological paradigm that induces a sequence of secondary incremental innovations and the emphasis is on the role of GPT diffusion for productivity and growth: in particular, the GPT approach provides theoretical foundations for the coexistence of a technological acceleration and a productivity slowdown.[3] Here, we develop the link between GPT and the dynamics of wage inequality.

In this paper we formalize two aspects of "generality" of a technology and we build a theoretical framework to understand how each affects wage inequality. The first aspect relates to human capital: a more general technology allows a larger degree of *transferability* of skills across the different sectors of the economy. For example, the ability to use computers for word-processing, database, or programming can be useful in a wide range of sectors and jobs in the economy. A recent survey by the Bureau of Labour Statistics concludes that the impact of computers has been *"...extensive because the technology, network systems, and software is similar across firms and industries. This is in contrast to technological innovations in the past, which often affected specific occupations and industries (for example, machine tool automation only involved production jobs in manufacturing). Computer technology is versatile and affects many unrelated industries and almost every job category*" (McConnell, 1996, page 5).

The second aspect relates to physical capital: a more general technological blueprint increases the degree of *compatibility* between old and new vintages of capital. The aforementioned report of the Computer Science and Telecommunications Board contains two striking examples. First, the increasing transfer of tasks from hardware to software, al-

[3]We refer the reader to the essays included in Helpman (1998) for an extensive discussion of the relationship between GPT's and growth dynamics. See also Helpman and Rangel (1999).

lowed by faster computing power, has the advantage of permitting a large set of functions of the new machines to be modified after manufacture to correct problems or meet evolving user needs, whereas the old machines, once manufactured, were "frozen" (page 116). A second key consequence of increasing processing power is the improved ability to process and transform data in communication systems. As a result, the scope for inter-operation among previously incompatible systems is larger: in the past the different broadcast video formats used in various part of the world were a barrier to interchange of video content, but today general converters exist. Similarly, digital and analogue telephone system which were originally incompatible, now interwork perfectly (page 117).

The framework we develop in the paper is a simple overlapping generation model with two-period lived agents and two production sectors. Technological progress results in capital-embodied innovations occurring in each of the two sectors in alternance. Capital fully depreciates after two periods so that at any time there are only two vintages of capital (old and new). Workers cumulate experience through learning-by-doing. The generality of the technology determines the degree of skill transferability and vintage compatibility. *Transferability* of skills refers to the fraction of accumulated knowledge a worker can carry over when moving to the leading-edge sector. *Compatibility* of physical capital, refers to the extent to which capital equipment embodying the old technology, can be retooled so as to embody the new leading-edge technology. Not all workers can be productive with the new technology, only those who are adaptable. *Adaptability* in our model is determined by the schooling investment of young workers. This link between education and ability to adopt new technologies goes back to the seminal work of Nelson and Phelps (1966). We then use this framework to study the effect of a rise in the generality of the technological platform on wage inequality.[4]

The main results of the paper are three. First, when adaptability is exogenous, an increase in both measures of generality of technology increases the long-run level of wage inequality. Intuitively, larger skill transferability increases the premium of adaptable workers through "skill deepening", and larger vintage compatibility has the same effect through "capital deepening". Interestingly, during the transition towards a more general technology, inequality might temporarily overshoot its new steady-state level. Second, when adaptability is endogenous, a rise in generality of the technology increases the de-

[4]Our structure is similar to that of Galor and Tsiddon (1997), who also examine the theoretical relationship between growth and wage-inequality using a two-period overlapping-generations model. They assume that each person works only in one period of life and that technological progress is not embodied in capital. As a consequence, neither dimension of "generality" that we study below can be represented in their model.

mand for education and thus the supply of adaptable workers, thereby counteracting the initial mechanism. We characterize the conditions under which the initial forces dominate and show, with a simple calibration, that this appears indeed to be the case for the U.S. economy. Third, our model can shed some light on one dimension of rising inequality which is less well understood than others, the increase in the experience premium: in the U.S. the ratio between the average wage of workers with 25 years of experience and 5 years of experience rose by 20% since the early 70's (Katz and Autor, 1999). Explanations based purely on the "acceleration hypothesis" would predict a fall in the experience premium, whereas this empirical fact is easily explained as resulting from an increase in the generality of technologies: a technological platform that allows skills to be more transferable on the new vintages can raise the relative wage of older workers, as it raises the premium to accumulated knowledge and experience to use on the new, and more productive machines.

The remainder of the paper is organized as follows. In the next section we describe the general model. In Section 3 we analyze the impact on steady-state wage inequality of the generality of technology in an economy with exogenous adaptability. In Section 4 we endogenize the acquisition of adaptability through schooling and check the robustness of the previous results. In Section 5 we calibrate our model to the U.S. economy to, tentatively, gauge the extent of the rise in technological generality. Section 6 analyzes the transitional dynamics between steady-states. Section 7 concludes.

2 The Environment

Demographics and Preferences

Time is discrete, and indexed by t. The economy is populated by a continuum of overlapping generations of ex-ante identical individuals, who live for two periods. Each generation has measure one. The preferences of an individual born at time t are given by

$$U_t = c_t^y + \beta c_{t+1}^o,$$

where β is the discount factor. Individuals are non-altruistic, thus from intertemporal consumption optimization one can obtain that in equilibrium $\beta = 1/(1+r)$, where r is the economy's rate of interest.[5] We assume that r exceeds the growth rate of the economy, to ensure dynamic efficiency.

[5] This presumes an interior equilibrium; i.e., that the equilibrium capital stock corresponding to a rate of interest r is small enough that young people can afford to buy it out of their current income with something left over for current consumption (recall that in a two-period overlapping generations

Technological Progress and Production

Technological progress in this economy is embodied in capital: at each date t an innovation takes place creating a new improved vintage of machines, each with a (labour-augmenting) productivity factor $A_t = (1+\gamma)^t$, where $\gamma > 0$. There is one final good in the economy, produced in two separate sectors, whose price is normalized to unity.[6] In odd periods the exogenous process of technological change produces an innovation specific to the first sector, while in even periods the innovation is specific to the second sector. Let the "new" sector at date t be the one that has just innovated and denote it by "0" to refer to the age of capital in that sector. Similarly, the "old" sector is the one that has innovated in the previous period and will be denoted by "1".

Output in each sector is produced by a Cobb-Douglas production function using physical capital and labour. Physical capital lasts for two periods, with no depreciation after the first period. At the beginning of the second period firms in the old sector can keep any amount of the old capital in production; what is not kept in the old sector can be relocated to the new sector where it will be retooled, at a cost, to embody the new technological innovation. When the amount D_t of old capital is retooled to embody the new technology, only a fraction $\kappa \in [0,1]$ is retained in the process. The parameter κ represents the degree of *technological compatibility* between old and new vintages of capital. Thus, κ captures the notion of generality of the technology based on physical capital that we mentioned in the Introduction.

The production technologies in the two sectors $i = 0, 1$ at date t are:

$$
\begin{aligned}
Y_{0t} &= K_t^{\alpha}(A_t x_{0t})^{1-\alpha} + (\kappa D_t)^{\alpha}\,(A_t \widetilde{x}_{0t})^{1-\alpha}, \\
Y_{1t} &= (K_{t-1} - D_t)^{\alpha}\,(A_{t-1} x_{1t})^{1-\alpha},
\end{aligned}
\tag{1}
$$

where K_t is the capital stock installed at date t, x_{0t} is the amount of labour used in production with new capital in sector 0, $\widetilde{x}_{0t}$ is the amount of labour used with retooled capital in sector 0, and x_{1t} is the amount of labour used in sector 1. The production of final goods in sector i is Y_{it} and α is capital's share of output.

setup there is no one from whom the representative young person can borrow to finance the purchase of capital). Otherwise the conditions of equilibrium involve a corner solution, with young people consuming nothing, and with a rate of interest that may exceed their rate of time preference. It is straightforward to demonstrate that the equilibria analyzed below (both steady-state and transitional) all satisfy this interiority condition if r is large enough or if capital's share of income α is small enough.

[6] The assumption of a unique final good is made in order to abstract from demand effects driven by relative prices which are outside the scope of the paper.

Adaptability and Education

All workers are capable of working with the old technology. However, not all workers are productive with the new technology; to do so they must be *adaptable*. We assume that adaptability depends on age and education, together with a stochastic component (i.e. luck in the labour market). Specifically, all young workers are adaptable, whereas only with probability $\sigma \in [0,1]$ can an old worker relocate to the newly innovating sector. Our analysis will first proceed under the assumption that the adaptability parameter σ is exogenous, and in Section 4 we shall extend it to the case where σ depends upon the amount of time $h \in [0,1]$ a worker devotes to education when young. This notion of education as a vehicle for workers to acquire skills that empower them to use the newest technologies goes back to the seminal work of Nelson and Phelps (1966) and since then it has been widely used in growth theory and macroeconomics.[7]

Vintage Human Capital

Each individual worker is endowed with one unit of time per period, any amount of which can be supplied —conditional on adaptability— to one sector or the other, but not to both at the same time. Young workers are all the same; each unit of time supplied to a sector by a young worker contributes one unit of labour towards production in that sector. When young, workers learn vintage specific skills that determine their productivity next period. Hence, each unit of time supplied by old workers provides an amount of labour that depends on the vintage of technology they used when young (human capital thus has a vintage-specific component).

In particular, one unit of time supplied by an old worker using the same vintage of technology she used last period, contributes $(1+\eta)$ units of labour, where $\eta > 0$ is a parameter indicating the rate of learning by doing. For an old individual working on a technology that is one period newer than the vintage used last period, her unit of time contributes $(1+\tau\eta)$ units of labour, where $\tau \in (0,1)$. Finally, for an old individual working on a technology that is two or more periods newer, her unit of time contributes only one unit of labour. Thus we are implicitly assuming that experience with a previous technology makes a worker more productive only if the previous technology is at most one period older. The *transferability* parameter τ captures the notion of generality of the technology based on human capital that we mentioned in the Introduction.

[7] In Greenwood and Yorukoglu (1997) educated labor is necessary in the adoption phase of the new technology. Bartel and Lichtenberg (1987) show micro-evidence for the U.S. that more educated workers have a comparative advantage in implementing new technologies. Flug and Hercowitz (2000) using a cross-country dataset find that new equipment investments raises the demand of more educated workers.

