ADJUSTING TO A NEW TECHNOLOGY: EXPERIENCE AND TRAINING

Elhanan Helpman
Antonio Rangel

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ABSTRACT

In this paper we study how aggregate output responds to the arrival of a new General Purpose Technology (GPT) by looking at adjustment mechanisms that operate through labor markets.

We show that under a wide set of circumstances the arrival of a new GPT that raises long-run output can trigger a recession in the short-run. Furthermore, we characterize features of the GPT that produce a cyclical adjustment path. An initial recession occurs whenever a higher education level is required to operate the new GPT. But a recession can also occur when the new GPT has lower educational requirements. A cyclical adjustment path is more likely when inexperienced workers are less productive with the new technology and the faster productivity rises with experience in the new sector.

Elhanan Helpman
Department of Economics
Harvard University
229 Littauer Center
Cambridge, MA 02138
and NBER
ehelpman@harvard.edu

Antonio Rangel
Department of Economics
Stanford University
Stanford, CA 94305

1 Introduction

The arrival of a new technology triggers a plethora of responses. Some are designed to take advantage of new opportunities, such as attempts to implement the new technology in the manufacturing of old products or to develop new ones. Others are defensive, such as attempts by users of the old technology to minimize damages from new sources of competition. And when the new technology is of major proportions, such as a General Purpose Technology (GPT for short), these responses are widespread, diffused across many sectors. As a result macroeconomic variables, such as aggregate output, are affected. David (1991), for example, suggested that the slowdown in productivity growth in US manufacturing at the beginning of the 20^{th} century was triggered by electrification, and that the slowdown in productivity growth in the 1970s might be related to computerization.

A small literature on GPTs has emerged in recent years. It has studied a number of channels through which a new technology affects the economy, such as secondary innovations and diffusion.[1] Our goal is to examine new channels of adjustment that operate through labor markets. For this purpose we distinguish between experience, that individuals acquire by working with a technology, and knowledge, that they acquire via education and training.[2]

Our distinction between experience and schooling plays a key role. Experience is acquired on the job, by working with a technology, while education and training take place mostly in schools. In practice, some human capital acquired via experience in the old sector can be useful in operating the new technology. But this type of human capital is less transferable across technologies than human capital acquired through schooling, because schooling provides more general skills such as literacy and numeracy. To emphasize this distinction we assume that experience is technology-

[1] See Bresnahan and Trajtenberg (1995) for the original article on General Purpose Technologies and Helpman (1998) for a collection of essays on the subject.

[2] Learning also plays a role in the adjustment processes studied by Greenwood and Yorukolgu (1997) and Hornstein and Krusell (1996). But their approach differs from ours. We emphasize human capital embodied in workers rather than learning that is firm or industry specific.

specific in the extreme; namely, it is not transferable across technologies. On the other hand, education and training provide human capital that applies to all technologies. In short, experience is technology-specific while schooling is not.

The central question addressed in this paper is how does aggregate output respond to the arrival of a new technology. We are interested in the entire trajectory, but especially in the short-run response. Can the arrival of a new technology of the GPT type trigger a recession even when it raises long-run output?

We begin our enquiry in section 2, by considering an economy that has technologies without schooling requirements. As a result a worker's productivity is determined only by his working experience. We show that under these circumstances the arrival of a superior technology may produce a continuous rise in output, or a cycle that starts with a recession and ends with a boom. Which pattern emerges depends on how the new technology differs from the old. Two main features determine wether a boom or a cycle occurs: the productivity of inexperienced workers and the speed of learning. When an inexperienced worker is more productive with the old technology, output declines with the arrival of the new one. As a result a recession is unavoidable. But even when an inexperienced worker is more productive with the new technology the adjustment can start with a recession. Furthermore, a recession is more likely the faster productivity rises with experience in the new sector. Such recessions can linger for long periods of time.

Experience-driven recessions result from the loss of human capital of experienced workers who switch from the old sector to the new one; we call this the *switch effect*. When a worker decides whether to switch or not, he compares his remaining lifetime income in the old sector with his remaining lifetime income in the new one. Whenever the latter is larger he switches sectors. If the productivity of labor rises fast with experience in the new sector, then even workers who are highly experienced with the old technology choose to switch, even if their initial wage rate is low in the new sector. Every worker who takes a wage cut while switching contributes to a temporary decline in output. Therefore, a recession occurs when many experienced workers switch.

Schooling introduces an *entry effect* that differs from the switch effect. The way in which the entry effect operates depends on whether there is technology-skill substitutability or complementarity. We model the relationship between technologies and skills in a simple way: to operate a technology it is necessary to acquire a certain minimal amount of schooling. If this schooling requirement is larger for the new technology, we have technology-skill complementarity. If it is larger for the old technology, we have substitutability.

Historical examples of technological change include both increased and decreased requirements for education and training. Goldin and Katz (1996) argue that the transition from the artisan shop to the factory most likely decreased the overall demand for skill; a case of technology-skill substitutability. They also argue that the shift to batch and continuous-process methods of production in the nineteen twenties changed the relative demand for skill in the opposite direction, towards skilled and educated workers, a case of technology-skill complementarity.

In more recent decades technology-skill complementarity appears to be a dominant feature of technological change. Bartel and Lichtenberg (1987) show that, for a cross-section of industries, implementation of new technologies was associated with an increase in the relative demand for highly educated workers. This trend has been reinforced since the nineteen seventies due to the spread of computers. In this period industries that adopted computer-based technologies have lead the increase in the demand for skilled workers. Autor, Katz and Krueger (1997) show that industries with greater growth in employee computer usage or with more computers per worker have upgraded faster the skill of their work-force.

In case of technology-skill substitutability the arrival of a new technology induces students to leave schools earlier than expected, thereby producing a positive entry effect into the labor force. As a result output rises. Nevertheless, aggregate output may not increase in the short-run because of a negative switch effect. We show in section 3 that in this case the adjustment may start with a recession and end with a boom. On the other hand, technology-skill complementarity induces a negative entry effect. Workers employed in the old sector can choose to upgrade their skills via schooling in order to switch to the new technology. Those who choose to switch do not produce during their training period. As a result output declines. It follows that in this case the adjustment starts with a recession independently of whether inexperienced workers are more productive in the old sector or whether learning is faster in the new one.

In sections 2 and 3 our analysis deals with adjustments to an unanticipated arrival of a new technology. We examine anticipated arrival dates in section 4. In the case of a known arrival date, the pattern of adjustment is very much the same as in the case of no anticipation. With technology-skill substitutability it is exactly the same, and no response occurs before the arrival of the new technology. With technology-skill complementarity expectations also do not affect the adjustment process markedly, except that it starts earlier, before the arrival of the new technology. Expecting the new technology to arrive, individuals stay in school longer in order to prepare to work with it. As a result a negative entry effect precedes the arrival date and therefore the recession starts before the technology becomes available. Consequently, when the new technology arrives, it is used immediately, unlike the case of no anticipation.

We also discuss in section 4 what happens when the arrival date is uncertain. This sort of uncertainty does not change the adjustment process in any significant way. When the Poisson arrival rate is low the adjustment is exactly as in the case of no anticipation. And when the arrival rate is high the adjustment is similar to the case of precise anticipation.

2 Experience

As explained in the introduction, we study the role of experience and schooling in an economy's adjustment to the arrival of a new technology. However, to isolate the role of experience, we first develop a model without education and training. Experience plays a key role in the adoption of a new technology because it raises productivity and wages. As a result, when experience with an old technology is not readily transferable to a new one, experienced workers find the new technology unattractive to switch to. On the other hand, young workers, who have accumulated little experience with the old technology, are more likely to switch. These incentives produce an initial output response that can be positive or negative. Moreover, combined with the speed of learning while working in the new sector, these considerations also affect subsequent output changes. By analyzing the resulting adjustment path we identify the main forces at work and the trajectory of aggregate output. In particular, we identify circumstances in which the new technology leads to rising output and circumstances in which output follows a cycle, declining initially and rising subsequently. Importantly, the cyclical response is not pathological but rather a natural feature of the adjustment process.

2.1 Model

There are overlapping generations of workers who enter and exit the economy in continuous time. A new cohort of measure one is born at each instant t. This cohort lives until $t+\delta$.

Workers supply one unit of labor at every point of their lives. Preferences are additively separable and linear, and future consumption is not discounted. In this case the utility of a worker born at time t is $u(t) = \int_t^{t+\delta} c(\tau)\, d\tau$, where $c(\tau)$ is consumption at time τ. An individual with such preferences cares only about lifetime consumption and seeks to maximize lifetime income. We use this structure of preferences to simplify the analysis, but our main insights do not depend on it.

The production function is linear homogeneous and labor is the only input. A worker's productivity depends on experience, which is technology specific. Let $\pi_i(e)$ denote the effective level of labor supply for technology i of a worker who has operated this technology for e units of time.

Our analysis begins with an economy that is operating an old technology $i = o$ and has done so for some time. In this initial steady state the experience is distributed uniformly among the existing δ workers. Thus, prior to the arrival of the new technology output is constant and equal to $\int_0^{\delta} \pi_o(e)de$.

A new technology becomes available at time $t = 0$ and is characterized by the labor productivity function $\pi_n(e)$. We make the following assumptions on the productivity functions:

Assumption 1: $\pi_i(e)$ is nondecreasing and differentiable for $i = o, n$.

Assumption 1 just ensures that experience is valuable. Empirical evidence suggests that the rate of productivity growth $\pi_i'(e)/\pi_i(e)$ is higher at lower experience levels (see Murphy and Welch (1990)). Although at this point we do not impose additional restrictions on the experience curves, we study below how the characteristics of the new technology affect the adjustment process.

Assumption 2: Experience with one technology does not affect productivity with another technology.

Assumption 3: The new technology is more productive over a worker's lifetime; i.e., $\int_o^\delta \pi_o(x)dx < \int_o^\delta \pi_n(x)dx$.

Assumption 4: $\pi_o(\delta) > \pi_n(0)$.

Assumption 2 captures the notion that human capital is lost by switching from a familiar technology to a new one. The form of this assumption is somewhat extreme. What matters for our purpose is not so much that no experience is transferable but rather that not *all* experience from the old sector is transferable to the new. Using an extreme form just simplifies the analysis. The assumption does not imply, however, that an experienced worker is always more productive with the old technology. In fact, Assumption 3 states that a young worker that has little experience with the old technology will be more productive over his remaining lifetime in the new sector. Thus, the new technology is better than the old one in a well defined sense.

