Journal of Economic Growth, 9, 167–207, 2004

Skill-Specific rather than General Education: A Reason for US–Europe Growth Differences?

DIRK KRUEGER dkrueger@econ.upenn.edu

Department of Economics, University of Pennsylvania, Philadelphia, PA 19104
Centre for Economic Policy Research, 90–98 Goswell Road, London EC1V 7RR, United Kingdom;
National Bureau of Economic Research, Inc., 1050 Massachusetts Avenue, Cambridge, MA 02138

KRISHNA B. KUMAR kbkumar@usc.edu

Department of Finance and Business Economics, USC Marshall School of Business, Los Angeles, CA 90089

In this paper, we develop a model of technology adoption and economic growth in which households optimally obtain either a concept-based, ''general'' education or a skill-specific, ''vocational'' education. General education is costly to obtain, but enables workers to operate new production technologies. Firms weigh the cost of adopting and operating new technologies against increased profits and optimally choose the level of adoption. We show that an economy whose policies favor vocational education will grow slower in equilibrium than one that favors general education. More importantly, the gap between their growth rates will increase with the growth rate of available technology. By characterizing the optimal Ramsey education policy we also demonstrate that the optimal subsidy for general education increases with the growth rate of available technology. Our theory suggests that European education policies that favored specialized, vocational education might have worked well, both in terms of growth rates and welfare, during the 1960s and 1970s when available technologies changed slowly. However, in the information age of the 1980s and 1990s when new technologies emerged at a more rapid pace, they might have contributed to an increased growth gap relative to the United States.

Keywords: education policy, technology adoption, balanced growth, Eurosclerosis

JEL classification: O40, O30, I21

1. Introduction

After strong economic growth until the 1980s, European growth has become weak relative to that of the United States. With a few exceptions, Europe has suffered from a ''technology deficit'' relative to the United States—as measured by manufacturing productivity, the share of information technology investment, or by its contribution to output growth, European technology has lagged behind. This has happened against the background of an increased rate of arrival of technologies, and a European tradition of fostering specialized, skill-specific, ''vocational'' education at the upper-secondary and higher levels.

In this paper, motivated by the above-mentioned empirical facts, we formalize the hypothesis that public policies favoring vocational education over a concept-based, ''general'' education may contribute to slower technology adoption and economic growth, especially during times of rapid technological change.

We posit that only workers with general education can operate new, risky technologies, whereas vocationally trained workers are more efficient in operating old, established technologies. The notion that education helps in coping with technical change dates back at least to Nelson and Phelps (1966), who use reduced form specifications to postulate a higher return to education in an economy with more rapid technological change, and to Welch (1970), who provides supportive evidence for the dynamic advantage of education using wages of college graduates.[1] The theoretical contribution of our paper is to embed this idea in an equilibrium growth model that jointly models the adoption decision of firms and the decision of individuals to acquire a particular type of education, and analytically characterize the effect of education policy on growth. As an applied contribution, we provide an explanation consistent with the ''Eurosclerosis'' view that holds rigid government policies responsible for inhibiting economic adjustment, thereby causing slow European growth.[2] Our focus is on continental Europe's education policies.

In our model, newly born individuals optimally and irreversibly choose between one of the two streams of education mentioned above, based on their intrinsic ability to absorb conceptual education, anticipated market conditions, and government subsidies for the two types of education. They weigh the higher wages associated with operating newer technologies against the higher cost of acquiring general education.

Firms have the choice of producing a single non-storable good either through technologies (production methods) *used* in the previous period—which have become well-understood and readily usable in the present period at no cost—or by adopting, at a cost, new technologies up to the available frontier. This technology frontier evolves exogenously. Non-adopting, ''low-tech'' firms can use the old technology without any adoption cost. The adopting, ''high-tech'', firms, have to pay a cost of adoption that depends on the distance between the new and the previously used level of technology in a convex fashion, as well as potentially higher wages to attract workers who face the risk of low task-specific productivity caused by their move to an unfamiliar and more complex technology.

We completely characterize the education choices of individuals and the adoption decision of firms, and show that the equilibrium growth rate is weakly lower in an economy that allocates more of a given amount of resources toward vocational education. The positive relationship between the fraction of the work force with general education and growth may intuitively follow from our assumption that only generally educated workers can operate new technologies, although demonstrating this requires a fully

---

1 While Welch (1970) uses R&D intensity as a proxy for technical change, Bartel and Lichtenberg (1987, 1991) use age of equipment as a proxy for lack of change and find that the labor cost share and the wage rate decrease with equipment age. Gill (1988) finds that higher TFP industries employ a larger proportion of educated workers and that the wage profile for highly educated workers shifts out with increasing TFP growth and is also steeper. Benhabib and Spiegel (1994) find that the human capital stock affects the speed of technology adoption in a cross-country context, lending support to a specification in Nelson and Phelps (1966). Thus, the advantage of education in adapting to technical change has both theoretical precedence and empirical support in the literature.

2 The economist Herbert Giersch is generally credited with coining the term ''Eurosclerosis.''

specified model such as the one we have developed. However, what is not obvious, even once all the equilibrium conditions are laid out, is the effect of an *increase* in the rate of available technology; the true value of the model lies in showing that in such an event, countries with different education systems that had comparable growth rates initially could diverge.[3]

As the exogenous rate of technological change increases, higher net profits are needed to make it worthwhile for firms to adopt technologies at the new maximal rate. But this requires lower wages in the adopting sector, which in turn demands a larger share of the population be generally educated and supply their labor services to that sector. Therefore, Europe, having a lower share of the labor force with general education, may fail to sustain maximal growth, while the United States can more readily exploit the new technologies and might, in fact, be constrained only by their availability.

We then go on to characterize the optimal education subsidy policy a benevolent Ramsey government should implement. It is shown that the optimal relative subsidy for general education increases with the growth rate of available technologies.

Our model suggests that while European education policies that favor specialized, vocational education may have worked well during the 1960s and 1970s when technologies were more stable, they may have contributed to slow growth and increased the European growth gap relative to the United States during the information age of the 1980s and 1990s when new technologies emerged at a more rapid pace. The following observations made in the European Commission's European Competitiveness Report 2001 directly speak to the possibility of sluggish adoption of information and communication technologies (ICT), as well as a paucity of labor qualified enough to work with these new technologies: ''The growing consensus that the strong growth and productivity performance in the United States is related to increased investment and diffusion of ICT goods and services has raised concerns that the weaker economic performance of EU Member States is caused by sluggishness in the adoption of these new technologies . . . in recent years skill shortages in important technology areas have been reported in several European countries . . .'' (pp. 10, 11).[4]

We do not intend to claim that the emphasis on skill-specific education alone is responsible for Europe's technology deficit or recent slow growth. Clearly, several other explanations such as generous unemployment insurance and inflexible labor laws would be required to complete the quantitative picture. Rather, our aim is to build a framework grounded in reasonable assumptions that focusses on hitherto neglected educational differences, delivers key observed stylized facts, and lays a theoretical foundation for future empirical and quantitative work. We view the development of a tractable growth

3 This result does not appear to hold in standard ''off-the-shelf'' growth models, which partially motivates the development of the new model presented here.

4 The unemployment rate among adults with university education in OECD Europe was much lower in 2000 (4.1 percent) relative to the rates among those with just upper secondary education (7.2 percent) and those with less than upper secondary education (10 percent) (*OECD Employment Outlook* 2002). This provides further indication that the limited pool of labor with general education (university degrees) was readily employed. The corresponding figures for the US were 1.8 percent, 3.6 percent, and 7.9 percent. Similar patterns are seen for most European countries for other years close to 2000.

model, featuring heterogeneity in the type of education and endogenous technology adoption decisions by firms as a goal in its own right.

The possibility that working with newer technologies could result in lower task-specific productivity is akin to Violante (2002), who posits a skill transferability function across jobs that depends on the technological distance between machine vintages and studies the relationship between the rate of technological change and wage dispersion. He is not concerned with endogenizing the education decision and studying the effect of education policy on growth. Gould et al. (2001) also focus on inequality caused by a depreciation of technology-specific skills, but this occurs randomly across sectors in their model; such ''depreciation'' is induced by a choice to work in the high-tech sector in our framework. Education is a choice variable for them, but there is no intentional adoption of new technology by firms.

In the important work of Galor and Tsiddon (1997), during times of rapid technological progress the return to ability rises and that to specific human capital declines, increasing mobility and the concentration of high-ability individuals in high-tech sectors, thereby fueling future growth. In their view, impediments to mobility in Europe could cause it to trail the United States in economic performance, while our primary focus is on educational policy differences between the United States and Europe. They do not distinguish between vocational and general education among skilled workers and therefore also do not discuss optimal policies, while we do. The same is true for Acemoglu (1998), who develops a model in which an increase in skilled labor induces faster upgrading of skill-complementary technologies by firms; in our setup, an increase in the measure of workers with general education would have a similar effect. Our paper is also complementary to the work of Galor and Moav (2000), who study a model in which education plays a dynamic role, but focus on the effect of technological change on wage inequality. Unskilled labor is assumed to count for less in a composite labor input when growth is higher, and ability enables individuals to cope with technological progress. As in these two papers, we also assume an exogenous ability distribution, but given our focus on education policies, we endogenously model the acquisition of general education based on this ability. Furthermore we characterize the response of equilibrium growth rates and education allocation to a change in the growth rate of technological progress, in order to explain the evolution of US–Europe growth differentials.[5]

The rest of the paper is structured as follows. We summarize the stylized facts that motivate our study in Section 2. In Section 3 we present the economic environment and define a balanced growth path (BGP). This BGP is analyzed in Section 4. Section 5 contains our central theoretical results: an increase in the relative subsidy for vocational education at the expense of general education will decrease growth, and the growth gap relative to an economy that focusses on general education will increase with the rate of arrival of new technologies. In Section 6 we characterize the optimal education subsidy

5 Even though the evolution of wage inequality is not our main focus, our model does have empirically relevant predictions for the differences in wage premia between the United States and Europe, and in particular their evolution over time.

policy, and Section 7 concludes the paper. Formal proofs and derivations are presented in the appendix, unless otherwise noted.

2. Stylized Facts

In this section we present the stylized facts that provide empirical support for the phenomena we seek to explain—slow European per capita growth and manufacturing productivity growth since the 1980s, and Europe's "technology deficit"—as well as for the building blocks used in our model to deliver the above outcomes—more rapid technological change since the 1980s and European focus on vocational education.

2.1. Slow European Growth and Technology Adoption

In the 1970s Germany (2.6 percent) and Italy (3.1 percent) had higher annualized per capita GDP growth than the United States (2.1 percent). In the 1980s, the United States grew at the faster rate of 2.3 percent, compared to 2.0 percent and 2.2 percent for Germany and Italy. The United States lead solidified in the 1990s; it grew at 2.0 percent, while Germany and Italy managed only 1.0 percent and 1.2 percent. While we have presented data for Italy and Germany, which quintessentially conform to our story, similar patterns can be seen for other European countries such as Austria, Belgium, France, and Greece.[6]

Since our theoretical framework focusses on technology adoption, productivity growth and technology usage might be more relevant indicators of economic performance for our purposes. Our model is most likely to apply to the manufacturing sector. Scarpetta et al. (2000, Table 15) provide data on manufacturing output per hour relative to the United States. It can be seen that the productivity level in many European countries was converging toward the US level until 1980 and has diverged since then. The widening gap is clearly visible if one examines manufacturing labor productivity growth—the 1986–1990 and 1991–2000 figures for the US are 2.3 percent and 4.3 percent, while those for the EU are 3.0 percent and 3.1 percent.[7]

The gap between the United States and Europe is even starker when one examines

6 Growth rates are from Scarpetta et al. (2000). Note that our model will have nothing to say on the faster growth of some European countries until the 1970s, since it does not feature any direct channel of international catch-up. Our aim is to explain why a region that was doing well slowed down and a gap emerged relative to the US, when the rate of available technologies actually increased. The theme voiced by Lawrence and Schultze (1987) is relevant in this regard: "The European economies ... now experienced problems in graduating from a catch-up economy to one on the frontier of technology ... Workers must have general training to adapt to new tasks, and European education, which has encouraged apprenticeships that provide specific skills, must adapt" (pp. 4, 5).

7 These figures for the growth rate of manufacturing output per worker are from Table IV.1 in *European Competitiveness Report* 2001. BLS data shows growth of manufacturing output per hour during 1979–

Table 1. ICT contribution to output growth (% points).

Economy	1980–1985	1985–1990	1990–1996
United States	0.28	0.34	0.42
Germany	0.12	0.17	0.19
Italy	0.13	0.18	0.21

technology-driven industries—in the United States, these industries recorded an average annual productivity increase of 8.3 percent in the 1990s, when compared to the 3.5 percent achieved in the same industries in the European Union.[8]

There is abundant direct evidence that Europe lags behind the United States in the usage of new technology. Schreyer (2000, Table 4), presents results from growth accounting studies which show the contribution of ICT capital to output growth; these are presented in Table 1.[9] The contribution of ICT capital to output growth has been increasing for all countries, but the *gap* between the United States and European countries has been increasing as well. Delivering a stylized version of this table is an important goal of our theoretical analysis.