3 Exogenous Adaptability

3.1 The Relative Labour Demand Schedule

Consider the economy of the previous section with σ exogenously given, $\kappa = 0$, and $\tau \in (0,1)$. Hence, skills are only partially transferable on new technologies, but capital is not transferable at any cost in its second period. Each firm chooses its demands for capital and labour so as to maximize the present value of profits over the lifetime of capital, given a constant rate of interest r and a wage in each sector i equal to $w_{it} \equiv \omega_{it} A_t$, for all t. Let $k_t \equiv K_t/A_t$ denote the normalized amount of new capital installed at date t. Then the representative firm in sector 0 at date t chooses k_t, x_{0t}, and $x_{1,t+1}$ so as to maximize:

$$-k_t + k_t^{\alpha} x_{0t}^{1-\alpha} - \omega_{0t} x_{0t} + \frac{1}{1+r}\left[k_t^{\alpha} x_{1,t+1}^{1-\alpha} - (1+\gamma)\,\omega_{1,t+1} x_{1,t+1}\right], \tag{2}$$

where we have normalized the price of the final good (consumption or investment) to one.[8] The first-order condition for maximization with respect to capital input yields:

$$k_t = \alpha^{\frac{1}{1-\alpha}}\left[x_{0t}^{1-\alpha} + \frac{1}{1+r} x_{1,t+1}^{1-\alpha}\right]^{\frac{1}{1-\alpha}}, \tag{3}$$

and the first-order conditions for x_{0t} and x_{1t} define the relative labour-demand schedule at each date t:

$$\frac{\omega_{0t}}{\omega_{1t}} = (1+\gamma)\left(\frac{k_t}{k_{t-1}}\right)^{\alpha}\left(\frac{x_{0t}}{x_{1t}}\right)^{-\alpha}. \tag{4}$$

Next, suppose that $\kappa \in (0,1)$. The owners of old capital can retool it to embody the new technology and employ it in the other sector, at a cost of losing a fraction $(1-\kappa)$ of the capital. Thus κ is an index of generality of the technological blueprint. Let $d_t \equiv D_t/A_t$ be the normalized amount of old capital that is retooled at each date t. The representative firm chooses k_t, x_{0t}, $x_{1,t+1}$, d_{t+1} and $\widetilde{x}_{0,t+1}$ so as to maximize:[9]

$$\begin{aligned} &-k_t + k_t^{\alpha} x_{0t}^{1-\alpha} - \omega_{0t} x_{0t} + \frac{1}{1+r}[(k_t - (1+\gamma)\,d_{t+1})^{\alpha}\, x_{1,t+1}^{1-\alpha} \\ &- (1+\gamma)\,\omega_{1,t+1} x_{1,t+1}] + \frac{1+\gamma}{1+r}\left[(\kappa d_{t+1})^{\alpha}\, \widetilde{x}_{0,t+1}^{1-\alpha} - \omega_{0,t+1}\widetilde{x}_{0,t+1}\right]. \end{aligned} \tag{5}$$

[8] According to the production relations (1), the present value of profits resulting from the use of capital newly aquired at t, when there is no compatibility ($\kappa = 0$), is:

$$-K_t + K_t^{\alpha}(A_t x_{0t})^{1-\alpha} - w_{0t} x_{0t} + \frac{1}{1+r}\left[K_t^{\alpha}(A_t x_{1,t+1})^{1-\alpha} - w_{1,t+1} x_{1,t+1}\right]$$

Dividing this expression by A_t and using the normalizations defined above produces (2).

[9] Expression (5) can be derived by an argument analogous to the one used in footnote 8 above to derive expression (2).

The first-order condition with respect to each d_t can be expressed as:

$$\kappa \left(\frac{\widetilde{x}_{0t}}{\kappa d_t} \right)^{1-\alpha} \leq \left[\frac{x_{1t}}{k_{t-1} - (1+\gamma)\, d_t} \right]^{1-\alpha}, \text{ with equality if } d_t > 0.$$

Thus the optimal amount of retooling d_t is such that the marginal productivity of using a unit of capital with the old technology equals the marginal productivity of embodying the new technology into $\kappa < 1$ units of old capital. Together with the first-order conditions for x_{1t} and $\widetilde{x}_{0t}$, the inequality above can be expressed as:

$$\frac{\omega_{0t}}{\omega_{1t}} \geq (1+\gamma)\, \kappa^{\frac{\alpha}{1-\alpha}} \text{, with equality if } d_t > 0. \tag{6}$$

In other words, for any given degree of compatibility κ there is a maximum wage premium to be paid to workers on the new technology that makes the retooling choice profitable to the firm. It also follows that equation (4) holds whenever $d_t = 0$. Hence, the general expression for the relative demand of skilled labor is:

$$\frac{\omega_{0t}}{\omega_{1t}} = (1+\gamma) \max \left\{ \left(\frac{k_t}{k_{t-1}} \right)^{\alpha} \left(\frac{x_{0t}}{x_{1t}} \right)^{-\alpha}, \kappa^{\frac{\alpha}{1-\alpha}} \right\}. \tag{7}$$

This relative demand curve is illustrated in Figure 1: when the relative wage of adaptable labour is above the limit defined by the second argument of the max operator in (7), firms are discouraged from embodying the new technology in the old capital and the relative demand curve is negatively sloped.

3.2 The Relative Labour Supply Schedule

We now determine the relative labour-supply schedule at each date t. To characterize the optimal behaviour of workers, note that the normalized wage of a worker will depend on which sector the worker is in, whether the worker is young or old, and (if old) where she worked last period, according to Table 1 below.

Table 1 here

Thus, an old adaptable worker going from sector 0 to sector 1 supplies $(1+\eta)$ units of labour as a result of learning by doing on the same technology, whereas the same worker could supply only $(1+\tau\eta)$ units of labour to sector 0, as a result of having to switch technology. An old worker going from sector 1 to 0 supplies only one unit of labour because experience with a technology is not transferable to one that is two periods newer, whereas the same worker could supply $(1+\tau\eta)$ units of labour to sector 1 because only the fraction $(1-\tau)$ of learning is lost when the worker switches sectors to work with a technology that is one period newer.

An old worker who is not adaptable must work on the old technology in sector 1. One who is adaptable will work where the wage is highest. A young worker will work where the expected present value is highest, given the probability σ of being adaptable when old.

The following argument shows that unless the normalized capital stock is falling (that is, unless $k_t < k_{t-1}$), all young workers at date t will start their careers working with the new technology (in sector 0). Suppose, on the contrary, that some young workers choose to work in sector 1. Because of partial skill transferability, Table 1 applied to $t+1$ implies that the worker's continuation value would have been higher if he had chosen sector 0 in date t; therefore $\omega_{1t} > \omega_{0t}$. But then according to Table 1 all old workers will choose to work on the old technology, no matter where they worked when young, since old workers do not value future skill transferability. Thus the supply of labour in sector 1 will be $x_{1t} > 1$ (the amount supplied by the full measure 1 of old workers, plus some young workers) and the supply in sector 0 will be $x_{0t} \leq 1$ (no more than the full measure 1 of young workers). Unless $k_t < k_{t-1}$ it then follows from equation (4) that $\omega_{1t} < \omega_{0t}$, which contradicts our earlier demonstration that $\omega_{1t} > \omega_{0t}$. This establishes:

Lemma 1 *If $k_t \geq k_{t-1}$, all young workers enter sector 0 at date t.*

In all of the conceptual experiments analysed below, the normalized capital stock is either constant (in the steady-state analysis) or rising (in the analysis of transitions), so Lemma 1 ensures that we can safely ignore the possibility of young workers entering sector 1.[10]

Let $s_t \in [0, \sigma]$ denote the fraction of old workers who choose to work in sector 0 at date t. The supply of labour to each technology will then depend on s_t according to:

$$\begin{aligned} x_{0t} &= 1 + s_t\left(1+\tau\eta\right), \\ x_{1t} &= \left(1-s_t\right)\left(1+\eta\right). \end{aligned} \tag{8}$$

There are three cases to analyze: (A) if $(1+\eta)\,\omega_{1t} < (1+\tau\eta)\,\omega_{0t}$, then every old worker who is adaptable prefers the new vintage, and $s_t = \sigma$; (B) if $(1+\eta)\,\omega_{1t} = (1+\tau\eta)\,\omega_{0t}$, then any fraction $s_t \in [0,\sigma]$ of old workers may choose the new vintage; (C) if $(1+\eta)\,\omega_{1t} > (1+\tau\eta)\,\omega_{0t}$, then all old workers choose the old vintage of technology, and $s_t = 0$. In cases (B) and (C) every old worker earns the same wage in equilibrium so that there is no

[10] See, however, footnote 12 below.

within-group inequality in those cases. Case (A) is the only case where there is a positive adaptability premium and where, when adaptability is endogenous, young workers choose to invest in education. For this reason, in the remaining part of the paper we shall concentrate our attention on the more relevant case where the equilibrium is of type (A).[11]

3.3 Steady-State Equilibrium Inequality

We focus on a balanced growth path in which the capital stock and all wage rates grow at the rate of labour-augmenting technological progress γ, and the equilibrium quantities of labour are constant: that is, $(k_t, \omega_{0t}, \omega_{1t,} x_{0t}, x_{1t}) = (k, \omega_0, \omega_{1,} x_0, x_1)$ for all t. Equations (8) and the taxonomy that follows them define the steady-state labour-supply schedule which is depicted in Figure 1.[12] The steady-state labour-demand schedule is given by (7) with $k_t/k_{t-1} = 1$. The equilibrium relative wage (ω_0/ω_1) determined by the intersection between these two schedules in the vertical region of the supply curve can be expressed as:

$$\frac{\omega_0}{\omega_1} = (1+\gamma)\max\left\{\left[\frac{(1-\sigma)(1+\eta)}{1+\sigma(1+\tau\eta)}\right]^{\alpha}, \kappa^{\frac{\alpha}{1-\alpha}}\right\}. \tag{9}$$

Our measure of aggregate wage inequality will be the ratio between the highest and the lowest wage in the economy, denoted as R. The model does not generate any inequality among young workers, given they are ex-ante equal and all work in the same sector. However, we can characterize wage inequality among old workers by the ratio R^o between the highest and lowest wage earned by an old worker in equilibrium. We can also characterize the experience premium R^x, defined as the ratio of the average wage of old workers to the wage of young workers.[13]

[11] Where interesting, we report in a footnote the comparative statics when the equilibrium is of type (B) or (C).

