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Chapter 7

From Solow Residual to Solow Paradox

7.1 Introduction

After Solow (1957), much research on economic growth focused on explaining the ‘Solow residual’; i.e. that part of growth in incomes that cannot be explained by either capital or labor accumulation. The residual, also called total factor productivity growth (TFP), is left unexplained in the Solow model. The ‘new’ theory of economic growth argues that research and development and innovations are an important determinant of total factor productivity growth in one way or the other. Perhaps the most important innovation of the last decades was the development, and widespread use, of the computer. Nevertheless, empirical studies have a hard time in discovering any positive effect of the computer on total factor productivity growth. This has led Solow (1987) to the famous remark that: “you can see the computer age everywhere but in the productivity statistics.” Maybe computers were not effectively used in the beginning implying a low rate of return from its services. Perhaps national accounts simply failed to measure much of the additional output produced. Or, as Oliner and Sichel (1994) argue, perhaps it is not that surprising after all since new technologies such as the computer account for only a minor share in the total capital stock.

At the same time however, it is often argued that technological change did have a major impact on the wage structure, contributing to increased income inequality both within and between wage categories (Autor, Katz, and Krueger (1998)). As has been discussed in Chapter 2, the rise in income inequality is a common phenomenon among advanced economies during the 1980s and 1990s (see also Davis, 1992). Krueger (1993, for the US),
DiNardo and Pischke (1997, for Germany), and Oosterbeek (1997, for The Netherlands) all conclude that computer usage at the workplace increases earnings. Moreover, it is often argued that skill-biased technological change, besides international trade, is the main reason for increased unemployment of less-skilled workers in OECD countries (Berman et al., 1997).

Following the Solow paradox, if productivity growth has been slow, how can technological progress have had a significant impact on labor markets? Of course, the answer to this question is not restricted to the amount of research and development in one's own economy. As has been argued in Chapter 2, globalization exposes countries to technologies from abroad, and there is no a-priori reason to expect that this technology transfer affects labor markets in the same way in different countries. In fact, one would expect that the effect on different labor markets of the transfer of new technologies in increased trade in goods and services as well as via more indirect ways, depends crucially on a number of labor market characteristics as given by the institutional framework.

In this chapter we will try to explain the effect on productivity of new technologies as well as their impact on labor markets, in particular we sketch a mechanism through which technological progress may increase unemployment of low-skilled workers as well as be responsible for higher income inequality. We do this by stressing that in general new technologies provide higher ability workers with the instrument to reveal their private information concerning their ability. If information a-symmetries between workers and firms are indeed reduced by new technologies, this provides an additional incentive to implement that new technology, at least from the point of view of some workers.\(^1\)

These distributional implications of new technologies together with one's view of the productivity paradox, give rise to the following two possible scenario's. First of all, take the measurement problems seriously.\(^2\) New technologies such as the computer have increased unmeasured productivity and therefore it is not surprising at all to see them all around us. Moreover, the skill-biased technological change story offers a possible explanation for the relationship between the arrival of new technologies such as the computer and increased income inequality (see Bound and Johnson, 1992). In a sense not made explicit

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\(^1\)In fact, all that is necessary is that individuals with different characteristics make different choices after the arrival of a new technology, whether individuals know their own characteristics or not (see also Stiglitz, 2000).

\(^2\)On the measurement problems that arise when one wants to calculate the effect of innovations, such as the computer, on TFP growth see, for example, Griliches (1994). For the measurement problems that arise when one wants to attribute the change in the wage structure to innovations such as the computer see DiNardo and Pischke (1997).
7.1. Introduction

In most of such papers,\(^3\) it is assumed that high skill workers are more complementary with new technologies than low skill workers (see Chapter 2 and Goldin and Katz (1996)). In other words, there is a skill-premium to new technologies. Then measurement problems explain the Solow paradox, and skill-complementarity explains why new technologies could contribute to increased wage inequality. We argue that the skill-complementarity theory might underestimate the effect of new technologies on the wage distribution. For, if we add the assumption that employers have imperfect information about worker quality and if workers respond differently to new technologies (skill-complementarity), then new technologies reveal information. As a consequence, separation of workers according to their ability is a by-product of innovations like the computer.

Concerning the second scenario, it has also been argued that the computer is like other general-purpose technologies such as the electric dynamo and that it will take a couple of decades before the productive potential of these technologies are fully realized (see David, 1990). Then the first part of the Solow paradox, the absence of productivity gains has been explained, but the second part, why we see the computer all around us, becomes a problem. For, if managers have a short time-horizon, why would they implement these costly new technologies given that they will increase productivity long after the managers themselves have left the firm? To answer this question, we again have to look at the possible distributional implications of new technologies. We show that there may be a range of parameters such that the information provided by new technologies may result in their adoption despite the fact that it is common knowledge that these technologies have no impact on productivity in the near future. Moreover, the fact that these technologies are expected to become productive in the future, could make them a relatively cheap signalling device and screening mechanism. Again we analyze the implications for the wage distribution.