Bessen (2002) estimates that technology adjustment costs peaked in the United States at 90 cents per investment dollar during 1984–1988, amounting to 10 percent of the manufacturing sector output. This is an indication of the high degree of costly technology adoption undertaken in the United States during this period.

For evidence that increased *usage* of such technology improves productivity, we turn to Stiroh (2002), who conducts econometric tests using industry-level data to show that IT-intensive industries experienced significantly larger labor productivity gains than other industries; he also finds a strong correlation between IT capital accumulation and labor productivity.[10]

2001 was also lower for Germany (2.4 percent) and Italy (2.2 percent) when compared to the US (3.2 percent). The difference was particularly pronounced during 1995–2000: 2.4 percent for Germany, 0.9 percent for Italy, and 4.5 percent for the United States.

8 See page 66, Graph IV.5, and Table IV.6 in *European Competitiveness Report* 2001. Pharmaceuticals, Office machinery and computers, Motor vehicles, Aircraft and spacecraft, are a few of the industries classified as Technology-driven industries.

9 The data from uses a ICT price index harmonized across countries. Again, France and the United Kingdom, the two other European countries for which data is presented, exhibit a similar pattern. When these figures are calculated in percentage terms instead of absolute percentage points, similar patterns persist. Schreyer, in his Table 1, also presents data that shows a similar widening gap in the share of IT equipment in total investment.

10 A positive correlation between the ICT share and TFP growth also emerges from Graph 6 in the European Commission (2000) report.

The widespread nature of productivity acceleration reported by Stiroh (2002) casts doubts on an alternate explanation for the United States productivity advantage, that the United States with its more liberal immigration policies attracts highly skilled specialists to the high-tech sectors. This would not explain why industries as far flung as ''Security and Commodity Brokers,'' not typically populated by immigrants, experienced huge increases in productivity growth. The assumption that only workers with high levels of general education immigrate to the United States is not tenable, and many immigrants first

Though the actual magnitude of the productivity boom in the United States during the 1990s continues to be debated (see, for instance, Gordon, 2000, for a skeptic's view), the facts that Europe has lagged behind the United States in the last two decades in technology usage and production, and experienced slower productivity growth, are unlikely to be overturned by recent evidence.

2.2. *The Building Blocks*

2.2.1. Increased Pace of Technological Change

Our claim is that the emergence of a gap between the United States and Europe since the 1980s is related to the almost concurrent increase in the rate of technological change. There is ample evidence that investment-specific technological change indeed quickened by the 1980s. Cummings and Violante (2002), construct an aggregate index of investment-specific technical change and show this index, ''grows at an average annual rate of 4 percent in the postwar period, with a sharp acceleration in the 1980s that leads to an average annual growth rate of more than 6 percent in the 1990s'' (p. 245). They also distinguish between the productivity of the best technology and the average practice, and claim this gap, ''. . . was 15 percent in 1975. In 2000, the figure had jumped to 40 percent'' (p. 246). These facts motivate the experiment with increased technological change we consider in Section 5.3.[11]

Empirical support for such an increase is also provided by Kortum and Lerner (1998), who examine patenting in the United States and find, ''Applications for US patents by US inventors have risen more since 1985 (in either absolute or percentage terms) more than in any other decade this century . . .'' (pp. 248–249, Figure 1).

2.2.2. European Bias Toward Vocational Education

Since we identify the educational system as an important source of US–Europe productivity and growth differences, we now present evidence on the European focus on vocational education. The classification of education into general and vocational should

acquire general education in US universities before they begin work. The immigration explanation also does not explain why there was a *change* in the US economic performance starting in the 1980s without a concurrent significant change in US immigration laws.

11 The gap between new and old technology is the gap between the best and the average practice in our model. Greenwood and Yorukoglu (1997), Hornstein and Krusell (1996), and Krusell et al. (2000) arrive at a similar conclusion. While some of these studies identify the mid-1970s as the onset of the IT revolution, they also highlight delays that exist between the arrival of technologies and their impact on productivity. It, therefore, does not appear unreasonable for our purposes to consider the 1980s, which lies in between the advent of affordable computation in the 1970s and the IT-boom of the 1990s, as the decade in which there was an upward shift in technological change.

be viewed as a metaphor for the rigidity and inflexibility of European upper secondary and post-secondary education. The issue under consideration is broader than the distinction of college versus school education or overall attainment. In Europe, the channeling of students into either stream starts earlier than college; indeed, a portion of the differences in university enrollment between the United States and Europe can be attributed to such early pegging of students. One indication of such rigidity: in Germany only about 20 percent of university entrants are from the upper secondary vocational stream; the figure is 30 percent for France.[12]

Table A1 in the appendix shows that in the EU, in 1995, more students were enrolled in the vocational stream (57.6 percent) at the upper secondary level than in the general stream (42.4 percent). In West Germany, 77 percent of upper secondary students, and in Italy 72 percent were enrolled in vocational or apprenticeship programs. The emphasis on vocational education at this level is also evident for other European countries presented in Table A1. In contrast, there is no separate stream of vocational education in the United States at this level; even the percentage of students who completed 30 percent or more of all credits in specific labor market preparation courses was just 6.8 percent in 1990.[13] Since education at this level is typically fully funded by the government, this data suggests that the European governments spend a greater fraction of their resources on vocational training than the United States.[14] Vocational education in the United States is typically imparted in two-year community colleges; of those students over the age of 18 enrolled in post-secondary education, only 13.8 percent were working toward a vocational Associate's degree in 1991; this figure fell to 10.5 percent in 1994.[15]

Table A1 also presents the net entry rate into universities, where general education is primarily imparted; it is 52 percent in the US but only 27 percent in Germany, 33 percent in France, and 26 percent in Austria. This lower European enrollment is reflected in attainment; while 25 percent of adults had completed university-level education and 8 percent had completed non-university tertiary education (vocational) in the United States in 1995, in Germany only 13 percent had completed university education and 10 percent non-university education.[16] Except for the Netherlands, no other country comes close to the US university attainment.[17] Incidentally, while the rate of return for men from such non-university tertiary education is 9 percent in the United States, it is generally higher in Europe—as high as 17 percent in Germany and 18 percent in France. This

12 The figures are from OECD's *Education Policy Analysis* 1997.

13 These figures are from Table 3.2 of Medrich et al. (1994). Also see the European Commission's 1998 report, *Young People's Training*.

14 The German apprenticeship program involves partial outlays by firms as well.

15 See Table 87 in Levesque et al. (2000).

16 OECD (2001, p. 129) identifies non-university tertiary education as well as tertiary B programs with vocational education, imparting occupation-specific skills.

17 Lazear's (2002) evidence that students who have taken a more general curriculum have a higher chance of becoming entrepreneurs is also relevant in this context. Entrepreneurship, which is an important channel for adoption of new technologies, is generally thought to lag behind in Europe relative to the United States. See for instance, the European Commission's September 2001 policy paper, *Entrepreneurial attitudes in Europe and the United States*.

differential might be an indication of better employment opportunities for the vocationally educated in those countries.

As seen in Table A2 in the appendix, the allocation of educational resources also differs between the US and continental Europe. The percentage of GDP devoted to primary and secondary education was comparable in the United States and the European countries in 1998—the 3.8 percent figure for the US was well matched by 3.7 percent for Germany and 3.5 percent for Italy. However, the percentage devoted to university tertiary (general) education in the US (2.3 percent) outstripped the percentages in Europe. For instance, Germany spent 1 percent, Italy 0.8 percent, and France 0.9 percent. The expenditure per student relative to GDP per capita on post-secondary non-tertiary (vocational) education was 48 percent in Germany for 1997, amounting to 10,924 PPP dollars; little happens on this front in the United States. The corresponding figures for university tertiary education was 44 percent in Germany but 61 percent in the US. In PPP dollars, the university tertiary education expenditure per pupil was $10,139 in Germany while in the United States it was $19,802 (it was $6,295 in Italy).[18] Expenditure per pupil in vocational tertiary education exceeds spending on university (general) tertiary education for Germany and the two are comparable for most of the other countries. This observation allows us to clarify our position—we do not claim education expenditure for all education is low in Europe as much as it is slanted toward a particular *type* of education, namely vocational education. This pattern holds not only for Germany and Italy, but also for other countries shown in Table A2.

The above data motivates our revenue-neutral policy experiment in which European vocational education subsidies per student are higher than those of the US. We will show that the equilibrium education attainment implied by the model presented below is qualitatively consistent with this data.

3. The Environment

The economy is populated by a continuum of households and two continua of identical firms. Firms in one sector potentially adopt new technologies in every period, and firms in the non-adopting sector do not.[19] There is a single non-storable consumption good in each time period and households supply labor to the firms. In this section we describe the

18 Per-pupil expenditure figures appear to provide a more complete comparison of education focus. The percentage of total education expenditures in a given category that is public does not provide any indication of the actual level or intensity of funding. Similarly, a comparison of tuition would not be indicative of the actual burden faced by households. For instance, college education in most European countries is nominally free, but is funded out of high taxes levied on households.

19 We have abstracted from important issues of industrial organization, such as free entry, to keep our model analytically tractable and to focus on the education channel as a source of growth differences between the United States and Europe.

If firms could enter the market by paying a fixed cost (in an industry equilibrium equal to the stream of future discounted profits), then an increase in the growth rate of available technologies may trigger firm entry. While we cannot characterize the impact of potential entry analytically, we conjecture that maximization problems of a typical firm in each sector and of a typical household, and finally define equilibrium and a balanced growth path.

3.1. Firms and Technology Adoption

Each firm in this economy is owned by infinitely lived entrepreneurs, who consume all profits from production in each period, as they, like workers, have no access to an intertemporal storage technology.

A representative firm n in the low-tech sector that does not adopt new technologies in the current period faces the production technology:

$$Y_{n,t} = A_t \left(H_{n,t}\right)^{\theta},$$

where $Y_{n,t}$ is output of the representative non-adopting firm in period t, $H_{n,t}$ is the labor input used by that firm in period t, A_t is the level of technology that is freely available in period t and $\theta \in (0, 1)$ is an intensity parameter. The non-adopting firms take A_t and the real wage rate (per effective unit of labor) $W_{n,t}$ in the non-adopting sector as given.

The firms in the high-tech sector of the economy that (potentially) adopt new technologies face the production technology

$$Y_{a,t} = A'_t \left(H_{a,t}\right)^{\theta},$$

where $Y_{a,t}$ is output of the adopting firm in period t, $H_{a,t}$ is the effective labor input used by that firm and A'_t is the level of technology used in period t, which is a choice variable for the adopting firms. We let $W_{a,t}$ denote the real wage rate (per effective unit of labor) in the adopting sector. The technology frontier grows exponentially, that is,

$$A_{f,t} = \lambda A_{f,t-1}, \tag{1}$$

where $\lambda > 1$ is the constant gross growth rate of the frontier technology. The technology choice of the adopting firm has to satisfy $A'_t \leq A_{f,t}$. We assume that $A_0 = A'_{-1} = A_{f,-1} = 1$; that is, the economy starts at the technology frontier. The parameter λ is the potential growth rate of the economy. If the economy keeps pace with these periodic inventions by adopting them as fast as they occur, the actual growth rate will be the same as the potential one. An increase in λ is later used to model an increased speed at which new technologies become available.

We further assume that all firms can use the highest technology that was *used* last period, and hence has become common practice; that is, $A_t = A'_{t-1}$ and there is complete spill-over of previously adopted technologies after one period.[20]

abstracting from this phenomenon is a conservative move for our results. The United States, with its education policy favoring general education, makes entry into the technology-adopting, growth generating sector more attractive than Europe.

20 This can be viewed as a reduced form modeling of learning by doing in which productivity gains spill over across sectors. See, for instance, Young (1993) and the references therein.

It is important to note: (1) it is the technology actually *adopted* in the previous period rather than the frontier technology that was *available* last period that spills over costlessly to the next period, and (2) the adopting firms are small and do not take into account the influence that their adoption choice A_t' today has on the next period's common practice A_{t+1}.[21] What we intend to capture with these assumptions is the notion that most gains from adopting new technologies come in the form of higher short-run profits, before its ''bugs'' are ironed out and they become available as common technologies to competitors.

Gaining this short-run advantage comes at a cost for the firm, however. To use a level of technology $A_t' \in [A_t, A_{f,t}]$, the firm incurs a cost of adopting the new technology, which is increasing and convex in the distance between A_t and A_t'. This cost captures the firm's outlays for training workers in the new technology, fixing the aforementioned ''bugs'' etc. that will allow the full potential of the new technology to be realized today before it is discovered and ironed out by competing firms. We assume that the cost of adoption takes the following form:

$$C(A_t, A_t') = \begin{cases} \frac{A_t}{2}\left(\frac{A_t'}{A_t} - 1\right)^2 & \text{if } A_t' > A_t, \\ 0 & \text{if } A_t' \leq A_t. \end{cases}$$

Since our analysis will focus on balanced growth paths (BGP) in which the growth rate $x = (A_t'/A_t) \leq \lambda$ is constant, whenever there is no ambiguity we drop time subscripts from A_t, A_t' and $A_{f,t}$. If A is viewed in units of machines, the cost function implies that along a BGP the cost of retooling each machine with the new technology, $C/A = \frac{1}{2}(x-1)^2$ is constant.[22]

3.2. Households

There is a measure one of two-period lived agents born in each period. We envision a model period to last roughly 20 years, which may serve as further justification for the assumption of perfect spillover of new technologies after one model period.[23]

We assume that there are no international spillovers of technology. If there are such spillovers, European technology would catch up to the US technology with whatever lag is assumed for the spillover. Data does not seem to support such automatic spillovers. Even with a mature technology such as personal computers, Microsoft data shows that in the United States 90 percent of white-collar workers use them, whereas only 55 percent in Western Europe do so. The International Data Corporation reports that the US market for PCs grew 15 percent in 1996, while the Western European market grew only by 7.1 percent. (See the article, ''Europe's Technology Gap is getting Scary,'' in the March 17, 1997, issue of *Fortune*.)

21 More formally, let $a_t'(i)$ denote the technology choice of adopting firm $i \in [0,1]$ and $A_t' = \int a_t'(i)di = A_{t+1}$ denote the common practice. Since firms are identical and will have a unique solution to their maximization problem, it follows that (a) every firm perceives $A_{t+1} = A_t'$ to be unaffected by its choice of $a_t'(i)$ and (b) $a_t'(i) = A_t' = A_{t+1}$. Thus in the main text we do not explicitly distinguish between $a_t'(i)$ and A_t' and let A_t' denote the technology adoption decision of a representative adopting firm.

22 The modeling choice of not making the cost of adoption depend directly on the measure of the labor force with general education appears to be a conservative one. Our results are likely to be strengthened if ''skilled'' labor is required to adopt new technologies.

23 Atkeson and Kehoe (2001), for instance, provide evidence that the main diffusion of electricity in US manufacturing establishments occurred over the 20 years from 1899 to 1919.

3.2.1. Education Choices

An agent is born with an ability $a \in [0,1]$ for higher education, which is distributed uniformly across the population; that is, according to the cumulative distribution function $F(a) = a$. In the first period of her life each agent has to choose between general education g and vocational education v. There is a utility cost for obtaining general education, $e(a)$, which is strictly decreasing in a. This captures the greater difficulty in learning conceptual material, cost of longer duration of education, lower subsidies relative to vocational training, etc. Once the education choice $i \in \{g, v\}$ has been made, it is irreversible until agents die.

3.2.2. Skill Accumulation

In the second period of an agents' life workers have a skill level for her current occupation of $H \in \mathscr{H} = \{1, h\}$. We assume that workers with vocational education can only work in the non-adopting sector and have job-specific skill level $h > 1$ for working in that sector. Workers with general education, in the second period of their life, can only work in the adopting sector and have skill level $H = 1$ with probability $T_l \in (0, 1)$ and $H = h$ with probability $1 - T_l$. Let

$$E_h = h - T_l(h - 1) < h,$$

denote the expected skill level of an agent with general education in the second period of its life. We assume a law of large numbers so that T_l is also the deterministic fraction of the population with general education that has skill level $H = 1$.[24]

Our assumption captures the job-readiness that vocational education imparts for the technology *currently* in use, whereas agents with general education face the possibility of a job-specific productivity loss when operating a new technology. Obviously agents have to be compensated for their lower expected skill level in the second period of their life when choosing general education; this happens through two channels: higher wages in the adopting sector and (possibly) higher direct education subsidies. Restricting agents with vocational education to work in the non-adopting sector and agents with general education

24 We could have directly assumed a lower productivity for those with general education in the adopting sector, instead of introducing the probability T_l of a loss in job-specific skill brought about by the new technology. While such an assumption would suffice for most of our purposes, explicitly identifying the probability of loss allows us to state Lemma 2, which deals with an increase in the skill-risk of new technologies. It also allows us, in Section A.4, to introduce the probability of skill loss for vocationally educated agents and provide sufficient conditions to justify our assumption that such agents work only in the non-adopting sector. And in Section 5.4, we argue differences in this probability can indirectly capture differences in the education system between the United States and Europe. Finally, it allows us to explicitly identify the cost (apart from the utility cost e) of working in the adopting sector, namely the risk of a skill loss arising from a mismatch with the new technology. Our cost thus differs from *resource* costs of moving, which are typically used to capture impediments to sectoral mobility and worker reallocation.

in the adopting sector is not crucial for our analysis. In Section A.4 we give sufficient conditions that make it optimal for v-agents to choose the non-adopting sector and for g-agents to choose the adopting sector.[25]

3.2.3. Endowments and Preferences

A newborn household of type a has preferences over stochastic consumption in the second period of her life. The only endowment the household has is one unit of time in each period that is used for education in the first and supplied to the labor market in the second period. An agent who chooses vocational education consumes $c_t = W_{n,t}h$ in the second period, whereas an agent with general education consumes

$$c_t = \begin{cases} W_{a,t} & \text{with probability } T_1, \\ W_{a,t}h & \text{with probability } 1 - T_l. \end{cases}$$

Households maximize:

$$U(c) = E_t \log(c_{t+1}) - I_g \log(e(a)),$$

by choosing the type of education, where $I_g = 1$ if the household chooses to obtain general education and 0 otherwise. The expectation E_t is taken with respect to the underlying stochastic process governing skill levels for agents with general education.[26]

3.3. Recursive Competitive Equilibrium

The aggregate state of this economy is given by the current level of technology A, the technology frontier A_f, and the cross-sectional distribution of workers over their education levels. Let μ_i denote the fraction of the work force with education $i \in \{g, v\}$ in the second period of their life, and let $\mu = (\mu_g, \mu_v)$. The aggregate state is then

25 An earlier version of this paper, available at http://siepr.stanford.edu/papers/pdf/01–35.pdf, demonstrates that the same qualitative results as in the current paper can be shown to hold in a more complicated model where agents face repeated productivity shocks and choose the sector to work in every period. CERGE-EI (1997, VII.2) reports that the age-wage profile for agents with vocational education in the Czech Republic is very flat, while the profile for those with university education starts around the same wage, but shows a steep growth with age. Similar differences are also reported for Canada by Allen (1998). This lends some credibility to our assumption that vocationally educated agents work in the non-adopting sector and do not experience the steep wage growth one would expect in an environment where technology changes rapidly.

26 Note that we abstract from time discounting by the households. Obviously our formulation of preferences, and hence the ensuing analysis is equivalent to having households discount the future and re-scaling the cost of education.

While a single working period precludes us from connecting the volatility of wages of the generally educated agents to its empirical counterpart, we can assert that if perfect insurance is provided to these agents so as to guarantee the certainty equivalent of the expected utility from wages, thereby eliminating all risk, their education decision would be unaffected.

given by $z = (A, A_f, \mu)$.[27] From our assumptions about the properties of $e(a)$ it is also clear that there exists a cutoff level $a^*(z) \in [0, 1]$ such that all agents with ability $a(z) \geq a^*(z)$ will choose to obtain general education ($I_g = 1$), whereas all agents with $a(z) < a^*(z)$ will choose to obtain vocational education ($I_g = 0$). The cutoff agent $a^*(z)$ is exactly indifferent between general education and vocational education; that is[28]

$$T_l \log(W_a(z)) + (1 - T_l) \log(W_a(z)h) - \log(e(a^*(z))) = \log(W_n(z)h).$$

Here $W_n(z), W_a(z)$ are wages per efficiency unit of labor in the adopting and non-adopting sectors, respectively. Let $\eta_v(z)$ denote the fraction of newborn agents deciding to get vocational education and $\eta_g(z)$ denote the fraction deciding to obtain general education; given the threshold ability $a^*(z)$ and a uniform ability distribution, these fractions are $\eta_v(z) = a^*(z)$ and $\eta_g(z) = 1 - a^*(z)$, respectively.[29]

We omit a formal definition of a recursive competitive equilibrium, since it is standard. Moreover, our focus is on the balanced growth path, which is defined precisely below.

3.4. *Balanced Growth Path*

A balanced growth path is defined to be a recursive competitive equilibrium for which all elements of the equilibrium, normalized by the current level of technology in an appropriate fashion, are constant. Since growth in this economy is driven exclusively by the adoption of new technologies, the growth rate along a balanced growth path is given by $x \equiv A'/A$. We normalize wage per skill unit as $w_n = W_n/A$ and $w_a = W_a/A$. The normalized firm maximization problems become:

$$\Pi_n = \max_{H \geq 0} H^\theta - w_n H, \tag{2}$$

$$\Pi_a = \max_{H \geq 0, 1 \leq x \leq \bar{x}} xH^\theta - w_a H - \frac{1}{2}(x - 1)^2, \tag{3}$$

where $\bar{x} = (A_f/A)$ is the maximal growth rate of technology that the adopting firm can choose. That is, the adopting firm's problem on the BGP now involves a choice of the growth rate of technology rather than its level. As for the workers, their expected utility in the second period of life is given by the two numbers

---

27 Note that an agent's ability level a will only affect her education decision in the first period of her life, but not subsequent consumption levels (other than via her education).

28 We shall later make assumptions to guarantee an interior $a^* \in (0, 1)$.

29 Given a state $z = (A, A^f, \mu)$ today, the state $z' = \Phi(z) = (A', A'_f, \mu')$ tomorrow is determined as follows. The frontier evolves exogenously, $A'_f = \lambda A_f$. Given the endogenously determined technology adoption function $A'(z)$ of adopting firms we have $A' = A'(z)$. Finally, next period's distribution over types, μ' is implied by today's education decision, that is,

$$\mu'_g(z) = \eta_g(z), \quad \mu'_v(z) = \eta_v(z).$$

$$v_v = \log(w_n h),$$
$$v_g = T_l \log(w_a) + (1 - T_l)\log(w_a h). \tag{4}$$

The BGP cutoff level a^* then satisfies the following indifference condition that governs educational choice:

$$v_g - v_v = \log(e(a^*)). \tag{5}$$

Finally, in a BGP the cross-sectional distribution over education and skill level μ is constant over time, that is, $\mu = \mu' = \bar{\mu}$ with

$$\bar{\mu}_g = \eta_g = 1 - a^*,$$
$$\bar{\mu}_v = \eta_v = a^*. \tag{6}$$

We therefore have the following definition.

Definition 1 *A balanced growth path consists of values* (v_g, v_v)*, labor supplies* (H_n^s, H_a^s)*, labor demands* (H_n^d, H_a^d) *and a growth rate of technology x, wages* (w_n, w_a)*, a cutoff ability level* a^* *and an invariant distribution* $\bar{\mu} = (\bar{\mu}_g, \bar{\mu}_v)$ *such that:*

1. *Given* (w_n, w_a) *the values* (v_g, v_v) *satisfy equation (4).*

2. *Given* (w_n, w_a)*,* H_n^d *solves (2) and* (x, H_a^d) *solve (3).*

3. $H_n^d = H_n^s$*; and* $H_a^d = H_a^s$*.*

4. *The cutoff* a^* *satisfies (5).*

5. *The distribution* $\bar{\mu} = (\bar{\mu}_g, \bar{\mu}_v)$ *satisfies (6).*

We are interested in how different educational policies affect the attainment of general education, and hence the growth rate of the economy along the BGP, as the speed of technological advancement, λ, increases.

4. Analysis of the BGP

We first outline the steps in our strategy for characterizing the BGP; the applicable subsections and figures are given within parentheses:

- Solve the firms' problems to obtain the relative labor demand function $H_a^d/H_n^d(w_a/w_n)$ and technology adoption schedule $x(\eta_g)$ from the problem for adopting firms (Section 4.1).

- Solve for the households' education decision to obtain relative labor supply functions $H_a^s/H_n^s(w_a/w_n)$. Combine with relative labor demand function $H_a^d/H_n^d(w_a/w_n)$ to characterize labor market equilibrium and to derive the ''education schedule'' $x^s(\eta_g)$ (Section 4.2).

- Combine $x(\eta_g)$ and $x^s(\eta_g)$ to solve for BGP η_g^* and x^* and characterize its properties (Section 4.3, Figure 1).

- Characterize how balanced growth and the education allocation changes with subsidies for general education, s (Section 5.2, Figure 2).

- Perform comparative statics with respect to the speed of technological innovation λ, and show how the results vary with education policy s (Section 5.3, Figure 3).

- Characterize the optimal education policy (Section 6, Figure 4).

We now consider each of the above steps in detail.

4.1. *Firms, Labor Demand and Technology Adoption*

For a given wage in the non-adopting sector w_n the labor demand of firms in that sector is given by, $H_n^d(w_n) = (\theta/w_n)^{1/(1-\theta)}$, and profits are obtained as, $\Pi(w_n) = (\theta/w_n)^{\theta/(1-\theta)}(1-\theta) > 0$. For the adopting sector we first solve for the conditional labor demand as a function of the wage w_a, and the growth rate, x, as:

$$H_a^d(w_a; x) = \left(\frac{\theta}{w_a}x\right)^{1/(1-\theta)}, \tag{7}$$

where $x = A'/A$ is the growth rate of technical progress chosen by firms.

In order to guarantee concavity of the objective function in the critical range and ensure the first order condition is sufficient, we make

Assumption 1 $\theta < \frac{1}{2}$.

Using the conditional labor demand function in the objective function we can rewrite the maximization problem of the adopting firm as:[30]

30 Given our earlier assumption that the economy starts out at the frontier, on a BGP we have $\bar{x} = \lambda$, or the constraint $x \leq \bar{x}$ is not binding.

$$\max_{1 \le x \le \bar{x}} x^{1/(1-\theta)} \left(\frac{\theta}{w_a}\right)^{\theta/(1-\theta)} (1-\theta) - \frac{1}{2}(x-1)^2$$
$$= \max_{1 \le x \le \lambda} x^{1/(1-\theta)} \left(\frac{\theta}{w_a}\right)^{\theta/(1-\theta)} (1-\theta) - \frac{1}{2}(x-1)^2.$$

The first-order condition for this problem is (see the appendix for further details; the constraint $1 \le x$ is never binding and hence neglected)

$$\left(\frac{x\theta}{w_a}\right)^{\theta/(1-\theta)} \ge x-1$$
$$= \text{if } x < \lambda. \tag{8}$$

This first-order condition can be simplified. Use (7) and the equilibrium condition in the labor market to obtain

$$\eta_g E_h = \left(\frac{\theta x}{w_a}\right)^{1/(1-\theta)}.$$

Substituting back into (8) yields

$$\left(\eta_g E_h\right)^{\theta} \ge x-1$$
$$= \text{if } x < \lambda,$$

which is an equation in the two endogenous variables (x, η_g). The technology adoption schedule of the adopting firm, as a function of the composition of the labor force η_g, is thus given as

$$x(\eta_g) = \min\{\lambda, 1 + (\eta_g E_h)^{\theta}\}. \tag{9}$$

The technology adoption decision x of the adopting firms is a weakly increasing function of the fraction of the population with general education, since either technology adoption is only constrained by the available technology λ (in which case x is independent of η_g), or an increase in share of agents with general education η_g drives wages in the adopting sector down and thus makes faster technology adoption profitable.

Define $\bar{\eta}_g = (\lambda - 1)^{1/\theta}/E_h$ as the minimal fraction of generally educated agents for which maximal growth occurs. We make the assumption that allows for the possibility of maximal growth.

Assumption 2 $\bar{\eta}_g = \frac{(\lambda-1)^{1/\theta}}{E_h} < 1$.

Finally, we can compute equilibrium profits of the adopting firm (and hence consumption of its owner), as:

$$\Pi(\eta_g) = \begin{cases} \lambda^{1/(1-\theta)}\left(\frac{\theta}{w_a}\right)^{\theta/(1-\theta)}(1-\theta) - \frac{1}{2}(\lambda-1)^2 & \text{if } \eta_{\mathrm{g}} \geq \eta_{\mathrm{g}}, \\ \left[1+\left(\eta_g E_h\right)^{\theta}\right]^{1/(1-\theta)}\left(\frac{\theta}{w_a}\right)^{\theta/(1-\theta)}(1-\theta) - \frac{1}{2}(\eta_g E_h)^{2\theta} & \text{if } \eta_{\mathrm{g}} < \eta_{\mathrm{g}}. \end{cases}$$

As λ increases, $\bar{\eta}_g$ increases, and thus the education interval over which maximal growth occurs, decreases. Intuitively, higher net profits are needed to make it worthwhile for firms to adopt technologies at the new (higher) maximal rate. But this requires lower wages in the adopting sector, which in turn demands a larger share of the population be generally educated and supply their labor services to that sector. As a prelude to our discussion below, note that therefore Europe, having a lower share of the labor force with general education, may fall behind in growth when the speed of available technologies, λ, increases.

For further reference we note that, as a function of x, relative labor demand is given by

$$\frac{H_a^d}{H_n^d} = \left(\frac{xw_n}{w_a}\right)^{1/(1-\theta)}. \tag{10}$$

Again from the labor market equilibrium we thus have

$$\frac{\eta_g E_h}{(1-\eta_g)h} = \left(\frac{xw_n}{w_a}\right)^{1/(1-\theta)}, \tag{11}$$

$$x = \frac{w_a}{w_n}\left(\frac{\eta_g E_h}{(1-\eta_g)h}\right)^{1-\theta}. \tag{12}$$

4.2. The Household Education Decision

In this section, we discuss how the equilibrium fraction of agents with general education, η_g, is determined. Recall that η_g is related to the threshold ability level a^*, above which all agents obtain general education and below which all agents obtain vocational education, by $a^*(\eta_g) = 1 - \eta_g$. Write (5) as follows in order to obtain the equilibrium threshold ability as a solution to the following equation:[31]

$$v_g(\eta_g) - v_v(\eta_g) = \log(e(a^*(\eta_g))). \tag{13}$$

This captures the fixed point problem induced by the education decision—newborn agents anticipate a certain fraction of the work force with general education, η_g, which determines the high-tech wage premium, and thus the value to getting general education; their

31 Note that even though the non-normalized value functions V_g and V_v grow over time, their difference is stationary and equal to the difference $v_v - v_g$, due to the assumption of logarithmic utility.

decision to obtain one or the other type of education has to be consistent with the conjectured η_g.

We now make a functional form assumption for the cost of obtaining general education.

Assumption 3 *The function* $e : [0,1] \to \Re_+$ *is given by:* $e(a) = \frac{1}{a}$.

With this assumption we see that for the ablest agents $(a = 1)$ the utility cost of obtaining general education, $\log(1/a)$ equals to 0, whereas for the least able agents this cost becomes prohibitively high. Then the right-hand side of equation (13), as a function of η_g, becomes $\log[e(a^*(\eta_g))] = \log[e(1-\eta_g)] = \log(1/1-\eta_g) = -\log(1-\eta_g)$. This is a strictly increasing function of η_g, approaching 0 when $\eta_g \to 0$ and approaching $-\infty$ as $\eta_g \to 1$.

Using equation (4), the utility differential is explicitly given as

$$(v_g - v_v)\left(\frac{w_a}{w_n}\right) = \log\left(\frac{w_a}{w_n}\right) - T_l \log(h). \tag{14}$$

Combining costs and utility differentials we have

$$\log\left(\frac{w_a}{w_n}\right) - T_l \log(h) = -\log(1-\eta_g),$$

or

$$\frac{w_a}{w_n} = \left(\frac{1}{1-\eta_g}\right) h^{T_l}. \tag{15}$$

Combining this equation with equation (12) yields the education schedule

$$\begin{aligned} x^s(\eta_g) &= \frac{w_a}{w_n}\left(\frac{\eta_g E_h}{(1-\eta_g)h}\right)^{1-\theta} \\ &= h^{T_l}\eta_g^{1-\theta}\left(\frac{1}{1-\eta_g}\right)^{2-\theta}\left(\frac{E_h}{h}\right)^{1-\theta}. \end{aligned} \tag{16}$$

The positive relation between growth and the share of agents with general education arises for the following reason. In order to induce a higher fraction η_g of the population to opt for general education, a higher growth rate x is needed; a higher growth rate, x, is associated with higher relative labor demand of the adoption sector and thus a higher wage differential.

4.3. Equilibrium Growth and Education

Using the technology adoption and the education schedule (9) and (16) one can prove the following:

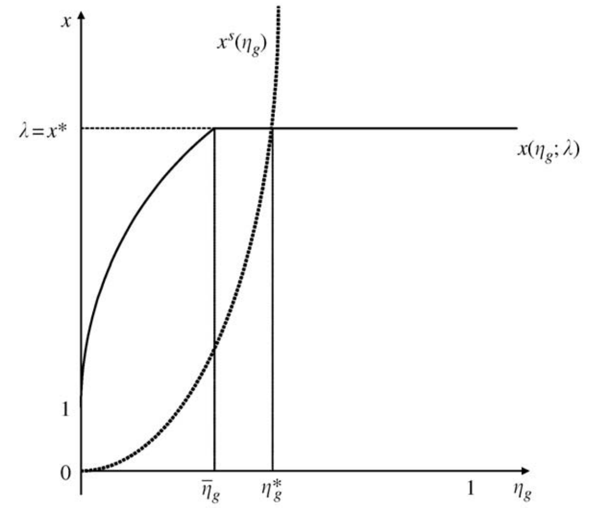

Figure 1. Equilibrium growth rate and education allocation.

Lemma 1 Suppose the assumptions made above are satisfied. Then there exists a unique BGP equilibrium $\eta_g^* \in (0, 1)$.

Proof. Both (9) and (16) are continuous functions on (0,1). Furthermore $x^s(0) = 0$, $x^s(1) \rightarrow \infty$, $x(0) = 1$ and $x(1) < \infty$, thus by the intermediate value theorem a solution exists. The proof of uniqueness is deferred to the appendix.[32] ■

For a graphical representation of this result, see Figure 1.[33]

The uncertainty inherent in the task-specific productivity of new technology is an important determinant of the decision to obtain general education. It is therefore instructive to analyze how equilibrium growth rates and education allocations change as

32 Existence and uniqueness of a BGP can be shown under a considerably weaker version of assumption 3. Instead of making the functional form assumption $e(a) = \frac{1}{a}$ it is sufficient to assume that $e(a)$ is differentiable and strictly decreasing and strictly convex in $a \in (0, 1)$, with $e(1) < \infty$ and $e(0) > 0$. The proof of the lemma goes through unchanged; however, since some of the results below cannot be shown without a particular functional form assumption, we shall maintain assumption 3 throughout.

33 We note that $x^s(\eta_g)$ may not necessarily be strictly convex as drawn, but that, as shown in the proof, the intersection is unique and the comparative statics presented below remain valid go even if $x^s(\eta_g)$ is not strictly convex on the entire interval $[0, 1]$.

With this characterization of equilibrium we can, in the appendix, provide sufficient conditions under which it is optimal for agents with general education to work in the adopting sector and for agents with vocational education to work in the non-adopting sector (rather than to assume that they have to work in a particular sector, as done in the main text for simplicity).

productivities in the adopting sector become more risky; the parameter T_l is handy for this analysis. In Section A.5 we prove the following:

Lemma 2 A mean-preserving increase in the spread of productivities $H \in \mathscr{H}$, which leaves the expected productivity E_h unchanged, leads to a (weak) decline in the equilibrium growth rate x^* and a (strict) decline in the fraction of the population obtaining general education, η_g^*.

Intuitively, as working with new technology becomes a riskier proposition, fewer agents find it worthwhile to obtain general education. Adopting firms, faced with a lower supply of appropriately skilled workers, scale back the rate of technology adoption; lower equilibrium growth results.

5. Comparing US and European Policies

In Section 2, we presented evidence on European educational policies that favor vocational education over general education, while in the United States the situation is the reverse. In this section, we study the effects of this policy difference on growth rates of and the growth gap between the two regions, as implied by our model.

5.1. *Policy Differences*

We will denote by G the normalized amount of government expenditure available for subsidizing *both* types of education. (In the original problem, since G will be multiplied by A, government subsidies grow at the rate of technology.) Let s_v denote the per student subsidy given to a vocational education student and let s_g denote the per student subsidy given to a general education student. Then the government resource constraint, given a uniform ability distribution and an ability threshold a^* is:

$$a^* s_v + (1 - a^*) s_g = G, \tag{17}$$

with $s_v, s_g > 0$. Even though we do not explicitly model it, one may imagine the government collecting taxes to finance education, through a proportional labor income tax. Given logarithmic preferences, it is the ratio of wages that matters for the education decision, and a proportional tax would not affect this ratio, and therefore our analysis.

We consider a revenue neutral experiment; that is, assume that G is the same for the United States and Europe. Define $s = s_g/s_v$ as the ratio of subsidy to general and vocational education. We now assume that agents have preferences, in the first period of their lives, given by

$$I_g(-\log(e(a)) + \log(s_g)) + (1 - I_g)\log(s_v),$$

that is, if they choose general education, they incur disutility $\log(e(a))$ and utility $\log(s_g)$

from the educational subsidy, and if they choose vocational education they obtain utility $\log(s_v)$ from the educational subsidy.[34]

Given this formulation the cost of obtaining general, as opposed to vocational education, is

$$\log\left(\frac{1}{1-\eta_g}\right) - \log(s) = \log\left(\frac{\eta_g}{1-\eta_g} * \frac{\frac{G-s_g\eta_g}{1-\eta_g}}{s_g}\right),$$

and equation (16) now becomes

$$x^s(\eta_g) = h^{T_t}\eta_g^{1-\theta}\left(\frac{1}{1-\eta_g}\right)^{2-\theta}\left(\frac{E_h}{h}\right)^{1-\theta}\left(\frac{\frac{G-s_g\eta_g}{1-\eta_g}}{s_g}\right), \tag{18}$$

with policy variable s_g, or alternatively

$$x^s(\eta_g) = \frac{h^{T_t}}{s}\eta_g^{1-\theta}\left(\frac{1}{1-\eta_g}\right)^{2-\theta}\left(\frac{E_h}{h}\right)^{1-\theta}, \tag{19}$$

with policy variable $s = s_g/s_v$. Note that, since we treat G as fixed, the levels of s_v and s_g have to adjust to guarantee government budget balance. We assume that s is restricted to be set in such a way as to guarantee $s_v, s_g > 0$. Evidently, the $x^s(\eta_g)$-schedule tilts to the right around the point $(\eta_g, x) = (0, 0)$ as s increases, since higher differential subsidies towards general education, for a given growth rate x, make more agents choose general education; this gives rise to the results in the next section.

5.2. *Growth Rates and Growth Gaps with Different Policies*

We model the stronger US focus on general education to mean, in the context of our model, that $s^{\text{US}} > s^{\text{EUR}}$. Denote by $\Delta(\lambda)$ the gap between the potential growth rate of the economy and the actual rate, when the frontier evolves exogenously at rate λ. Formally, the growth gap is $\Delta(\lambda) \equiv \lambda - x^*(\lambda)$, where x^* is the BGP growth rate associated growth rate λ for the frontier technology. We have the following:

Proposition 1 *Suppose the assumptions made above are satisfied. Then:*

1. $\eta_g^{\text{US}} > \eta_g^{\text{EUR}}$.
2. *Either* $x^{\text{US}} = x^{\text{EUR}} = \lambda$ *or* $\lambda \geq x^{\text{US}} > x^{\text{EUR}}$.
3. *Either* $\Delta^{\text{US}}(\lambda) = \Delta^{\text{EUR}}(\lambda) = 0$ *or* $\Delta^{\text{EUR}}(\lambda) > \Delta^{\text{US}}(\lambda) \geq 0$.

---

34 What is crucial for our results is not so much the particular functional form of utility from the education subsidy, but the separability between utility from the subsidy and from consumption.

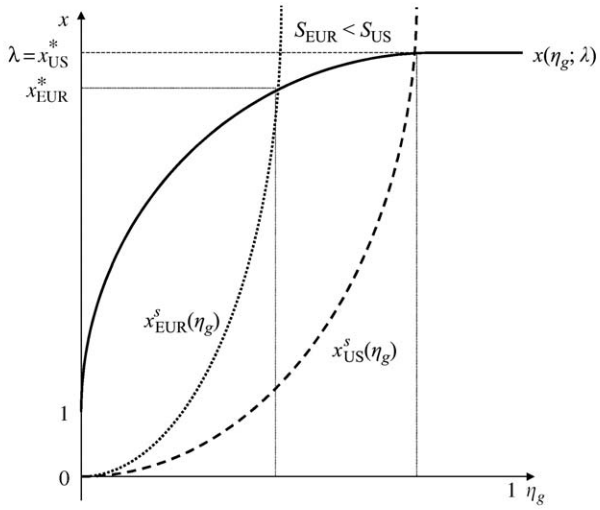

Figure 2. Comparing US and European Education Policies.

Proof. This follows directly from the fact that the $x^s(\eta_g)$-schedule tilts down around the point $(\eta_g, x) = (0, 0)$ as s increases. ■

The first statement asserts that the fraction of workers with general education is higher in the United States. The second statement asserts that either the United States and Europe both grow at the potential rate λ, or the United States grows at a strictly higher rate. If both grow at the maximal rate, the growth gap of both countries with respect to the potential is zero; otherwise the growth gap of Europe is strictly higher. The difference between the United States and Europe is illustrated in Figure 2.

This proposition is evidently consistent with the observation in Cummings and Violante (2002, pp. 246–247): ''The growth rate of average practice moves nearly one-for-one with the technological gap and is correlated with measures of adaptable labor (such as the shares in the labor force of college graduates and of young workers).''

5.3. Effect of an Increase in Speed of Innovation

We now analyze whether an increase in the rate of technological progress widens the growth gap between the United States and Europe. We are thus interested in comparative statics with respect to λ.[35] We have the following proposition:

35 This can be viewed as a low-frequency version of Ljungqvist and Sargent's (1998) high-frequency thought experiment of increasing economic turbulence to study its effect on European unemployment.

Proposition 2 *Equilibrium general education attainment* η_g^* *and growth* x^* *increases with* λ: $d\eta_g^*(\lambda)/d\lambda \geq 0$ *and* $dx^*(\lambda)/d\lambda \geq 0$. *The increase is strict if and only if* $\eta_g^*(\lambda) \geq \bar{\eta}_g(\lambda)$.

Proof. The proof of this and the following two propositions follow directly from the fact that the $x^s(\eta_g)$ schedule is independent of the potential growth rate λ and the $x(\eta_g, \lambda)$ schedule shifts up one for one with λ only in the region where $\min\{\lambda, 1 + (\eta_g E_h)^\theta\} = \lambda$. ■

The higher λ increases the demand for labor in the adopting sector and thus the high-tech wage premium w_a/w_n in equilibrium; this increases the incentive to acquire general education.

Proposition 3 $(d\Delta(\lambda)/d\lambda) \geq 0$. *The increase is strict if and only if* $\eta_g^*(\lambda) \geq \bar{\eta}_g(\lambda)$. *Almost surely* $(d\Delta(\lambda)/d\lambda) \in \{0, 1\}$.[36]

That is, the gap in the growth rate of an economy relative to the potential growth rate λ, is itself (weakly) increasing in λ. This leads us to the central proposition of the paper.

Proposition 4 $(d\Delta^{\mathrm{EUR}}(\lambda)/d\lambda) \geq (d\Delta^{\mathrm{US}}(\lambda)/d\lambda)$ *with strict inequality if* $x^{\mathrm{US}} = \lambda > x^{\mathrm{EUR}}$.

Though the proposition is phrased in terms of the growth gap of each region relative to the (new) potential growth rate, its implication for the gap in growth rates *between* the two regions is obvious. As the rate of change of available technologies, λ, increases, the fraction of agents with general education above which maximal growth occurs, $\bar{\eta}_g$ increases and Europe may fall out of the maximal growth region, whereas the United States may continue to be constrained only by the available technology.

As discussed in Section 2.2.1, the rate at which new technologies arrived increased by the 1980s, reaching its peak in the 1990s. Our model suggests that the United States, with a much higher fraction of its work force possessing general education was able to adopt these available technologies at a faster rate than Europe could. Even if both regions adopt technology at faster rate, our model predicts that there may be a gap in their rate of adoption, consistent with the data in Table 1. This effect is illustrated in Figure 3. The United States continues to be constrained only by the availability of technologies, while Europe potentially falls behind.[37]

---

36 ''Almost surely'' is intended to mean, for the measure one of parameter combinations for which λ is not equal to the unique threshold $\bar{\lambda}$ corresponding to $\eta_g^*(\bar{\lambda}) = \bar{\eta}_g(\bar{\lambda})$. The number $\bar{\lambda} > 2$ uniquely solves the equation

$$\frac{(\lambda - 1)^{(2-\theta)/\theta}}{\lambda} = h^{1-T_l} E_h^{1-\theta} > 1.$$

37 We have been silent on transitions and focussed on the change in balanced growth that arises from an unexpected permanent change in λ. In a technical appendix, available from the authors on request, we characterize the transition from the λ – BGP to the λ' – BGP. The transition path can take one of the following forms: (1) An immediate jump to the new BGP with growth rate λ' if the η_g at the original

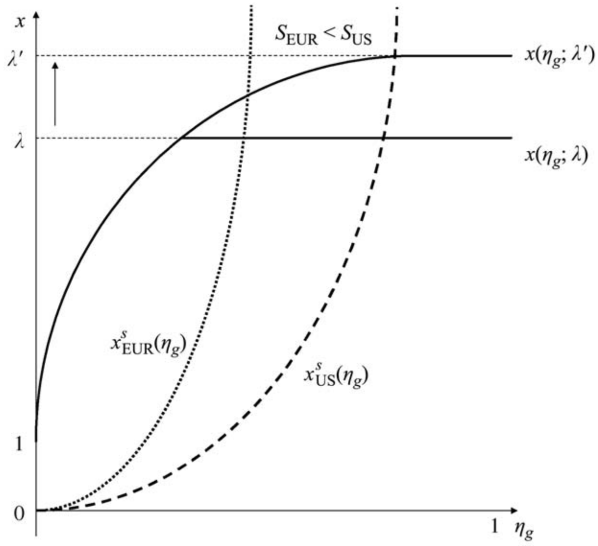

Figure 3. An Increase in λ.

Workers with general skills in the US benefit from the faster adoption of new technology to a larger extent than their brethren in Europe, as the next proposition shows.

Proposition 5 *Let* $s^{\text{US}} > s^{\text{EUR}}$. *Then*

$$\frac{d\log\left(\frac{w_a}{w_n}(s^{\text{US}},\lambda)\right)}{d\log\lambda} \geq \frac{d\log\left(\frac{w_a}{w_n}(s^{\text{EUR}},\lambda)\right)}{d\log\lambda},$$

with strict inequality if $x(s^{\text{US}},\lambda) = \lambda$.

The proposition implies that the increase in the speed of technology induces an increase in the wage premium for general education in both regions, but with a larger increase predicted for the US (strictly so, if the US grew at maximum speed in the 1970s). Strictly speaking, the wage premium of our model is between workers with general and vocational education, rather than the much-documented premium between workers with college and

BGP is large enough, which is the most likely scenario for the United States. (If the orginal η_g is not large enough but the new BGP is λ', the transitional growth rate overshoots λ' and eventually settles down to λ'.) Or (2) a monotonic increase to a BGP growth rate less than λ', if the starting η_g is lower, which is the likely situation for Europe. Therefore, including the transition does not alter the fact the United States has a strictly higher growth rate and general education attainment; the growth gap relative to Europe could actually be higher along the transition than at the new BGP.

school education.[38] Nevertheless, it is interesting that the above prediction, which was *not* one of the main empirical targets of our model, is broadly consistent with the empirical evidence on the evolution of wage premia over time in different countries; for example, see Gottschalk and Smeeding (1997), and the observation in Cummings and Violante (2002, p. 247) that the ''technological gap may be a key determinant of wage inequality.''

5.4. Discussion

We have pointed to a new channel, namely the focus on general versus vocation education, as a potential determinant of US–Europe growth differences. We have simplified our model to capture the essence of this channel, while being fully aware that other channels might also be operative. However, even within this simple structure it is possible to discuss how other, related, channels would operate and interact with the education system.[39]

For instance, a high minimum wage in Europe is thought to be an impediment to the flexibility of firms and to technology adoption. Suppose the government mandates a minimum wage (normalized by the technological level) of $\underline{w}$ in the non-adopting sector. Since η_g is predetermined, so are the effective units of labor available in that sector, $(1-\eta_g)h$. This labor supply could well exceed the demand for labor at the minimum wage; therefore, we also assume that $\underline{w}$ is also the unemployment insurance that is provided to workers who are rationed out of jobs. Since wages are flexible in the adopting sector, the firm's adoption schedule continues to be given by (9). The minimum wage condition will bind in $[0, \widehat{\eta}_g]$, where

$$\widehat{\eta}_g \equiv 1 - \frac{1}{h}\left(\frac{\theta}{\underline{w}}\right)^{1/(1-\theta)}.$$

In this region, the household's education schedule is given by

$$x^s(\eta_g) = h^{T_l}\eta_g^{1-\theta}\left(\frac{1}{1-\eta_g}\right)(\underline{w}/\theta)(E_h)^{1-\theta},$$

which is larger than the original x^s given by (16).[40] In terms of Figure 1, the modified x^s schedule will lie above the original one in this region. Given the cushion of minimum wage and unemployment benefits, agents are induced into general education and working in the adopting sector only by higher adoption rates and wages. Condition (16) will continue to hold in $[\widehat{\eta}_g, 1]$. If $\underline{w}$, and thus $\widehat{\eta}_g$, are low, there will be no effect of the minimum

38 OECD (1997) provides the relative earnings of persons aged 25–64 for tertiary and non-university tertiary (vocational) categories (Table E4.1a). For the United States the general education wage premium is 1.46, and for Germany this ratio is slightly higher at 1.47.

39 Krueger and Kumar (2004) consider labor and product market regulations in addition to the education system in a calibrated framework to *quantify* the relative importance of the education system in explaining US–Europe growth differences.

40 Details can be found in the technical appendix, available from the authors on request.

wage on the equilibrium growth rate. However, for large values of these variables, it is possible that the intersection of the two schedules occurs in the binding region and growth and general education attainment are reduced, potentially from the maximal rate to a submaximal rate. This case is more likely to be relevant for Europe—where minimum wage levels are higher—and further widen the gap between the United States and European growth rates delivered by our model.

Consider another observation that is made about European education subsidies—it is more readily available to low ability students than it is in the United States. There are two ways this phenomenon can be viewed using the lens of our theory. If the less able students, who are attracted by the subsidy, graduate successfully from college and are employed by the adopting sector, European workers could be viewed as facing a higher skill-risk from new technologies. Assuming that the task-specific productivity of agents with general education in Europe is a mean-preserving increase in spread of those in the United States, Lemma 2 can be used to yield lower general education attainment and growth for Europe. Alternately, if such students just drop out and end up becoming workers in the non-adopting sector, one could interpret T_l as the probability of failure. If the quality of general education in the United States is assumed to be higher—the success probability exhibits a mean-preserving increase in spread in Europe—a growth difference between the two regions can again be derived. In terms of policy, one could capture this by a lower relative subsidy, s, for Europe. The resources spent on the low ability students only nominally count toward general education; given the eventual outcome they should really count as subsidies for other types of education. In this case, Proposition 1 would imply lower attainment and growth in Europe. While our model is flexible enough to permit these alternate interpretations, we prefer our approach based on education policy differences, which is both novel and well-grounded in the data.

6. Optimal Policies

While the previous section showed that a stronger focus on general education subsidies fosters growth, this need not mean that a growth-maximizing education subsidy policy is *optimal* from a social welfare perspective. In this section, we therefore characterize the socially optimal subsidy level. While other unmodeled factors could affect the optimality of policy, considering education policy in isolation should nevertheless shed light on the tradeoffs involved in allocating a limited education budget across different types of education.

6.1. The Government Objective Function

In order to analyze the optimal education policy a Ramsey government should follow, we first have to take a stand on the objective of such a benevolent government. This issue is not a trivial one in our model, since with two-period lived agents there are many generations to consider, and even within each generation there is a continuum of agents, indexed by ability $a \in [0, 1]$, who may potentially receive different Pareto weights in the government objective function. We assume that within each generation all agents receive equal weight in the social welfare functional and that the benevolent government discounts future generations at social discount factor $\beta \in [0,1)$. We also assume that the Ramsey government can perfectly commit to future policies and, in order to enable comparison with previous sections, we restrict the government to choose time-constant policies associated with BGP equilibria.

In the appendix we show that the objective function of the government, as a function of its policy choice $s = s_g/s_v \in (0, \infty)$ can be written as (absent constants that are irrelevant for maximization)

$$W(s) = -\ (2-\theta)\log(1-\eta_g(s)) - \eta_g(s) \\ - \log[\eta_g(s)s + (1-\eta_g(s))] + \frac{2\beta\log(x(s))}{1-\beta}, \tag{20}$$

where $\eta_g(s)$ and $x(s)$ are

$$x(s) = \frac{h^{T_l}}{s}\eta_g(s)^{1-\theta}\left(\frac{1}{1-\eta_g(s)}\right)^{2-\theta}\left(\frac{E_h}{h}\right)^{1-\theta}, \tag{21}$$

$$x(s) = \min\left\{\lambda, 1 + \left(\eta_g(s)E_h\right)^{\theta}\right\}, \tag{22}$$

the equilibrium growth rate and education allocation associated with subsidy level s. In contrast to a social planner the Ramsey government has to respect equilibrium behavior of all agents in the economy, given its selected policy s.[41]

The last term in the government objective function captures the effect that future generations obtain higher utility with higher growth rates; if the benevolent government does not value future generations, then $\beta = 0$ and this term disappears. The second to last term summarizes the welfare effects from the differential subsidies directly, whereas the first two terms stem from the utility of consumption, net of the disutility of obtaining general education.

6.2. *Characterization of Optimal Policies*

For what follows it is useful to define the minimal relative subsidy level for general education $\bar{s}(\lambda)$ that is required to generate maximal growth $x^* = \lambda$ in the BGP equilibrium. It is explicitly given as $\bar{s}(\lambda) = (\kappa/\lambda\bar{\eta}_g)\left(\bar{\eta}_g/(1-\bar{\eta}_g)\right)^{2-\theta} \in (0, \infty)$, a function that is strictly increasing in λ. Here $\kappa = E_h^{1-\theta}/(h^{1-\theta-T_l})$ is a constant.

41 Note that we also abstain from the analysis of a social planner's internalization of the technological spillover in order to focus on education policy analysis of a Ramsey government.

Exploiting the fact that for all higher subsidy levels $s \geq \bar{s}(\lambda)$, the growth rate remains constant at λ, we can show (by using (21) in (20)) and with the help of arguments spelled out in the appendix.[42]

Lemma 3

1. For all $s \geq \bar{s}(\lambda)$ we have $W'(s|s \geq \bar{s}) > 0$ for s < 1, $W'(s = 1|s \geq \bar{s}) = 0$ and $W'(s|s \geq \bar{s}) < 0$ for s > 1.

2. There exists a $\bar{\beta} \in (0, 1)$ such that for all $\beta \geq \bar{\beta}$ we have $W'(s|s < \bar{s}) > 0$ for all $s \in (0, \bar{s}(\lambda))$.

The first result immediately implies that the benevolent government should choose a higher subsidy for general education only to obtain maximal growth, that is $s^*(\lambda) \leq \max\{1, \bar{s}(\lambda)\}$. For the region $s < \bar{s}(\lambda)$, part 2 of the lemma argues that a high enough social discount factor makes growth so desirable that, as long as maximal growth is not reached, a higher subsidy level s is preferred, since it generates higher growth.

Therefore the optimal education subsidy s and its changes with λ depends crucially on whether maximal growth is attainable without higher subsidies for general education or not, that is, whether $\bar{s}(\lambda) \geq 1$. Note that this inequality is based purely on fundamentals, and is more likely to hold for large λ, all other things being equal. We shall assume that this condition is satisfied and state the following proposition:[43]

Proposition 6 *Suppose that $\bar{s}(\lambda) \geq 1$. Then there exists a $\bar{\beta} \in (0, 1)$ such that for all $\beta \geq \bar{\beta}$, the optimal solution to the government problem is $s^*(\lambda) = \bar{s}(\lambda) \geq 1$ and for $\lambda' > \lambda$, we have that $s^*(\lambda') > s^*(\lambda)$. Growth is maximal, that is, $x(s^*) = \lambda$.*

Proof. Follows directly from the previous lemma. ■

---

42 For the derivation of the lemma, note that from (21) and (22) it follows that

$$\lim_{s\to\infty} x(s) = \lambda, \quad \lim_{s\to\infty} \eta_g(s) = 1,$$
$$\lim_{s\to 0} x(s) = 1, \quad \lim_{s\to 0} \eta_g(s) = 0,$$

and $\eta_g(s)$ is a strictly increasing function, whereas $x(s)$ is increasing in s, strictly so, as long as $x(s) < \lambda$. Both functions are continuous in s. Therefore $W(s)$ is a continuous function in s, with $\lim_{s\to 0} W(s) = \log(\kappa)$ and $\lim_{s\to\infty} W(s) = (1 + \beta)/(1 - \beta)\log(\lambda) - 1$.

43 A second part of this proposition can be stated for the case in which $\bar{s}(\lambda) < 1$. More precisely, let $\lambda < \lambda'$ be such that $\bar{s}(\lambda) < \bar{s}(\lambda') < 1$. Then $s^*(\lambda) = s^*(\lambda')$ and $x(s^*(\lambda)) = x(s^*(\lambda'))$. Either $s^*(\lambda) = s^*(\lambda') = 1$ and growth is maximal or $s^*(\lambda) = s^*(\lambda') < 1$ and $x(s^*(\lambda)) = x(s^*(\lambda')) < \lambda$.

In this case, even without differential subsidies for general education maximal growth can be attained in the competitive equilibrium (that is, the potential growth rate is not too high). The optimal subsidy satisfies $s^* \leq 1$, and is independent of the potential growth rate of the economy.

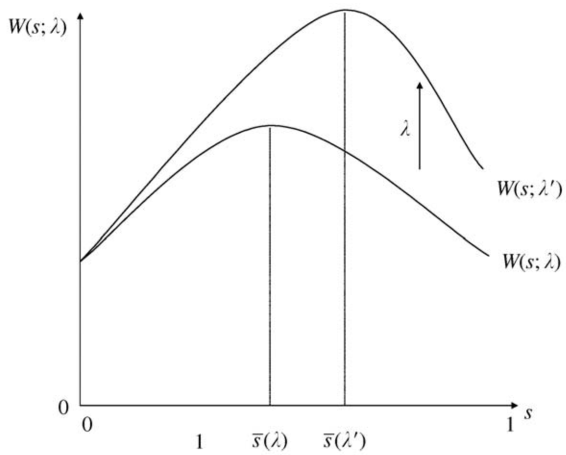

Figure 4. Optimal Subsidy *s*.

Figure 4 plots the Ramsey government objective function against the relative subsidy, under the assumption that the social discount factor β exceeds the threshold $\bar{\beta}$ in Lemma 3 and Proposition 6. It shows that under the assumption maintained in the proposition, the optimal subsidy level $s^*(\lambda)$ is strictly increasing in λ.

We interpret this result as follows. Under the assumption $\bar{s}(\lambda) \geq 1$ it is optimal for the benevolent government to provide greater incentives for obtaining general education in order to generate growth. If the government values future generations (and hence economic growth) sufficiently highly, then it is optimal to subsidize general education exactly to the point where maximal growth is assured (but not more).[44] The optimal subsidy is a strictly increasing function of the potential growth rate of the economy λ.

How does this proposition on optimal policies relate to the empirical observations discussed in Section 2 of the paper? Subject to the above-mentioned caveat on considering education policy in isolation, one possible interpretation is that when the growth rate of the available technology λ was low it might have been the case that the United States oversubsidized general education, whereas European policy was optimal. As λ increased to λ' in the 1980s and 1990s, and with it the optimal general education subsidy level (that is, $s^*(\lambda') = \bar{s}(\lambda')$) it is likely the US policy is optimal while the European policy (that is, $s < \bar{s}(\lambda')$) might not be. Therefore, in addition to the growth gap between the United States and Europe our model also suggests a recent welfare gap between the two regions.[45]

---

44 We need the condition on β in order to assure that it is in fact optimal for the Ramsey government to enact policies that assure maximal growth.

45 In this paper we do not explore the political-economic reasons for the persistence of a policy whose optimality is in doubt, but we view future research in this direction as particularly fruitful and interesting.

This discussion also shows that our model, by no means, implies that subsidizing general education to the maximal extent and pushing the economy to maximal growth at any cost is optimal.[46]

7. Conclusion

We have developed a growth model featuring an occupational advantage of general over vocational education, endogenous technology adoption by firms and educational decisions by households, to argue that two economies that grow at potential when the rate of technological progress is low, could diverge when this rate increases. Our analysis thus provides one possible explanation for the growth gap that Europe, which focusses on skill-specific education, has suffered since the 1980s relative to the United States, which focusses more on conceptual education. It also shows that education policies that were optimal for Europe in the 1960s and 1970s may have become suboptimal for the information technology age.

It must be emphasized that the use of BGP analysis is mostly an analytically convenient way to study the issue of slow European technology adoption. One could instead construct a steady state model and cast European catch-up or falling behind purely as a transitional issue, relying on numerical instead of analytical characterization. If educational reforms are instituted, such as the much discussed reforms to make German universities more competitive, then the growth gaps we have analyzed are necessarily transitional.[47] Indeed, one needs to be cautious about literally empirical mapping variations in general education policy to *permanent* growth rate differences; an analysis using a panel data set with shorter run growth rates and policy variables applicable for those shorter periods might be more appropriate.

While casual evidence suggests that manufacturing productivity growth is strongly correlated with the share of the work force with tertiary education (*European Competitiveness Report* 2001, Table IV.2), rigorous attempts to extend our analysis along quantitative dimensions are warranted. One possibility is to conduct a cross-country, cross-industry, econometric study to assess whether the acceleration in technology adoption rates has been particularly higher in the United States relative to Europe in those industries that have seen greater increases in available technologies. Using years of education as a proxy, cross-country growth studies have found only a weak effect of

46 Note that a social planner who is constrained to use resources G for ''subsidies'' (s_g, s_v) would optimally choose to equate these across agents, that is, $s^{SP} = 1$. It is also obvious that the planner equates consumption across agents and thus completes the insurance markets that are missing in the competitive equilibrium. Therefore the Ramsey government cannot implement fully socially optimal allocations; the second part of the previous proposition shows that at least the Ramsey education subsidy is socially optimal.

47 See, for instance, Hyde Flippo's, ''Can the German University be Saved?'' an online supplement (http://www.german-way.com), to *The German Way* (Passport Books), which reports a steep increase in the percentage of high school students earning the academic diploma that leads to college study in the city-state of Hamburg, and points to the emergence of private universities such as Universität Witten/Herdecke.

human capital in explaining growth. Our study points out that the *type* of education obtained, rather than the number of years of education *per se*, could have a crucial bearing on the rate of economic growth.[48] These are topics of ongoing research.

A. Appendix

A.1. Education Data

Table A1. Education indicators.

Country	% Upper Sec. in General	% Upper Sec. in Vocational	University Net Entry Rate	Non-university Tertiary Attainment	University Tertiary Attainment	Non-university Tertiary Return	University Tertiary Return
Austria	23	77	26	2	6		
Finland	48	52		9	12	11	15
France	47	53	33	8	11	18	14
Germany	23	77	27	10	13	17	11
Italy	28	72			8		10
Netherlands	30	70	34		22		11
Sweden	44	53		14	14	7	8
EU	42.4	57.6					
United States			52	8	25	9	13

Notes: Variable description and data sources (all measures are for 1995):
All data from Education at a Glance: OECD Indicators 1997, from specified tables.
% of students enrolled in upper secondary education in general and vocational streams: Table C3.2.
University net entry rate: Table C4.1.
Non-university tertiary (vocational) and tertiary attainment (% adult population): Table A2.1.
Non-university tertiary (vocational) and tertiary rates if return: Table E5.1.

48 Also see Murphy et al. (1991) in this regard.

Table A2. Education expenditures.

Country	Exp./GDP (Prim. + Sec.)	Exp./GDP (Vocational Tertiary)	Exp./GDP (Univ. Tertiary)	Exp. Per Student (Vocational Tertiary)	Exp. Per Student % of Per Cap. GDP (Vocational Tertiary)	Exp. Per Student (Univ. Tertiary)	Exp. Per Student % of Per Cap. GDP (Univ. Tertiary)
Austria	4.2	0.3	1.2	7,245	31	11,279	48
Finland	3.7	0.2	1.5	5,776	27	7,582	35
France	4.4	0.3	0.9	7,636	36	7,113	34
Germany	3.7	0.4	1	10,924	48	10,139	44
Italy	3.5	0.1	0.8	6,283	36	6,295	28
Netherlands	3.1		1.2	7,592	31	10,796	44
Sweden	4.5		1.7				
United States	3.7		2.3			19,802	61

Notes: Variable description and data sources (all measures are for 1998):
All data from Education at a Glance: OECD Indicators 2001, from specified tables.
Education expenditure as a % of GDP (all levels): Table B2.1c.
Expenditure per student (in PPP $): Table B1.1.
Expenditure per student as a % of per capita GDP: Table B1.2.
For Austria and Germany, non-university tertiary expenditure per pupil are presented under vocational tertiary; for other countries, expenditure per pupil in tertiary B is presented.

A.2. Further Details on the Firms' Problem

The first-order necessary and sufficient condition for the firm is

$$(x^*)^{\theta/(1-\theta)}\left(\frac{\theta}{w_a}\right)^{\theta/(1-\theta)} \geq x^* - 1$$
$$= \text{ if } x^* < \bar{x}.$$

Suppose there exists BGP with $x = \lambda$. Then

$$\bar{x} = \frac{A_f}{A} = \frac{A_f^{-1}}{A} * \frac{A_f}{A_f^{-1}} = 1 * \lambda = \lambda,$$

where $A_f^{-1}/A = 1$ because in a BGP with growth rate λ the actual level of technology must equal the potential level at each point of time (remember that we assumed that $A_0 = A_{f,-1}$). In order for the firm to optimally choose $x^* = \lambda$ a necessary and sufficient condition is hence

$$\eta_g \geq \bar{\eta}_g = \frac{(\lambda - 1)^{1/\theta}}{E_h}.$$

Suppose there exists BGP with $x < \lambda$.

First we show that $x^* < \bar{x} = A_f/A$. Suppose not; that is, suppose $x^* = \bar{x}$. But then

$$x^* = \frac{A_f^{-1}}{A} * \frac{A_f}{A_f^{-1}} \geq \lambda,$$

since $A \leq A_f^{-1}$. For a BGP we need $\lambda \leq x^* = x < \lambda$, a contradiction. Hence $x^* < \bar{x}$. But then the optimal choice x^* satisfies

$$(x^*)^{\theta/(1-\theta)} \left(\frac{\theta}{w_a}\right)^{\theta/(1-\theta)} = x^* - 1. \tag{23}$$

But the unique solution x^* to this equation satisfies $x^* < \lambda$ if and only if

$$(\lambda)^{\theta/(1-\theta)} \left(\frac{\theta}{w_a}\right)^{\theta/(1-\theta)} < \lambda - 1,$$

or $\eta_g < \bar{\eta}_g$.

A.3. Uniqueness of the BGP

We want to argue that the solution η_g^* to the equation

$$\min\left\{\lambda, 1 + \left(\eta_g E_h\right)^{\theta}\right\} = h^{T_l} \eta_g^{1-\theta} \left(\frac{1}{1-\eta_g}\right)^{2-\theta} \left(\frac{E_h}{h}\right)^{1-\theta}, \tag{24}$$

is unique. We established in the main text that any solution η_g^* satisfies $\eta_g^* > 0$. Now multiply both sides of (24) by $\eta_g^{1-\theta}$ to obtain

$$\min\{\lambda \eta_g^{1-\theta}, \eta_g^{1-\theta} + \eta_g E_h^{\theta}\} = h^{T_l} \eta_g^{2(1-\theta)} \left(\frac{1}{1-\eta_g}\right)^{2-\theta} \left(\frac{E_h}{h}\right)^{1-\theta}.$$

Since the left-hand side of this equation is concave and the right-hand side is strictly convex, there is at most one positive solution $\eta_g^* > 0$ to this equation, which is the unique solution to equation (24).[49]

A.4. Optimality of Working in the Adoption or Nonadoption Sector

In the main text we have assumed that only agents with general education work in the adopting sector, and characterized a corresponding BGP. We now provide sufficient conditions on the parameters of our model to guarantee that agents with general education would *optimally* choose to work in the adoption sector and agents with vocational education would optimally choose to work in the non-adopting sector. Suppose that

49 For a general cost function $e(1-\eta_g)$ this equation becomes

$$\min\{\lambda \eta_g^{1-\theta}, \eta_g^{1-\theta} + \eta_g E_h^{\theta}\} = h^{T_l} \frac{\eta_g^{2(1-\theta)}}{(1-\eta_g)^{1-\theta}} \left(\frac{E_h}{h}\right)^{1-\theta} e(1-\eta_g).$$

As long as $e(\cdot)$ is strictly decreasing, strictly convex and differentiable, the right hand side of this equation is still strictly convex and the argument goes through unchanged.

g-agents working in the non-adopting sector have productivity h with probability 1 (as v-people have) and that v-agents working in the adopting sector have productivity 1 with probability T_l^v and productivity h with probability $1 - T_l^v$,

Thus for g-agents to optimally work in the adopting sector one requires

$$T_l \log(w_a) + (1 - T_l) \log(w_a h) \geq \log(w_n h) \text{ or } \frac{w_a}{w_n} \geq h^{T_l},$$

which is always satisfied in equilibrium by (15). For the v-agents to optimally work in the non-adopting sector requires

$$\frac{w_a}{w_n} \leq h^{T_l^v}. \tag{25}$$

To provide sufficient conditions for (25) to hold, it is convenient to consider the cases $x^* = \lambda$ and $x^* < \lambda$ separately.

Suppose $x^* < \lambda$. Then $\eta_g^* < \bar{\eta}_g = (\lambda - 1)^{1/\theta}/E_h$. For (25) to hold a sufficient condition is, using (15)

$$\eta_g^* < \bar{\eta}_g \leq 1 - \frac{1}{h^{T_l^v - T_l}}. \tag{26}$$

For $x^* < \lambda$ to obtain in equilibrium a necessary and sufficient condition is $x^s(\bar{\eta}_g) > \lambda$. But since $x^s(\eta_g)$ is strictly increasing in $\eta_g, x^s(\bar{\eta}_g) > \lambda$ if

$$x^s\left(1 - \frac{1}{h^{T_l^v - T_l}}\right) > \lambda, \tag{27}$$

as long as (26) is satisfied. Using the explicit form of $x^s()$ yields, after some algebra, the condition

$$E_h^{1-\theta}\left(h^{T_l^v - T_l} - 1\right)^{1-\theta} h^{T_l^v - 1 + \theta} \geq \lambda. \tag{28}$$

For all parameter combinations jointly satisfying (26) and (28) (obviously not an empty set) the equilibrium features growth below potential growth and agents with v-education finding it suboptimal to work in the adopting sector. In particular, the conditions are satisfied if agents with vocational education have a lot to lose by working in the adopting sector (T_l^v high and h high).

A similar argument applies to the case $x^* = \lambda$ and therefore $\eta_g^* \geq \bar{\eta}_g$. Now from (12) is optimal for v-agents to work in the non-adopting sector if

$$\lambda \leq h^{T_l^v} \frac{\bar{\eta}_g E_h}{(1 - \bar{\eta}_g)h},$$

and the equilibrium features maximal growth if $x^s(\bar{\eta}_g) \leq \lambda$. But $x^s(\bar{\eta}_g) \leq \lambda \leq h^{T_l^v}(\bar{\eta}_g E_h/(1 - \bar{\eta}_g)h)$ if and only if (after some algebra)

$$\frac{E_h^{1-\theta}}{h^{T_l^v - T_l - \theta}} \leq \left[E_h - (\lambda - 1)^{1/\theta}\right](\lambda - 1)^{1/\theta}.$$

If this condition, again purely on fundamentals, is satisfied, then equilibrium growth is maximal and households with vocational education have no incentive to work in the adopting sector. As before, this condition is satisfied if h and T_l^v are high.

A.5. A Mean Preserving Increase in the Spread of Productivities

Suppose we change the parameter T_l, but in such a way as to keep expected productivity E_h constant. Suppose the low productivity state equals $\kappa < h$ instead of 1, and thus

$$E_h = \kappa T_l + (1 - T_l)h.$$

Hence

$$\frac{d\kappa}{dT_l} = \frac{h - \kappa}{T_l} > 0. \tag{29}$$

Intuitively, making the low state more likely and keeping expected productivity constant requires a productivity increase in the low state. Thus a reduction in T_l (and therefore a decrease in κ) can be interpreted as a mean-preserving increase in the spread of the productivity process. We want to analyze how equilibrium growth and education allocations change with such an increase.

First, the firm's adoption decision (9) and relative labor demands, and thus equation (12) remain unchanged. Now agents will opt for general education if

$$T_l \log(\kappa w_a) + (1 - T_l)\log(w_a h) - \log(w_n h) \geq \log e(a) = -\log(1 - \eta_g).$$

Using this result in (12) yields

$$x^s(\eta_g) = g(T_l)\frac{1}{\eta_g}\left(\frac{\eta_g}{(1 - \eta_g)}\right)^{2-\theta}\left(\frac{E_h}{h}\right)^{1-\theta},$$

where $g(T_l) = (h/\kappa(T_l))^{T_l}$. This is exactly the equation (16), with $\kappa = 1$. In order to obtain comparative statics results with respect to T_l we simply need to characterize the function $g(T_l)$, or, more easily, the function $f(T_l) = \log(g(T_l)) = T_l[\log(h) - \log(\kappa(T_l))]$. Using (29) we find

$$f'(T_l) = \log\left(\frac{h}{\kappa(T_l)}\right) - T_l\frac{\kappa'(T_l)}{\kappa(T_l)} = \log\left(\frac{h}{\kappa(T_l)}\right) - \left(\frac{h}{\kappa(T_l)} - 1\right) < 0,$$

since $h > \kappa(T_l)$. Therefore $g(T_l)$ is a decreasing function of T_l and the $x^s(\eta_g)$ schedule tilts upwards with a decrease in T_l. Therefore, a mean-preserving increase in the spread on productivity (a decrease in T_l) equilibrium growth x^* weakly decreases and equilibrium general education strictly decreases. As the productivity process for working in the adopting sector becomes more risky, the incentives for acquiring general, growth-driving education declines.