[12] When $\omega_0/\omega_1 < \Omega \equiv 1 - (1-\tau)\eta(1+\gamma)/(1+r)$, then young workers will choose to enter sector 1, despite the higher continuation value to be had from entering sector 0, in which case the relative supply falls to zero as indicated in Figure 1. Lemma 1 implies, however, that this segment of the relative supply curve always lies below the relative demand curve in a steady-state equilibrium.

[13] Inequality among old workers (R^o) depends only on two wage rates, thus there is no loss of generality in choosing the wage ratio as its measure. The experience premium (R^x) is a function of three wage rates instead. In Aghion, Howitt and Violante (2000) we argue that the behaviour of inequality measures such as the Gini coefficient or the variance of log wages is qualitatively similar to that of wage ratios.

Within-group inequality

It is easy to see that the measure of within-group inequality among old workers is

$$R^o = \frac{(1+\tau\eta)\,\omega_0}{(1+\eta)\,\omega_1}. \tag{10}$$

To focus first on the effects of human capital generality, consider the case of full specificity of physical capital, i.e. $\kappa = 0$. An increase in the generality of technology as measured by the transferability parameter τ raises the degree of within-group inequality. It does so by allowing adaptable workers to benefit even more from their experience on last period's leading-edge technology, and therefore to earn an even larger wage premium relative to the less fortunate workers in their cohort who are not adaptable. Notice that the higher skill transferability raises the aggregate labour input of the adaptable workers, inducing downward pressure on their wage, but this force is always dominated by the former "skill deepening" effect.

Suppose now to be in a case where $\kappa > 0$ and firms exploit this partial compatibility across vintages to embody the new technologies in old capital. As before, an increase in the generality of technology as measured by the transferability parameter τ will have a positive effect on within-group inequality, by increasing the premium earned by adaptable workers. Note that the effect of τ on within-group inequality is amplified by the possibility of retooling. That is, the elasticity of R^o with respect to $1+\tau\eta$ is unity, whereas in the previous case with no retooling it was less than unity. This is because when τ increases, firms respond to the increase in the available supply of labour in sector 0 by raising the amount of capital in which they embody the new technology. This induced increase in the supply of capital to sector 0 serves to amplify the increase in wages of adaptable workers in that sector, by raising their marginal product.

In an equilibrium with retooling (i.e. $d_t > 0$), the effect of an increase in generality of technology as measured by the compatibility of capital κ is also to increase the degree of within-group inequality. It does so by increasing the amount of capital that is transferred to sector 0 to embody the new technological blueprint, thereby increasing the premium earned by adaptable workers in that sector ("capital deepening" effect). The elasticity of inequality to the technological compatibility parameter κ is $\frac{\alpha}{1-\alpha}$. A large capital share requires a big fraction of the capital stock to be moved from the old to the new sector in order to equate marginal productivities of capital, with sharp effects on the capital-labour ratios and the wage differentials between technologies.[14]

[14] Finally, note that in cases (B) and (C) the aggregate adaptability constraint is not binding and all old workers earn the same, so $R^o = 1$.

Experience premium

When $\kappa = 0$ and capital is fully specific, all adaptable old workers earn an experience premium of $1 + \tau\eta$, whereas the non-adaptable earn an experience premium of $(1 + \eta)(\omega_1/\omega_0)$. Since both of these individual premiums are increasing in τ, the average experience premium R^x is also increasing in τ. That is, an increase in the generality of technological knowledge raises skill transferability and amplifies the experience premium of adaptable workers, who are able to transfer more of their cumulated skills. It also indirectly raises the experience premium of non-adaptable old workers by making adaptable labour relatively less scarce.

This result is particularly interesting in light of the fact that models based on the "acceleration hypothesis" would predict a decline in the experience premium. This is evident from the expressions above showing that R^x is (weakly) decreasing in the growth rate of embodied productivity γ: larger productivity differentials between the young and the old vintages represent a relative advantage to young workers who are more adaptable.

Next, consider an equilibrium with retooling of old capital. The experience premium earned by the non-adaptable fraction $(1 - \sigma)$ is

$$\frac{1 + \eta}{(1 + \gamma)\,\kappa^{\frac{\alpha}{1-\alpha}}}, \tag{11}$$

whereas the adaptable fraction σ will earn an experience premium equal to $1 + \tau\eta$. Therefore the average experience premium R^x is increased by a larger τ, as before, but it is now *reduced* by an increase in the generality of technology as measured by the compatibility of capital. That is, a rise in κ allows to transfer more capital to sector 0 where it benefits the *in*experienced workers. [15]

Overall inequality

Overall inequality is always given by $R = \max\{1 + \tau\eta, R^o\}$, depending on whether the lowest wage in the economy is the wage of the inexperienced young workers or that

[15] In an equilibrium with $\kappa = 0$, in case (B), the condition of indifference that defines this case implies that $R^x = 1 + \tau\eta$, thus, an increase in the generality of technology as measured by τ increases the experience premium because in equilibrium arbitrage ensures that all old workers —irrespectively of where they work— earn the same premium as those who are benefiting from the transferability of experience. In case (C) an increase in the generality of technology as measured by the transferability parameter τ has no effect on the experience premium because in equilibrium no worker is actually transferring any skills to the new technology. In an equilibrium with retooling, only case (C) remains relevant, since case (B) (where old workers are indifferent between working in sectors 0 and 1) would now require a razor's edge condition to put us on the horizontal segments of both the supply and the demand curves (see Figure 1). In case (C), the experience premium is given by (11). As in the benchmark case (A), R^x is unaffected by an increase in the transferability parameter τ but it is reduced by a rise in κ.

of the experienced but non-adaptable old workers. It follows from our previous results that R is (weakly) increasing in the generality of technology, along both dimensions. That is, an increase in the transferability parameter τ will raise the relative wage of the already privileged old adaptable workers, whereas a rise in the degree of technological compatibility κ will induce firms to give these privileged workers more capital to work with thereby further increasing their relative wage. As with our measure of within-group inequality, the possibility of retooling will amplify the effects of τ on overall inequality by inducing a secondary transfer of more capital to sector 0.

To summarize, we state:

Proposition 1 *Suppose the adaptability rate σ is exogenous. In a stationary equilibrium with no retooling of physical capital, all three measures of steady-state inequality are (weakly) increasing in the degree of generality of technology as measured by the transferability of experience across vintages. In a stationary equilibrium where firms retool a positive fraction of old capital to embody the new technology: (i) all three measures of inequality are (weakly) increasing in the degree of generality of technology as measured by the transferability of experience τ, (ii) within-group inequality is (weakly) increasing in the generality of physical capital as measured by κ, and (iii) the effects of transferability on within-group inequality and on overall inequality are (weakly) amplified by the possibility of retooling; however (iv) the experience premium is (weakly) decreasing in the generality of physical capital.*

4 Endogenous Adaptability

We now extend the model by allowing young workers to optimally choose their degree of adaptability σ when old. Acquiring adaptability is a time consuming activity and we denote by $h = \varphi(\sigma)$ the amount of time a young individual must divert from production in order to achieve adaptability level σ, with $\varphi' > 0$, $\varphi'' > 0$, $\varphi(0) = 0$, and $\varphi(1) < 1$. We think of h as being the fraction of individuals' youth spent acquiring education, and of education as an investment into future adaptability (see Nelson and Phelps, 1966).

Lemma 1 will continue to hold in this case, so that young workers will still find it optimal to work initially on the new vintages. The same reasoning as used in section 3 above can be used, because once again the young worker will strictly prefer to work in sector 0 if $\omega_{0t} \geq \omega_{1t}$. That is, let $V_{it}(\sigma)$ be the continuation value of a young worker that enters sector i at t and acquires an adaptability probability σ. According to Table 1:

$$V_{0t}(\sigma) \equiv \frac{1+\gamma}{1+r}\left[\sigma \max\left\{(1+\tau\eta)\,\omega_{0,t+1},(1+\eta)\,\omega_{1,t+1}\right\}+(1-\sigma)\,(1+\eta)\,\omega_{1,t+1}\right],$$

$$V_{1t}(\sigma) \equiv \frac{1+\gamma}{1+r}\left[\sigma \max\left\{\omega_{0,t+1},(1+\tau\eta)\,\omega_{1,t+1}\right\}+(1-\sigma)\,(1+\tau\eta)\,\omega_{1,t+1}\right].$$

Since $\tau\eta > 0$ and $0 < \tau < 1$, therefore $V_{0t}(\sigma) > V_{1t}(\sigma)$ for all values of σ. It follows that if $\omega_{0t} \geq \omega_{1t}$, then:

$$\max_{\sigma}\left\{\omega_{0t}\,(1-\varphi(\sigma))+V_{0t}(\sigma)\right\} > \max_{\sigma}\left\{\omega_{1t}\,(1-\varphi(\sigma))+V_{1t}(\sigma)\right\},$$

i.e. all young workers will start on the new capital. The optimal adaptability choice by a young worker, σ^*, will then solve:

$$\max_{\sigma}\left\{\omega_0\left[1-\varphi(\sigma)\right]+\frac{1+\gamma}{1+r}\left[\sigma\max\left\{(1+\tau\eta)\,\omega_0,(1+\eta)\,\omega_1\right\}+(1-\sigma)\,(1+\eta)\,\omega_1\right]\right\}.$$

The first order condition for this problem leads to:

$$\omega_0\varphi'(\sigma^*) = \frac{1+\gamma}{1+r}[(1+\tau\eta)\omega_0-(1+\eta)\omega_1]. \tag{12}$$

At the optimum, the foregone earnings from a marginal investment in adaptability when young (LHS of (12)) must equal the discounted marginal wage gain associated with the correspondingly higher probability of working with the new technology when old (RHS of (12)). Not surprisingly, therefore, young workers will forego earnings to invest in adaptability only if they receive a positive return from doing so, that is if wages for experienced workers on new vintages are strictly higher than wages on the old technology. This in turn implies that in any equilibrium with $\sigma^* > 0$ there must be inequality among the old workers.[16]

Two questions are of relevance when workers can choose optimally their level of adaptability. First, how does the equilibrium level σ^* respond to an increase in the degree of technological generality? Intuitively, if human or physical capital is more easily transferable to the new sector because technologies are more general, the incentives to invest in adaptability —i.e. the option of using this additional knowledge or capital on the more productive technology— rise. Second, how does equilibrium inequality respond to a rise in generality? The answer depends on whether the direct effect of τ or κ dominates the labour supply effect induced by the larger fraction of adaptable workers in the population.