Assumption 4 states that switching to the new technology is not profitable for the oldest workers that have accumulated a lot of experience with the old technology. For these workers a switch to the new sector represents a severe loss of human capital. It follows from Assumptions 3 and 4 that some young workers find it profitable to switch to the new technology while some old workers prefer to stay with the old one.

Assumption 5: There is a unique level of experience $e \in (0, \delta)$ at which $\int_e^\delta \pi_o(x)dx = \int_e^\delta \pi_n(x-e)dx$. This level of experience is denoted by $\bar{e}$.

Assumption 5 ensures that every worker younger than $\bar{e}$ switches to the new technology while all the older workers do not. A worker with experience $\bar{e}$ earns $\int_{\bar{e}}^\delta \pi_o(x)dx$ in the remaining part of his life if he continues to work with the old technology and $\int_{\bar{e}}^\delta \pi_n(x-\bar{e})dx$ if he switches to the new one. At the cutoff level $\bar{e}$ both options are equally profitable. Note that the crucial element in this assumption is the uniqueness of $\bar{e}$; its mere existence is guaranteed by Assumptions 3 and 4. We therefore have the following lemma:

LEMMA 1: *There exists a unique value of experience, $\bar{e} \in (0, \delta)$, such that at $t = 0$ all workers with experience $e \in [0, \bar{e}]$ switch to the new technology and all workers with experience $e \in (\bar{e}, \delta]$ continue to work with the old technology.*

This simple characterization of who switches to the new technology at time 0 allows us to analyze the response of aggregate output on impact as well as its dynamic evolution. We discuss the impact effect in the next subsection and the transitional dynamics afterwards.

2.2 Impact

When the new technology arrives at time 0 all the workers with experience less than $\bar{e}$ switch immediately to the new sector. They form a fraction $\bar{e}/\delta$ of the labor force. How does their shift affect aggregate output?

To answer this question observe that when a group of workers with experience smaller than e switches to the new technology the output of this group equals $e\pi_n(0)$ while the output of the remaining workers, who keep operating the old technology, equals $\int_e^\delta \pi_o(x)\,dx$.[3] Therefore, aggregate output after the switch equals $e\pi_n(0) +$

[3] As is customary in the national income accounts, our measure of output does not include the value of experience that workers accumulate.

$\int_e^\delta \pi_o(x)\,dx$. Since before the switch aggregate output was $\int_0^\delta \pi_o(x)\,dx$ it follows that the change in output is

$$\phi(e) = e\pi_n(0) + \int_e^\delta \pi_o(x)\,dx - \int_0^\delta \pi_o(x)\,dx. \tag{1}$$

The actual change at time 0 is $\phi(\bar{e})$.

Every worker that switches to the new technology produces $\pi_n(0)$ units of output, which is constant. On the other hand, his forgone output in the old sector, $\pi_o(e)$, depends on his experience. Therefore, the more experienced the marginal worker who switches the larger the aggregate output losses in the old sector. As a result, the function $\phi(e)$ has the following properties:

$$\phi(0) = 0;$$
$$\phi'(e) = \pi_n(0) - \pi_o(e);$$
$$\phi''(e) \leq 0.$$

Evidently, output drops on impact whenever a worker with no experience is less productive in the new sector, because every worker who switches causes a larger marginal output loss than the inexperienced worker. As a result, $\pi_n(0) < \pi_o(0)$ is a sufficient condition for output to fall on impact. On the other hand, it does not follow that output must increase on impact when inexperienced workers are more productive with the new technology. Output can still fall if a sufficiently large number of experienced workers change sectors. The aggregate output loss of the experienced group can nullify the productivity gains of the inexperienced group. Thus, when $\pi_n(0) > \pi_o(0)$ output can increase or decline. The following linear example illustrates the forces at work.

LINEAR EXAMPLE: The productivity functions are given by

$$\pi_i(e) = \alpha_i + \beta_i e \text{ with } \alpha_i, \beta_i > 0 \text{ for } i = o, n. \tag{2}$$

In view of (2) the productivity functions satisfy Assumption 1. The following restrictions provide, respectively, necessary and sufficient conditions for Assumptions 3 and 4:

$$2(\alpha_n - \alpha_o) > \delta(\beta_o - \beta_n), \tag{3}$$

$$\alpha_o + \beta_o \delta > \alpha_n. \tag{4}$$

Inequalities (3) and (4) imply that Assumption 5 is also satisfied.

We can use these functions to calculate

$$\bar{e} = \frac{2(\alpha_n - \alpha_o) + \delta(\beta_n - \beta_o)}{\beta_n + \beta_o}$$

and

$$\phi(e) = \left(\alpha_n - \alpha_o - \frac{1}{2}\beta_o e\right) e.$$

It then follows that in the linear case aggregate output decreases on impact if, and only if,

$$2(\alpha_n - \alpha_o) < \delta(\beta_n - \beta_o)\frac{\beta_o}{\beta_n}.$$

Clearly, output declines when $\alpha_n < \alpha_o$ (i.e., $\pi_n(0) < \pi_o(0)$), because in this case (3) implies $\beta_n > \beta_o$. On the other hand, when $\alpha_n > \alpha_o$ output can rise or decline. It rises, for example, when $\beta_n = \beta_o$.

Figures 1 and 2, with $\alpha_n > \alpha_o$, provide the intuition. In Figure 1 we depict the case $\beta_n = \beta_o$. The cutoff experience level $\bar{e}$ is found at the intersection of a horizontal line at the level α_n with the π_o line at point A. This ensures that the area between 0 and $\delta - \bar{e}$ under the π_n line, which represents the remaining lifetime income of an individual with experience $\bar{e}$ who switches to the new technology, just equals the area between $\bar{e}$ and δ under the π_o line, which represents the remaining lifetime income of a similar individual who does not switch. It follows that all individuals with experience below $\bar{e}$ switch while those with experience above $\bar{e}$ do not.

Before the switch aggregate output equaled the area between 0 and δ below the π_o line. After the switch aggregate output equals the area between 0 and $\bar{e}$ below the horizontal line through A, which represents the output generated with the new technology, plus the area between $\bar{e}$ and δ below the π_o line, which represents the output generated with the old technology. Since every worker who switches is instantly more productive with the new technology, aggregate output increases by the shaded area. It is also easy to see that a lower value of

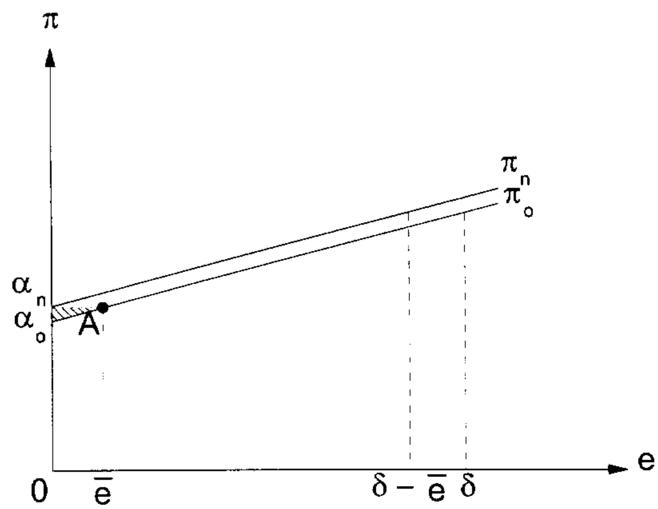

Figure 1: An immediate output increase

β_n reduces the value of $\bar{e}$, placing it to the left of A. In this case, since every worker who switches to the new technology becomes instantly more productive, output also increases on impact.

Now turn to Figure 2, in which all the parameters are the same as in Figure 1 except that β_n has increased. A worker's willingness to switch sectors, and thus to temporarily forgo larger earnings with the old technology, depends now on how fast productivity increases with experience in the new sector. In other words, the cutoff level $\bar{e}$ increases with the slope of the π_n line. Note that in Figure 2 $\bar{e}$ is to the right of point A. In this case the productivity of the marginal worker temporarily decreases with the switch. Just after the switch, aggregate output is given by the area between 0 and $\bar{e}$ under the horizontal line through A plus the area between $\bar{e}$ and δ under the π_o line, while output prior to the switch remains the area between 0 and δ under the π_o line. Thus, the net output increase equals the shaded area to the left of point A minus the shaded area to its right. If the π_n line is very steep $\bar{e}$ is large enough to make this difference negative, in which case aggregate output declines.

The key feature that makes this outcome different from Figure 1 is that now

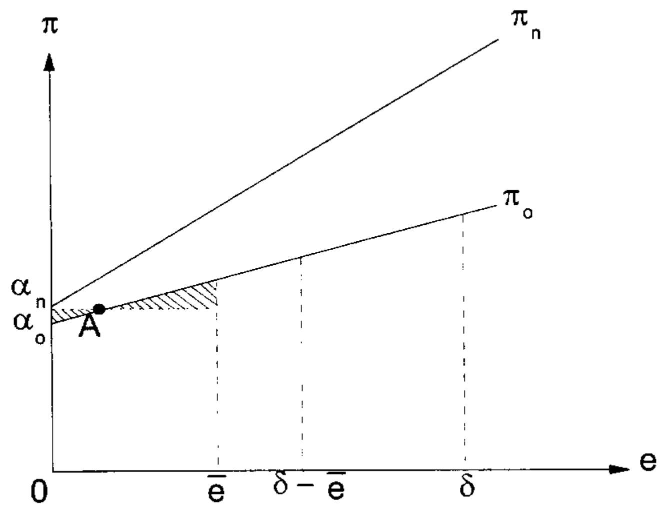

Figure 2: An immediate output decline

some workers that switch to the new technology produce less than their forgone output in the old sector. Workers with little experience, those to the left of A, do produce more. But more experienced workers, those to the right of A, produce less. Note that the decision to switch sectors is voluntary. With fast experience-driven productivity growth on the new technology even workers with significant experience in the old sector find it profitable to switch, because they expect fast wage growth after the switch. Temporarily, however, they take a wage cut. In Figure 2 the decline in the wages of this group is larger than the aggregate wage increases of less experienced workers.

