Adjusting to a New Technology: Experience and Training*

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Abstract

How does the economy react to the arrival of a new major technology? The existing literature on General Purpose Technologies (GPTs) has studied the role that mechanisms like secondary innovations, diffusion, and learning by firms play in the adjustment process. By contrast, we focus on a new mechanism, based on the interplay between technological change and two types of human capital: technology-specific experience and education. We show that technological change that requires more education and training, like computerization, necessarily produces an initial slowdown. On the other hand, technological change that lowers the training requirement, like the move from the artisan shop to the factory, can produce either a bust or a boom.

We identify three key properties that determine the outcome: (1) productivity of inexperienced workers; (2) the speed with which experience raises productivity; and (3) the level of general skills required to operate the new technology.

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1 Introduction

The arrival of a new technology triggers many responses. Some are designed to take advantage of new opportunities, such as attempts to use it 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. When the new technology is of major proportions, however, such as a General Purpose Technology (GPT for short), these responses are widespread and diffused across many sectors. As a result, major technological changes can have major macroeconomic effects. David (1991), for example, suggests that the slowdown in productivity growth in US manufacturing in the beginning of the 20th century was triggered by electrification, and that the slowdown in productivity growth in the 1970s might be related to computerization.

The main question that we address in this paper is: How do economies, and in particular macroeconomic variables like aggregate output, respond to the arrival of a new technology? After all, the experiences of the steam engine and electrification suggest that adjustments to large-scale technological shocks can take dozens of years and that long-run benefits can be preceded by significant short and medium-run disturbances. We are particularly interested in understanding the conditions under which technological change produces a cyclical adjustment process, with an initial slowdown in output growth. That is, does the arrival of a new technology necessarily reduce productivity initially? Or does the answer depend on how the new technology differs from the old? And if so, how?

To understand this complex problem we need to study it from a variety of perspectives. A small literature on GPTs has emerged in recent years, examining the channels through which a new technology affects the economy. Secondary innovations, diffusion, and learning by firms, are some of the mechanisms that have been

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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.

investigated. By contrast, here we examine the role of human capital. In particular, we focus on changes that are driven by two types of human capital: technology-specific experience that individuals acquire mostly by working with a technology, and general knowledge that they acquire in education and training.

In the rest of the paper we call these two types of human capital experience and education. Education includes the schooling that takes place outside the labor force and general training in the work place. Thus, the key distinction between education and experience is not whether they are acquired on the job or in school, but whether the skills are transferable across technologies. In practice, some of the experience acquired in the old sector can be useful in operating the new technology. However, this type of human capital is less transferable across technologies than education, which provides more general skills such as literacy and numeracy. To emphasize this distinction we assume that experience is not transferable at all, whereas education provides human capital that applies to all technologies. In short, experience is technology-specific while education is not.

Experience and education are two different types of human capital. Both of them increase the productivity of the labor force, but they operate through different mechanisms. Education increases the set of technologies that a worker can operate, whereas experience increases the productivity of a worker with a given technology. This distinction has not been emphasized in the previous literature and it plays an important role in understanding how the economy reacts to the arrival of a new technology.

We study a simple model in which labor is the only input of production. Wages are determined by labor productivity, which in turn depends on a worker’s experience with the technology and on his education level. However, these two types of

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4Learning 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.
human capital affect productivity in different ways. Experience with a given technology increases productivity with *that* technology. By contrast, there is a minimal educational requirement to operate each technology.

This gives rise to two types of technological change: (1) technology-education complementarity, when the new technology requires more education; and (2) technology-education substitutability, when it requires less. There are historical examples of both types of technological change. Goldin and Katz (1998) argue that the transition from the artisan shop to the factory most likely decreased the overall demand for education – a case of technology-education 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-education complementarity. In more recent decades technology-education 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 (1998) show that industries with greater growth in employee computer usage or with more computers per worker have upgraded faster the skills of their work-force.

In the model the only agents making decisions are workers. Their objective is to maximize lifetime wages. They need to make two decisions: (1) how much to invest in education; and (2) whether to switch sectors when the new technology arrives. We assume that labor productivity depends on individual characteristics and, in particular, that it is independent of the decisions of other agents. This assumption is violated, for example, in the presence of network effects. In our case every worker faces a simple decision problem and macroeconomic behavior is determined by an aggregation of these independent decisions.

The arrival of a new technology produces two effects: a *switch effect* and an *entry*
**effect.** Aggregate output is determined by their interplay.

The switch effect occurs when experienced workers switch to the new sector. A loss of output may occur under these circumstances because experience is not transferable to the new sector. But it need not occur; the switch effect can be positive or negative. It is positive, for example, if the new technology is more productive at all levels of experience. Here every worker changes sectors when the new technology arrives and output increases. By contrast, a negative switch effect can occur when inexperienced workers are less productive with the new technology. Young workers may voluntarily switch – taking a wage cut in the process – in expectation of higher wages in the future, when they will have more experience with the new technology. However, until enough experience has been gained in the new sector the switch can produce a recession.

A key feature of technological change that influences the sign of the switch effect is the speed with which experience raises productivity. When productivity increases significantly faster in the new sector, even workers who are very experienced with the old technology may find it profitable to switch. Their productivity losses can be strong enough to generate experience-driven recessions even when the new technology is more productive at comparable levels of experience.