[16] In contrast, when $R^o = 1$ it is not individually rational to invest, which implies that case (B) can no longer be an equilibrium, as it would feature both $\sigma^* > 0$ and $R^o = 1$. Case (C) would be a trivial equilibrium with no investment in education and no within-group inequality, thus we continue focusing our analysis on the benchmark case (A) where $\sigma^* > 0$.

Dividing both sides of (12) by ω_0 and rearranging, we get:

$$\varphi'(\sigma^*) = \frac{(1+\gamma)(1+\tau\eta)}{1+r}\left[1 - \frac{1}{R^o}\right], \tag{13}$$

which defines implicitly a function $\sigma^*(R^o, \tau)$ representing the aggregate supply of adaptable labour which is increasing in both arguments. The aggregate relative labour supply schedule in the economy is now determined by: $x_0 = 1 - \varphi(\sigma^*) + \sigma^*(1+\tau\eta)$, and $x_1 = (1-\sigma^*)(1+\eta)$, where $\sigma^* = \sigma^*(\omega_0/\omega_1, \tau)$; hence the relative labour supply to the new technology

$$\frac{x_0}{x_1} = \frac{1 - \varphi(\sigma^*) + \sigma^*(1+\tau\eta)}{(1-\sigma^*)(1+\eta)} \tag{14}$$

will also be increasing in both R^o and τ.[17]

We can now define the adaptability demand curve of the economy: plugging the demand schedule (7), together with (14) and the steady-state condition $k_t/k_{t-1} = 1$ into the definition of within-group inequality (10), we obtain a function $R^o(\sigma^*, \tau, \kappa)$ which is decreasing in the economy's adaptability rate and increasing in the two parameters measuring technological generality. The supply and demand curves determine a unique equilibrium pair (σ^*, R^o) depicted in Figure 2.

Within-group inequality

Let us start by assuming full specificity of physical capital, i.e. $\kappa = 0$. The effect of a rise in the generality of technological knowledge τ on steady-state within-group inequality R^o is now ambiguous: a higher τ increases the premium to adaptability for given σ^* (direct effect), but it also increases the incentives to invest in adaptability, and the resulting increase in the supply of adaptable labour σ^* will tend to reduce the wage ratio $\frac{\omega_0}{\omega_1}$ (indirect effect). Which of these two counteracting effects dominates, will depend on the particular cost function $\varphi(\sigma)$. Consider the following general specification:

$$\varphi(\sigma) = a^{-\lambda}\frac{\sigma^{1+\lambda}}{1+\lambda},$$

where the parameter $\lambda > 0$ measures the convexity of the cost function $\varphi(\cdot)$, $a \in (0, \overline{\sigma})$ and $\sigma \in [0, \overline{\sigma}]$.

We examine first the two polar cases where $\lambda \to \infty$ and $\lambda = 0$. In the case where λ is very large, the supply curve is close to vertical at $\sigma^* = a$, in other words, the economy

[17] In deriving these last comparative-statics results, note that, according to (13):

$$\varphi'(\sigma^*) < \frac{1+\gamma}{1+r}(1+\tau\eta) < (1+\tau\eta),$$

where the last inequality follows from the dynamic efficiency of the economy.

is essentially the same as in the case of exogenous σ analyzed in section 3 above; thus, as we saw in that section, an increase in transferability τ will have only the direct effect of raising inequality (see the upper panel of Figure 2) .

On the other hand, for $\lambda = 0$, the supply curve is infinitely elastic whenever $\sigma^* \in (0, \overline{\sigma})$, and equilibrium within-group inequality R^o is obtained from (13) with $\varphi'(\sigma^*) = 1$. This implies immediately that R^o is strictly decreasing in τ. In other words, the indirect effect dominates the direct effect in this case (see the lower panel of Figure 2).

In the more general case where $\lambda > 0$ but finite, the supply curve is positively sloped and the comparative statics are ambiguous (see the upper panel of Figure 3). By taking a logarithmic approximation (of the type $\ln(1+x) \simeq x$) of the supply and demand curves around the initial equilibrium, we can establish the following sufficient condition for a rise in within-group inequality:

Lemma 2 *With no retooling, a rise in τ in an economy initially at the equilibrium (σ^*, R^o) increases within-group inequality R^o if*

$$\sigma^* < \frac{\lambda}{\alpha\left[(1+\lambda) + (1+\tau\eta)\right]}. \tag{15}$$

We prove this Lemma in the Appendix. The conclusion is that inequality will rise for initial values of equilibrium adaptability which are low enough. Intuitively, it is the labour supply effect that limits the rise in inequality and this effect is stronger the higher is σ^*. We already showed that a more pronounced convexity in φ, corresponding to high values of λ (and to a low elasticity of supply of adaptability to its relative price, i.e. wage inequality) makes it more likely that in equilibrium inequality will rise, as it dampens the shift of the supply curve. A smaller fraction of transferable skills η leads to a weaker labour supply effect as it limits the rise in the supply of adaptable labour input. Finally, a larger capital share α increases the (negative) marginal effect of an additional unit of adaptable labour input on ω_0 and makes the rise in inequality less likely.

Let us now consider an economy with a sufficiently high degree κ of compatibility between vintages of capital, so that retooling takes place. The supply curve of adaptability is unchanged since it does not depend explicitly on κ. The relevant portion of the demand curve of adaptability is now given by the flat region, which displays infinite elasticity to σ^*, as explained earlier. It is immediate to see that an increase in the generality of the technologies, captured by a rise in κ, shifts upward the demand curve along the supply curve, therefore it unambiguously raises both equilibrium adaptability σ^* and within-group inequality R^o. A rise in generality of skills τ inducing a similar shift in the demand curve has the same effect on inequality, but will induce a larger supply response (the adaptability supply curve shifts to the right). The comparative statics in an economy with retooling are depicted in lower panel of Figure 3. We now turn to the experience premium.

Experience Premium

Assume first full specificity of capital, $\kappa = 0$. When adaptability is endogenous, the fraction σ^* of adaptable workers earn an experience premium of $(1 + \tau\eta)$, whereas the fraction $(1 - \sigma^*)$ of non-adaptable workers earns a lower experience premium equal to: $\frac{1+\eta}{1+\gamma}\left[\frac{1-\psi(\sigma^*)+\sigma^*(1+\tau\eta)}{(1-\sigma^*)(1+\eta)}\right]^{\alpha}$. Thus an increase in the generality parameter τ has an even more positive effect on the average experience premium R^x than when σ is exogenously fixed; by increasing σ^* it raises both the fraction of adaptable workers among the old, and the experience premium of the non-adaptable, as their supply on old technologies becomes relatively more scarce than in the case with exogenous adaptability.[18]

We showed in section 3 that, in an equilibrium with capital upgrading and σ exogenous, the experience premium falls when the technological blueprint becomes more general. When workers control their adaptability, there is an additional force contributing to push up the experience premium following a rise in κ or τ: the increase in σ^* induces a composition effect among the old that increases their relative average wage. Thus, under some parametric restrictions (e.g. α small enough), the experience premium could rise.

Finally, aggregate inequality is given by $R = \max\{1 + \tau\eta, R^o\}$, thus this is also unambiguously rising with κ, while the effect of τ is now ambiguous in sign, as it depends on the elasticity of the adaptability-supply response. Under the conditions of Lemma 2, also aggregate inequality will rise.

To summarize, we state

Proposition 2 *Consider an economy with endogenous adaptability: (i) with full specificity of capital, a rise in skill transferability τ increases the equilibrium adaptability rate σ^*, but has ambiguous effects on within-group inequality. Inequality will increase if condition* (15) *holds, in particular for sufficiently high values of λ and low values of α, η and aggregate adaptability in the initial steady-state; (ii) with retooling, a rise in the generality of technology increases the equilibrium adaptability rate and within-group inequality; (iii) in the absence of retooling, the supply response due*

[18] Note that we have used the result in Footnote 18 to draw this conclusion.

to endogenous adaptability amplifies the surge in the experience premium following a rise in technological generality and (iv) when retooling takes place, the endogenous supply response counteracts the direct effect of a rise in κ, introducing the possibility of a rise in the experience premium.

5 A Simple Calibration

The theoretical model guided us to understand the qualitative impact of an increase in the generality of the technology on wage inequality. Direct measures of generality of skills and compatibility of capital that would allow us to assess the magnitude of the rise in generality are not available.[19] In this section, we use our model (the version with endogenous adaptability) in conjunction with the aggregate data in order to learn about the *quantitative* changes in the key parameters of the model τ and κ.

The exercise consists of calibrating the 7 parameters of the model $\{\beta, \alpha, \gamma, \eta, \lambda, \tau, \kappa\}$ to match some key aggregate features of the data (among which within-group inequality and the experience premium) before the start in the rise of inequality, i.e. say the early 70's , and then simulating the model to measure how large the rise in τ and κ should have been to explain, by themselves, the rise in inequality in the next three decades. It is an exercise in reverse-engineering, where we ask the data to shed some light on the two key parameter values of the model. By definition, it will provide an upper bound on the increase in generality, since no other type of shock is considered.

For the calibration, we choose a period of 25 years, thus in the first period of active life individuals are aged 15 to 40 and in the second period 40 to 65, their retirement age. We start the life of our agents at 15 to allow them to spend some extra years of the first period in school. The calibration for some parameter values is standard. For example, we choose β to match an annual rate of return to capital of 5% and α to match the aggregate capital share in the economy, roughly 30%, as commonly done in the Real Business Cycle literature (Cooley, 1995). To parametrize γ, we follow a large literature in macroeconomics suggesting that capital-embodied technological progress can be measured off the decline in the relative price of capital goods. Since the type of technologies we refer to in this paper are mainly embodied in equipment, we choose to match the average rate of decline in (quality-adjusted) relative price of equipment, around 4.5% per year in

[19] The empirical micro studies on costs of adjustment in labor and capital when implementing new technologies are very rare (see for example Doms, Dunne and Troske, 1997) and they are far from being representative of the whole economy.

the post-war period (Krusell et al. 2000).[20] The parameter η measures the productivity increase of a worker who spends all her working life on the same type of technology. This can probably be approximated by the wage growth accruing to workers with very long tenures. From Topel (1991, Table 2) we estimate that cumulative wage growth over 40 years of tenure would be around $45 - 50\%$. However, even workers with long tenures in the data are likely to be subject to upgrading of technology with some frequency, hence to loss of knowledge. Therefore this number is a lower bound for η, and to account for this fact we choose to set η to .7.