To make the assumption of imperfect information as strong as possible, we start our discussion with a situation in which a cohort of workers has similar observable characteristics from the point of view of the firm. As a consequence, lower ability employees are able to hide behind the backs of higher ability workers. Then, high ability workers have an incentive to train themselves to be able to work with the new technology. Not only are they complementary to the new technology but also more complementary than lower ability workers and the computer thus offers these workers with an instrument to reveal

\(^3\)An exception is Acemoglu (1998) who analyses a model in which the market for technologies complementary to skilled workers increases with the number of skilled workers. An increase in the number of skilled workers first decreases the skill-premium, but after a while it becomes more profitable to create new technologies that skilled workers can use. This directed technology effect increases the skill premium.
their private information. In that sense, innovations could play a role in enabling workers to transmit, in an imperfect way, their ability to their employers.

Innovations convey information and, as a result, innovations can be developed and implemented even if their effect on TFP growth is small, or even zero, in the short-run. By separating workers according to their abilities, they do have an effect on income inequality, although the ultimate cause for this inequality results from, previously unobservable, worker heterogeneity. Moreover, if new technologies allow employers to identify workers’ ability, the lowest ability types could become unemployed permanently offering a potential channel through which new technologies could be responsible for the observed increase in unemployment of low-skilled workers in the US in the early 1990s and in other advanced countries in the later half of the decade (see Chapter 2). If this happens, measured productivity, defined as output divided by the number of employed, should increase and the productivity paradox becomes even more paradoxical.

The ideas contained, and conclusions derived, in this chapter are close in spirit to Stiglitz (1975) and Krugman (1999). For example, Krugman argues that labor markets can be characterized by multiple-equilibria. In his specific setting there is a human capital and a signalling/screening equilibrium. Small shocks either due to trade liberalization, skill-biased technological change, or both can push the economy from an egalitarian equilibrium to a process of increasing income inequality. It is interesting to see that his model has the empirical implication that measured total factor productivity actually falls after a small shock that results in more and more workers investing in education for signalling purposes.

This chapter is in seven parts. In Section 7.2 we discuss employment, wages, and profits when there is a-symmetric information between workers and firms. Then, in Section 7.3 we study the incentives of workers to separate themselves after a new technology has arrived. Section 7.4 looks at the implications for the wage distribution under scenario 1; i.e. assuming that the new technology has an unmeasured productivity effect. Section 7.5 discusses the second scenario; i.e. we analyze whether the distributional implications can be a sufficient reason for why we see new technologies all around us although they do not have a short-run impact on productivity. Furthermore, Section 7.6 is concerned with the implications of the new technology for employment.\footnote{See Aghion and Howitt (1994) for a discussion of the relationship between growth and unemployment.} while Section 7.7 concludes.
7.2. Employment, Wages, and Profits

Since the economy will immediately be in a new steady state after a new technology arrives in our framework, we can restrict ourselves to a two period framework. We use a simplified version of the model used in Chapter 6, based on Pissarides (1992), to determine employment, wages and profits at time $t$. There is a cohort of $2L$ workers in total, two firms, and we assume that at $t$, $L$ workers decide to search for a job in each firm. The workers in this cohort are completely identical, except for the unobservable attribute ability. That is, unobservable at the beginning of $t$. There are four worker types indicated by, arranged from lowest to highest ability, $a$, $b$, $c$, and $d$, with marginal productivity $\theta^a$, $\theta^b$, $\theta^c$, and $\theta^d$. These productivities are constant, increasing in ability, the same in each firm, and the fractions of each ability type in the population and among the job seekers in each firm is set equal to $\frac{1}{4}$ for simplicity. Workers know their own ability and average productivity is denoted by $\bar{\theta}$. Workers and employers have no outside opportunities and jobs last for one period only.

When a vacancy and a job seeker meet, the firm and the worker have to negotiate how to divide the production. If they cannot reach an agreement the vacancy ends up unfilled and the worker is unemployed. Then wages are determined by a static Nash-bargain and workers and employers both receive half of the output. Employment in sector $i$ ($e_i^t$) is equal to the matching probability between jobs and workers in sector $i$ ($q_i^t$) times the number of job seekers in firm $i$ ($L_i^t$), for $i = 1, 2$. Then the probability that a vacancy is filled is equal to:

$$\frac{e_i^t}{J_i^t} = \frac{q_i^t L_i^t}{J_i^t}, \quad (7.1)$$

where $J_i^t$ denotes the number of jobs offered (vacancies created) by firm $i$ at time $t$. Given that firms cannot observe the ability of job seekers at $t$ and that output is equally shared between workers and employers, the number of vacancies created by each firm is determined by the following expected profit maximization condition:

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5 The reason why we have four types of workers is as follows. The structure of our model will be such that initially types $a$ and $b$ do not train themselves to be able to work with the new technology. On the other hand, types $c$ and $d$ do and, therefore, will be pooled as well. If we decided to combine $c$ and $d$ in one type, denoted by $C$, there would be no incentive for firms to actually implement the new technology as they already know that type $C$ is high ability. By including both types $c$ and $d$ on the other hand, we maintain incentives for type $d$ to further separate themselves after the training. As we will see in a moment, this desire will be satisfied by employers who are competing for the highest ability workers. Furthermore, as will be discussed in Section 7.6, the possibility of becoming unemployed will affect the training incentives of types $a$ and $b$ and to study this we cannot combine these two types into one as well.
where $\frac{1}{k}$ is the cost to the firm of opening a vacancy.\(^6\) Then the number of vacancies opened by each firm is:

$$J_i = \frac{1}{2} \frac{\vartheta}{k} k q_i^i L_i^i$$  \hspace{1cm} (7.3)