The linear example suggests the following sufficient condition for an output increase. Let $\pi_n(0) > \pi_o(0)$. Then there exists a level of experience $e_{on} > 0$ at which $\pi_n(0) = \pi_o(e_{on})$. The immediate wages of a worker with this level of experience in the old sector do not change if he moves to the new one. Next suppose that $\pi_n'(e - e_{on}) < \pi_o'(e)$ for all $e > e_{on}$. Under this condition an e_{on} year experienced worker earns higher wages every period of his life if he stays with the old technology and as a result is better off not switching sectors. Workers with more than e_{on} years of experience have even less of an incentive to switch. Therefore $\bar{e} < e_{on}$. Namely, the oldest worker who finds it profitable to switch to the new technology has a level of experience lower than e_{on}. As a result aggregate output must increase on impact, because the wage rate of every worker changing sectors increases immediately; i.e., $\pi_n(0) > \pi_o(e)$ for all $e \leq \bar{e} < e_{on}$.[4] We have thus proved the following

PROPOSITION 1: *The arrival of a new technology may increase or reduce aggregate output at $t = 0$.*

(i) Output declines whenever $\pi_n(0) < \pi_o(0)$.

(ii) Output increases whenever $\pi_n(0) > \pi_o(0)$ and $\pi_n'(e - e_{on}) < \pi_o'(e)$ for all $e > e_{on}$, where e_{on} satisfies $\pi_n(0) = \pi_o(e_{on})$.

This result characterizes properties of the productivity functions that determine whether the arrival of a new technology generates immediate output gains or losses. What are the key economic properties of technologies that determine the short-run output response?

One important property is the degree to which the new technology is suitable for inexperienced workers; it is less suitable than the old technology whenever $\pi_n(0) < \pi_o(0)$. If this is the case, then every worker that switches sectors takes a temporary wage cut and therefore aggregate output decreases on impact. Observe, however, that Assumption 3 ensures that productivity rises fast enough with experience in the new sector to induce workers to accept low wages initially. Otherwise no one would change sectors.

[4] More formally, observe that by definition we have that $\int_{\bar{e}}^{\delta} \pi_n(x - \bar{e})\, dx = \int_{\bar{e}}^{\delta} \pi_o(x)\, dx$. However,

$$\begin{aligned}
\int_{e_{on}}^{\delta} \pi_o(x)\, dx &= \int_{e_{on}}^{\delta} \left[\pi_o(e_{on}) + \int_{e_{on}}^{x} \pi_o'(y)\, dy\right] dx > \int_{e_{on}}^{\delta} \left[\pi_o(e_{on}) + \int_{e_{on}}^{x} \pi_n'(y - e_{on})\, dy\right] dx \\
&= \int_{e_{on}}^{\delta} \left[\pi_n(0) + \int_{e_{on}}^{x} \pi_n'(y - e_{on})\, dy\right] dx = \int_{e_{on}}^{\delta} \pi_n(x - e_{on})\, dx.
\end{aligned}$$

And therefore we can conclude that $\bar{e} < e_{on}$. But this allows us to establish that $\phi(\bar{e}) > 0$, because

$$\begin{aligned}
\bar{e}\pi_n(0) + \int_{\bar{e}}^{\delta} \pi_o(x)\, dx &= \bar{e}\pi_o(e_{on}) + \int_{\bar{e}}^{\delta} \pi_o(x)\, dx \\
&> \bar{e}\pi_o(\bar{e}) + \int_{\bar{e}}^{\delta} \pi_o(x)\, dx > \int_0^{\bar{e}} \pi_o(x)\, dx + \int_{\bar{e}}^{\delta} \pi_o(x)\, dx = \int_0^{\delta} \pi_o(x)\, dx.
\end{aligned}$$

On the other hand, it does not follow that output increases when the new technology is more suitable for inexperienced workers; i.e., when $\pi_n(0) > \pi_o(0)$. For this type of technological change, aggregate output can increase or decrease on impact. The key additional property that determines the outcome is the speed of learning. If productivity rises with experience much faster in the new sector, then some experienced workers find it profitable to switch. They take a temporary wage cut in exchange for higher wages in the future that will be attained as a result of accumulated experience with the new technology. The faster the speed of learning in the new sector, the larger the mass of experienced workers that find it profitable to take a temporary wage cut. As we saw in the linear example, this effect can outweigh the short-term productivity gains of inexperienced workers.

Therefore low initial productivity and fast learning in the new sector tend to have an immediate negative effect on output. On the other hand, when inexperienced workers are more productive in the new sector and learning is slow, output rises on impact. In the latter case workers with substantial experience in the old sector do not tend to switch.

2.3 Transitional dynamics

We now characterize the transition path to the new steady state. Recall that every worker born after the arrival of the new technology adopts it because, by Assumption 3, it yields higher lifetime earnings. Therefore at $t = \delta$ the economy converges to a new steady state and aggregate output rises from $\int_o^\delta \pi_o(x)dx$ just before time 0 to $\int_o^\delta \pi_n(x)dx$ at the end of the transition.

At $t = 0$ all workers with experience smaller or equal than $\bar{e}$ switch to the new technology. The rest of the labor force remains with the old technology. It remains in use as long as the workers who do not switch are alive. Only the new technology is used afterwards. As a result the transition can be divided into two phases: Phase 1 during $t \in [0, \delta - \bar{e})$ in which the old technology is still being used, and Phase 2 during $t \in [\delta - \bar{e}, \delta]$ in which it is not.

In Phase 1 output is produced by three types of workers. First, there is a mass of $\overline{e}$ individuals who switched to the new technology at time 0 and whose experience with it at time t is $e = t$. Their output is given by $\overline{e}\pi_n(t)$. Second, there is the group that works with the old technology. Their output at t equals $\int_{\overline{e}+t}^{\delta} \pi_o(x)dx$, because t of them die in the time interval $(0, t]$. Finally, there are those who are born after time 0. This group operates the new technology and its output equals $\int_0^t \pi_n(x)dx$. Therefore, aggregate output in Phase 1 equals

$$\overline{e}\pi_n(t) + \int_{\overline{e}+t}^{\delta} \pi_o(x)dx + \int_0^t \pi_n(x)dx.$$

By the end of Phase 1 all the agents who operated the old technology have departed. Therefore there are only two relevant groups of workers in Phase 2, both operating the new technology. One group consists of individuals who switched to the new technology at time 0 and whose experience with the new technology is $e = t$ at time t. The only difference with the previous phase is that now only $\delta - t$ of them are alive. As a result this group's output equals $(\delta - t)\,\pi_n(t)$. A second group is made up of individuals born after time 0. Their output is $\int_0^t \pi_n(x)dx$. It follows that aggregate output is described by

$$Y(t) = \begin{cases} \overline{e}\pi_n(t) + \int_{\overline{e}+t}^{\delta} \pi_o(x)dx + \int_0^t \pi_n(x)dx & \text{for} \quad t \in 0, \delta - \overline{e}) \\ (\delta - t)\pi_n(t) + \int_0^t \pi_n(x)dx & \text{for} \quad t \in [\delta - \overline{e}, \delta] \end{cases} \tag{5}$$

and that changes in output are given by

$$Y'(t) = \begin{cases} \overline{e}\pi_n'(t) - \pi_o(\overline{e} + t) + \pi_n(t) & \text{for} \quad t \in 0, \delta - \overline{e}) \\ (\delta - t)\pi_n'(t) & \text{for} \quad t \in [\delta - \overline{e}, \delta] \end{cases} . \tag{6}$$

Output changes in Phase 1 are driven by three different forces: (i) $\overline{e}\pi_n'(t)$ represents an increase in output that results from the fact that the initial mass of workers who switched sectors at time 0 is gaining experience with the new technology; (ii) $-\pi_o(\overline{e}+t)$ represents a loss due to the death of experienced middle-aged workers who used the old technology (they are not replaced, because the new middle-aged workers operate the new technology); and (iii) $\pi_n(t)$ represents output gains resulting from the increase in number and average experience of workers born after the arrival of the new technology.

The forces at work in Phase 2 are rather different. Since no one operates the old technology in this phase, output changes are due to changes in the average level of experience with the new technology. This is given by $(\delta - t)\pi_n'(t)$, which represents the aggregate increase in experience of the surviving agents that switched sectors at time 0. Note that some of the workers in this group die during Phase 2, with a marginal effect $-\pi_n(t)$, but they are replaced by workers born after the arrival of the new technology, with a marginal effect $\pi_n(t)$. Therefore, output rises in Phase 2 as long as productivity rises with experience. Aggregate output cannot decrease during this phase, but it can stagnate if there is no learning at higher levels of experience. These results are summarized in

PROPOSITION 2: *(i) During Phase 1 output increases if and only if* $\bar{e}\pi_n'(t) + \pi_n(t) > \pi_o(\bar{e} + t)$; *(ii) During Phase 2 output is nondecreasing and increases as long as the productivity of the mass of workers who switched at time* 0 *rises with experience; i.e., as long as* $\pi_n'(t) > 0$.

The interesting question is whether output can decline during the first phase, and in particular whether it can both drop on impact and continue to decline for a while before starting to rise. When output evolves in this manner the arrival of the new technology leads to a cycle in which the economy initially suffers continuous output losses and only later grows in earnest.

We answer this question with the help of the linear example. In the linear case the necessary and sufficient condition for a rising output in Phase 1 can be rewritten as $\alpha_n + \beta_n(\bar{e} + t) > \alpha_o + \beta_o(\bar{e} + t)$, or $\pi_n(\bar{e} + t) > \pi_o(\bar{e} + t)$.

First observe that a downturn is not an inevitable consequence of the arrival of a new technology. To see why consider functions with $\alpha_n > \alpha_o$ and $\beta_n = \beta_o = \beta$, which are depicted in Figure 1. In this case, as explained in the previous subsection, output rises on impact. In addition we have $\pi_n(\bar{e} + t) > \pi_o(\bar{e} + t)$ for all $t \in [0, \delta - \bar{e}]$ and thus the initial boom is followed by sustained output growth during Phase 1 (with $Y'(t) = \alpha_n - \alpha_o$, a constant). Since aggregate output also rises during Phase 2, with $Y'(t) = (\delta - t)\beta$, the arrival of the new technology triggers an economic boom that

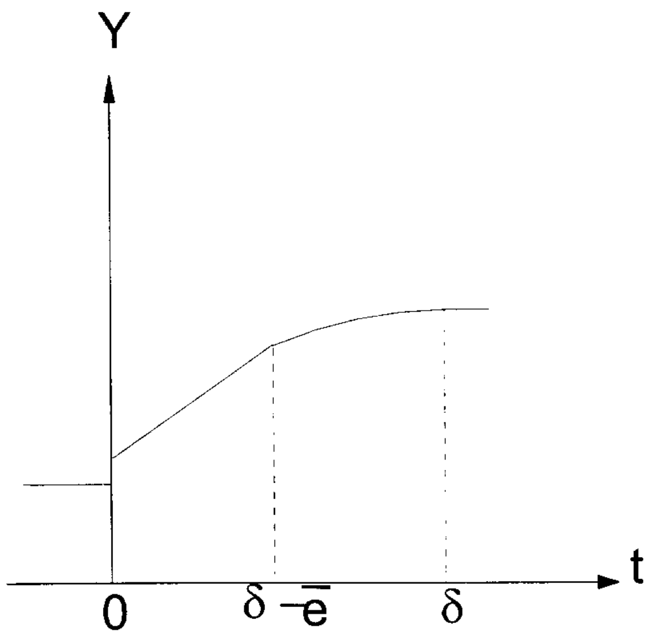

Figure 3: Output rises on impact and continues to increase during phase one

continues until time δ. At this time the transition to the new steady state has been completed and output stabilizes. A path of this sort is depicted in Figure 3. Note that in this case the rise of output on impact is followed by a positive but declining rate of growth Y'/Y.

Now turn to Figure 4, in which $\alpha_n < \alpha_o$ and $\beta_n > \beta_o$. These productivity curves have been designed so that the area from 0 to δ below the π_n line is only slightly larger than the area from 0 to δ below the π_o line. As a result only workers with little experience switch at 0 to the new technology, as indicated by the low value of $\overline{e}$ in the figure. From Proposition 1 we know that output falls on impact in this case, because $\alpha_n < \alpha_o$. And Proposition 2 implies that output continues to decline in the interval $[0, e_c - \overline{e})$, because in this period $\pi_n(\overline{e}+t) < \pi_o(\overline{e}+t)$. We therefore conclude that in this case output follows a cyclical pattern, as depicted in Figure 5.

We have seen that – depending on the ways in which the new technology differs from the old – output can rise throughout, or it can follow a cycle that starts with a

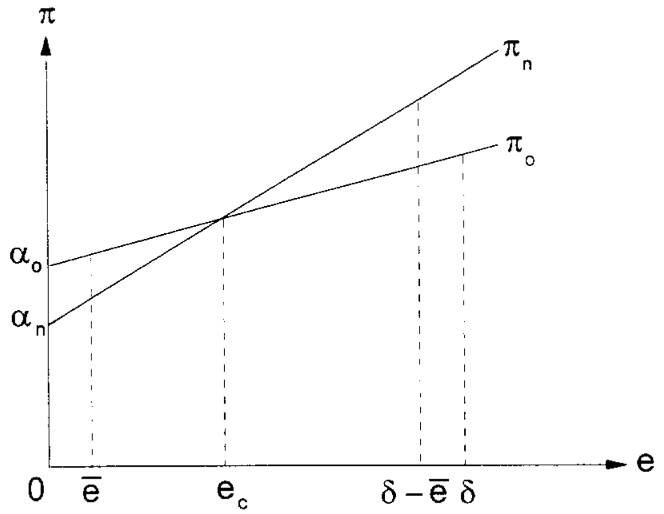

Figure 4: An immediate output decline followed by further declines

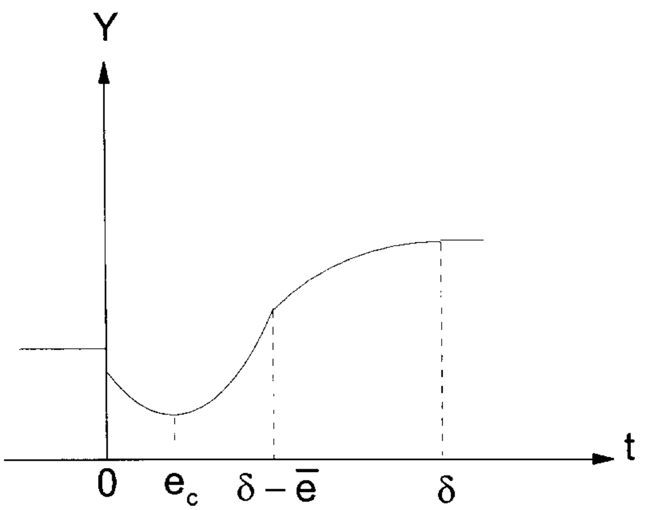

Figure 5: Output drops on impact and follows a cycle

bust followed by rapid growth.[5]

As before, two economic characteristics of the productivity functions determine the form of the transition path: productivity at low experience levels and the speed of learning. Proposition 2 shows that output increases during Phase 1 if and only if $\bar{e}\pi_n'(t)+\pi_n(t) > \pi_o(\bar{e}+t)$. Therefore whenever the new technology is less productive at low experience levels (i.e., if $\pi_n(0) < \pi_o(0)$) and learning is initially slow, a recession is likely to occur at the early stages of transition. In this case output decreases because in the beginning not enough experience has been accumulated in the new sector to offset losses in productivity that result from the departure of experienced middle-aged workers in the old sector. The speed of learning plays an additional role in the transition; the faster it is the faster productivity grows in the new sector and the shorter the recession.

3 Education and Training

In this section we extend the analysis to include education and training. Education and training are important because they provide essential skills. Naturally, education interacts in many ways with experience to determine labor productivity. We, however, ignore most of these interactions and focus on one important feature: whether technology and skills are complements or substitutes.

A new technology can be more or less user-friendly. The more complicated it is

[5]There is a discontinuous change in aggregate output at time 0. Afterwards this variable follows a continuous trajectory. Moreover, after the inital impact the change in output Y' is also continuous, except for time $\delta - \bar{e}$. As a result the rate of growth Y'/Y is continuous except for time $\delta - \bar{e}$. In addition, (6) implies that

$$\lim_{t^+ \to \delta - \bar{e}} Y'(t) = \bar{e}\pi_n'(\delta - \bar{e}) + \pi_n(\delta - \bar{e}) - \pi_o(\delta);$$

$$\lim_{t^- \to \delta - \bar{e}} Y'(t) = \bar{e}\pi_n'(\delta - \bar{e}).$$

Therefore the rate of growth jumps upwards at $\delta - \bar{e}$ if and only if $\pi_n(\delta - \bar{e}) < \pi_o(\delta)$. Evidently, in Figure 4 we have $\pi_n(\delta - \bar{e}) > \pi_o(\delta)$ and thus the rate of growth of output jumps downwards at time $\delta - \bar{e}$, as depicted in Figure 5.

to operate a technology, the higher the level of skill and thus the level of education and training, that is required to operate it effectively. A new technology exhibits technology-skill complementarity if it increases the level of schooling that is required to operate it. Technology-skill substitutability is defined inversely.

It is important to emphasize that user-friendliness is related to the degree of complexity in use, which is different from the complexity of the technology itself. For example, a modern digitally controlled drilling machine can be operated by an unskilled worker with little training. On the other hand, forty years ago the use of a mechanically controlled drilling machine required a substantial level of training and skill. As a result, the modern drilling machine is more user-friendly even though it is technologically more sophisticated and complex.[6]

As we argue in the introduction, there are historical examples of technological change that include both increased and decreased requirements of human capital (see Goldin and Katz (1996)). And more recently, particularly with the increased use of microprocessors, technology-skill complementarity appears to be a dominant feature of technological change (see Autor, Katz and Krueger (1997)). This is also supported by the fact that companies with higher Information Technology capital stocks train larger fractions of their staff (see Brynjolfsson and Hitt (1998)). Evidently, modern technologies require a better educated and better trained labor force.

3.1 Model

We use a one-dimensional measure of education and training that we call "schooling". Schooling uses up time that could be devoted to work. It takes place on the job or outside it. In any event the cost of schooling is forgone income.

We denote by $\Pi_i(e, s)$ the productivity of a person working with technology i

[6] However, the modern machine needs to be programmed, and programming can be done only by workers with substantial education and training. It is therefore not clear that "operation" of a modern machine of this sort requires less training when programming is included in the definition of work. Our theory does not allow for multiple tasks, some of which may be more skill-intensive, and others less skill-intensive, in the new technology.

who has s years of schooling and e years of experience working with this technology. Experience and schooling interact in a rather simple way. Every technology i requires its own minimum level of schooling s_i. A worker who does not have this level of schooling is not able to work the technology and therefore has zero productivity. On the other hand, a person who has at least s_i years of schooling can operate this technology and gain productivity with experience. Therefore

$$\Pi_i(e, s) = \begin{cases} 0 & \text{if} \quad s < s_i \\ \pi_i(e) & \text{if} \quad s \geq s_i \end{cases}, \quad \text{for } i = o, n;$$

where the productivity functions $\pi_i(\cdot)$ have the same interpretation as in the previous section. When $s_n > s_o$ there is technology-skill complementarity. When $s_n < s_o$ there is technology-skill substitutability. Note that this formulation is a straightforward generalization of the previous model.[7]

To incorporate the schooling requirements we need to generalize our assumptions about the productivity functions as follows:

Assumption 1a: $\pi_i(e)$ is nondecreasing and differentiable for $i = o, n$.

Assumption 2a: Experience with one technology does not affect productivity with another technology.

Assumption 3a: The new technology is more productive over a worker's lifetime; i.e., $\int_o^{\delta-s_o} \pi_o(x)dx < \int_o^{\delta-s_n} \pi_n(x)dx$.

The first two assumptions are exactly as before; we reproduce them for convenience. Assumption 3a states that a young worker that has little experience with the

[7] In the case of technology-skill complementarity and an unanticipated arrival of the new technology, this specification of the productivity function implies the same adjustment pattern as in the previous section whenever inexperienced workers produce no output with the new technology for very low experience levels. It is nevertheless useful to proceed with the current specification in order to highlight the entry effect described below. The two specifications are quite distinct, however, when workers anticipate the arrival of the new technology, with certainty or uncertainty. The reason is that schooling can be acquired before the arrival of the new technology while technology-specific experience cannot.

old technology is more productive over his lifetime if he switches to the new sector. Note that given the schooling requirement, now an agent who operates technology i works only $\delta - s_i$ years.

Assumption 4a: $\pi_o(\delta - s_o) > \pi_n(0)$.

Assumption 4a states that switching to the new technology is not profitable for workers with the largest experience because they suffer a severe loss of human capital. The largest possible experience with the old technology is $\delta - s_o$. As before, it follows from Assumptions 3a and 4a that some younger workers find it profitable to switch to the new technology while some older workers prefer to stay with the old one.[8]

Assumption 5a: There is a unique level of experience $e \in (0, \delta - s_o)$ at which $\int_e^{\delta - s_o} \pi_o(x)dx = \int_e^{\delta - s_n} \pi_n(x-e)dx$ when $s_n > s_o$, or $\int_e^{\delta - s_o} \pi_o(x)dx = \int_e^{\delta - s_o} \pi_n(x-e)dx$ when $s_n < s_o$. This level of experience is denoted by $\bar{e}$.

Assumption 6a: Schooling can be acquired in doses at different points in time, and the same schooling applies to new and old technologies.

Assumption 5a ensures that all workers with experience lower than $\bar{e}$ switch to the new sector while all more experienced workers do not. As before, Assumption 5a merely guarantees the uniqueness of $\bar{e}$; its existence follows from Assumptions 3a and 4a. Assumption 6a ensures that skills can be upgraded whenever a new technology arrives. And moreover, there is no loss of skills acquired through schooling when a person switches from an old to a new technology.

Unlike experience, education and training are transferable across technologies. Namely, a person that has s_o years of schooling that enable him to work in the old sector needs to acquire only $s_n - s_o$ additional years of schooling in order to operate the new technology, provided $s_n > s_o$. In this formulation schooling is not technology specific while experience is. We make this sharp distinction between experience and education in order to simplify the analysis. The important feature is that experience

[8]When the new technology requires more schooling than the old, elderly workers may prefer to remain in the old sector even when Assumption 4a is not satisfied.

is less transferable across technologies than education and training. Learning how to read and add up numbers is useful for all technologies. Becoming skilled in using a mechanical drill, however, may be only partly useful in operating a computer-driven machine.

Consider the incentives of the marginal worker $\bar{e}$, who has $\bar{e}$ years of experience in the old sector. He earns $\int_{\bar{e}}^{\delta-s_o} \pi_o(x)dx$ in the remaining part of his life if he continues to work with the old technology. If he switches to a new technology that requires more education and training he needs to complete $s_n - s_o$ additional years of schooling before starting to work with it. In this event his remaining lifetime income is $\int_{\bar{e}}^{\delta-s_n} \pi_n(x - \bar{e})dx$. Assumption 5a states that the marginal worker $\bar{e}$ is indifferent between staying in the old sector and switching to the new one. Clearly, every older worker is better off staying in the old sector and younger workers are better off switching. On the other hand, if $\bar{e}$ switches to a new technology that does not require more schooling, this worker's remaining lifetime income is $\int_{\bar{e}}^{\delta-s_o} \pi_n(x - \bar{e})dx$. In the case of technology-skill substitutability not only does the worker have enough schooling to operate the new technology, he is in fact overeducated for the job. We therefore have the following variant of Lemma 1:

LEMMA 1a *There exists a unique value of experience, $\bar{e} \in (0, \delta - s_o)$, such that at $t = 0$ all workers with experience $e \in [0, \bar{e}]$ switch to the new technology and all workers with experience $e \in (\bar{e}, \delta]$ continue to work with the old one.*

Note that the assumptions in the previous section are a special case in which $s_o = s_n = 0$. Naturally, Assumption 6a is irrelevant in the absence of schooling requirements.

We now proceed to discuss the response of aggregate output to the arrival of a new technology, both on impact and during the transition to the new steady state. The discussion proceeds in two parts. First, we study the case in which the new technology requires more schooling. Second, the case in which it requires less.

3.2 Technology-skill complementarity

Let the new technology require more education and training; i.e., $s_n > s_o$. As we discussed in the introduction to this section, this seems to be the relevant case for the technological developments of recent decades.

A major difference between this model of technology-skill complementarity and the model without education lies in the need to upgrade skills. Now workers who switch to the new technology cannot start producing until they complete $\sigma = s_n - s_o > 0$ additional years of schooling. In view of our broad interpretation of schooling, these additional years may consist of education outside the workplace or on-the-job training. In either case these workers temporarily drop out of production. Thus, the adjustment to a new technology is complicated by changes in the size of the effective labor force. We refer to this as the negative *entry effect.* This effect is absent in the model without education and training.

There are both temporary and permanent negative entry effects. The temporary effect is caused by the mass of workers who switch at time 0 to the new technology. This temporary effect disappears as soon as they have acquired the additional σ units of schooling. The permanent effect arises because in the new steady state every individual takes more schooling, which in turn decreases permanently the size of the effective labor force. However, by Assumption 3a, this smaller labor force produces a larger output.

Prior to the arrival of the new technology agents left school after s_o years of schooling. As before, by Assumption 3a, every generation born after time 0 adopts the new technology. But so does every worker born after $t = -s_o$. Workers that are in school at the time the new technology arrives simply stay in school longer. This implies that the transition to the new steady state is completed at $t = \delta - s_o$. At this time every individual who joined the labor force in the old sector has departed. Aggregate output increases from $\int_o^{\delta-s_o} \pi_o(x)dx$, just before time 0, to $\int_o^{\delta-s_n} \pi_n(x)dx$ at the end of the transition.

The transition path can be divided into three phases. Phase 1 lasts until time σ. During this phase the only agents that contribute to output are workers who stay with the old technology; all the other individuals are in school. Furthermore, the size of the labor force keeps shrinking because elderly workers operating the old technology are dying and the workers that will operate the new one do not complete their education during Phase 1. Therefore, aggregate output equals $\int_{\bar{e}+t}^{\delta-s_o} \pi_o(x)dx$ for all $t \in [0, \sigma)$.

Phase 2 spans the interval $t \in [\sigma, \delta - s_o - \bar{e})$. This phase lasts until time $\delta - s_o - \bar{e}$ when the last worker using the old technology departs. Output is produced by three different types of workers. First, there is the mass $\bar{e}$ of individuals who switched sectors at time 0. At time t their contribution to output is $\bar{e}\pi_n(t - \sigma)$, where $t - \sigma$ is the experience that they have accumulated with the new technology. Second, there are workers in the old sector. Their output is, as before, $\int_{\bar{e}+t}^{\delta-s_o} \pi_o(x)dx$. Finally, there is the group of new entrants to the labor force who after time σ have completed s_n years of schooling. This group contributes $\int_0^{t-\sigma} \pi_n(x)dx$. Therefore, during this phase aggregate output is $\int_{\bar{e}+t}^{\delta-s_o} \pi_o(x)dx + \bar{e}\pi_n(t - \sigma) + \int_0^{t-\sigma} \pi_n(x)dx$.

At the end of Phase 2 no one operates the old technology and those who switched at time 0 are at the upper end of the age distribution. At this point the economy enters the last phase of the transition which spans the time interval $[\delta - s_o - \bar{e}, \delta - s_o]$. In Phase 3 aggregate output is $(\delta - s_o - t)\, \pi_n(t - \sigma) + \int_0^{t-\sigma} \pi_n(x)dx$. The first term represents the contribution of those who switched at time 0. Note that some members of this group have died at time t and $\delta - s_o - t$ denotes the mass of survivors. The second term is the contribution of those who joined the labor force after the appearance of the new technology.

Putting these pieces together, output is given by

$$Y(t) = \begin{cases} \int_{\bar{e}+t}^{\delta-s_o} \pi_o(x)dx & \text{for} \quad t \in [0, \sigma) \\ \int_{\bar{e}+t}^{\delta-s_o} \pi_o(x)dx + \bar{e}\pi_n(t - \sigma) + \int_0^{t-\sigma} \pi_n(x)dx & \text{for} \quad t \in [\sigma, \delta - s_o - \bar{e}) \\ (\delta - s_o - t)\, \pi_n(t - \sigma) + \int_0^{t-\sigma} \pi_n(x)dx & \text{for} \quad t \in [\delta - s_o - \bar{e}, \delta - s_o] \end{cases} . \tag{7}$$

We can use (7) to examine the response of output to the arrival of the new technology. Before time 0 every worker uses the old technology. When the new technology arrives a fraction of workers go into training, to upgrade their skills. Aggregate output declines as a result, because the effective labor force shrinks on impact. This is a manifestation of the negative entry effect.

The negative entry effect produces an additional discontinuity at time σ. At this point the mass of workers $\bar{e}$ that changed sectors at time 0 has accumulated enough education and training and is ready to rejoin the labor force. If $\pi_n(0) > 0$ this entry effect produces a boom at the beginning of Phase 2. Clearly, there is no upward jump in aggregate output if $\pi_n(0) = 0$; i.e., when the productivity of inexperienced workers operating the new technology is negligible. We have thus established the following result

PROPOSITION 3: *When the new technology requires more schooling (i.e., $s_n > s_o$) aggregate output drops on impact with the arrival of the new technology. Furthermore, when $\pi_n(0) > 0$ output jumps upwards at the beginning of Phase 2.*

In the absence of schooling an initial fall in aggregate output was a possibility, but not a necessity. With technology-skill complementarity the fall in output is inevitable. Larger educational requirements produce a negative entry effect and thereby a fall in output.

Now we characterize the rest of the adjustment path. For this purpose we calculate marginal changes in output during the transition. Differentiating (7) yields

$$Y'(t) = \begin{cases} -\pi_o(\bar{e}+t) & \text{for} \quad t \in [0,\sigma) \\ -\pi_o(\bar{e}+t) + \bar{e}\pi_n'(t-\sigma) + \pi_n(t-\sigma) & \text{for} \quad t \in [\sigma, \delta - s_o - \bar{e}) \\ (\delta - s_o - t)\,\pi_n'(t-\sigma) & \text{for} \quad t \in [\delta - s_o - \bar{e}, \delta - s_o] \end{cases} \quad . \quad (8)$$

It is useful to compare (7) and (8) with the equations that characterize the transition in the case of no schooling (equations (5) and (6)). The current Phase 3 is analogous to the previous Phase 2. During this last part of the transition the old technology is no longer used, but the new steady state has not been reached because some of the workers that changed sectors at time 0 are still alive. Clearly, output increases in this phase as long as productivity increases with experience.

The current Phase 2 is similar to the first phase in the case of no schooling requirements. In both cases output is produced by three groups of workers: those operating the old technology, those who switched sectors at time 0, and those who never worked in the old sector. The contribution to aggregate output of the first group decreases with time due to the departure of some of its members and the aging of the others. On the other hand, the contribution of the two groups using the new technology increases with time because they accumulate experience with it. As shown in the previous section, the balance of these changes can go either way, depending on the functional forms of the productivity functions. Output increases in this phase as long as $\bar{e}\pi_n'(t-\sigma) + \pi_n(t-\sigma) > \pi_o(\bar{e}+t)$.