We are left with the three parameters λ, τ, and κ. These three parameters are calibrated jointly by matching the fraction of the first period spent in school h, the experience premium R^x and within-group inequality R^o. From the *U.S. Current Population Survey* data, we obtained that the average years of schooling of the male population in the period just prior to the rise in inequality (early 70's) were approximately 11.75. Since individuals in the model start their life at 15, it means that they spend 2.75 extra years in school on average, corresponding to $h = .11$. For the experience premium, we match a value $R^x = 1.35$ and for within-group inequality a value of $R^o = 1.65$. [21] Table 2 below summarizes our calibration.

TABLE 2
Summary of Calibration

Parameters	Moment to match	Source
$\beta = .29$	rate of return on capital	Cooley (1995)
$\alpha = .30$	capital share	Cooley (1995)
$\gamma = 2.0$	growth of rel. price of equipment	Krusell et al. (2000)
$\eta = .7$	returns to life-time tenure	Topel (1991)
$\lambda = 2.65$	average years of schooling	CPS data
$\tau = .68$	within-group inequality	CPS data
$\kappa = .34$	experience premium	Katz-Autor (1999)

[20] Taken at face value, this number implies that output in our model grows at a rate of 4.5%. Two considerations are in order. First, although this may seem a large number, when quality-adjusted appropriately, US output grows at nearly 4% per year in the postwar period. Second, all the results of the model would be unchanged if we introduced neutral technical change (or total factor productivity), as it would affect equally all vintages of capital. Negative total factor productivity growth (as implied by the last thirty years of data) would bring output growth in the model in line with the data.

[21] We define the experience premium as the ratio between the average weekly wage for male workers with 25 years of experience and 5 years of experience, which we take from Katz and Autor (1999, Figure 5). Our measures of within-group inequality and educational attainment are constructed from the CPS March Files data used in Violante (2002). The sample is constructed with white males, aged 18-60, who worked full time at least 14 weeks. The "residual" wages are computed through a log-wage regression that includes a quartic in age, educational dummies and interaction terms. We refer the reader to that paper for more details. We define within-group inequality as the $75th - 25th$ residual weekly wage ratio for males. We use this measure rather than the more common $90th - 10th$ wage ratio because our model has only a two-point residual wage distribution.

Next, we simulate the model in order to "estimate" the values τ' and κ' that match the higher levels of the experience premium and within-group inequality in the late 1990's, respectively, $R^x = 1.57$ and $R^o = 1.9$. The model predicts new values $\tau' = .94$ and $\kappa' = .37$, thus both measures of generality increase. The index of generality of technology-specific skills increases sharply, while the index of vintage compatibility shows only a moderate rise. How plausible are these numbers? A simple way to check is to explore the implications of our exercise for the rise in educational attainment. Our data suggest that in the late 1990's average educational attainment of the working male population rose to 13.5 years corresponding to a fraction of .18 of the first period in the model. Our simulation predicts a rise of h from .11 to .17, hence fairly in line with the data.

Given the simplicity of the model –which was designed to be solvable analytically– one should take these quantitative results with some caution. However, at the very least, the exercise was useful to understand that, quantitatively, it is likely that τ increased faster than κ. The reason is that, as explained earlier, a sharp rise in κ would have reduced the experience premium, which instead increased in the U.S. economy.

6 Transitional Dynamics

One important advantage of our two-period overlapping generations structure is that it allows us to characterize the transitional dynamics of the economy in the wake of a technological shock that increases generality. In what follows we concentrate on the case where the aggregate adaptability constraint is binding (case A), so that in equilibrium young workers choose a positive amount of education and there is within-group inequality among old workers.

6.1 Exogenous Adaptability

Suppose the economy is in the old steady state at date t, with transferability rate equal to τ and that, between t and $t+1$, a new technology is introduced with generality $\tau' > \tau$. When capital can be partly upgraded and a positive fraction of capital is being retooled before and after the transition, then the economy displays no transitional dynamics and the various measures of inequality will immediately jump from their old steady-state to their new steady-state values at date $t+1$. The reason is that the wage ratio ω_{0u}/ω_{1u} at time u is independent of the capital stocks in the new and old sectors, namely:

$$\omega_{0u}/\omega_{1u} = (1+\gamma)\kappa^{\frac{\alpha}{1-\alpha}}.$$

In particular, a shock between dates t and $t+1$ that increases either the compatibility between old and new vintages of technologies from κ to $\kappa' > \kappa$, or the degree of skill transferability across technologies from τ to $\tau' > \tau$ will induce an *immediate jump* to the new long-run steady state for both R^o and R^x, with no transitional dynamics in-between; this simply follows from the wage ratio ω_{0u}/ω_{1u} being independent of capital stocks as long as retooling takes place (i.e. $d_t > 0$).

In the absence of compatibility across technologies ($\kappa = 0$), the economy will display interesting dynamics. The innovating sector at date $t+1$ is free to increase the optimal amount of capital input from k to $k' > k$ in order to exploit the higher labour supply on the new technology due to the larger degree of skill transferability. However, firms with capital embodying the old technology are stuck with the capital chosen at time t. Eventually, at time $t+2$, it will be the turn of the other sector to innovate, so also the other sector will choose the new amount of capital k' and the economy will converge to the new steady-state. Hence, there is only one transitional period for inequality, $t+1$, between the steady-state levels characterized by Proposition 1.

Within-group inequality for old workers is determined by the wage ratio between adaptable and non-adaptable workers. Adaptable workers at time $t+1$ have the additional advantage over non-adaptable workers that they can work with more capital ($k' > k$) embodying the new technology, which further increases their productivity compared to that of non-adaptable workers in the old sector. But from period $t+2$ onward, this additional wedge disappears as both sectors invest the same steady-state normalized amount of capital k'. Thus, within group-inequality *overshoots* its final steady-state level along the transition, i.e. $R^o_{t+1} > R^o_{t+2} > R^o_t$.

Next, consider the dynamics of the experience premium. In contrast to the evolution of within-group inequality, there is no overshooting in the experience premium, that is: $R^x_{t+2} > R^x_{t+1}$. This is, in fact, a direct consequence of the overshooting of within-group inequality: the experience premium for non-adaptable workers increases between period $t+1$ and period $t+2$ as young workers no longer benefit from working with a higher normalized capital stock than old non-adaptable workers. The comparison between R^x_{t+1} and R^x_t is less straightforward: on the one hand for given capital investment, a rise in skill-transferability increases the experience premium of both adaptable and non-adaptable workers (while allowing adaptable workers to transfer more experience, this also raises the experience premium of non-adaptable workers by making adaptable labour relatively less scarce); on the other hand, the increase in normalized capital stock in the new sector reduces the experience premium of non-adaptable workers who suffer from a relative shortage of capital compared to the young workers in the new sector. As it turns out, this latter effect is always dominated.

Finally, the dynamics followed by our measure of overall inequality R, is quite similar to the dynamics of R^o except when the lowest wage in the economy is the entry wage of young workers on young technologies; in this case there is simply no transitional period and the economy reaches the new steady-state immediately. Figure 4 depicts the dynamics of R^o and R^x along the transition.

6.2 Endogenous Adaptability

Introducing endogenous adaptability does not change qualitatively the transitional dynamics of within-group inequality R^o when $\kappa > 0$: if we allow for capital upgrading and a positive fraction of capital is being retooled before and after the transition, then the transitional dynamics disappear and within-group inequality immediately jumps from its old steady-state to the new steady-state value at date $t+1$. However, even when retooling takes place, endogenous adaptability introduces some dynamics in the experience premium. Even though R_u^o jumps immediately to its new steady-state, in the intermediate period $t+1$ the old workers inherit the degree of adaptability chosen before the shock at time t, i.e. $\sigma^*(\tau)$, which is lower than $\sigma^*(\tau')$. Thus, $R_t^x < R_{t+1}^x < R_{t+2}^x$, where the first inequality follows from the immediate adjustment of within-group inequality to its new steady-state level, while the second inequality follows from the rise in σ^* between $t+1$ and $t+2$.

Consider now an economy with no compatibility between old and new vintages of technologies. When σ is endogenous, at date $t+1$, i.e. immediately after the positive shock on transferability has occurred, within-group inequality will increase by more than when σ is exogenous. With exogenous adaptability, a rise in technological generality from τ to τ' induces a change in x_0 at date $t+1$ equal to $\sigma\eta\left(\tau' - \tau\right)$, whereas with endogenous adaptability the change in x_0 equals

$$\sigma^*(\tau)\eta\left(\tau' - \tau\right) - \left[\varphi\left(\sigma^*\left(\tau'\right)\right) - \varphi\left(\sigma^*\left(\tau\right)\right)\right] < \sigma\eta\left(\tau' - \tau\right).$$

Thus the labour supply effect in the transitional period is weaker with endogenous adaptability, which in turn will amplify the increase in the wage rate ω_0^u between dates t and $t+1$. The explanation is that when σ is exogenous in the transitional period the adaptability of old workers is predetermined, while when σ is endogenous the optimal choice of adaptability σ^* for young workers increases, hence their labour supply to the new sector is reduced by the corresponding extra time they spend in school. There will still be overshooting in within-group inequality as the transferability shock will again induce firms in the new sector to increase their capital investment from k to some $k' > k$, which in turn implies that adaptable workers will work with more capital than non-adaptable workers in period $t+1$, but not in period $t+2$.

With endogenous adaptability, the experience premium in periods $t+1$ and $t+2$ becomes

$$\begin{aligned} R^x_{t+1} &= (1+\tau'\eta)\left[\sigma^*(\tau) + (1-\sigma^*(\tau))\frac{1}{R^o_{t+1}}\right], \\ R^x_{t+2} &= (1+\tau'\eta)\left[\sigma^*(\tau') + (1-\sigma^*(\tau'))\frac{1}{R^o_{t+2}}\right]. \end{aligned} \tag{16}$$

Given that $R^o_{t+1} > R^o_{t+2}$ and $\sigma^*(\tau') > \sigma^*(\tau)$, we have: $R^x_{t+1} < R^x_{t+2}$. The fact that $R^x_{t+1} > R^x_t$ follows from the same reasoning we made for the case where σ is exogenous. Thus, as in the previous section, there is no overshooting in the experience premium. Finally, the dynamics of overall inequality R with σ endogenous do not change qualitatively in comparison with the case where σ is fixed.