Now the job department has to match the vacancies to the workers. As in Pissarides (1992) we assume a Cobb-Douglas matching function:

$$\chi (J_i, L_i) = (J_i)^{\frac{1}{2}} (L_i)^{\frac{1}{2}}$$ \hspace{1cm} (7.4)

This matching technology determines the level of employment in \(i\). Therefore, we have $\chi (J_i, L_i) = e_i = q_i^i L_i$ and, using (7.3) and (7.4), this amounts to:

$$q_i^i = \left( \frac{1}{2} \frac{\vartheta}{k} q_i^i L_i^i \right)^{\frac{1}{2}} \frac{(L_i)^{\frac{1}{2}}}{L_i} = \frac{1}{2} \frac{\vartheta}{k}$$ \hspace{1cm} (7.5)

As a consequence, we have full employment in this economy with \(L\) workers working in each sector when $k \geq \frac{2}{\vartheta}$.\(^7\) For $k < \frac{2}{\vartheta}$ there is no production in both sectors: $q_i^i = 0$.\(^8\)

There is no wage inequality in this economy as all workers earn: $w_i = \frac{1}{2} \vartheta$ which is the workers share of average output. In a sense, lower ability workers are able to hide behind the backs of the more productive workers. As output is shared equally between workers and employers, $E\pi_i^t = \left( \frac{1}{2} \frac{\vartheta}{k} - \frac{1}{2} \right) L$ in the absence of innovations.

Given this model without wage inequality, we are now going to characterize the optimal investment in training by workers when this economy is unexpectedly hit, during \(t\), by the introduction of a new technology. This will allow us to study to what extent technological advancement can explain the stylized facts of OECD labor markets as outlined in Chapter 2 of this dissertation.

\(^6\)Note that this cost is sunk as soon as workers and firms start to negotiate on the division of output. As a consequence it does not affect these negotiations.

\(^7\)For $k > \frac{2}{\vartheta}$, we set $q_i^i = 1$ since creating vacancies is costly and each vacancy is supposed to meet one type from the opposite side of the market only.

\(^8\)Notice that in this case we have a ‘lemons problem’ (see Akerlof, 1970)).
7.3 Investment by Workers

So in our model so far, a-symmetric information between workers and firms results in the pooling of workers. When a new technology arrives, the workers that are more complementary with this technology may use it to try to separate themselves from other workers. Our discussion of these incentives will be closely related to Spence (1973) and we will focus attention on one specific signalling equilibrium.

Signalling ability will only affect wages the next period as the firm and the worker have already agreed on how to share production when they met at the beginning of $t$. We assume that the cost of $y$ units of training during $t$ is equal to $\frac{\gamma_a}{\theta^a}$, $\frac{\gamma_b}{\theta^b}$, $\frac{\gamma_c}{\theta^c}$, and $\frac{\gamma_d}{\theta^d}$ for each type respectively. These costs are common knowledge. Thus, training costs are decreasing in ability and, as a result, the costs of signalling will be negatively correlated with ability. This is a necessary requirement to have informative signals and can be the result of higher ability workers being more complementary to new technologies.

Higher ability workers are not only more complementary to new technologies in the sense that it takes less effort for them to learn how to work with this new technology. Also, if they work with the computer, their productivity increases by more. Denote the increase in productivity for each worker type by $\gamma^a$, $\gamma^b$, $\gamma^c$, and $\gamma^d$ and these values are common knowledge as well.

Suppose that the employer believes that there is some level of training, $y^*$, such that if $y > y^*$ then the worker belongs to the highest two ability groups and if $y < y^*$ the worker belongs to the lowest two ability groups.\(^9\) Moreover, suppose that workers believe that firms will always implement the new technology to screen its workers.\(^10\)

We will first determine the optimal amount of training for the lowest ability group of workers under the best case scenario for them; that is, making the case for following training by him as strong as possible. This case arises if this group is the only group that has followed no training in case of a decision not to follow training. This decreases the pay-off from not following training as employers then know for sure that these workers are type $a$. Moreover, these workers know that if they are willing to follow an amount of training $y$ such that $y > y^*$ the employer will screen him. In that case: $w_{t+1}^a = \frac{1}{2} (\theta^a + \gamma^a)$. They will set $y = 0$, if:

$$\frac{1}{2} \theta^a > \frac{1}{2} (\theta^a + \gamma^a) - \frac{y^*}{\theta^a}, \quad (7.6)$$

\(^9\)As a consequence, workers set $y = y^*$ at most and if $y < y^*$ is optimal they set $y = 0$.

\(^10\)In Section 7.5 we show that this belief by workers can be confirmed by the actual behavior of the firm.
that is, when $y^* > \frac{\gamma b}{2}$. Let's assume that $y^*$ is indeed larger than $\frac{\gamma b}{2}$ so that the least able workers will decide not to follow the training.

Now consider the third least able group of workers, $b$. This group of workers is also capable of determining that for $y^* > \frac{\gamma b}{2}$, the least able group will not follow training.$^{11}$ Again we will make the case for following training by this group as strong as possible by assuming that if this group of workers does decide not to follow training, the two highest ability groups will follow the training.$^{12}$ Then, this group of workers will set $y = 0$ anyway. If:

$$\frac{1}{4} (\theta^a + \theta^b) > \frac{1}{2} (\theta^b + \gamma^b) - \frac{y^*}{\theta^b},$$

which is the case if $y^* > \frac{1}{4} \theta^b (\theta^b - \theta^a + 2 \gamma^b)$. Recall that the incentive for workers to follow training arises because one wants to separate from lower ability types. If differences in productivity between the lowest two ability types is small ($\theta^b - \theta^a$ is small) and the productivity effect of working on a computer is not too large, the incentives for type $b$ workers to follow training are small as well. For then, these workers do not suffer much when they are pooled with type $a$. We assume this to be the case; i.e. we assume $y^* > \frac{1}{4} \theta^b (\theta^b - \theta^a + 2 \gamma^b)$.

Consider the decision by the second highest ability group of workers, $c$. Now assume that the case for them to follow training is as small as possible, given that the two least able groups of workers will not follow the training. Then, if he decides not to follow the training, we want his pay-off to be as large as possible. This is the case if all four groups decide not to follow training. The pay-off to type $c$ is then: $w_{c+1} = \frac{1}{2} \theta$. Despite the fact that we look at the case in which training is least profitable, this group will choose $y = y^*$ if:

$$\frac{1}{2} \theta < \frac{1}{2} (\theta^c + \gamma^c) - \frac{y^*}{\theta^c},$$

which is the case if $y^* < \frac{1}{4} \theta^c (\theta^c - \theta + \gamma^c)$. So a large marginal product of $c$ and/or a low average product of all worker types creates the incentives for $c$ to follow training, especially

$^{11}$As employers, all workers know the ability levels of each group of workers. Unlike employers, they know they are in the second lowest ability group of workers. As a consequence, this group of workers is able to determine whether the least able group will follow the training or not.

$^{12}$Again this last assumption makes sure that the payoff from not following training is as small as possible. If the two highest ability groups will follow training, this group can be sure that the employer sees them as one of the two least able groups of workers and, as a result, their pay-off from this situation is as small as possible.
if his productivity increases a lot if he works on the computer. Then, the highest ability group will follow the training as well. From now on, we assume $\frac{1}{2}\theta^b (\theta^b - \theta^a + 2\gamma^b) < y^* < \frac{1}{2}\theta^c (\theta^c - \theta + \gamma^c)$, so that the two least able groups of workers, a and b, will not follow any training, while the two highest groups of workers, c and d, will follow the costly training. This in effect creates a demand for computers by some workers.

As a consequence we have that, provided that the beliefs of employers are given by $\frac{1}{4}\theta^b (\theta^b - \theta^a + 2\gamma^b) < y^* < \frac{1}{2}\theta^c (\theta^c - \theta + \gamma^c)$, training is an imperfect signalling device if workers believe that the firm will always decide to screen its workers after they have followed the training. We will now analyze whether this believe by workers can be confirmed by the actual behavior of firms.

### 7.4 Productive New Technologies

After workers have decided on whether or not to follow training, and firms have observed their choice, firms now have to decide whether they want to implement the new technology. If they buy the new technology for their trained workers, they are able to perfectly observe the ability of these workers. Thus, then he is able to discriminate between the two highest ability groups. Completing the computer course is not a perfect signal: firms have to see what their workers are really capable of on these computers.

However, the firm also knows that implementing the new technologies comes at a cost. $C = \psi L$, the total cost of buying computers is equal to the constant marginal cost of buying and installing one computer ($\psi$) times the number of people for who you buy these computers. This cost $\psi$ can be interpreted as the return to some firm, exogenous to our model, which developed the new technology in the first place. As a consequence, it is the return for doing research and development.

So the firm will never install more computers than there are workers that are able to work with them. So it will buy $\frac{1}{2}L$ of the new technology at most since the lowest two ability groups have not trained themselves, since for them the adjustment costs to the new technology are larger than the maximum possible benefits. Given that the firm observes that only two groups of workers, which are then necessarily the highest two ability groups, have trained themselves it has to determine whether the productivity effects of the computer are sufficient to cover the marginal cost $c$ of installing the new technology. Suppose first that $\psi = \gamma^c$, where the case $\psi > \gamma^c$ is the subject of the remainder of the chapter.

Then we are in the case of the familiar skill-complementary case. High ability workers are more complementary with new technologies which, in our case, takes the form of
lower training costs and a larger increase in productivity. Firms implement the new technology and average productivity goes up with $\frac{1}{4} (\gamma^c + \gamma^d)$. Wage inequality will arise, not only because the highest two ability groups work with technology that makes them more productive, but also because this new technology has separated them from the lowest two ability groups. $w_{t+1} = \frac{1}{4} (\theta^b + \theta^c)$, $w_{t+1} = \frac{1}{2} (\theta^c + \gamma^c)$, and $w_{t+1} = \frac{1}{2} (\theta^d + \gamma^d)$.

When some workers are more complementary with new technologies than others, working on a computer is also informative about ability. If the employer faced uncertainty about this ability before the new technology arrived, this information should result in a larger increase in wage inequality than in the standard stories of skill-complementarity in which income inequality arises only because of the productivity effects of new technologies. So the effects of new technologies on the wage distribution is larger than in the standard story if employers face uncertainty over the ability of its workers, and if new technologies reduce this uncertainty.\footnote{If $\psi < \gamma^c$, we actually have under investment in new technologies. Then the unwillingness of some workers to acquire the skills to be able to work with computers prevents the optimal introduction of these technologies.}

### 7.5 Unproductive New Technologies

Above we argued that imperfect information about workers' ability could offer an explanation for why technological progress seems to have had a significant effect in labor markets although (measured) productivity growth has been slow. A second explanation for why productivity growth has been slow stresses that it takes time before a regime switch has been completed. Therefore it should not be surprising to find limited short-run productivity gains of new technologies. This explains the productivity paradox, but not why we see such new technologies as the computer everywhere.

This question becomes especially important if managers have a short time-horizon so that one might wonder why they invest in these new technologies despite the fact that benefits will only materialize when the manager has already left the firm. Moreover, why do workers have an incentive to learn how to work with these new technologies given the absence of short-run productivity gains? Therefore we focus in the remainder of this chapter on the case where $\psi > \gamma^c$. To take an extreme view we set $\gamma = 0$ for all ability types and analyze whether competition between firms for the highest ability workers could be a sufficient reason to see the computer everywhere despite the fact that it is common knowledge that this piece of new technology has no effect on productivity in the near future.
7.5. Unproductive New Technologies

So given that it is common knowledge that $\gamma = 0$ for all ability types, can incentives for firms be such that we still see the computer everywhere? With $\gamma = 0$ we have that for $\frac{1}{4} \theta^b (\theta^b - \theta^a) < y^* < \frac{1}{2} \theta^c (\theta^c - \theta^d)$ the highest two ability types will follow the training and the two lowest ability groups of workers refrain from training themselves. What are the incentives for the two firms to screen their workers given that $k \geq \frac{4}{(\theta^a + \theta^b)}$? Notice that for these values of $k$ there will always be full employment at $t + 1$ since then expected profit from the, indistinguishable, two groups of least able workers ($\frac{1}{2} (\theta^a + \theta^b)$) is sufficient to compensate for the firm’s cost of opening a vacancy ($\frac{1}{k}$).\(^{14}\)

Suppose first that both firms decide not to screen their workers. Then, workers have no incentive to search for a job at the other firm at $t + 1$. As both firms remain completely identical in this case, each ability type cannot increase his wages by moving. As a consequence, profits for each firm at $t + 1$ are equal to profits at $t$:

$$E\pi_{t+1}^i = E\pi_i = \left( \frac{1}{2} \bar{\theta} - \frac{1}{k} \right) L,$$

for $i = 1, 2$. Next consider the case in which both firms will screen their workers. By similar reasoning as above, both firms remain identical and thus workers have no incentive to move between sectors at $t + 1$. In this case,

$$E\pi_{t+1}^i = E\pi_i^i - \frac{1}{2} \psi L$$

(7.10)

Profits would decrease between $t$ and $t + 1$.

Finally consider the case in which only one firm decides to screen its workers. Then, firms are no longer identical at $t + 1$ and workers may have an incentive to move. In particular the highest ability group of workers will move from the sector that did not screen to the firm that did screen since at the latter they can earn half their marginal product, $\frac{1}{2} \theta^d$, while at the former they cannot be separated from the second highest ability group of workers and therefore will earn less, $\frac{1}{2} (\theta^c + \theta^d)$.

Since there is always full employment in each sector all the workers, except type $d$, will stay where they are and profit for the firm that screens, let’s say firm 1, is equal to:

$$E\pi_{t+1}^1 = \frac{1}{2} L \frac{1}{4} (\theta^a + \theta^b) + \frac{1}{4} L \frac{1}{2} (\theta^c) + \frac{1}{2} L \frac{1}{2} (\theta^d) - \frac{3}{4} \psi L - \frac{5}{4} L \frac{1}{k},$$

(7.11)

where the first term on the rhs shows that the employer receives half of the average product of types $a$ and $b$ ($\frac{1}{4} L$ workers in total), the second term shows that in total $\frac{1}{4} L$

\(^{14}\)We consider the case where $k < \frac{4}{(\theta^a + \theta^b)}$ in the next section.
job seekers at firm 1 are type c, while the third term shows that all the highest ability workers are searching for a job, and employed, in the firm that screens; i.e. in firm 1 at \( t + 1 \). But then the firm has to open \( \frac{3}{4}L \) vacancies to hire all of them. This is captured by the last term in (7.11). In a sense, labor mobility perfectionizes the screening device of the total cohort of workers. Since \( \theta^a + \theta^b + \theta^c + \theta^d = 4 \bar{\theta} \), we have:

\[
E\pi^1_{t+1} = E\pi^1_t + \frac{1}{8} \theta^d L - \frac{1}{4k} L - \frac{3}{4} \psi L
\]  

(7.12)

Profit for firm 2 that did not screen its workers during \( t \) by installing the new technology is:

\[
E\pi^2_{t+1} = \frac{1}{2} L \left( \frac{1}{8} \theta^d + \theta^b \right) + \frac{1}{4} L \left( \frac{1}{2} \theta^c - \frac{3}{4} L \frac{1}{k} \right) = E\pi^2_t - \frac{1}{8} \theta^d L + \frac{1}{4k} L
\]  

(7.13)

for \( i = 1, 2 \). Notice that this firm creates only \( \frac{3}{4}L \) vacancies.

For \( 0 < \psi < \frac{1}{6} (\theta^d - \frac{2}{k}) \) both firms find themselves in a prisoners' dilemma in which both will implement the new technology as a screening device which in the end will lower their profits. In effect, implementing the new technology is a way to prevent adverse selection of workers by each firm. New technologies provide the highest ability workers with the instrument to reveal their private information and if one firm prevents this, these workers move to the other firm. Since we have assumed \( k \geq 4 \left( \frac{\theta^a + \theta^b}{\theta^d} \right) \) to make sure that there is full employment at \( t \) and at \( t + 1 \), it is obvious that there is a range of positive values of \( \psi \) for which screening by each firm is the dominant strategy. According as \( \theta^d \) and \( k \) are larger, the incentives for the firm to screen increase. For then the competition between firms for type \( d \) is fiercer, and the costs of employing them in case they search for a job at your firm is smaller. Again, the \( \psi \) for which the condition above is true is one equilibrium of our model, but not the only one.

So the internal demand by workers for new technologies created by distributional considerations and the competition by firms for the highest ability workers could result in a configuration in which we see the computer everywhere although it is common knowledge that it has no effect on productivity in the short-run. Indeed, the possibility that computers become productive in the near future may actually make them a relatively cheap way to reveal information.

What are the implications of this equilibrium, in which training is an imperfect signalling device and screening by employers is possible? First of all, it can be attractive for some firm, outside our model, to spend resources on developing a new technology that has no short-run productivity effects as firms may be willing to spend money on its implementation. Some of the workers are willing to follow costly training although they do know.
that their productivity will not increase soon. Furthermore, competition between firms for the highest ability workers may result in the adoption of the new technology, although again it is common knowledge that productivity effects will be small (zero in our case) in the short-run. In the end there is still full employment, output remains constant in both sectors, profits for both firms in the short-run decrease with the amount of screening costs, and wage inequality will arise: \( w^a_{t+1} = w^b_{t+1} = \frac{1}{4} (\theta^a + \theta^b) \), and the highest two ability types, c and d, will earn half of their marginal product: \( w^c_{t+1} = \frac{\theta^c}{2}, w^d_{t+1} = \frac{\theta^d}{2} \).

This wage inequality is ultimately the result of differences in ability, but it is the new technology, the computer, that could potentially make these differences observable. Because of skill-complementarity, working on a computer is a sign of high ability. Then the skill premium is mainly a reflection of unobserved worker heterogeneity.

Starting with a situation in which a cohort of workers is observationally equivalent from the employers point of view may seem rather strong. However, income inequality among workers with similar observational characteristics has in fact risen steadily and substantially after 1970 and this rise in income inequality is probably hardest to explain. By looking at a cohort of workers which at the beginning of \( t \) are homogeneous from the point of view of the employer, the increase in income inequality that will arise as off \( t + 1 \) in our approach can shed some light on this empirical phenomenon. How does our analysis in this section change when we assume that the costs of opening a vacancy are large. We discuss this in the next section.

7.6 The Consequences for Employment

Above we discussed a mechanism through which new technologies such as the computer, despite the apparent absence of short-run productivity gains, could have a significant impact on wage inequality. Another stylized fact of recent developments in labor markets in the OECD countries has been increased unemployment of less skilled workers. Despite the lack of consensus, a majority of the studies claims that skill-biased technological change rather than increased trade with the developing world is mainly responsible for both the rise in income inequality and the rise in unemployment of less-skilled workers (see Berman et al., 1997, for example).

In this section we are going to discuss how technological progress may create unemployment of less-skilled workers. Again, if new technologies reveal information about worker quality, some workers may be identified by the employer as being unprofitable. However, this also implies that the productivity paradox becomes even more paradoxical.

\(^{15}\)See Juhn, Murphy, and Pierce (1993).
For, if the least skilled workers become unemployed, measured productivity, defined as output divided by the number of employees, should increase.

In the previous sections we assumed that $k$ was sufficiently large so that there is always full employment at $t$ and at $t + 1$. We are now going to analyze what happens to our conclusions so far if we assume different values for $k$. The case we consider is $\frac{3}{\theta} \leq k < \frac{4}{(\theta^a + \theta^r)}$ so that only the lowest ability group of workers, 1, is no longer productive enough to be employed in case the employer is able to observe their productivity. Moreover, the personnel department allows firms to separate their supply of vacancies between the different ability groups. As a matter of fact, this was also the case at the beginning of $t$ but then the employer could not yet distinguish the workers.

When $\frac{2}{\theta} \leq k < \frac{4}{(\theta^a + \theta^r)}$, the two lowest ability groups taken together are no longer productive enough to compensate the firm for hiring them and they will become unemployed if they both become separated from types $c$ and $d$. Since the pay-off from unemployment is equal to zero, one might expect that the incentive for types $a$ and $b$ to follow training will increase. We will now determine whether this intuition holds in our model, again under the assumption that $\gamma = 0$ for all types.

If the least able group of workers does not follow training his pay-off will be zero, but he will also be fired if he does follow the training. Thus for $y^* > 0$ we again have that the least able workers will set $y = 0$. So despite the fact that low ability workers know they will move from employment into unemployment if they don’t train themselves, they are not going to follow training for sure if they believe the firm will screen them.

The second lowest group of workers receives zero as well if they don’t train since the average product of types $a$ and $b$ is smaller than $\frac{1}{k}$. They receive $\frac{1}{2}\theta^b - \frac{y}{\theta}$ if they do train. The employer then receives $\frac{1}{2}\theta^b$ which is sufficient to compensate him for hiring these workers for the given range of $k$. Then this worker will not follow training if: $0 > \frac{1}{2}\theta^b - \frac{y}{\theta}$. Thus this worker sets $y = 0$ if $y^* > \frac{1}{2}(\theta^b)^2$, i.e. they only follow no training when the required level of training is very high. We do not assume this to be the case and maintain the assumption that the firms beliefs are given by: $\frac{1}{4}\theta^b (\theta^b - \theta^r) < y^* < \frac{1}{2}\theta^c (\theta^c - \theta)$. Then type $b$ will follow the training and we can be sure that types $c$ and $d$ follow the training as well. The threat of unemployment makes training a less effective signal.

It can easily be seen that profits for both firms if they decide not to screen their trained workers, are given by:

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16 Considering the case in which $\frac{2}{\theta} \leq k < \frac{3}{\theta}$ will only strengthen the results derived in this section. Recall that for $k < \frac{2}{\theta}$ there will be no production at all in these two firms at $t$. 

Recall that the lowest ability group will no longer be hired. In case both employers screen their workers,

\[ E\pi_{t+1}^i = \frac{1}{2}L \left( \bar{\theta} - \frac{\theta^a}{4} - \frac{3}{2k} \right) \]  

(7.14)

Now suppose only firm 1 screens its workers. Wages in the sector that does not screen (firm 2) at \( t + 1 \) will be equal to \( \frac{1}{2} \left( \theta^b + \theta^c + \theta^d \right) \) for types \( b, c, \) and \( d \). As a result, the highest ability workers, \( d \), move to the screening sector since there they can earn \( \frac{1}{2} \theta^d \).

The second highest ability group of workers, \( c \), is also able to determine this. They then have the choice between staying at firm 2 where they earn \( \frac{1}{4} \left( \theta^b + \theta^c \right) \) or moving to firm 1 where they will be screened and as a result will earn half their marginal product: \( \frac{1}{2} \theta^c \). So type \( c \) will move as well to the screening firm leaving only type \( b \) in sector 2. Profits are then respectively:

\[ E\pi_{t+1}^1 = \frac{1}{4}L \left( \theta^b + \frac{\theta^b}{2} + \frac{\theta^c}{2} + \frac{\theta^d}{2} \right) - \frac{5L}{4} - C = \]

\[ \frac{1}{2}L \left( \theta^b + \frac{\theta^b}{2} - \frac{\theta^c}{4} - \frac{5}{2k} \right) - \frac{5}{4} \psi L. \]  

(7.16)

and:

\[ E\pi_{t+1}^2 = \frac{1}{4}L - \theta^b + \frac{1}{4}L - \theta^c + \frac{1}{4}L - \theta^d = \frac{1}{2}L \left( \frac{\theta^b - \frac{1}{2k}}{4} \right) \]

(7.17)

and screening by each firm will be the dominant strategy if the expression in (7.16) is larger than the one in (7.14) and if the expression in (7.15) is larger than the one in (7.17). If \( 0 < \psi < \min \left( \frac{1}{10} \left( \theta^c + \theta^d \right) - \frac{1}{5k}, \frac{1}{6} \left( \theta^c + \theta^d \right) - \frac{2}{3k} \right) \), this is the case. Then firms will again find themselves in a prisoners dilemma and both will implement the costly new technology, workers will not move between sectors, and profits for both firms will again decrease. The incentive to screen workers increases if the costs of opening vacancies are smaller and according as the highest two ability groups of workers are more productive. Then there is stronger competition between firms for these workers.

Under these conditions for \( \psi, \gamma^* \), and \( k \) we again have that a firm, outside our model, may be willing to conduct research and development to invent a new technology. Moreover,
even a larger fraction of the population will follow costly training, and firms implement more of the costly new technology although everyone knows it will not affect productivity in the near future. Income inequality increases even more than in the previous case since wages are, from lowest to highest ability, $0, \frac{\theta^a}{2}, \frac{\theta^c}{2}$ compared to $\frac{(\theta^a + \theta^c)}{4}, \frac{(\theta^a + \theta^c)}{4}, \frac{\theta^c}{2}, \frac{\theta^a}{2}$ in the case where opening vacancies was relatively cheap. Production falls in both firms (with $\frac{1}{4}L\theta^a$), profits decrease from $t$ to $t + 1$ (with $\frac{3}{4}\psi L + \frac{1}{4}L\frac{1}{2}\theta^a - \frac{1}{4}L\frac{1}{2}$), a quarter of the labor force becomes permanently unemployed, and measured productivity increases in both firms from $\bar{\theta}$ at $t$ to $\frac{1}{3}(\theta^b + \theta^c + \theta^d) = \bar{\theta} + \frac{1}{3}[\theta - \theta^a]$ at $t + 1$. So measured productivity in both firms may increase in the short-run after the computer has been implemented, not because the computer has increased the productivity of workers, but because the least able workers have been fired. Measured productivity increases more when $\theta^a$ is more below average.

We can give the following interpretation to the differences between Sections 7.5 and 7.6. In some countries, with a low value of $k$, it may seem that the computer did have a positive impact on productivity. Other countries, with a high values of $k$, on the other hand may not experience any measured positive effects of the computer on productivity in the short-run. The country for which the effect on firm labor productivity seems to be the largest, may actually be the one for which the introduction of the computer comes at the largest social cost since income inequality will increase more in this country, unemployment will (a)rise, production will fall, and workers and firms invest more in costly training respectively in the new technology. As a consequence, the experience with the same technology in different countries can diverge. Since technologies spread quickly around the globe, at least among OECD countries, the labor market situation in each country, as formalized here by the parameter $k$, determines their effect on income inequality as well as unemployment of low-skilled workers.

So suppose that we formulate skill-complementarity in such a way that higher ability workers are able to learn how to work with new technologies at lower cost than lower ability workers. Suppose furthermore that the computer is a general-purpose technology so that productivity will not increase by much in the short-run and that an employer faces some uncertainty about the ability of his workers. This explains the productivity paradox. We can nevertheless see computers all around us (as discussed in Section 7.5) because of their distributional implications. Then we can understand the Solow paradox. Moreover, the lack of productivity increases in the short-run goes in hand with an increase in income equality. However, when the creation of vacancies is expensive, our framework suggests that not only income inequality will be a consequence of new technologies, but also unemployment of less-skilled workers. But then the productivity paradox returns.
with a vengeance. For in that case, skill-biased technological change implies that measured productivity should increase even if the new technology has no effect on productivity in the short-run.\textsuperscript{17}

\section*{7.7 Conclusion}

If you believe in rationality and efficient markets then it seems obvious that new technologies are efficiency improving because else we wouldn't see them all around us. Then new technologies should be an important factor behind the Solow residual. This chapter argued that an additional reason for why we may be working with some new technologies is related to the fact that they provide information if one combines theories of imperfect information with theories that emphasize skill-complementarities.

Notice the difference between the effect of trade reform on labor markets, as analyzed in Chapter 6, and the role of new technologies as studied in this Chapter. Trade liberalization affects relative prices which makes understanding the effects of labor mobility among sectors crucially important to understand its impact on labor markets. However, the introduction of a general-purpose technology, if implemented by all firms, does not affect relative prices. This gives rise to the prisoner's dilemma observed above that in the end leaves all the workers at the firm they were.

New technologies make previously unobserved heterogeneity observable which has distributional implications. If the learning potential of workers increases with ability, new technologies may provide a vehicle to reduce these information a-symmetries. High ability workers don't want low ability workers to hide behind their backs. If this prevention of free riding is imperfect, firms can find themselves in competition for the highest ability workers and implementing the new technology is a way to prevent adverse selection of workers.

The natural result that new technologies provide information implies that income inequality increases because of a second channel besides the standard skill-complementarity theories of technological change. Then the productivity paradox can be explained by taking the measurement problems seriously and the income inequality is the result of skill-complementarity: higher ability workers have a learning advantage and their (unmeasured) productivity increases by more when they use the new technology. If one sees the computer as a general-purpose technology, the productivity paradox is a short-run

\textsuperscript{17}May be new technologies initially cause productivity slowdowns which are more or less compensated in the data because the least-skilled workers become unemployed. For a study investigating the relationship between technology improvements and productivity slowdowns see Hornstein and Krusell (1996).
Again the role of new technologies as information providers could play an important role here and if the computer will become productive in the future it may be a relatively cheap source of information. We argued that if signalling by workers is indeed imperfect, screening by employers is possible, and the costs of opening a vacancy are small, it is possible for resources to be devoted to develop a technology. workers to follow costly training to be able to work with this technology, and firms spending money on its implementation (to prevent adverse selection of workers), although it is common knowledge that the new technology has no short-run effect on productivity. Income inequality increases along the way within a given cohort of workers. The skill premium arises because of unobserved worker heterogeneity. When the costs of opening a vacancy are large, these conclusions remain valid, while additionally persistent unemployment of less-skilled workers arises and more workers invest in training (which makes signalling less effective), firms implement more of the new technology, income inequality increases even more, production falls in both firms, and measured productivity increases.

This last aspect of skill-biased technological change implies that the productivity paradox becomes even more paradoxical. Moreover different countries may have different experiences with the introduction of new technologies depending on the costs of opening a vacancy in that country. Countries for which the effect on productivity growth seems to be the largest, may actually be the ones for which the introduction of new technologies comes at the largest social cost.