The entry effect is caused by changes in the educational requirements of workers, and thereby the proportion of individuals who stay out of the labor force. It is negative in the case of technology-education complementarity, because individuals need to acquire more education before operating the new technology. It is important to emphasize that the additional skills can be acquired by going back to school, or on the job, through training. In either case the effective labor force shrinks in the short-run, because switchers stop working temporarily in order to upgrade their skills. As a result, the arrival of a new technology that exhibits technology-education complementarity generates a short-run slowdown.\(^5\)

By contrast, the entry effect is positive in the case of technology-education sub-

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\(^5\)In fact, the effective size of the labor force also shrinks in the long-run, because students stay longer in school. But this effect is outweighed by the long-run increase in average productivity.
stitutability, because individuals can leave school earlier than expected, thereby increasing the labor force. However, this is not enough to guarantee a boom. Aggregate output can decrease if the positive entry effect is accompanied by a sufficiently large negative switch effect. This happens when the speed of learning on the new technology is sufficiently fast or inexperienced workers are less productive in the new sector.

The possibility of a productivity slowdown following the arrival of a new technology has been well documented by economic historians. Evidently, an economy adjusts to a new major technology in a complex way, through many mechanisms. A key question is which of these mechanisms produce slowdowns. In this paper we study one such mechanism, focusing on the interplay between technological change and human capital accumulation. Other mechanisms, such as learning by firms, have been examined by others (see Greenwood and Yorukoglu (1997) and Hornstein and Krusell (1996)). We do not view our mechanism and those studied by others as competing theories, but rather as different pieces of a much larger model of technological change. The fact that different mechanisms yield similar adjustment paths reinforces our understanding of how a process like electrification, or more recently computerization, affects the economy. In addition to suggesting a new mechanism that produces a cyclical adjustment path, we identify features of technological change – such as the productivity of inexperienced workers, the speed of learning, and technology-skill complementarity – that determine whether the arrival of a new technology is followed by a boom or a bust.

The rest of the paper is in four parts. In sections 2 and 3, which contain the main analysis, we deal with the case in which the arrival of the new technology is unanticipated. In section 4 we examine the effects of anticipation. Whereas unanticipated technological change does not allow individuals to acquire schooling that is suitable for the new technology, anticipated technological change allows this sort of adjustment. Section 5 concludes.
2 Experience

As discussed in the introduction, we study the role of experience and education in an economy’s adjustment to the arrival of a new technology. However, in order to understand better the role of experience and to gain intuition, we first develop a special case of the model in which there is no schooling.

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 $\tau$. 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 the initial steady state experience is distributed uniformly among the existing $\delta$ 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 non-decreasing 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., $\int_0^\delta \pi_o(x)dx < \int_0^\delta \pi_n(x)dx$.

**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. Although this assumption is somewhat extreme, what matters for our purposes is not so much that no experience is transferable, but rather that not all experience can be transferred. 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 with little experience will be more productive over his remaining lifetime in the new sector. Thus, the new technology is better in a well defined sense.

Assumption 4 states that switching to the new technology is not profitable for the oldest workers who have accumulated a lot of experience. 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 while some old workers prefer to stay with the old technology.

**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 $\overline{e}$.

The crucial element in this assumption is the uniqueness of $\overline{e}$; its mere existence is guaranteed by Assumptions 3 and 4. Together these assumptions imply:
**Lemma 1:** There exists a unique value of experience, \( \tau \in (0, \delta) \), such that at \( t = 0 \) all workers with experience \( e \in [0, \tau] \) switch to the new technology and all workers with experience \( e \in (\tau, \delta] \) continue to work with the old technology.

### 2.2 Impact

How does the arrival of a new technology affect aggregate output? When a group of workers with experience smaller than \( e \) switches, aggregate output at time 0 becomes \( e\pi_n(0) + \int_e^\delta \pi_o(x) \, dx \).\(^6\) It follows that the change in output is

\[
\phi(e) = e\pi_n(0) + \int_e^\delta \pi_o(x) \, dx - \int_0^\delta \pi_o(x) \, dx,
\]

with the actual change given by \( \phi(\tau) \). The function \( \phi(e) \) has the following properties:

\[
\begin{align*}
\phi(0) &= 0; \\
\phi'(e) &= \pi_n(0) - \pi_o(e); \\
\phi''(e) &\leq 0.
\end{align*}
\]

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 output loss. Evidently, if \( \pi_n(0) < \pi_o(0) \) output drops on impact. On the other hand, it does not follow that output must increase when inexperienced workers are more productive with the new technology. Output can still fall if enough experienced workers change sectors. In this case, the loss in human capital of experienced workers who switch sectors outweighs the productivity gains of the inexperienced group. We refer to this phenomena as the *switch effect*. We thus conclude that when \( \pi_n(0) > \pi_o(0) \) output can increase or decline. The following linear example illustrates the forces at work.

\(^6\)As is customary in the national income accounts, our measure of output does not include the value of experience that workers accumulate.
\[ \pi_i(e) = \alpha_i + \beta_i e \text{ with } \alpha_i, \beta_i > 0 \text{ for } i = o, n. \] (2)

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 \( \pi \) is found at the intersection of a horizontal line at the level \( \alpha_n \) with the \( \pi_o \) line at point A. Before the switch aggregate output equaled the area between 0 and \( \delta \) below the \( \pi_o \) line. After the switch aggregate output equals the area between 0 and \( \pi \) below the horizontal line through A, which represents the output generated with the new technology, plus the area between \( \pi \) and \( \delta \) below the \( \pi_o \) 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.

Now turn to Figure 2, in which all the parameters are the same as in Figure 1 except that \( \beta_n \) has increased. A worker’s willingness to switch sectors depends

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7The productivity functions satisfy Assumptions 1-6 as long as \( 2(\alpha_n - \alpha_o) > \delta (\beta_o - \beta_n) \) and \( \alpha_o + \beta_o \delta > \alpha_n. \)
on how fast productivity increases with experience in the new sector. Thus, the
cutoff level $\bar{e}$ increases with the slope of the $\pi_n$ line. Note that in Figure 2 $\bar{e}$
is to the right of point A. In this case the productivity of the marginal worker
decreases temporarily with the switch. Immediately 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 $\delta$ under the $\pi_o$ 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 $\pi_n$ line is very steep, $\bar{e}$ is large enough to make this difference negative
and aggregate output declines.

The key feature that makes this outcome different from Figure 1 is that now
not every worker that switches produces more with the new technology. The
decision to switch sectors is voluntary. With fast experience-driven productivity
growth on the new technology even workers with significant experience find it
profitable to switch because they can expect fast wage growth in the new sector.
Temporarily, however, they take a wage cut.

The linear example suggests the following sufficient condition for an output in-
crease. 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 wage of a worker with this level of experience does not change if he changes sectors. Next suppose that \( \pi'_n(e - e_{on}) < \pi'_o(e) \) for all \( e > e_{on} \). Under this condition a worker with experience \( e_{on} \) earns higher wages every period of his life if he stays with the old technology and as a result is better off not switching. Workers with more than \( e_{on} \) years of experience have even less of an incentive to switch. Therefore \( \bar{e} < e_{on} \) and, since \( \pi_n(0) > \pi_o(e) \) for all \( e \leq \bar{e} < e_{on} \), aggregate output must increase on impact.\(^8\) 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 identifies two properties of the productivity functions that determine the immediate impact of a new technology. The first property is the degree to which the new technology is suitable for inexperienced workers. The second property is the speed of learning. The switch effect is negative when there is low initial productivity and fast learning in the new sector, and positive when inexperienced workers are more productive in the new sector and learning is slow.

\(^{8}\)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,

\[
\int_{\bar{e}_{on}}^{\delta} \pi_o(x)dx = \int_{\bar{e}_{on}}^{\delta} \left[ \pi_o(e_{on}) + \int_{\bar{e}_{on}}^{x} \pi'_o(y)dy \right]dx > \int_{\bar{e}_{on}}^{\delta} \left[ \pi_o(e_{on}) + \int_{\bar{e}_{on}}^{x} \pi'_o(y - e_{on})dy \right]dx
\]

\[
= \int_{\bar{e}_{on}}^{\delta} \left[ \pi_n(0) + \int_{\bar{e}_{on}}^{x} \pi'_n(y - e_{on})dy \right]dx = \int_{\bar{e}_{on}}^{\delta} \pi_n(x - e_{on})dx.
\]

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

\[
\bar{e} \pi_n(0) + \int_{\bar{e}}^{\delta} \pi_o(x)dx = \bar{e} \pi_o(e_{on}) + \int_{\bar{e}}^{\delta} \pi_o(x)dx
\]

\[
> \bar{e} \pi_o(e) + \int_{\bar{e}}^{\delta} \pi_o(x)dx > \int_{\bar{e}}^{\delta} \pi_o(x)dx + \int_{\bar{e}}^{\delta} \pi_o(x)dx = \int_{\bar{e}}^{\delta} \pi_o(x)dx.
\]
2.3 Transitional dynamics

We now characterize the transition path to the new steady state. Since every worker born after the arrival of the new technology works in the new sector, the transition is completed at \( t = \delta \). The transition can be divided into two phases: Phase 1 during \( t \in [0, \delta - \tau] \) in which the old technology is still being used, and Phase 2 during \( t \in [\delta - \tau, \delta] \) in which it is not.

In Phase 1 output is produced by three types of workers: (1) the workers that do not change sectors, (2) the mass of \( \tau \) individuals who switches technologies at time 0, and (3) those born after the arrival of the new technology. By the end of Phase 1 all the agents who operated the old technology have died and some of the workers that switched at time 0 start to die. In fact, during Phase 2 only \( \delta - t \) of them are alive. It follows that aggregate output is described by

\[
Y(t) = \begin{cases} 
\int_{\tau+t}^{\delta} \pi_o(x)dx + \tau \pi_n(t) + \int_{0}^{t} \pi_n(x)dx & \text{for } t \in [0, \delta - \tau) \\
(\delta - t)\pi_n(t) + \int_{0}^{t} \pi_n(x)dx & \text{for } t \in [\delta - \tau, \delta]
\end{cases}
\]

and that changes in output are given by

\[
Y'(t) = \begin{cases} 
-\pi_o(\tau + t) + \tau \pi'_n(t) + \pi_n(t) & \text{for } t \in [0, \delta - \tau) \\
(\delta - t)\pi'_n(t) & \text{for } t \in [\delta - \tau, \delta]
\end{cases}
\]

Output changes in Phase 1 are driven by three different forces: (i) \( \tau \pi'_n(t) \) 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) \( -\pi_o(\tau + t) \) 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. Some of these workers 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 $\bar{\pi}'_n(t) + \pi_n(t) > \pi_o(\bar{\tau} + t)$; (ii) During Phase 2 output is non-decreasing 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 $\pi'_n(t) > 0$.