The main results on the transitional dynamics of the economy can be summarized in:

Proposition 3 *Consider an economy with exogenous adaptability: (i) with full specificity of capital, within-group inequality overshoots its final steady state along the transition, while the experience premium is monotonically increasing; (ii) with retooling, there are no transitional dynamics and all measures of inequality jump immediately to the new steady-state. Endogenous adaptability (iii) amplifies the overshooting behaviour of within-group inequality when capital is fully specific, and (iv) introduces monotonic dynamics in the experience premium in the presence of retooling of old capital.*

We provide a formal proof of part (i) of this Proposition in the Appendix. The proof of the other parts follows naturally.

7 Concluding Remarks

We have developed a simple two-sector OLG model with two-period lived agents and two-period technological vintages to analyze the effects of an increase in the *generality* of technologies on wage inequality. We have modelled generality, both in relation to human capital and the transferability of skills across sectors, and in relation to physical capital and its ability to be upgraded towards other sectors using more advanced technologies. We have focused our attention on two measures of wage inequality, namely the ratio between high and the low wages within a generation of ex-ante equal workers, which we took as a measure of within-group inequality, and the ratio between the average wages of old and young workers, the experience premium. Our main findings can be summarized as follows:

First, whether it relates to human or to physical capital, an increase in the generality of technology increases long-run within-group inequality, and during the transition towards a more general technology, within-group inequality overshoots its new steady-state level. Second, the steady-state experience premium reacts positively to an increase in the generality of technologies with regard to human capital, whereas it reacts negatively to an increase in the generality of technologies with regard to physical capital; moreover, during the transition period following an increase in the former, the experience premium increases monotonically over time towards its long-run steady state. Third, the above findings appear to be robust to endogenizing old workers' adaptability to new technologies provided the marginal cost of adaptability increases sufficiently fast. Fourth, a simple calibration exercise on US data suggests that the dimension of generality that increased most is that related to human capital.

To obtain analytical results we had to keep our model stylized, and as such it should be seen as a benchmark model that can be extended in several interesting directions. A first extension would explore the dynamics of wage inequality when agents live for more than two-periods. Our analysis on a related model with infinitely-lived agents (Aghion, Howitt, and Violante, 2000) shows that our approach based upon random adaptability to new technologies and its effects on the distribution of labour market histories can account for an important observation about wage inequality, which the two-period OLG model in this paper could not capture, namely that a sizeable part of the observed increase in within-group inequality relates to the temporary component of earnings (Gottschalk and Moffitt, 1994, Gittleman and Joyce, 1996, Blundell and Preston, 1999).

A second extension, which we begin investigating in the Appendix, is to model another dimension of between-group inequality, namely the educational premium. Based on the assumption that more educated workers are also more adaptable to new technologies when old, one can show that the comparative statics across steady-states of the educational premium mirror those of within-group inequality, and in particular also the educational premium increases with the generality of technologies.

Finally, the past thirty years have witnessed economy-wide evolutions in the organization of firms, in particular a generalized move towards flatter and more decentralized hierarchical forms. Recent empirical work (e.g. Caroli and Van Reenen, 2001) has pointed to the skill-biased nature of organizational change. But equally important is the *generality* of this change, which has affected a broad range of sectors in manufacturing and services, and involved considerable wage premia for the most adaptable managers and labourers. This suggests that the model in this paper could also be used to analyze the effects of this type of organizational change on the wage structure.

Appendix

Proof of Lemma 2.

It is useful to re-express equation (13) as

$$(\sigma^*)^\lambda = a^\lambda \frac{(1+\gamma)(1+\tau\eta)}{1+r}\left[1 - \frac{1}{R^o}\right], \tag{17}$$

and the demand schedule as

$$R^o = \frac{(1+\tau\eta)(1+\gamma)}{1+\eta}\left(\frac{x_0}{x_1}\right)^{-\alpha}. \tag{18}$$

By taking a log-approximation of (17) and (18), where we substitute for $\frac{x_0}{x_1}$ as a function of σ^* using (14), we obtain respectively

$$\widetilde{\sigma} = \widetilde{a} + \frac{1}{\lambda}\left[\gamma + \tau\eta - r - \exp(-\widetilde{R}^o)\right],$$

$$\widetilde{R}^o = \gamma + \tau\eta - (1-\alpha)\eta - \alpha\left[(2+\tau\eta)\exp(\widetilde{\sigma}) - \frac{a^{-\lambda}}{1+\lambda}\exp((1+\lambda)\widetilde{\sigma})\right],$$

where, the "$\sim$" symbol denotes the logarithm of the corresponding variable. For the supply curve, the amplitude of the shift after an increase in τ (measured at the initial level of equilibrium inequality $\widetilde{R}^o$) is:

$$\frac{\partial\widetilde{\sigma}^*}{\partial\tau}|_{\widetilde{R}^o} = \frac{\eta}{\lambda},$$

and for the demand curve, the magnitude of the shift is

$$\frac{\partial\widetilde{\sigma}^*}{\partial\tau}|_{\widetilde{R}^o} = \frac{1-\alpha\sigma^*}{\alpha\left[(2+\tau\eta)\sigma^* - a^{-\lambda}(\sigma^*)^{1+\lambda}\right]}\eta.$$

We can conclude that a sufficient condition for the shift in the demand curve to be larger, and within-group inequality to rise, is the inequality stated in Lemma 2. ||

Proof of Proposition 3, part (i)

Suppose that the economy is in the old steady state at date t, with transferability rate equal to τ and that, between t and $t+1$, a new technology is introduced with generality $\tau' > \tau$. From (3) it follows that the innovating sector at date t (resp. at date $t+1$) will optimally choose a normalized amount of new capital k (resp. k') equal to:

$$k = \alpha^{\frac{1}{1-\alpha}}\left[x_0^{1-\alpha} + \frac{1}{1+r}x_1^{1-\alpha}\right]^{\frac{1}{1-\alpha}}$$

$$k' = \alpha^{\frac{1}{1-\alpha}}\left[x_0'^{1-\alpha} + \frac{1}{1+r}x_1'^{1-\alpha}\right]^{\frac{1}{1-\alpha}},$$

where (x_0, x_1) (resp. (x_0', x_1')) are the equilibrium labour inputs to the new and the old sectors respectively in the old (resp. the new) steady-state, namely:

$$
\begin{aligned}
x_0 &= 1 + \sigma(1 + \tau\eta), \\
x_0' &= 1 + \sigma(1 + \tau'\eta) > x_0, \\
x_1 &= x_1' = (1 + \eta)(1 - \sigma).
\end{aligned}
\tag{19}
$$

These follow from Lemma 1 and the fact that $k' > k$. At dates $u \le t$, before the shock to τ occurs, both sectors use the same normalized amount of capital k, so that the normalized wage rates in the new and old sectors are still given by:

$$\omega_{0u} = (1 - \alpha)\left(\frac{k}{x_0}\right)^{\alpha},$$

$$\omega_{1u} = \frac{1}{1+\gamma}(1 - \alpha)\left(\frac{k}{x_1}\right)^{\alpha}.$$

Next period, at date $t + 1$, the firms in the old sector (say, sector b) are stuck with the same amount of capital k embodying the low-transferability technology, but firms in the new sector (sector a) realize that the (permanent) increase in skill transferability will make capital investments more profitable; this, in turn leads them to choose an amount of capital $k' > k$ corresponding to the new level of transferability τ'. The normalized wages at date $t + 1$ are thus:

$$\omega_{0,t+1} = (1 - \alpha)\left(\tfrac{k'}{x_0'}\right)^{\alpha},$$

$$\omega_{1,t+1} = \frac{1}{1+\gamma}(1 - \alpha)\left(\tfrac{k}{x_1}\right)^{\alpha}.$$

Finally, at date $t+2$, sector b becomes the innovating sector; facing the same maximization problem as for sector a in period $t+1$, it will choose the same normalized amount of capital k' corresponding to the new steady-state with transferability τ'. If transferability remains constant from date $t + 1$ onwards, then for all dates $u \ge t + 2$ the normalized equilibrium wage rates in the new and old sectors are given by:

$$\omega_{0u} = (1 - \alpha)\left(\tfrac{k'}{x_0'}\right)^{\alpha},$$

$$\omega_{1u} = \frac{1}{1+\gamma}(1 - \alpha)\left(\tfrac{k'}{x_1}\right)^{\alpha}.$$

Within group inequality in period $u \in \{t, t + 1, t + 2\}$, is given by:

$$R_u^o = \frac{(1 + \tau_u\eta)}{(1 + \eta)}\frac{\omega_{0u}}{\omega_{1u}},$$

where: $\tau_u = \tau$ if $u \leq t$, and $\tau_u = \tau'$ if $u > t$. Substituting for the normalized wage rates $(\omega_{0u}, \omega_{1u})$, we immediately obtain:

$$R_u^o = \frac{(1+\tau_u \eta)(1+\gamma)}{1+\eta} \left[\frac{(1-\sigma)(1+\eta)}{1+\sigma(1+\tau_u \eta)} \right]^\alpha \left(\frac{k_u}{k_{u-1}} \right)^\alpha$$

Thus,

$$R_{t+1}^o = R_{t+2}^o \left(\frac{k'}{k} \right)^\alpha > R_{t+2}^o > R_t^o.$$

In particular, we have just shown within-group inequality *overshoots* its new long-run level during the transition period $t+1$. Let us now turn to the experience premium.