The main difference between the two transition paths is that the current Phase 1 does not exist in the absence of schooling requirements. The existence of this phase is due to entry effects that do not arise in the previous model. The effective size of the labor force decreases continuously during this phase. Furthermore, the marginal loss in output increases with time. This marginal loss is due to the death of middle-aged workers who use the old technology. The more experienced these workers, the larger their productivity and the larger the loss of output. Therefore, since the entry effect worsens during Phase 1, output decreases at ever increasing rates until time σ. We have thus established the following:

PROPOSITION 4: *When the new technology requires more schooling (i.e., $s_n > s_o$) output declines in Phase 1 at ever increasing rates, rises in Phase 3 as long as productivity increases with experience in the new technology, and rises in Phase 2 if and only if $\pi_n(t-\sigma) + \bar{e}\pi_n'(t-\sigma) > \pi_o(\bar{e}+t)$.*

The last two propositions show that the arrival of a new technology that has higher schooling requirements necessarily produces a cyclical response of aggregate output. Output drops on impact and continues to decline at ever increasing rates during Phase 1. Therefore a recession is bound to happen at the beginning of the adjustment process. Then, in the transition from Phase 1 to 2, output jumps up and then either declines further before it starts rising or rises continuously throughout Phase 2. After the last worker using the old technology departs, output continues to rise until it reaches the new higher steady-state level.

3.3 Technology-skill substitutability

Next let the new technology require less schooling; i.e., $s_n < s_o$. The main difference between this and the case of technology-skill complementarity is that now agents that change sectors do not need to acquire additional education and training. In fact, they are overeducated for the operation of the new technology. This implies that the negative entry effect is absent. Furthermore, students that have completed enough education to operate the new technology, but not enough to operate the old one, can leave school earlier. This increases the labor force at time 0 thereby producing a positive entry effect. Note that there is also a permanent entry effect. This permanent effect arises because, with the new technology, agents spend less time in school and more time working. As a result the effective labor force is larger in the new steady state.

In the previous case the negative entry effect was responsible for an initial recession, both on impact and during the first phase of the transition. Therefore, one might expect that, given a positive entry effect, the reverse will be true for the case of technology-skill substitutability. However, this need not be the case. The adjustment process to a new technology that has a lower schooling requirement may also start with a recession.

In order to see why we study the adjustment process. The transition has only two phases: Phase 1 in which the old technology is used, and Phase 2 in which it is not. Phase 1 spans the interval $t \in [0, \delta - s_o - \bar{e})$. During this phase four groups contribute to output: workers in the old sector who remained there; new workers who joined the labor force after time 0; young workers who switched sectors; and students who left school at time 0. Note that the mass of agents leaving school at time 0 is $\eta = s_o - s_n > 0$. Thus, at time t the contribution of the last two groups is $(\bar{e} + \eta)\,\pi_n(t)$. The contributions of the other two groups are similar to the previous cases. Therefore during Phase 1 aggregate output is $\int_{\bar{e}+t}^{\delta-s_o} \pi_o(x)dx + (\bar{e} + \eta)\,\pi_n(t) + \int_0^t \pi_n(x)dx$.

Phase 2 starts after the last worker using the old technology departs. It ends at time $\delta - s_n$ with the death of the last student that left school at time 0. During this phase those who switched at time 0 produce $(\delta + \eta - s_o - t)\,\pi_n(t)$ units of output while the new entrants to the labor force produce $\int_0^t \pi_n(x)dx$ units. As a result aggregate output equals $(\delta + \eta - s_o - t)\,\pi_n(t) + \int_0^t \pi_n(x)dx$ in Phase 2. It follows that during the transition output is given by

$$Y(t) = \begin{cases} \int_{\bar{e}+t}^{\delta-s_o} \pi_o(x)dx + (\bar{e}+\eta)\,\pi_n(t) + \int_0^t \pi_n(x)dx & \text{for} \quad t \in [0, \delta - s_o - \bar{e}) \\ (\delta + \eta - s_o - t)\,\pi_n(t) + \int_0^t \pi_n(x)dx & \text{for} \quad t \in [\delta - s_o - \bar{e}, \delta - s_n] \end{cases}, \tag{9}$$

and marginal output equals

$$Y'(t) = \begin{cases} -\pi_o(\bar{e}+t) + (\bar{e}+\eta)\,\pi_n'(\bar{e}+t) + \pi_n(t) & \text{for} \quad t \in [0, \delta - s_o - \bar{e}) \\ (\delta + \eta - s_o - t)\,\pi_n'(t) & \text{for} \quad t \in [\delta - s_o - \bar{e}, \delta - s_n] \end{cases}. \tag{10}$$

Just prior to the arrival of the new technology output equals $\int_0^{\delta-s_o} \pi_o(x)dx$, and it jumps to $\int_{\bar{e}}^{\delta-s_o} \pi_o(x)dx + (\bar{e}+\eta)\,\pi_n(0)$ at time 0 (see (9)). Therefore output rises on impact if and only if

$$\phi_s(\bar{e}) = (\bar{e}+\eta)\,\pi_n(0) + \int_{\bar{e}}^{\delta-s_o} \pi_o(x)dx - \int_0^{\delta-s_o} \pi_o(x)dx$$

is positive. Note that although $\phi_s(\cdot)$ is similar to $\phi(\cdot)$ (see (1)), there are two differences. First, there is the entry effect. Now a mass η of students leave school and joint the labor force upon the arrival of the new technology. Second, the working lifetime on the old technology is shortened to $\delta - s_o$ due to the schooling requirement.[9] When $\eta = s_o = 0$ the functions $\phi_s(\cdot)$ and $\phi(\cdot)$ are identical and therefore the analysis in the previous section can be used to show that $\phi_s(\bar{e})$ can also be either positive or negative. As a result, in the case of technology-skill substitutability, output can rise or decline on impact.

[9] This equation can be rewritten as

$$\phi_s(\bar{e}) = (\bar{e}+\eta)\,\pi_n(0) - \int_0^{\bar{e}} \pi_o(x)dx.$$

Thus, at first glance it may seem that it is independent of the length of the schooling requirement. However, this is deceiving because the cutoff experience level $\bar{e}$ depends directly on s_o (but not on s_n).

Note that

$$\phi_s(0) = \eta\pi_n(0);$$
$$\phi_s'(e) = \pi_n(0) - \pi_o(e);$$
$$\phi_s''(e) \leq 0.$$

In the model without education $\pi_n(0) < \pi_o(0)$ was a sufficient condition for a decline in output on impact. Clearly, this condition is not sufficient now. The difference is the entry effect. However, $\pi_n(0) < \pi_o(0)$ is a sufficient condition for an output drop on impact whenever one of the following two conditions holds: (1) The mass of students leaving school at time 0 to join the labor force is small; i.e., s_n is very close to s_o; or (2) An inexperienced worker's productivity is low in the new sector; i.e., $\pi_n(0) \approx 0$. Evidently, $\eta\pi_n(0) = 0$ and $\pi_n(0) < \pi_o(0)$ is sufficient for output to decline on impact.[10] Output can also rise on impact. In fact, due to the entry effect, it is more likely to rise in this case than in the absence of schooling requirements. We therefore have

PROPOSITION 5: *The arrival of a new technology that requires less schooling (i.e., $s_n < s_o$) may increase or decrease aggregate output on impact.*

The intuition behind this result is based on the insights developed in the previous section. In the case of decreased schooling requirements two main forces affect aggregate output at the beginning of the adjustment process: first, the entry effect that tends to increase output; second, a switching effect that may increase or reduce output. For example, when the new technology's learning curve is very steep, many experienced workers leave the old sector at time 0, even if they become temporarily less productive. When the mass of experienced workers changing sectors is large enough, this negative switching effect dominates the positive entry effect.

Now we characterize the rest of the transition path. This analysis is also similar to the case of no schooling requirements. Equation (10) implies

[10] Please note that this is a generalization of the sufficient condition in part (i) of Proposition 1, because there $\eta = 0$.

PROPOSITION 6: *When the new technology requires less schooling (i.e., $s_n < s_o$) output rises in Phase 2 as long as experience leads to productivity gains and output rises in Phase 1 if and only if* $(\bar{e} + \eta)\, \pi_n'(\bar{e} + t) + \pi_n(t) > \pi_o(\bar{e} + t)$.

It follows from the last two propositions that technology-skill substitutability can lead to an adjustment path with rising output as well as to a cyclical adjustment pattern. The cycle starts with a recession and ends with an expansion.

It is useful to end this section with a comparison of how schooling requirements affect the adjustment path. We have seen that technology-skill complementarity leads to a cyclical adjustment process that starts with a recession and ends with an expansion. The initial recession is driven by the negative entry effect that reduces temporarily the effective size of the labor force and prolongs the training of new generations. In the new steady state the economy attains a higher level of output. However, due to the cyclical adjustment path it may take a long time for output to return to its original level. Also note that the greater educational requirements produce a time lag between the arrival of the new technology and its implementation.

By contrast, under technology-skill substitutability no additional schooling is required. As a result the working population is overeducated for the new jobs. This produces a positive entry effect. Students that have accumulated enough skills to operate the new technology, but not enough to operate the old one, can leave school immediately and join the labor force, thereby generating a one-time productivity gain. However, this positive entry effect is not enough to avoid a cyclical adjustment pattern. A destruction of human capital occurs because the experience acquired with the old technology by workers who switch to the new one is no longer useful. If this effect is small a recession is avoided. But this effect is large when inexperienced workers are not very productive with the new technology. In this event a recession follows the arrival of the new technology, just as in the case of technology-skill complementarity.

4 Anticipated Technological Change

In the previous sections we disregarded decisions that can be made in anticipation of the arrival of a new technology, such as the possibility that an agent can accumulate additional schooling in his youth if he expects a more demanding yet more productive technology to arrive during his lifetime. We study the affects of such expectations below.

Absent schooling requirements, expectations of the arrival of a new technology have no effect, because in this case a worker's productivity depends only on his experience. Since agents cannot accumulate experience with the new technology until it arrives, there are no decisions to be made in advance. As a result, individuals work with the old technology as long as no new one is available, regardless of whether technological change is expected. As before, when the new technology arrives they decide whether to switch sectors.

By contrast, anticipation matters when education and training affect productivity in the new sector, because individuals have the option to adjust their schooling before the arrival of the new technology. In this section we study the conditions under which agents optimally choose schooling in advance and the impact it has on the adjustment path. We divide the discussion into two cases: (1) Fully anticipated technological change, in which the precise date of arrival of the new technology is known in advance; and (2) Imperfectly anticipated technological change, in which the arrival follows a Poisson process. In both cases the characteristics of the new technology are known.

We show that our main results are robust to the introduction of these types of expectations. In the case of technology-skill substitutability little changes. In the case of technology-skill complementarity the exact form of the transition path can change, but output follows a cycle that starts with a recession and ends with a boom. Importantly, now the recession starts before the arrival of the new technology.

4.1 Fully Anticipated Technological Change

In this case both the exact date and the form of the new technology are known in advance. The economy is initially in a steady state in which every worker uses the old technology. At time $-T$ everyone learns that at time 0 a new technology $\pi_n(.)$ satisfying Assumptions 1a-6a will become available. To simplify the discussion we assume that T is large. This rules out situations in which the adjustment path depends on the lead time T.[11]

We first consider the case of technology-skill complementarity. Recall that $\sigma = s_n - s_o$ represents the additional level of education and training that agents need in order to operate the new technology.

How do different generations react to the time $-T$ information that a new technology will be available at time 0? First, all newborns after $-s_n$ can avoid working in the old sector. These generations remain in school until age s_n and then work with the new technology throughout their lives. This is in contrast to the case of no anticipation where everyone born before $-s_o$ joined the labor force in the old sector. Also note that generations born early enough cannot react usefully to the news because, by the time the new technology arrives, they are too old.

To characterize the entire transition path we need to consider two separate cases. In Case 1 $\bar{e} \leq \sigma$ while in Case 2 $\bar{e} > \sigma$. In Case 1 full anticipation changes not only the timing of the switch to the new sector, but also the group that switches. In Case 2 only the timing is affected.

First consider Case 1. Now $\bar{e}$ denotes the maximum level of experience with the old technology at which a worker finds it profitable to change sectors, given that he has not accumulated additional schooling. In the model without anticipation, generations born before time $-(s_o + \bar{e})$ operate the old technology throughout their lives, generations born between $-(s_o + \bar{e})$ and $-s_o$ join the labor force with the old technology but change sectors at time 0, and generations born afterwards always work with the new technology. But now every generation born after $-s_n$ only works with

[11] As the reader will see below, the extension of the analysis to the case of T small is straightforward. Furthermore, the key characteristics of the transition path would remain unchanged.

the new technology. Thus, in contrast to the case of no anticipation, generations born in the interval $(-s_n, -s_o - \bar{e})$ always work with the new technology. And as a result, an additional mass of $\sigma - \bar{e}$ workers switches sectors during the transition.

Note that the time it takes to complete the transition to the new steady state has been shortened to $\delta - s_n$. The transition is composed of three phases. In Phase 1, which spans the interval $t \in [-T, -\sigma)$, no changes occur and thus output remains at the old steady-state level. Although generations born later in this phase never operate the old technology, output is not affected because, even without any change in circumstances, these workers would not have entered the labor force until time $-\sigma$. Changes start occurring in Phase 2. Output decreases in the interval $[-\sigma, 0)$, because every worker born after time $-s_n$ stays longer in school and thus the labor force is shrinking in the time interval $[-\sigma, 0)$. Output equals $\int_{t+\sigma}^{\delta-s_o} \pi_o(x)dx$ during this phase, where $t + \sigma$ is the minimum level of experience in the labor force at time t. Phase 3 starts with the arrival of the new technology and lasts until time $\delta - s_n$. In this phase two groups of workers contribute to aggregate output: $\int_0^t \pi_n(x)dx$ units are produces by those who have accumulated enough schooling to operate the new technology and $\int_{t+\sigma}^{\delta-s_o} \pi_o(x)dx$ units are produced by those who still operate the old technology. Naturally, the size of the first group increases with time while the size of the second group declines. As a result, during the transition in Case 1 aggregate output is given by

$$Y(t) = \begin{cases} \int_0^{\delta-s_o} \pi_o(x)dx & \text{for} \quad t \in [-T, -\sigma) \\ \int_{t+\sigma}^{\delta-s_o} \pi_o(x)dx & \text{for} \quad t \in [-\sigma, 0) \\ \int_{t+\sigma}^{\delta-s_o} \pi_o(x)dx + \int_0^t \pi_n(x)dx & \text{for} \quad t \in [0, \delta - s_n] \end{cases} . \tag{11}$$

Equation (11) shows the effects of anticipation. First note that the adjustment process is cyclical. There is a negative entry effect similar to the effect that generates a recession in the initial stages of transition in the model without anticipation. Furthermore, as Case 1 reveals, anticipation can exacerbate this effect. Also note that in this case no one switches to the new technology at time zero.[12] Moreover, the recovery need not start at time 0, when the first workers start operating the new

[12] As we show below, it is different in Case 2.

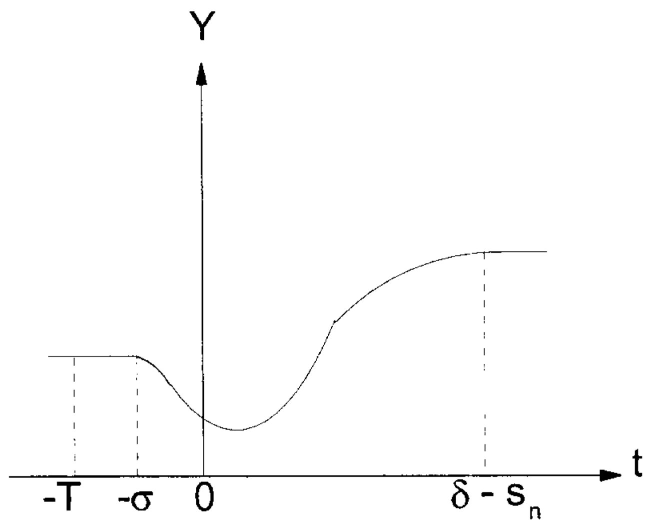

Figure 6: Path of adjustment to anticipated technological change

technology. If the new technology is not productive at low levels of experience (i.e., if $\pi_n(0) < \pi_o(\sigma)$) the recession continues in the initial stages of Phase 3. As a result the adjustment pattern of this economy is very similar to the one that arises without anticipation: an initial recession followed by a boom. The main difference is that the downturn starts before the arrival of the new technology and ends sooner than before. A typical trajectory is depicted in Figure 6.

Now consider Case 2 (i.e., $\bar{e} > \sigma$). As in the previous case, everyone born after time $-s_n$ works in the new sector only. Things are not so simple for those born between $-(s_o + \bar{e})$ and $-s_n$. These workers are born too early to avoid the old technology; they work in the old sector for a while and switch to the new one at time 0. But they need to choose whether to get all their schooling at the beginning of their lives or in two doses as before. They are in fact indifferent between these options, as long as the future is not discounted. However, a slight discount of the future makes them choose schooling in two doses. For this reason we assume that they do indeed complete the extra schooling when the new technology arrives. Finally, every worker born before $-(s_o + \bar{e})$ works only in the old sector.

Under these circumstances the transition consists of five phases, as described by the following equation:

$$Y(t) = \begin{cases} \int_0^{\delta - s_o} \pi_o(x)dx & \text{for} \quad t \in [-T, -\sigma) \\ \int_{t+\sigma}^{\delta - s_o} \pi_o(x)dx & \text{for} \quad t \in [-\sigma, 0) \\ \int_{t+\bar{e}}^{\delta - s_o} \pi_o(x)dx + \int_0^t \pi_n(x)dx & \text{for} \quad t \in [0, \sigma) \\ \int_{t+\bar{e}}^{\delta - s_o} \pi_o(x)dx + (\bar{e} - \sigma)\pi_n(t - \sigma) + \int_0^t \pi_n(x)dx & \text{for} \quad t \in [\sigma, \delta - s_o - \bar{e}) \\ (\delta - s_n - t)\pi_n(t - \sigma) + \int_0^t \pi_n(x)dx & \text{for} \quad t \in [\delta - s_o - \bar{e}, \delta - s_n] \end{cases}, \tag{12}$$

where the cutoff point $\bar{e}$ is implicitly defined by

$$\int_0^{\bar{e}} \pi_o(x)dx + \int_0^{\delta - s_n - \bar{e}} \pi_n(x)dx = \int_0^{\delta - s_o} \pi_o(x)dx.$$

In the last equation the left-hand side describes lifetime income of a person who switches to the new technology after accumulating $\bar{e}$ years of experience with the old one, while the right-hand side describes lifetime income of a person who does not switch. A person with experience $\bar{e}$ is therefore just indifferent between the two options.

It is evident from (12) that output is constant in the time interval $[-T, -\sigma)$, which represents the first phase, and that it declines in Phase 2 (the time interval $[-\sigma, 0)$). The reason output declines in the second phase is that youngsters stay longer in school and therefore the labor force is shrinking. At time zero, when the new technology becomes available, output decreases on impact due to the negative entry effect; a mass of workers $\bar{e} - \sigma$ temporarily leaves the labor force in order to acquire additional schooling. Furthermore, output may continue to decrease in Phase 3 if the new technology is not productive enough at low levels of experience (i.e., $\pi_n(0)$ is small). At the beggining of Phase 4 there is a positive entry effect. Finally, output increases during the last phase, which starts after the departure of the last worker who always operated in the old sector.

Our discussion is summarized in

PROPOSITION 7: *In the case of technology-skill complementarity, anticipation of the date of arrival of the new technology produces a cyclical adjustment path similar to the case of no anticipation: it starts with a recession followed by a* *boom. The main difference is that the adjustment process (and therefore the recession) starts before the arrival of the new technology.*

Now consider the case of technology-skill substitutability, for which the analysis is much simpler. In this case workers cannot successfully adjust schooling decisions. A worker born before time $-s_o$ remains in school for s_o units of time and, upon completion of his studies, joins the labor force in the old sector. At time 0, when the new technology arrives, he decides whether or not to switch to the new sector. Also, every worker born after time $-s_n$ leaves school upon completion of s_n years of training and works all his life in the new sector. Thus, these two groups behave exactly as in the case of no anticipation.

The only workers for whom anticipation is relevant are those born in the time interval $(-s_o, -s_n)$. They face two choices: stay in school until time 0, even though they know that they will never use the additional education, or complete s_n years of schooling and wait until time 0 to join the labor force when the new technology arrives. Regardless of what they do, however, aggregate output is not affected before time 0, because even without anticipating the arrival of the new technology they do not join the labor force until that time. As a result, the adjustment process is exactly as in the case of no anticipation. We have thus established

PROPOSITION 8: *In the case of technology-skill substitutability the adjustment path with accurate anticipation of the date of arrival of the new technology is identical to the adjustment path with no anticipation.*

4.2 Imperfectly Anticipated Technological Change

Finally consider expectations that a new technology will arrive, this time with uncertainty about the arrival date. As before, however, the characteristics of the new technology are known in advance. The economy is initially in a steady state in which every worker uses the old technology. At time 0 the form of the new technology $\pi_n(.)$ and the nature of the stochastic arrival process are revealed. The arrival process is Poisson with an arrival rate $\lambda > 0$. The cumulative distribution function is $F(t) = 1 - e^{-\lambda t}$, and $f(t) = \lambda e^{-\lambda t}$ is the density function.

A nice feature of this process is that it is memoryless. Let $F_\tau(t)$ denote the conditional cumulative distribution function faced by generation $\tau \geq 0$. Then $F_\tau(t) = 1 - e^{-\lambda(t-\tau)}$ for all $t \geq \tau$. Therefore the probability that the new technology arrives in the first x years of a person's life is the same for every generation, as long as the technology has not arrived before its birth. As a result, every generation born before the arrival of the new technology faces the same decision problem.

In the case of technology-skill substitutability (i.e., $s_n < s_o$) the analysis is straightforward and independent of the exact nature of the arrival process. Every agent stays in school at least for s_n units of time. At this point the agent joins the labor force if the new technology has arrived or continues his education if it has not. The first part of this conditional decision follows directly from the fact that the new technology is more productive (Assumption 3a). The second part is slightly more complicated. The agent has two choices when the new technology has not arrived: stay in school a bit longer or wait in the hope that the technology will arrive in the next instant. Since the only cost of schooling is forgone wages, the agent is better off attending school because this prepares him to operate the old technology. In fact, the agent's optimal strategy is to accumulate s_o units of schooling as long as the new technology has not arrived and then join the labor force in the old sector. Thus, we get

PROPOSITION 9: *For the case of technology-skill substitutability knowledge of the new technology's stochastic arrival process does not change the economy's adjustment path.*

The case of technology-skill complementarity is significantly more complicated. The complication arises because now agents can profit from acquiring additional education before joining the labor force in the old sector. Consider, as an extreme example, the decision problem of a generation that believes the new technology is very likely to arrive early on in its lifetimes (i.e., λ is very large). These individuals are better off accumulating the additional $\sigma = s_n - s_o$ years of schooling early on in their lives instead of waiting for the arrival of the new technology, because they can reap almost all the productivity gains of the technological innovation. More generally, the degree to which agents acquire extra schooling depends on the arrival rate λ. We therefore need to analyze the decision problem of an agent in this stochastic environment. Since every cohort faces the same decision problem as long as the new technology has not arrived, we describe in detail the decision problem of the generation born at time 0. This simplifies the notation without any loss of generality.

Agents of generation 0 stay in school at least until time s_o, because otherwise they cannot operate any technology. If the new technology has arrived at this time they stay in school until s_n and then join the new sector. But, how long should they stay in school if the technology has not arrived? Let σ_o denote the additional schooling that they undertake; i.e., they leave school at time $s_o + \sigma_o$ if the new technology has not arrived by that time. Obviously, it is not in their interest to acquire $\sigma_o > \sigma = s_n - s_o$ years of additional education. Therefore $\sigma_o \in [0, \sigma]$. Note that individuals make a conditional decision at time s_o; they stay in school for σ_o additional years as long as the technology does not arrive before the end of this schooling period. If it arrives before they acquire σ_o additional years of schooling they stay in school until they complete s_n years of schooling overall and join the labor force in the new sector.

Let $V(\sigma_o)$ denote the expected lifetime earnings of an agent that decides to acquire σ_o additional years of schooling. All the possible dates of arrival of the new technology can be divided into three groups: (1) those in which the technology arrives before time $s_o + \sigma_o$ and generation 0 never joins the old sector; (2) those in which the technology arrives after the agent has joined the old sector but in time for him to switch to the new sector when the technology arrives; and (3) those in which the agent always operates the old technology because the new one arrives too late.

Consider the last two types of dates first. In these cases the agent gets σ_o units of additional schooling and then starts accumulating experience with the old technology. Now suppose that the new technology arrives during the worker's lifetime. Should he switch to the new sector? As before, it depends on how much experience he has accumulated with the old technology. Let $\theta(\sigma_o)$ denote the maximum level of experience at which this worker switches sectors. Note that $\theta(0) = \bar{e}$. This cutoff experience-level is given by the following condition

$$\int_{\theta(\sigma_o)}^{\delta-s_o-\sigma_o} \pi_o(x)dx = \int_{\theta(\sigma_o)}^{\delta-s_n} \pi_n\left[x-\theta(\sigma_o)\right]dx = \int_0^{\delta-s_n-\theta(\sigma_o)} \pi_n(x)dx. \qquad (13)$$

We assume that the solution of $\theta(\sigma_o)$ is unique and differentiable[13] for every $\sigma_o \in [0,\sigma]$, by extending assumption 5a as follows:

Assumption 5a: $\theta(\sigma_o)$ is a differentiable function with domain $[0,\sigma]$. It is implicitly defined in (13).

Let $\hat{\Pi}(t,\sigma_o)$ denote lifetime income of an agent who stays in school for $s_o + \sigma_o$ years, when the new technology arrives at time t. This function is given by

$$\hat{\Pi}(t,\sigma_o) = \begin{cases} \int_0^{\delta-s_n} \pi_n(x)dx & \text{if } t \leq s_o+\sigma_o \\ \int_0^{t-s_o-\sigma_o} \pi_o(x)dx + \int_0^{\delta-(t+\sigma-\sigma_o)} \pi_n(x)dx & \text{if } s_o+\sigma_o < t \leq s_o+\sigma_o+\theta(\sigma_o) \\ \int_0^{\delta-s_o-\sigma_o} \pi_o(x)dx & \text{if } t > s_o+\sigma_o+\theta(\sigma_o) \end{cases}.$$

His expected lifetime income is $V(\sigma_o) = \int_0^\infty \hat{\Pi}(t,\sigma_o)f(t)dt$. A person born at time 0 chooses $\sigma_o \geq 0$ to maximize $V(\sigma_o)$.

It is useful to decompose $V(\sigma_o)$ into three events, as described above, and to express it as

$$\begin{aligned} V(\sigma_o) = {} & F(s_o+\sigma_o)\int_0^{\delta-s_n} \pi_n(x)dx \\ & + \left[1 - F(s_o+\sigma_o-\theta(\sigma_o))\right]\int_0^{\delta-s_o-\sigma_o} \pi_o(x)dx \\ & + \int_{s_o+\sigma_o}^{s_o+\sigma_o+\theta(\sigma_o)} \left[\int_0^{t-s_o-\sigma_o} \pi_o(x)dx + \int_0^{\delta-(t+\sigma-\sigma_o)} \pi_n(x)dx\right] f(t)\,dt. \end{aligned}$$

The effects on expected income of increasing σ_o can be seen from this equation. Additional schooling has both positive and negative effects. More schooling increases the likelihood of an agent joining the new sector and reduces the cost of switching to the new technology in case it arrives after he has joined the labor force. But

[13] This assumption reduces somewhat the set of feasible technologies.

more schooling also reduces earnings in the case in which the technology arrives after time $s_o + \sigma_o + \theta(\sigma_o)$, because in this case the agent has a shorter working life with the old technology. Since $V(\sigma_o)$ is differentiable, $V'(\sigma_o)$ is well defined. The general derivative is not particularly revealing, except for providing a decomposition into positive and negative effects. However, it implies that

$$\lim_{\lambda \to 0} V'(\sigma_o) = -\pi_o(\delta - s_o - \sigma_o) < 0.$$

Therefore for small values of λ it is optimal to avoid additional schooling; i.e., $\sigma_o = 0$.

PROPOSITION 10: *In the case of technology-skill complementarity the economy's adjustment path is not affected by the new technology's stochastic arrival process as long as the arrival rate λ is small.*

The intuition behind this result is straightforward. Acquiring additional schooling is beneficial only when it is likely that the new technology arrives early on in an individual's life. Therefore when λ is small the expected date of arrival is large and acquiring extra schooling yields little benefits. Furthermore, the costs of extra schooling are large in this case, because when λ is small the agent will most likely work in the old sector. In this case the cost of an extra year of schooling is one year of forgone wages. And the relevant earnings in the old sector are at the height of the worker's experience.

Whatever the optimal level of additional schooling, when the new technology arrives it triggers an adjustment process that looks very much the same as the process described in the previous section (with no anticipation). All we need to do is to replace s_o with $s_o + \sigma_o$, which represents the actual years of schooling acquired by individuals as long as the new technology does not arrive. Upon its arrival workers who switch from the old to the new sector complete additional $s_n - s_o - \sigma_o$ years of schooling and thereby produce a negative entry effect. The result is an initial recession followed by a boom. The recession can be prolonged by a negative switch effect if productivity in the new sector is initially low and learning is rapid.

5 Conclusion

Major technological changes have macroeconomic effects. A key question is how do economies adjust to such changes and what are their macroeconomic implications. Historical evidence about the steam engine and electricity suggests that adjustments to large-scale technological shocks take dozens of years and that long-run benefits can be preceded by significant short- and medium-run disturbances.[14]

To understand this complex problem we need to study it from a variety of perspectives. Earlier studies considered the roles of diffusion, secondary innovations and learning by firms.[15] By contrast, we have examined the role of two types of human capital embodied in workers: technology-specific experience and general schooling. An important finding of this investigation is that each of them plays a distinct role in the adjustment process and that each can trigger a recession with the arrival of a new technology. Such recessions are driven by what we identified as negative *switch* and *entry* effects; the former associated with experience, the latter with schooling. When combined with previous findings about the roles of diffusion, secondary innovation and learning by firms, one is led to conclude that the arrival of a new major technology unleashes powerful forces that slow output growth.

Importantly, the time dimension of these slowdowns is very different from regular business cycles. While the latter can be detected in high frequency data the former requires low frequency data; cycles driven by technologies of the GPT type require a much longer perspective than is commonly used in macroeconomic analysis. And the widely used Summers-Heston data set is too short for this purpose.

[14]See von Tunzelmann (1978) on the steam engine and Du Boff (1964) and David (1991) on electricity.

[15]See David (1991), Bresnahan and Trajtenberg (1995), Hornstein and Krusell (1996), Greenwood and Yorukolgu (1997), Aghion and Howitt (1998) and Helpman and Trajtenberg (1998a, 1998b). Disorganization mechanisms of the sort studied by Blanchard and Kramer (1997) can also be applied to this adjustment problem.

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