A.6. The Change in the Wage Premium

Fix s. From the household education decision we have that

$$\log \frac{w_a}{w_n}(s,\lambda) = T_l \log(h) - \log(s) - \log(1-\eta_g(s,\lambda)),$$

so that

$$\frac{\log \frac{w_a}{w_n}(s,\lambda)}{d\log\lambda} = \frac{\eta_g(s,\lambda)}{1-\eta_g(s,\lambda)} * \frac{d\log \eta_g(s,\lambda)}{d\log\lambda}.$$

Thus we have to determine $d\log\eta_g(s,\lambda)/d\log\lambda$. For that we note that if $\eta_g(s,\lambda) < \bar{\eta}_g$ then $(d\log\eta_g(s,\lambda)/d\log\lambda) = 0$ and thus $(d\log w_a/w_n(s,\lambda)/d\log\lambda) = 0$. Now suppose $\eta_g(s,\lambda) \geq \bar{\eta}_g$. Then $\eta_g(s,\lambda)$ is implicitly defined by (19) so that

$$\log\lambda = (1-\theta)\log\eta_g(s,\lambda) - (2-\theta)\log(1-\eta_g(s,\lambda)) + \log\left(\frac{h^{T_l}}{s} * \left(\frac{E_h}{h}\right)^{1-\theta}\right).$$

Totally differentiating with respect to $\log\lambda$ yields

$$\frac{d\log\eta_g(s,\lambda)}{d\log\lambda} = \left[(1-\theta) + \frac{(2-\theta)\eta_g(s,\lambda)}{(1-\eta_g(s,\lambda))}\right]^{-1},$$

so that for $\eta_g(s,\lambda) \geq \bar{\eta}_g$

$$\begin{aligned}\frac{\log \frac{w_a}{w_n}(s,\lambda)}{d\log\lambda} &= \frac{\eta_g(s,\lambda)}{1-\eta_g(s,\lambda)} * \frac{d\log\eta_g(s,\lambda)}{d\log\lambda} \\ &= \left[(2-\theta) + \frac{(1-\theta)(1-\eta_g(s,\lambda))}{\eta_g(s,\lambda)}\right]^{-1},\end{aligned}$$

a strictly increasing function of $\eta_g(s,\lambda)$. But since $\eta_g(s,\lambda)$ is strictly increasing in s, so is $\log(w_a/w_n)(s,\lambda)/d\log\lambda$, as long as $\eta_g(s,\lambda) \geq \bar{\eta}_g$.

A.7. The Social Welfare Function of the Government

Along a balanced growth path, wages, education subsidies and total government expenditures grow at rate x. Therefore the lifetime utility of an agent of ability a, born at date t in a balanced growth path with growth rate x equals

$$\begin{aligned}u_t(a) = I_g&\Big[T_l\log(W_{at}) + (1-T_l)\log(W_{at}h) - \log(e(a)) + \log(S_{gt})\Big] \\ &+ (1-I_g)[\log(W_{nt}h) + \log(S_{vt})] \\ &= u(a) + 2\log(A_0) + 2t\log(x),\end{aligned}$$

where

$$u(a) = I_g\Big[T_l\log(w_a) + (1-T_l)\log(w_a h) + \log(s_g) - \log(w_n h) + \log(s_v)\Big] \\ + \log(w_n h) + \log(s_v) - I_g\log(e(a)). \tag{30}$$

The social welfare function we employ is

$$\hat{W} = \sum_{t=0}^{\infty}\beta^t\int u_t(a)da = \frac{2\log(A_0) + \int u(a)da + \frac{2\beta\log(x)}{1-\beta}}{1-\beta},$$

and thus the benevolent government maximizes

$$\bar{W} = \int u(a)da + \frac{2\beta\log(x)}{1-\beta}, \tag{31}$$

by choice of the policy parameters (s_g, s_v), subject to the government budget constraint (17) and the entities (w_a, w_n, x, η_g) forming a BGP equilibrium, given policies (s_g, s_v). Since we are silent about how taxes are collected to finance government expenditure for education G (and its distortions), we take G as a parameter of the government problem and not as a choice of the government.

We can simplify (31) further by noting that in equilibrium the benefit from general education has to equal its cost for the marginal agent,

$$T_l\log(w_a) + (1-T_l)\log(w_a h) + \log(s_g) - \log(w_n h) + \log(s_v) = -\log(1-\eta_g),$$

and that from (17) and the first order conditions of the non-adopting firms

$$s_v = \frac{G}{\eta_g s + (1-\eta_g)},$$
$$w_n = \theta\Big[(1-\eta_g)E_h\Big]^{\theta-1},$$

so that

$$\bar{W} = \int u(a)da + \frac{2\beta\log(x)}{1-\beta} \\ = \psi - (2-\theta)\log(1-\eta_g) - \eta_g - \log\Big[\eta_g s + (1-\eta_g)\Big] + \frac{2\beta\log(x)}{1-\beta},$$

where ψ is a constant, so that finally, by the choice of $s \in (0, \infty)$, the government maximizes

$$W(s) = -(2-\theta)\log(1-\eta_g(s)) - \eta_g(s) \\ - \log\Big[\eta_g(s)s + (1-\eta_g(s))\Big] + \frac{2\beta\log(x(s))}{1-\beta},$$

where $\eta_g(s)$ and $x(s)$ solve

$$x(s) = \frac{h^{T_l}}{s}\eta_g(s)^{1-\theta}\left(\frac{1}{1-\eta_g(s)}\right)^{2-\theta}\left(\frac{E_h}{h}\right)^{1-\theta},$$

$$x(s) = \min\left\{\lambda, 1 + \left(\eta_g(s)E_h\right)^{\theta}\right\},$$

as in the main text.

A.8. Derivatives of the Government Objective Function

For all $s \geq \bar{s}(\lambda)$ we have, since growth is maximal,

$$W(s \geq \bar{s}) = W(s = \infty) - \log\left(\frac{\eta_g^{2-\theta} + \frac{\lambda}{\kappa}(1-\eta_g)^{3-\theta}}{e^{1-\eta_g}}\right),$$

and thus

$$W'(s|s \geq \bar{s}) = \frac{\eta_g^{2-\theta} + \frac{\lambda}{\kappa}(1-\eta_g)^{3-\theta}}{e^{1-\eta_g}} * \eta_g'(s) * \frac{-e^{1-\eta_g}\left(2-\theta+\eta_g\right)\eta_g^{1-\theta}}{\left[\eta_g^{2-\theta} + \frac{\lambda}{\kappa}(1-\eta_g)^{3-\theta}\right]^2} * (s-1),$$

from which the first part of the proposition follows.

For the case $s < \bar{s}(\lambda)$, from (20) we obtain

$$W'(s|s < \bar{s}) = \frac{\eta_g'(s)}{\eta_g(s)}\left[\left(\frac{1+\beta}{1-\beta}\right)\left(\frac{\theta(\eta_g(s)E_h)^{\theta}}{1+(\eta_g(s)E_h)^{\theta}}\right) - (1-\theta+\eta_g(s)) + \frac{1-s-(\eta_g(s)/\eta_g'(s))}{s+(1/\eta_g(s)-1)}\right].$$

We observe that for $\beta \in (0,1)$ sufficiently big we have that $W'(s|s < \bar{s}) > 0$.

Acknowledgments

We are grateful to Oded Galor (the editor) and two anonymous referees for helpful comments. We also benefitted from discussions with Daron Acemoglu, Dean Corbae, Felix Kubler, Aris Protopapadakis, Victor Rios-Rull, Richard Rogerson, Harald Uhlig, seminar participants at IIES, ECARES, Penn State, Princeton, Stockholm School of Economics, UCLA, Universite de Montreal, University of Texas-Austin, University of Washington, Wharton and participants at the Stern macro lunch and USC research lunch, the 2001 SED meeting at Stockholm, and the 2002 winter meetings of the Econometric Society at Atlanta. Remaining errors are our own. Marcela Rubio provided excellent research assistance. Krueger acknowledges support from NSF grant SES-0004376 and Kumar from the USC Marshall School's research fund.

References

Acemoglu, D. (1998). ''Why Do New Technologies Complement Skills? Directed Technical Change and Wage Inequality,'' *Quarterly Journal of Economics* 113(4), 1055–1089.

Allen, R. C. (1998). ''The Employability of University Graduates in the Humanities, Social Sciences, and Education: Recent Statistical Evidence,'' Discussion Paper No.: 98-15, Department of Economics, The University of British Columbia.

Atkeson, A., and P. J. Kehoe. (2001). ''The Transition to a New Economy After the Second Industrial Revolution,'' Federal Reserve Bank of Minneapolis Research Department Staff Report.

Bartel, A. P., and F. R. Lichtenberg. (1987). ''The Comparative Advantage of Educated Workers in Implementing New Technology,'' *The Review of Economics and Statistics* LXIX, 1–11.

Bartel, A. P., and F. R. Lichtenberg. (1991). ''The Age of Technology and its Impact on Employee Wages,'' *Economic Innovation and New Technology* 1, 215–231.

Benhabib, J., and M. M. Spiegel. (1994). ''The role of human capital in economic development: Evidence from aggregate cross-country data,'' *Journal of Monetary Economics* 34, 143–173.

Bessen, J. (2002). ''Technology Adoption Costs and Productivity Growth: The Transition to Information Technology,'' *Review of Economic Dynamics* 5(2), 443–469.

CERGE-EI. (1997). *Czech Republic 1997: The Year of Crises*.

Cummings, J., and G. Violante. (2002). ''Investment-Specific Technical Change in the US (1947–2000): Measurement and Macroeconomic Consequences,'' *Review of Economic Dynamics* 5(2), 243–284.

Galor, O., and O. Moav. (2000). ''Ability-Biased Technological Transition, Wage Inequality, and Economic Growth,'' *Quarterly Journal of Economics* 115(2), 469–497.

Galor, O., and D. Tsiddon. (1997). ''Technological Progress, Mobility, and Economic Growth,'' *The American Economic Review* 87(3), 363–382.

Gill, I. (1988). ''Technological Change, Education and Obsolescence of Human Capital: Some Evidence for the US,'' Ph.D. thesis, The University of Chicago.

Gottschalk, P., and T. Smeeding. (1997). ''Cross-National Comparisons of Earnings and Income Inequality,'' *Journal of Economic Literature* 35(2), 633–687.

Gordon, R. J. (2000). ''Does the 'New Economy' Measure up to the Great Inventions of the Past?'' *The Journal of Economic Perspectives* 14(4), 49–74.

Gould, E. D., O. Moav, and B. A. Weinberg. (2000). ''Precautionary Demand for Education, Inequality, and Technological Progress,'' *Journal of Economic Growth* 6(4), 285–315.

Greenwood, J., and M. Yorukoglu. (1997). ''1974,'' *Carnegie-Rochester Conference Series on Public Policy* 46, 49–95.

Hornstein, A., and P. Krusell. (1996). ''Can Technology Improvements Cause Productivity Slowdowns?'' *NBER Macroeconomics Annual* 209–259.

Kortum, S., and J. Lerner. (1998). ''Stronger Protection or Technological Revolution: What is Behind the Recent Surge in Patenting?'' *Carnegie-Rochester Conference Series on Public Policy* 48, 247–304.

Krueger, D., and K. B. Kumar. (2004). ''US–Europe differences in technology-driven growth: quantifying the role of education,'' *Journal of Monetary Economics* 51, 161–190.

Krusell, P., L. Ohanian, J.-V. Rios-Rull, and G. L. Violante. (2000). ''Capital Skill Complementarity and Inequality: A Macroeconomic Analysis,'' *Econometrica* LXVIII, 1029–1054.

Lawrence, R. Z., and C. L. Schultze. (1987). ''Overview.'' In R. Z. Lawrence and C. L. Schultze (eds), *Barriers to European Growth: A Transatlantic View*. Washington, DC: The Brookings Institution.

Lazear, E. P. (2002). ''Entrepreneurship,'' NBER Working Paper 9109, August.

Levesque, K. et al. (2000). ''Vocational Education in the United States: Toward the Year 2000,'' National Center for Education Statistics, February.

Ljungqvist, L., and T. J. Sargent. (1998). ''The European Unemployment Dilemma,'' *Journal of Political Economy* 106(3), 514–550.

Merdich, E. A., S. A. Kagehiro, and J. Houser. (1994). ''Vocational Education in G-7 Countries: Profiles and Data,'' National Center for Education Statistics, Research and Development Report, August.

Murphy, K. M., A. Schleifer, and R. W. Vishny. (1991). ''The Allocation of Talent: Implications for Growth,'' *Quarterly Journal of Economics* May, 503–530.

Nelson, R. R., and E. S. Phelps. (1966). ''Investment in Humans, Technological Diffusion, and Economic Growth,'' *The American Economic Review* May, 69–75.

OECD. (1977a). *Education at a Glance: OECD Indicators 1997*. OECD: Paris, France.

OECD. (2001). *Education at a Glance: OECD Indicators 2001*. OECD: Paris, France.

OECD. (1997b). *Education Policy Analysis 1997*. OECD: Paris, France.

Scarpetta, S. et al. (2000). ''Economic Growth in the OECD Area: Recent Trends at the Aggregate and Sectoral Level,'' OECD Working Paper 248.

Schreyer, P. (2000). ''The Contribution of Information and Communication Technology to Output Growth: A Study of the G7 Countries,'' OECD STI Working Paper 2000/2.

Stiroh, K. J. (2002). ''Information Technology and the US Productivity Revival: What Do the Industry Data Say?'' *American Economic Review* 92(5).

Violante, G. L. (2002). ''Technological Acceleration, Skill Transferability, and the Rise in Residual Inequality,'' *Quarterly Journal of Economics* CXVII, 297–338.

Welch, F. (1970). ''Education in Production,'' *Journal of Political Economy* 78(1), 35–59.

Young, A. (1993). ''Invention and Bounded Learning by Doing,'' *Journal of Political Economy* 101(3), 443–472.