In any period u, the average experience premium (across adaptable and non-adaptable workers) is given by:

$$R_u^x = \sigma(1+\tau_u \eta) + (1-\sigma)(1+\eta) \frac{\omega_{1u}}{\omega_{0u}}.$$

Substituting for the appropriate value of τ_u and the appropriate expressions for the normalized wage rates ω_{1u} and ω_{0u} for all u, we immediately get:

$$\begin{aligned} R_u^x &= (1+\tau\eta) \left[\sigma + (1-\sigma) \frac{1}{R_t^o} \right] \text{ for } u \leq t, \\ R_{t+1}^x &= (1+\tau'\eta) \left[\sigma + (1-\sigma) \frac{1}{R_{t+1}^o} \right], \\ R_u^x &= (1+\tau'\eta) \left[\sigma + (1-\sigma) \frac{1}{R_{t+2}^o} \right] \text{ for } u \geq t+2. \end{aligned}$$

Given the dynamics of R_u^o, this proves that $R_{t+2}^x > R_{t+1}^x$. Now, to prove that $R_{t+1}^x > R_t^x$, it suffices to show that:

$$\frac{1+\tau'\eta}{R_{t+1}^o} > \frac{1+\tau\eta}{R_t^o},$$

or equivalently that:

$$\frac{k}{k'} > \frac{1+\sigma(1+\tau\eta)}{1+\sigma(1+\tau'\eta)}. \tag{20}$$

But from equation (3) we know that:

$$\left(\frac{k}{k'} \right)^{1-\alpha} = \frac{x_0^{1-\alpha} + \frac{1}{1+r} x_1^{1-\alpha}}{x_0'^{1-\alpha} + \frac{1}{1+r} x_1^{1-\alpha}} = \frac{[1+\sigma(1+\tau\eta)]^{1-\alpha} + \frac{1}{1+r} x_1^{1-\alpha}}{[1+\sigma(1+\tau'\eta)]^{1-\alpha} + \frac{1}{1+r} x_1^{1-\alpha}},$$

which immediately implies (20). This establishes part (i) of the Proposition. $\|$

The above proof can be explained in more intuitive terms. Namely, between periods t and $t+1$ the capital stock in the new sector increases in order to adjust to the rise in the supply of adaptable labour from x_0 to x_0'. However, it adjusts by less than the increase in adaptable labour as the optimal choice of capital stock must also take into account the supply of non-adaptable labour x_1 to work with old capital in the following period. The key insight is that this supply does not change throughout the whole transition (see the equations in (19)).

An Extension: The Educational Premium

Consider an extension of the framework in Section 4 where the economy is populated by individuals who differ in their education cost $\varphi(\sigma) = a^{-\lambda} \frac{\sigma}{1+\lambda}^{1+\lambda}$. In particular, assume that the scaling parameter a is distributed in the population according to the distribution function F, with support $(0, \overline{\sigma})$. The first-order condition for the individual choice of education (13) is unchanged, hence the aggregate adaptability rate σ^* in the economy is determined by

$$\sigma^* = \left\{ \frac{(1+\gamma)(1+\tau\eta)}{1+r} \left[1 - \frac{1}{R^o} \right] \right\}^{\frac{1}{\lambda}} \overline{a},$$

where $\overline{a}$ is the population mean of the random variable a. Within-group inequality R^o is given exactly as in Section 4. It follows immediately that without retooling a larger τ raises R^o under the conditions of Lemma 2, while in an equilibrium with retooling R^o is increasing in both τ and κ.

To characterize the educational premium R^e, we need to split the population in two groups: consistently with the rule normally adopted in empirical work, we define "educated" those workers who spent at least a period of length h_e in school and "uneducated" all the rest. It is simple to prove that the marginal educated worker will have an individual cost parameter equal to

$$a_e = \frac{(1+\lambda)h_e}{\left\{ \frac{(1+\gamma)(1+\tau\eta)}{1+r} \left[1 - \frac{1}{R^o} \right] \right\}^{\frac{1+\lambda}{\lambda}}}, \tag{21}$$

and all workers with $a \geq a_e$ are also educated. It follows from (21) that an increase in the generality of technology that raises the adaptability premium will induce workers to spend a longer part of their youth in school, thus the marginally educated worker will be of lower quality and will have a lower adaptability rate ("extensive-margin" effect).

The equilibrium adaptability rate among educated workers σ_e^* will be

$$\sigma_e^* = \left\{ \frac{(1+\gamma)(1+\tau\eta)}{1+r} \left[1 - \frac{1}{R^o} \right] \right\}^{\frac{1}{\lambda}} \left[\frac{\int_{a_e}^{\overline{\sigma}} a dF(a)}{1 - F(a_e)} \right].$$

Thus, beyond the extensive margin effect that reduces the average level of adaptability in both pools, we recognize an *intensive margin* effect due to the fact that, following a rise in generality, all workers invest more in schooling and increase their level of adaptability.

Thus, in general the overall impact on σ_e^* is ambiguous and depends, among other things, on the shape of the distribution function F.

Similarly, for uneducated workers

$$\sigma_u^* = \left\{ \frac{(1+\gamma)(1+\tau\eta)}{1+r} \left[1 - \frac{1}{R^o} \right] \right\}^{\frac{1}{\lambda}} \left[\frac{\int_0^{a_e} a dF(a)}{F(a_e)} \right].$$

The educational premium, defined as the ratio between the average wage of educated workers and the average wage of uneducated workers, can be conveniently expressed as

$$R^e = \frac{\sigma_e^* R^o + (1-\sigma_e^*)}{\sigma_u^* R^o + (1-\sigma_u^*)}$$

For given σ_e^* and σ_u^*, the comparative statics of the educational premium across steady-states are qualitatively similar to those for within-group inequality. Intuitively, given that among the educated labour force a larger fraction is adaptable to new vintages, on average educated workers can benefit more from the appearance of a new technology that increases the degree of skill generality τ or capital compatibility κ. Differences in the way the endogenous adaptability rates for the two groups respond to a rise in generality can either amplify or dampen the response of R^o.

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TABLE 1

Wages by workers' age and vintage of technology

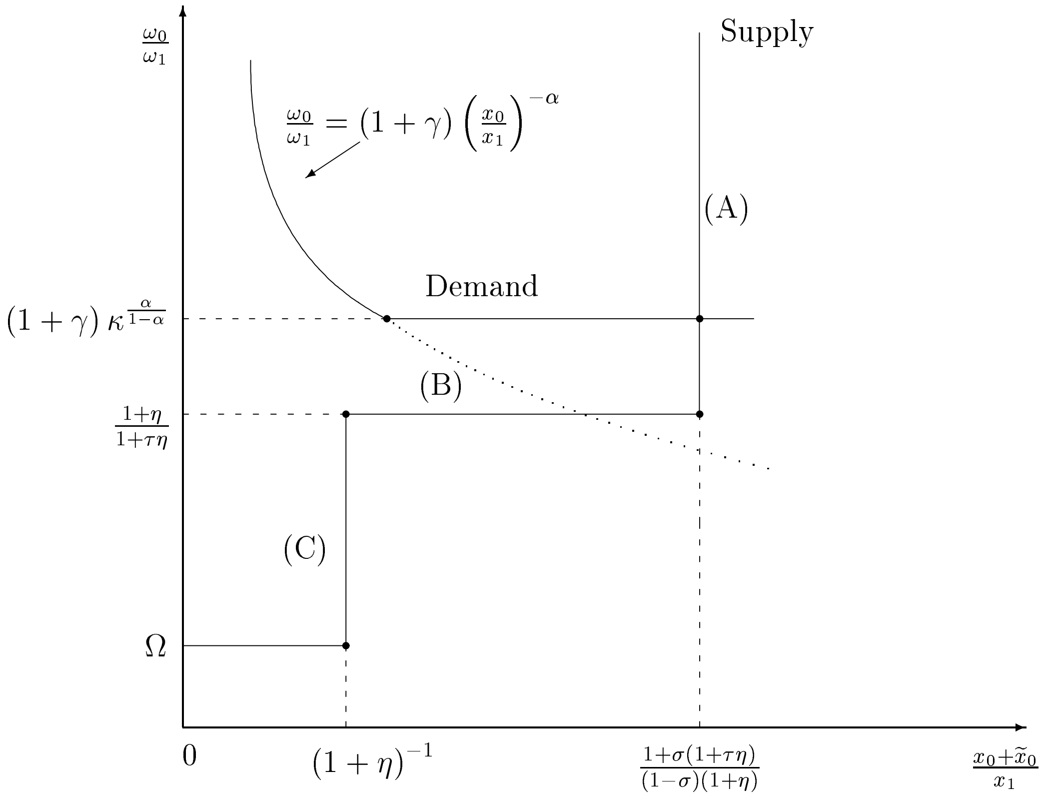
	Sector	
	0	1
Wage of young worker	ω_{0t}	ω_{1t}
Wage of old worker coming from 0	$(1+\tau\eta)\omega_{0t}$	$(1+\eta)\omega_{1t}$
Wage of old worker coming from 1	ω_{0t}	$(1+\tau\eta)\omega_{1t}$

Caption for Figure 1: Relative supply and demand schedules in the economy of Section 3 with exogenous adaptability σ, partial skill transferability, i.e. $\tau \in (0, 1)$, and partial vintage compatibility, i.e. $\kappa \in (0, 1)$. The Figure depicts a case where the economy is in an equilibrium of type (A). As clear from this picture, with retooling, case (B) is knife-edge.

Caption for Figure 2: This figure refers to the economy of Section 4 with endogenous adaptability and $\kappa = 0$. The upper panel of the figure depicts the case where $\lambda = \infty$. A rise in τ shifts the demand curve upward and inequality rises unambiguously (from E to E'). In the lower panel, the case $\lambda = 0$ is represented. The equilibrium is on the flat region of the supply curve, so the supply response is very large and inequality falls (from E to E').