Note that output can drop on impact and continue to decline for a while. In this case technological change leads to a cycle in which the economy initially suffers continuous output losses and only later grows in earnest. This possibility is easily explored 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 $\alpha_n + \beta_n(\bar{\tau} + t) > \alpha_o + \beta_o(\bar{\tau} + t)$, or $\pi_n(\bar{\tau} + t) > \pi_o(\bar{\tau} + t)$.

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. The initial boom is followed by sustained output growth during Phase 1, with $Y'(t) = \alpha_n - \alpha_o$, and during Phase 2, with $Y'(t) = (\delta - t) \beta$. Thus, the arrival of the new technology triggers an economic boom that continues until time $\delta$. 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.

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 $\delta$ below the $\pi_n$ line is only slightly larger than the area from 0 to $\delta$ below the $\pi_o$ line. As a result only workers with little experience switch at 0 to the new technology, as indicated by the low value of $\bar{\pi}$ in the figure. From Proposition 1 we know that output falls on impact in this case,
Figure 3: Output rises on impact and continues to increase during phase one

because $\alpha_n < \alpha_o$. And Proposition 2 implies that output continues to decline in the
interval $[0, \epsilon_c - \bar{e})$, because in this period $\pi_n(\bar{e}+t) < \pi_o(\bar{e}+t)$. 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
bust followed by rapid growth.\footnote{There is a discontinuous change in aggregate output at time 0. Afterwards this variable follows
a continuous trajectory. Moreover, after the initial impact the change in output $Y''$ and the growth
rate $Y'/Y$ are also continuous, except at time $\delta - \bar{e}$.}

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
Figure 4: An immediate output decline followed by further declines

Figure 5: Output drops on impact and follows a cycle
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.

The model of this section is related to studies of leapfrogging, in which experience with a technology raises labor productivity. For example, Brazis, Krugman and Tsiddon (1993) show that a country that has acquired more experience with an old technology, and therefore has a productivity advantage in its implementation, may not adopt a new superior technology because of this advantage. At the same time the new technology is adopted by a lagging country, that has less experience with the old technology, and as a result the lagging country becomes the new leader after it accumulates enough experience with the new technology. In these circumstances the leading country does not act efficiently. At the core of this inefficiency is an externality that arises because learning is not specific to individual workers but rather to the industry; every firm benefits from the entire industry’s experience. This sort of inefficiency does not occur in our model because all the learning benefits are internalized by the individual workers.

3 Experience and Education

Now we are ready to analyze the complete model that includes both types of human capital: experience and education. Education provides essential skills that are necessary to operate a technology; for example, basic mathematics. This type of human capital can be acquired on the job, as training, or outside, in schools.

Education and experience interact in complex ways to determine labor productivity. However, in this paper we ignore most of these interactions and focus on one important feature: whether the new technology raises or lowers the educational requirements of the labor force. A new technology exhibits technology-education complementarity if it increases the level of schooling necessary to operate it. Technology-education substitutability is defined inversely. As we discussed in the introduction, economic historians have documented both instances of technological change.
3.1 Model

We use a one-dimensional measure of education. The cost of acquiring education is forgone income.\(^{10}\) We denote by \(\Pi_i(e, s)\) the productivity of a person working with technology \(i\) who has \(s\) years of education and \(e\) years of experience working with this technology. Experience and schooling interact in a rather simple way. 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. 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

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

where the productivity functions \(\pi_i(\cdot)\) have the same interpretation as in the previous section. When \(s_n > s_o\) there is technology-education complementarity. When \(s_n < s_o\) there is technology-education substitutability. Note that this formulation is a straightforward generalization of the previous model.\(^{11}\)

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

**Assumption 1a:** \(\pi_i(e)\) is non-decreasing and differentiable for \(i = o, n\).

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

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\(^{10}\)If a worker acquires education outside the labor force the cost is forgone wages. By contrast, if a worker acquires the education through on the job training, the cost are low wages due to temporarily low labor productivity.

\(^{11}\)In the case of technology-education complementarity and unanticipated technological change, this specification yields an adjustment pattern that is similar to the one discussed in the previous section. The similarity arises for the case in which it takes a minimum level of experience before workers can produce with the new technology. It is nevertheless useful to proceed with the current specification in order to highlight the difference between the two types of human capital and the entry effect described below. The two specifications are quite distinct, however, when workers anticipate the arrival of the new technology. The reason is that schooling can be acquired before the arrival of the new technology while technology-specific experience cannot.
Assumption 3a: The new technology is more productive over a worker’s lifetime; i.e., \( \int_{0}^{\delta} \pi_o(x)dx < \int_{0}^{\delta} \pi_n(x)dx \).

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

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 old technology is more productive over his lifetime if he switches to the new sector. Note that given the educational requirement, now an agent who operates technology \( i \) works only \( \delta - s_i \) years. 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.\(^{12}\)

Assumption 5a: There is a unique level of experience \( \tau \in [0, \delta - s_o) \) at which:

(i) \( \int_{e}^{\delta - s_o} \pi_o(x)dx \geq \int_{e}^{\delta - s_o} \pi_n(x - e)dx \) if and only if \( e \geq \tau \), for the case \( s_n > s_o \); or

(ii) \( \int_{e}^{\delta - s_o} \pi_o(x)dx \geq \int_{e}^{\delta - s_o} \pi_n(x - e)dx \) if and only if \( e \geq \tau \), for the case \( s_n < s_o \).

As before, Assumption 5a merely guarantees the uniqueness of \( \tau \); its existence follows from Assumptions 3a and 4a. Assumptions 1a-5a imply the following lemma:

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

Assumption 6a: Education can be acquired in doses at different points in time and is fully transferable across technologies.

Assumption 6a implies that older workers can upgrade their education when the new technology arrives. Unlike experience, education is fully transferable across technologies. We make this sharp distinction in order to simplify the analysis. The important feature is that experience is less transferable across technologies than general

\(^{12}\)With technology-education complementarity, elderly workers may prefer to remain in the old sector even when Assumption 4a is not satisfied.
skills. 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.

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.

### 3.2 Technology-education complementarity

This seems to be the relevant case for the technological developments of recent decades. The increase in educational requirements implies that workers who switch cannot start producing until they acquire \( \sigma = s_n - s_o > 0 \) additional years of education. In view of our broad interpretation of education, these additional years may consist of schooling outside the workplace or on-the-job training. In either case the worker is not part of the effective labor force. Thus, education adds a new ingredient to the adjustment process: changes in the size of the effective labor force. We refer to this as the negative *entry effect*.

There are both temporary and permanent negative entry effects. The temporary effect is caused by the mass of workers who at time 0 switch to the new technology, and disappears as soon as they have acquired the additional education. The permanent effect arises because in the new steady state every agent spends more time acquiring education, which reduces permanently the size of the 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. Every generation born after time 0 and every student who has never joined the labor force adopt the new technology; they simply stay longer in school. Thus, the transition is completed at \( t = \delta - s_o \), when every individual who joined the labor force with the old technology has died.

The transition path can be divided into three phases. Aggregate output is given
by:

\[
Y(t) = \begin{cases} 
\int_{c+t}^{c_0} \pi_o(x) \, dx & \text{for } t \in [0, \sigma) \\
\int_{c+t}^{c_0} \pi_o(x) \, dx + \pi_n(t - \sigma) + \int_0^{t-\sigma} \pi_n(x) \, dx & \text{for } t \in [\sigma, \delta - \sigma_0 - \tau) \\
(\delta - \sigma) \pi_n(t - \sigma) + \int_0^{t-\sigma} \pi_n(x) \, dx & \text{for } t \in [\delta - \sigma_0 - \tau, \delta - \sigma_0]
\end{cases}
\]  

(5)

The key feature of this transition is that during phase 1 the labor force consists solely of workers who stay with the old technology and is shrinking. The labor force shrinks because elderly workers operating the old technology are dying and the workers that will operate the new one have not completed their education.

The negative entry effect produces two discontinuities in the transition. First, it decreases output on impact. Second, if \( \pi_n(0) > 0 \) it produces a boom at the beginning of phase 2 when the mass \( \tau \) of switchers rejoin the labor force.

To characterize the entire adjustment path it is useful to compare equation (5) with the transition equation for the case of no schooling. 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. As before, output increases in this phase as long as productivity increases with experience.

The current phase 2 is similar to the previous phase 1. 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 born with the new technology. As shown in the previous section, the path of output during this phase depends on the exact shape of the productivity functions, and in particular on the productivity of inexperienced workers and the speed of learning.

The main difference between the two transition paths is phase 1; which does not arise in the previous model. In this phase, the shrinking of the labor force generates a negative effect on output that worsens with time. The loss is due to the death of middle-aged workers who use the old technology. The more experienced these workers, the larger the loss of output. Clearly, the negative entry effect worsens during phase 1 and output decreases at ever increasing rates. We have thus established the following:
PROPOSITION 3: When the new technology requires more education (i.e., \( s_n > s_o \)):

(i) Output drops on impact with the arrival of the new technology and jumps upwards at the beginning of phase 2 when \( \pi_n(0) > 0 \).

(ii) 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 \( \pi_n(t - \sigma) + \bar{e}n_n'(t - \sigma) > \pi_o(\bar{e} + t) \).

Without education a fall in aggregate output was a possibility, but not a necessity. An initial fall in output is inevitable with technological change that exhibits technology-education complementarity. An increase in educational requirements necessarily produces a negative entry effect and thereby a fall in output.

3.3 Technology-education substitutability

Next let the new technology require less schooling; i.e., \( s_n < s_o \). In this event individuals that switch sectors do not need to acquire additional schooling. In fact, they are overeducated. Furthermore, students that have completed enough education to operate the new technology, but not enough to operate the old one, can leave school earlier. As a result, some students leave school earlier to join the labor force, thereby producing a positive entry effect.

With technology-education complementarity there was a negative entry effect. The negative entry effect was responsible for an initial recession, both on impact and during the first phase of the transition. Thus, one might expect a boom to take place when there is a positive entry effect. Nevertheless, even in this case a boom is not guaranteed. A negative switch effect that outweighs the positive entry effect is possible when the new technology’s learning curve is very steep, and the productivity of inexperienced workers is not too low.

To characterize the adjustment process one needs to recognize that with technology-education substitutability a switch effect may not take place (more on this below). However, consider first the case in which there is a switch effect. A mass of workers
\( \tau > 0 \) switches sectors at time zero, and the mass of students \((\eta = s_o - s_n > 0)\) who have completed enough education leave school and join the new sector. Here the adjustment process has two phases: phase 1 in which the old technology is used, and phase 2 in which it is not. Aggregate output is given by

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

(6)

where \( t = 0 \) is the time of arrival of the new technology.

Before the arrival of the new technology output equals \( \int_0^{\delta - s_n} \pi_o(x)dx \) and from (6) it jumps to \( \int_{\bar{\tau}}^{\delta - s_n} \pi_o(x)dx + (\bar{\tau} + \eta) \pi_n(0) \) at time 0. Therefore, output rises on impact if and only if

\[
\phi_s(\bar{\tau}) = (\bar{\tau} + \eta) \pi_n(0) + \int_{\bar{\tau}}^{\delta - s_n} \pi_o(x)dx - \int_0^{\delta - s_n} \pi_o(x)dx
\]

is positive. Although \( \phi_s(\cdot) \) is similar to \( \phi(\cdot) \) (see (1)), now there is an extra term for the entry effect. \( \phi_s(\cdot) \) satisfies

\[
\phi_s(0) = \eta \pi_n(0); \\
\phi'_s(e) = \pi_n(0) - \pi_o(e); \\
\phi''_s(e) \leq 0.
\]

In the model without education, \( \pi_n(0) < \pi_o(0) \) was a sufficient condition for a decline in output on impact. Now, due to the entry effect, this condition is no longer sufficient. However, output declines on impact if \( \eta \pi_n(0) = 0 \) and \( \pi_n(0) < \pi_o(0) \).\(^{13}\) The first condition holds if either the mass of students leaving school at time 0 is small \( (s_n \) is very close to \( s_o) \) or if inexperienced workers are unproductive in the new sector \( (\pi_n(0) \approx 0) \).

Using this characterization it is easy to see that, in the presence of a negative switch effect, output can decrease on impact. Consider the following example in which \( \delta = 1 \). In the old sector \( \pi_o(e) = 1 \) for all \( e \geq 0 \), provided the worker has \( s_o < 1/2

\(^{13}\)This is a generalization of the sufficient condition in part (i) of Proposition 1 because there \( \eta = 0 \).
Figure 6: Productivity functions that raise output on impact

years of schooling, and zero otherwise. On the other hand, no schooling is required to operate the new technology \((s_n = 0)\) and productivity rises with experience in the new sector up to an individual’s half lifetime:

\[
\pi_n(e) = \begin{cases} 
\frac{1}{2} + 2e & \text{for } 0 \leq e \leq \frac{1}{2} \\
\frac{3}{2} & \text{for } e \geq \frac{1}{2} 
\end{cases}
\]

Both productivity functions are depicted in Figure 6.\(^{14}\) It is evident from the figure that a worker switches sectors at time \(t = 0\) only if his remaining lifetime is \(1/2\) or more. Otherwise he stays in the old sector. As a result, \(\phi_s(\tau) = s_o - 1/4\) and output increases on impact only if the school requirement for the old technology exceeds a quarter. There is a negative switch effect in both cases, because a mass \(\tau = 1/2 - s_o > 0\) of workers switch sectors and they experience a temporary productivity loss. Moreover, whenever \(s_o < 1/4\) the negative switch effect overrides the positive entry effect and output declines on impact.

There are some natural examples of technology-education substitutability in which there is no switch effect. To this end, consider a modification of the previous example

\(^{14}\)The steady-state output equals \(Y_o = 1 - s_o\) when all workers use the old technology and \(Y_n = 5/4\) when they use the new technology. Evidently, \(Y_n > Y_o\).
in which the productivity function in the new sector is given by \( \pi_n(e) = \bar{\pi}_n < 1 \) for all experience levels and the other detail remain unchanged. Assumption 3a requires \( \bar{\pi}_n > 1 - s_o \). Clearly, no worker in the old sector has now an incentive to switch. But, in addition, some students remain in school after the new technology arrives, because those close to graduation are better off completing their schooling and joining the old sector. This reduces the size of the positive entry effect. A student with \( \eta \) years of schooling is just indifferent between staying in school and leaving if

\[
1 - s_o = (1 - \eta) \bar{\pi}_n, \tag{7}
\]

where the left hand side is the value of completing school in order to work in the old sector, and the right hand side is the value of joining the new sector immediately.\(^{15}\) Using (7) we get a transition path given by

\[
Y(t) = \begin{cases} 
(1 + t) \bar{\pi}_n & \text{for } t \in [0, s_o - \eta) \\
1 - (t + \eta) (1 - \bar{\pi}_n) & \text{for } t \in [s_o - \eta, 1 - \eta]
\end{cases}
\]

\(^{15}\)A positive entry effect requires \( (1 - s_o)/\bar{\pi}_n < 1 \), which is satisfied as long as Assumption 3a holds.
which is depicted in Figure 7. Output equals $Y_o = 1 - s_o$ at the initial steady state. When the new technology arrives, no worker switches sectors ($\pi = 0$) and only students who have been in school for less than $\eta$ years leave school to join the new sector. Thus, there is a positive entry effect and no switch effect. Output rises during the first phase of the transition in response to an increasing labor force, and output decreases afterwards because the more productive old sector contracts.

The discussion in this example can easily be extended to establish the following result:

**PROPOSITION 4:** When the new technology requires less education (i.e., $s_n < s_o$):

(i) Output may increase or decrease on impact.

(ii) If there is a switch effect ($\pi > 0$), output increases in phase 2 as long as experience raises productivity in the new sector, and output increases in phase 1 if and only if $(\pi + \eta) \pi_n'(\pi + t) + \pi_n(t) > \pi_o(\pi + t)$.

Thus, we conclude that technology-education substitutability can lead to an adjustment path with rising output, as well as to a cycle that starts with a recession and ends with an expansion, or a cycle that starts with a boom and ends with a recession. The type of transition that takes place depends on the presence and strength of the negative switch effect. As before, this effect is stronger when inexperienced workers are less productive with the new technology and productivity increases with experience faster in the new sector.

### 3.4 Productivity

So far we have focused on how the arrival of a new technology affects output. Now we explore the effects on labor productivity. Without educational requirements, labor productivity evolves exactly like output. However, when the new technology changes the educational requirement, labor productivity may evolve differently from output. For the sake of brevity, we confine most of the analysis to a time interval around the date of arrival of the new technology; i.e., around $t = 0$.  

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The definition of labor productivity is straightforward: output divided by the size of the labor force (or hours worked). It is not always clear, however, how to define the labor force. In particular, in the case of technology-education complementarity, are the workers that acquire additional schooling part of the labor force? If the extra schooling is provided on the job, they are included in the labor force. But if they temporarily leave their jobs to acquire more education, they are not. In order to avoid a taxonomy, we adopt the definition most likely to approximate what is measured in practice: the labor force includes all individuals except those who have never left school. Namely, workers who upgrade their education in order to switch to a new technology remain in the labor force.

Not surprisingly, the evolution of labor productivity depends on the type of technological change. First consider the case of technology-education complementarity ($s_n > s_o$). In the initial steady state labor productivity equals $Y_o / (\delta - s_o)$, where $Y_o$ is the level of output before $t = 0$ and $\delta - s_o$ is the size of the labor force. By (5), labor productivity is given by

$$l(t) = \frac{1}{\delta - s_o - t} \int_{x_0}^{x(t)} \pi_o(x) \, dx$$

in phase 1 of the transition. During this phase the labor force equals $\delta - s_o - t$. It is shrinking because elderly workers in the old sector pass away and the workers who plan a career in the new sector have not yet completed their education. And labor productivity declines on impact in proportion to the decline in output. Also, since $l'(0) = [(l(0) - \pi_o(\tau)] / (\delta - s_o)$, the local behavior of labor productivity depends on the number of workers who switch sectors. If $\tau$ is large, then $l'(0) < 0$ and productivity continues to fall after the initial impact. It follows from our previous discussion that this is more likely to occur when, in the new sector, productivity increases quickly with experience and the productivity of inexperienced workers is high.\footnote{Recall that in phase 1 output declines over time. The fall in output produces a decline in productivity. But this decline is offset by a shrinking labor force. For this reason labor productivity may also rise over time.}

Now consider the case of technology-education substitutability ($s_n < s_o$). Labor
productivity equals \( Y_o / (\delta - s_o) \) prior to the arrival of the new technology. And we need to distinguish once more between to cases: a positive switch effect (\( \tau > 0 \)) and no switch effect (\( \tau = 0 \)).

In the first case, the size of the labor force increases to \( \delta - s_n \) and remains there during the entire transition. This implies that labor productivity declines on impact whenever output declines, but it may decline even when output rises if the increase in the labor force is large enough. Since the size of the labor force is constant for the rest of the transition, labor productivity fluctuates proportionally to output. As a result, we conclude that labor productivity may rise or decline over time, depending on the characteristics of the two technologies.

The final case, technology-education substitutability and no switch effects, provides a nice insight about the adequacy of standard measures of labor productivity. Consider the example exhibited in Figure 7, where productivity does not increase with experience in the old or the new sector. Here, the response of labor productivity is counter-intuitive: output rises on impact but labor productivity declines.\(^{17}\) A similar, but sharper, contrast arises from a comparison of steady states. After the arrival of the new technology the economy reaches a steady state in which output equals \( \pi_n \) and all people work, implying labor productivity \( \pi_n < 1 \). By contrast, in the initial steady state output equaled \( 1 - s_o \) and the labor force also equaled \( 1 - s_o \), implying labor productivity 1. As a result, there is a permanent decrease in labor productivity but a permanent increase in output per capita. Furthermore, individuals are better off in the new steady state in which labor productivity is lower.

The difficulty arises from the fact that the old technology requires schooling while the new technology does not. Without education a worker cannot operate the old technology, yet students are not counted as part of the labor force. This biases the calculation of labor productivity in favor of technologies that require more schooling. But since the schooling is required in order to operate the technology, it would make sense to add the time spent in school to the time spent working; schooling is

\(^{17}\)Labor productivity equals 1 prior to the arrival of the new technology and declines to \( \pi_n / (1 - s_o + \eta) \) on impact. In view of (7), the former is larger.
complementary to work and needs to be accounted for as part of the input. With this correction labor productivity is indeed higher when the economy uses the new technology.\footnote{A similar difficulty arises in the case of technology-education complementarity.}

This example suggests that standard productivity indexes provide inadequate measures of the economy’s productivity, because they disregard the time it takes to get inputs ready for production. The example shows that technological change that decreases the educational and training requirements of workers can be very valuable, even if it decreases the amount of output per unit labor on the shop floor.

4 Anticipated Technological Change

In the previous sections we have assumed that the arrival of the new technology was unanticipated. In this section we add anticipation to our analysis and study how it affects the adjustment path.

Suppose that there is uncertainty about the arrival date of the new technology but that its characteristics are known in advance.\footnote{See our working paper, Helpman and Rangel (1998), for a discussion of anticipated technological change with a known arrival date.} In particular, suppose that the form of the new technology \( \pi_n(.\,) \) and the nature of the stochastic arrival process are revealed at time 0. The arrival process is Poisson with arrival rate \( \lambda > 0 \); with cumulative distribution function \( F(t) = 1 - e^{-\lambda t} \), and density \( f(t) = \lambda e^{-\lambda t} \).

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-education 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\textsuperscript{20} 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.

The case of technology-education complementarity is significantly more complicated, because now agents can profit from acquiring additional education before joining the labor force. Consider, as an extreme example, the decision problem of a generation that believes the new technology is very likely to arrive early on its lifetime (i.e., \( \lambda \) is very large). These individuals are better off accumulating the additional \( \sigma = s_n - s_o \) years of schooling, then 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 \( \lambda \). 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 \( \sigma_o \) 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

\textsuperscript{20}If the technologies are such that there is no switch effect (\( \tau = 0 \)) then students that are close enough to graduation stay in school. However, unlike the case of technology-education complementarity, no changes take place before the new technology arrives.
conditional decision at time \( s_0 \); they stay in school for \( \sigma_o \) additional years as long as the technology does not arrive before the end of this schooling period. If it arrives before \( s_0 + \sigma_o \) they remain students until they have completed enough schooling to join the new sector.

Let \( V(\sigma_o) \) denote the expected lifetime earnings of an agent that decides to acquire \( \sigma_o \) 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 \( s_0 + \sigma_o \) 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 and 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 \( \theta(0) = \bar{\tau} \). The cutoff experience-level is given by the following condition

\[
\int_{\theta(\sigma_o)}^{\delta - s_o - \sigma_o} \pi_o(x) \, dx = \int_{\theta(\sigma_o)}^{\delta - s_o} \pi_n \left[ x - \theta(\sigma_o) \right] \, dx = \int_{0}^{\delta - s_o - \theta(\sigma_o)} \pi_n(x) \, dx. \tag{8}
\]

We assume that the solution of \( \theta(\sigma_o) \) is unique and differentiable\(^{21}\) for every \( \sigma_o \in [0, \sigma] \), by extending assumption 5a as follows:

**Assumption 5a**: \( \theta(\sigma_o) \) is a differentiable function, has domain \( [0, \sigma] \), and it is implicitly defined by (8).

Let \( \hat{\Pi}(t, \sigma_o) \) denote lifetime income of an agent who stays in school for \( s_0 + \sigma_o \) years, when the new technology arrives at time \( t \). This function is given by

\[
\hat{\Pi}(t, \sigma_o) = \begin{cases} 
\int_{0}^{\delta - s_o - \sigma_o} \pi_o(x) \, dx & \text{if } t \leq s_0 + \sigma_o \\
\int_{0}^{\delta - s_o - \sigma_o} \pi_o(x) \, dx + \int_{0}^{\delta - (t + \sigma - \sigma_o)} \pi_n(x) \, dx & \text{if } s_0 + \sigma_o < t \leq s_0 + \sigma_o + \theta(\sigma_o) \\
\int_{0}^{\delta - s_o - \sigma_o} \pi_o(x) \, dx & \text{if } t > s_0 + \sigma_o + \theta(\sigma_o)
\end{cases}
\]

\(^{21}\)This assumption reduces somewhat the set of feasible technologies.
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

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

The effects on expected income of increasing $\sigma_o$ can be seen from this equation. Additional schooling has both positive and negative effects. More schooling increases the likelihood of joining the new sector and reduces the cost of switching. But more schooling also reduces earnings in the case in which the technology arrives after time $s_o + \sigma_o + \theta(\sigma_o)$, because it reduces the amount of years that an agent can work in the old sector. 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 $\lambda$ it is optimal to avoid additional schooling; i.e., $\sigma_o = 0$.

**PROPOSITION 5:** (i) In the case of technology-education substitutability knowledge of the new technology’s stochastic arrival process does not change the economy’s adjustment path.

(ii) 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 $\lambda$ is small.

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
with \( s_o \) with \( s_o + \sigma_o \). Upon the arrival of the new technology workers who switch complete additional \( s_o - s_o - \sigma_o \) 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 of inexperienced workers is low and learning is fast in the new sector.

Anticipation of the arrival of a new technology that exhibits technology-education complementarity can trigger an extension of schooling beyond the requirements of the old technology. It therefore provides a simple explanation of the observation that the number of college graduates began to increase in the US way before the rise of the college wage premium in the 1980s. A thorough analysis of this issue is provided by Acemoglu (1998), who also explains the induced direction of technological change that leads to technology-education complementarity. Our point is that the timing of these events emerges naturally from our analysis, which also predicts a productivity slowdown with the arrival of the new technology, that is also consistent with the evidence.

5 Conclusion

Major technological changes can have major macroeconomic effects. An important question is how do economies adjust to such changes and, in particular, what happens to macroeconomic variables during the transition. 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.

Given the number and complexity of mechanisms involved in the adjustment process, we need to study these questions from a variety of perspectives. Earlier studies considered the roles of diffusion, secondary innovations and learning by firms. By contrast, we have examined the role of two types of human capital embodied in workers: technology-specific experience and general education. 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 *switch* and *entry* effects; the former associated with experience, the latter with schooling. When combined with previous findings about the roles of diffusion, secondary innovations 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.

Finally, our analysis of labor productivity has demonstrated a shortcoming of conventional measures that disregard the schooling requirements of various technologies. This omission biases the calculations in favor of technologies with large schooling requirements. The quantitative importance of this bias is as yet unknown, nor is it clear at this point how to measure it empirically.
References