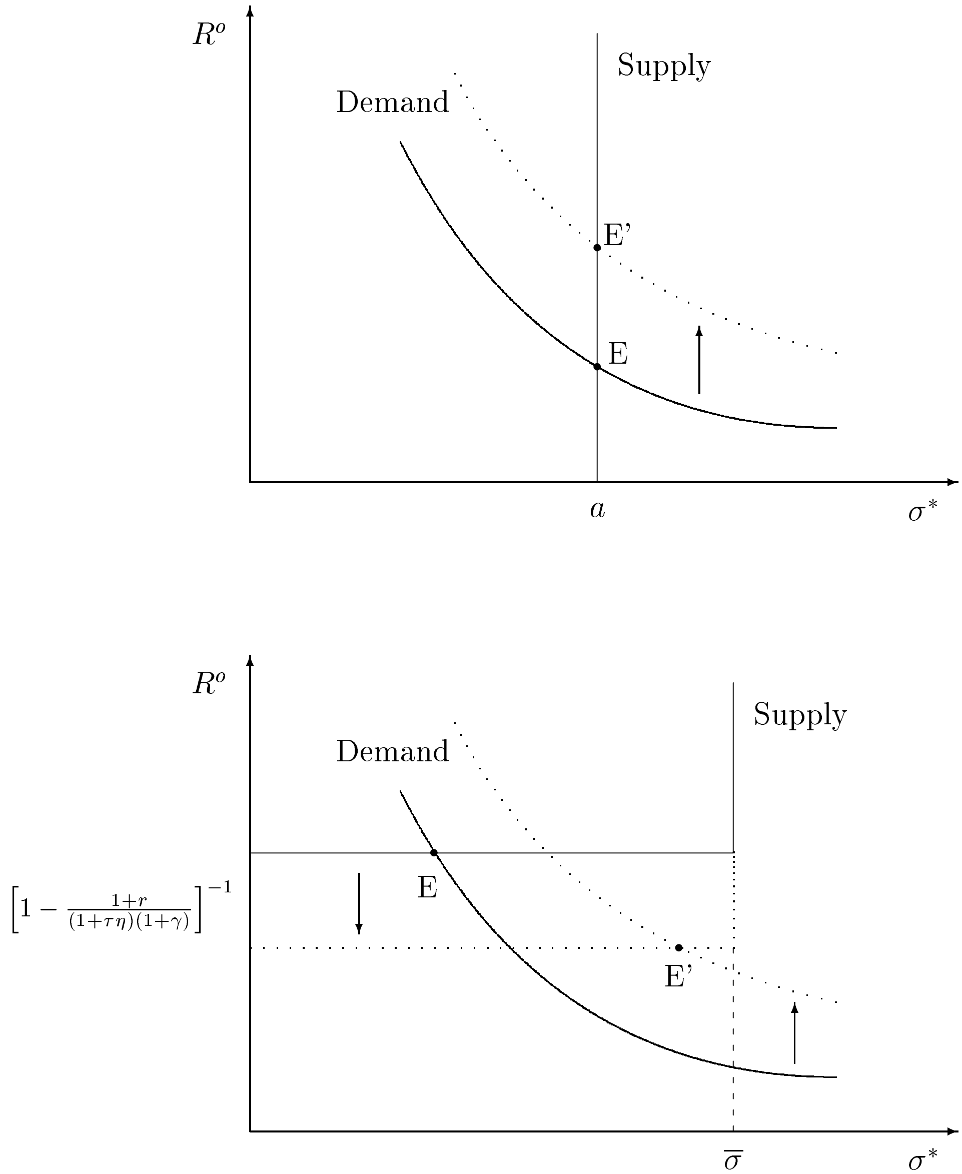
Caption for Figure 3: This figure refers to the economy of Section 4 with endogenous adaptability. The upper panel of the figure depicts the case where and $\kappa = 0$ and $\lambda \in (0, \infty)$. A rise in τ shifts both the demand curve and the supply curve upward and the effect on inequality, in general, is ambiguous. In the lower panel, the economy with retooling is represented. The equilibrium is on the flat region of the demand curve, so inequality increases unambiguously following a rise in both skill transferability (from E to E_τ) and in capital compatibility (from E to E_κ).

Caption for Figure 4: Transitional dynamics for the economy of Section 3, following an increase in τ. The panel on top depicts the dynamics of within-group inequality R^o and the panel below the dynamics of the experience premium R_x.



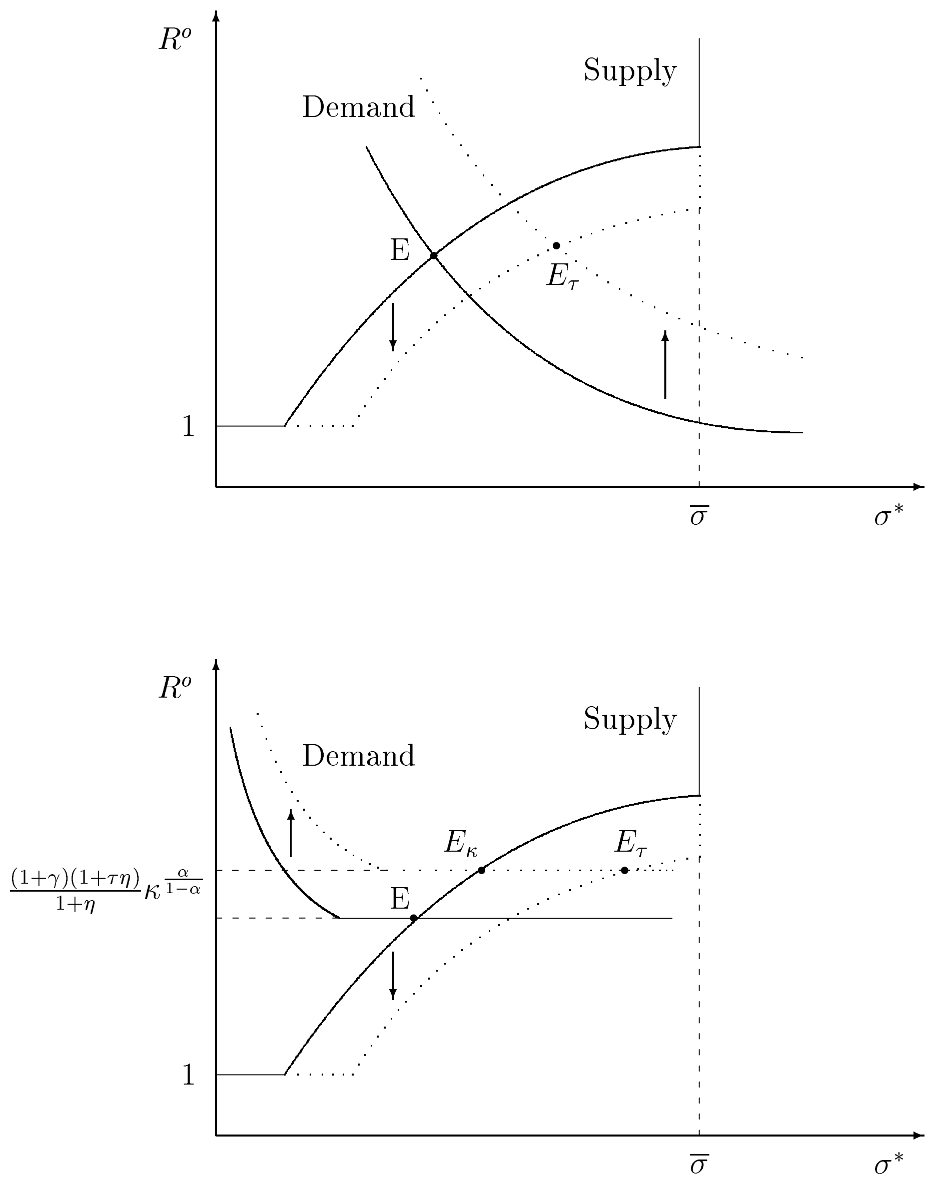
$\frac{\omega_0}{\omega_1}$
Supply
$\frac{\omega_0}{\omega_1} = (1+\gamma)\left(\frac{x_0}{x_1}\right)^{-\alpha}$
(A)
Demand
$(1+\gamma)\,\kappa^{\frac{\alpha}{1-\alpha}}$
(B)
$\frac{1+\eta}{1+\tau\eta}$
(C)
Ω
0
$(1+\eta)^{-1}$
$\frac{1+\sigma(1+\tau\eta)}{(1-\sigma)(1+\eta)}$
$\frac{x_0+\widetilde{x}_0}{x_1}$

Figure 1:



R^o
Supply
Demand
E'
E
a
σ^*
R^o
Supply
Demand
$\left[1 - \frac{1+r}{(1+\tau\eta)(1+\gamma)}\right]^{-1}$
E
E'
$\overline{\sigma}$
σ^*

Figure 2:



R^o
Supply
Demand
E
E_τ
1
$\overline{\sigma}$
σ^*
R^o
Supply
Demand
E_κ
E_τ
$\frac{(1+\gamma)(1+\tau\eta)}{1+\eta}\kappa^{\frac{\alpha}{1-\alpha}}$
E
1
$\overline{\sigma}$
σ^*

Figure 3:

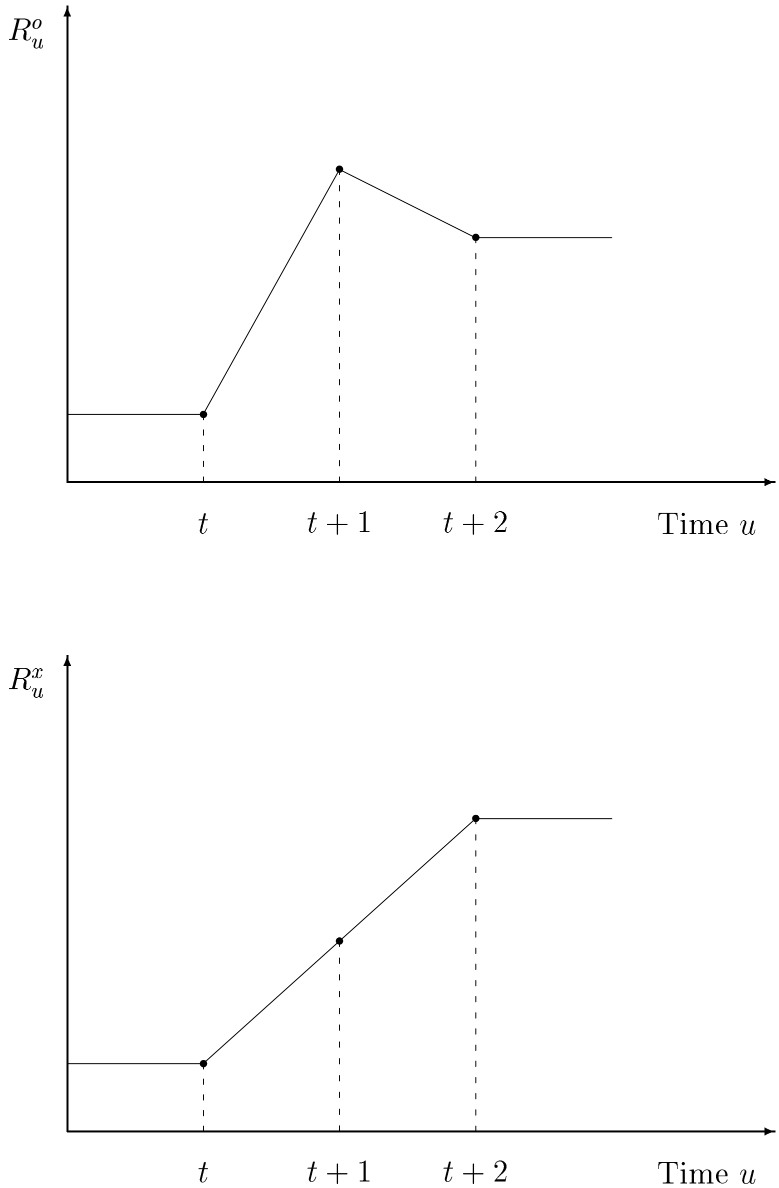


Figure 4: