Federal Reserve Bank of Boston

TECHNOLOGY AND GROWTH

Conference Proceedings

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June 1996

Conference Series No. 40

Jeffrey C. Fuhrer
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Technology and Growth: An Overview

Jeffrey C. Fuhrer and Jane Sneddon Little*

During the 1990s, the Federal Reserve has pursued its twin goals of price stability and steady employment growth with considerable success. But despite—or perhaps because of—this success, concerns about the pace of economic and productivity growth have attracted renewed attention. Many observers ruefully note that the average pace of GDP growth has remained below rates achieved in the 1960s and that a period of rapid investment in computers and other capital equipment has had disappointingly little impact on the productivity numbers. Others see faster growth as softening the impact of widening income inequality or the stagnant real wages earned by many citizens.

Most of the industrial world has experienced a similar decline in trend and productivity growth, an increase in income inequality, and even slower job creation than we have seen here in the United States. While some (particularly Asian) developing countries are rapidly joining the ranks of the industrialized, most remain mired in poverty. According to the World Bank's recent report on poverty, over 20 percent of the world's population lives on less than one dollar a day. This situation wastes human talent and contributes to political instability.

While raising trend growth rates would not directly address distributional issues, increasing growth rates by even a fraction of 1 percent would, with compounding, have profound implications. As Robert Lucas has pointed out, "the consequences for human welfare are simply staggering. Once one starts thinking about them, it is hard to think of anything else." Unfortunately, economists and policymakers do not

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know how to engineer such an outcome. While the determinants of growth are widely agreed to be capital, labor, and a composite including managerial skills and organizational culture that Robert Solow abbreviated as "technology," the interrelationships among these variables are not clearly understood. In the developed economies, at least, recent large capital investments have shown surprisingly little positive impact on productivity or potential growth. Accordingly, attention has increasingly turned to the role of such intangibles as human capital, social organization, and technology.

Because these puzzles are so compelling, the last few years have seen a resurgence in research on the economics of growth. This groundswell reflects the availability of new data bases and an improved ability to model imperfectly competitive conditions. Primarily, however, this enthusiasm indicates that many members of the economics profession concur with *The Economist* (June 1, 1996) that "understanding growth is surely the most urgent task in economics." For these reasons, the Federal Reserve Bank of Boston devoted its fortieth economic conference, held in June 1996, to *Technology and Growth*. We hoped to explore what we know and clarify what we do not know about these issues.

A number of themes emerged from the discussions. For the most part these themes took the shape of questions repeated in various contexts. For example, one fundamental question asked throughout the meeting was just how important is technology—to growth, to productivity, to convergence? The answer, it was generally agreed, depends on one's definition of technology, with the majority favoring an inclusive approach. Most participants were sympathetic with the need to decompose technology into its constituent parts—innovation, development, and diffusion—and to include intangibles like organizational structure, management skills, and culture in the package labeled technology. Another theme that arose early on and reappeared throughout the conference was the unpredictable nature of technological change and the consequences of our uncertainty (or lack of imagination) concerning its ultimate path.

A third motif involved the role of innovation and the importance of knowledge-based spillovers within the growth process. While early work based on Robert Solow's model attributed most growth to exogenous technological change, more recent neoclassical research, exemplified by Dale Jorgenson's work, has greatly reduced technology's role by broadening our definition and improving our measures of capital. Indeed, Jorgenson concludes that human and physical capital accumulation, properly measured, explains almost all growth with little scope for innovation or knowledge-based spillovers.

But not everyone is fully persuaded that capital accumulation, however defined, can by itself account for the great bulk of welfare improvements experienced in recent decades. Noting a major inconsistency between the rate of convergence to steady state growth rates predicted by the neoclassical approach and the slower rate observed in fact, the new growth theorists give technological change, rather than capital, a bigger role in the growth process. They argue that technological change requires human effort and is, therefore, not exogenous, that the returns to R&D and other knowledge-based investments are not fully appropriable, and that spillovers from innovation have contributed importantly to growth. Naturally, thus, the new growth theorists stress the need to model the innovative process and the role played by these spillovers. While participants of both camps generally favored developing fully endogenous models, they disagreed about our current or potential ability to meet this challenge and, more basically, about its actual importance. In this regard, most, but not all, of the participants believe that spillovers are pervasive and significant.

A further theme was the need to be realistic in at least two areas. First, we need to acknowledge that potential growth may not return to its pace in the 1960s and that we may have to be satisfied with raising the level of output rather than the rate of growth. Economists also need to admit how little we understand about the growth process and how small are the likely consequences of the policy measures we advocate.

The conferees did agree on several points. Since the previous heyday of growth economics in the late 1950s, economists have greatly improved their ability to model the growth process by broadening their definitions and measures of physical and human capital. This development has reduced the role of exogenous technological change and narrowed the differences between the neoclassical and new growth theorists. Remaining areas for dispute and research include the need for modeling the various components of technology and the interactions between the determinants of growth and the growth process itself. Moreover, although research has not clearly demonstrated that the technology embodied in widely available capital equipment has much impact on productivity, participants generally concurred that technology defined to include management, social organization, and culture is likely to be important.

As for policy recommendations, conference participants largely agreed that the path of technical development and diffusion is highly unpredictable. Given this uncertainty and the gap between the social and private returns to R&D, most participants favored modest and balanced public support of basic research and other pro-competitive policies. They were less convinced about the benefits of the patent system.

On the macro side, participants universally endorsed the need to reduce fiscal deficits in order to promote saving and investment and the desirability of maintaining open trading systems in order to spur innovation. Several attendees advocated greater use of consumption-based tax systems. Many also saw an ongoing need for government investment in education and training, in limited amounts of R&D, and in improved statistical capabilities. Monetary policy's contribution was generally seen to be limited to maintaining price stability, but Bob Solow reminded us that balancing relatively tight fiscal policy with relatively accommodative monetary policy tends to favor growth. He also noted that below-potential growth discourages investment and innovation. Finally, if increasing productivity growth remains out of reach, some participants saw a need for more generous redistributive policies.

KEYNOTE ADDRESS: THE NETWORKED BANK

In his keynote address, **Robert M. Howe** provided an intriguing view of how one industry—financial services—has responded to rapid technological change, and a vision of how that industry will be transformed with the introduction of technologies already in the development pipeline. Howe's vision is that of the networked economy: "the integration of people and institutions obtaining information, transacting business, and entertaining and educating themselves in a connected world, with electronic networks as the underlying backbone." In addition to detailing the modifications required of banks to survive in this networked environment, Howe shows where consumers fit into this system.

The networked bank has three components. The first component includes the access channels that link the consumer to the bank—ATMs, telephones, PCs, and bank tellers. Control over these channels rests in the hands of consumers and of third-party providers, such as on-line services. The second component is the "customer information and relationship management system," the bank's data base tracking customer activities to glean information about customer preferences. Howe suggests that effective use of this information—to tailor products to individual consumers or to determine the bank's most profitable market segments—will become the bank's "most valued asset and source for competitive advantage." The third component of the networked bank is the "core back-office system," which coordinates the operational systems, retail and commercial banking functions, and alliances with other service providers—for example, insurance firms or travel agents—that offer their services through the bank.

Howe forecasts the emergence and widespread distribution of a suite of new technologies that will support the networked bank. These include improved communications interfaces, such as speech and handwriting recognition; three-dimensional, high-resolution graphics; and touch screens. Network infrastructure will improve rapidly in speed and price, and user-screening and encryption will enhance security. In addition, the continued miniaturization of processor and storage technology will allow smart cards with PC capabilities for financial transactions, inventory control, or transmission of medical patient information. "Intelligent agent" software will respond to a consumer's complex queries; for example, "Go find me the lowest-priced Brand X automobile with the following features." Finally, networked banks will make greater use of new tools for data management, to analyze customers and transactions for targeted marketing campaigns.

These changes in the competitive environment pose new challenges to banks. Because the provision of a service will often involve a number of players, banks must establish "electronic value chains" that link the bank, the customer, perhaps a vendor, and a network infrastructure provider. Howe foresees a notable shift of power from banks to consumers and providers of access channels. With easy access to many options, a consumer may have little loyalty to a particular financial institution. A bank will need to differentiate its product from its easily accessible competitors, even when its product may appear only as a menu item on a screen. The bank's most valuable asset will shift from its branches, the current interface with its customers, to its customer data base and its expertise in extracting useful information from that data base.

How can the networked bank respond to these challenges? Howe proposes three possible strategies. The first, the "customer-centric" strategy, uses the bank's customer data base and data base analysis to serve each customer with unique, customized services. A second response is the "life-event" strategy: The bank becomes the provider of a cluster of services required by the consumer at key life events, such as buying a house or planning for retirement. A third option is the commodity strategy, in which the bank competes by providing standardized services through a wide range of access channels at the lowest cost.

Finally, Howe points out that these technological advances pose difficult questions for financial regulators. For example, does a global electronic financial system imply greater systemic risk to the payments system? How are standards of security and reliability established for new products? Will new clearinghouse organizations be required for new products? How are consumers to be protected if non-regulated industries can offer bank-like services? Who guards the consumer's right to privacy?

TECHNOLOGY IN GROWTH THEORY

Dale Jorgenson's paper traces the economics profession's understanding of technology and economic growth from the seminal works of Harrod (1939), Domar (1946), Solow (1956), and Kuznets (1971) to the more recent "endogenous growth models" of Grossman and Helpman (1994). In Jorgenson's view, the profession formed a rare and temporary consensus in the 1970s around the neoclassical growth model of Solow and the empirical work of Kuznets. Solow's simple theoretical framework, which decomposed contributions to output according to a constant-returns-to-scale production function with capital and labor as inputs, "provided conceptual clarity and sophistication." Kuznets' complementary work linking measures of capital and labor inputs to final output provided "persuasive empirical support" for the neoclassical growth model by documenting the correlation among inputs and outputs for the United States and 13 other developed countries over a long historical span. What stands out most for Jorgenson about these twin pillars of early growth theory, theoretical and empirical, is the lack of integration between them.

In early implementations of the Solow growth model, growth arose primarily as a result of increases in productivity. Because the reasons behind productivity increases were not understood, most economic growth was attributed to exogenous causes that largely reflected, as Abramovitz (1956) phrased it, a "measure of our ignorance." The contribution of investment in physical and human capital was assumed to be relatively minor.

Work by Jorgenson and others in the 1980s has attempted to diminish our ignorance by using carefully constructed measures of the inputs to production in an econometric model. The product of this research strategy is a model that fully characterizes the accumulation of human and physical capital and attributes almost all of economic growth to increases in the rate of capital accumulation, once properly measured. A truly satisfactory model of endogenous investment in new technology has eluded the profession thus far, however, in large part because of the difficulties inherent in measuring the output of the research and development sector (a problem first identified by Griliches in 1973).

Interest in growth theory waned in the 1970s, in the aftermath of the oil price shocks and a renewed attention to the determinants of business cycle fluctuations, but the debate over "convergence" in the 1980s and early 1990s revived interest, even as it challenged the validity of the Solow framework. Because the convergence debate focused on the long-run growth experience of nations, it brought to light a key question that had not previously been addressed: Could private investment, whose returns accrue only to the investor, account for the leaps and bounds in output that some countries have observed over centuries? Or do we need "spillovers" in "knowledge capital," which may result from individuals' investment but which benefit all, to explain growth over long spans of time?

Jorgenson describes the essence of the convergence debate as follows: If Solow's model is approximately correct, then over a long enough period of time, a country will converge to its "steady state" or long-run rate of per capita income growth, which is determined by its saving and population growth rates. The Solow model predicts that the rate of convergence to the steady state will depend upon the share of capital in GDP, the rate of population growth, the rate of productivity growth, and the rate of depreciation of capital equipment. Using plausible estimates of these determinants for many countries implies a rate of convergence of about 4 percent per year. While empirical studies have found evidence of convergence, the estimated rate of convergence—about 2 percent per year—is too slow to be consistent with the Solow model.

An influential paper by Paul Romer (1986) highlights the inconsistency between the simple Solow model and the evidence on rates of convergence. Romer deduced that, for the slow observed rates of convergence to be consistent with the Solow model, the share of national income devoted to capital accumulation must be about twice as large as normally assumed. The reasoning is as follows: The larger is the share of national income devoted to capital accumulation, the more investment is required to increase output; the more investment is required, the slower will be the convergence to the steady state for a given investment rate.

Because doubling the share of income going to investment is just a "crazy explanation" of the slow-convergence puzzle, Romer and others suggest what they consider to be more plausible alterations to the standard growth model, such as increasing returns to scale in the aggregate production function, and spillovers of the returns to private investment to the rest of the economy. In their view, only these alterations can reconcile the standard growth model with the convergence data.

Mankiw, David Romer, and Weil (1992) find, however, that Paul Romer's crazy explanation is unnecessary and the Solow model can be resurrected once one controls for differences in human capital across countries. Allowing for these differences again reconciles the basic Solow model with the share of capital in the value of output and with the slow rates of convergence observed over time across countries.

A recent paper by Islam (1995) extends this work, allowing for different levels of productivity across countries. Islam's work shows that once one accounts for differences in the level of productivity, the Solow model captures well the endogenous accumulation of physical capital, without any need to account for the accumulation of human capital. Islam suggests human capital's contribution to changes in growth may not be as evident because it changes so slowly: While physical capital may completely adjust to changes in tax policy in a matter of decades, human capital may require a century to respond to changes in educational policy!

Despite this evidence, Jorgenson continues, the proposition that private investment in physical and human capital is a more important source of growth than productivity remains as controversial today as it was in the early 1970s. Jorgenson believes that he has largely resolved this issue, however, with a perfectly competitive, constant-returns-to-scale neoclassical model that employs constant-quality indexes of both labor and capital input and investment goods output. The complete econometric model developed over many years by Jorgenson and his colleagues attributes fully 83 percent of growth to the endogenous changes in capital and labor inputs, with the remaining 17 percent accounted for by technological change and fertility rates. This finding essentially reverses the attribution of growth from that of Solow who found that only 12.5 percent of growth in per capita output could be attributed to capital accumulation (he did not consider human capital).

Discussant **Susanto Basu** assesses the success of the Jorgenson (and coauthors) research program according to its ability to explain three "fundamental questions of growth theory": (1) Why does per capita income increase over time? (2) Why are some countries rich and others poor? (3) Why has economic growth slowed down in developed countries?

With regard to the first question, Basu points out that Jorgenson treats technology as knowledge, which is a form of capital and behaves just like any other capital. The New Growth theory, by contrast, believes that the knowledge that propels technological advance differs from other capital in one crucial aspect: "Investors cannot fully internalize the benefits from accumulating knowledge." The presence of strong spillovers from private investment in knowledge can imply significant differences in the answers that Jorgensonian and New Growth theories give to the first question. The Jorgensonian rendering implies that in the very long run, no growth in per capita income can occur, since growth arises only from capital accumulation, and the marginal product of capital must diminish as capital accumulates. By contrast, the New Growth theory implies that the long-run growth rate of the economy will depend on the rate of accumulation of "knowledge" capital. Jones (1995) provides compelling evidence against the latter hypothesis for the United States and other advanced economies. Taking the inherent plausibility of knowledge spillovers together with Jones's evidence, Basu favors an intermediate position with modest spillovers, consistent with the Jones evidence and with the Jorgenson position.

The work of Islam (1995) highlights a deficiency in Jorgenson's approach with respect to the second question, namely that differences across countries in income per worker cannot be explained by differences in capital per worker, as required by the Jorgenson model. That is, countries' production functions cannot be the same. To explain income differences, we require another factor of production that varies across locations, perhaps a factor that involves differences in the diffusion of technology or the degree of infrastructure in place, and thus drives a wedge between technological change and productivity.

Could this wedge also explain the observed slowdown (since the early 1970s) in productivity in advanced countries? Basu suggests that it may. Using the methods of Basu and Fernald (1995), he presents estimates showing that only a small portion of the slowdown in productivity growth can be attributed to a reduction in the growth rate of technology. Basu suggests that changes in the allocation of inputs across sectors may account for the bulk of the productivity slowdown. He concludes by agreeing that Jorgenson's paper documents the explanatory power of the neoclassical model augmented by careful measurement. He believes, however, that the model will need to be amended to allow for some spillover effects.

Discussant **Gene Grossman** focuses on four key questions about the role of technology in growth theory. First, "Is technological progress needed to sustain growth?" Grossman notes that, technically, our economy could grow indefinitely without technological enhancements if we continue to invest in physical and human capital *and* if the returns to doing so always remain above a minimum level. However, he suggests that long-run growth with such static technology is implausible. In the presence of factors in fixed supply, such as land and fuels, capital must eventually experience severely diminishing returns. Would the world economy have evolved as it has over the past 200 years in the absence of all the innovations introduced in that period—without steam engines, electricity, or semiconductors? Adding more and more shovels and horses would not have allowed us to reach today's level of output. A role for technology in long-run growth seems mandatory.

A second question is whether innovation represents the product of intentional activity and is thus "endogenous" to the economy, or not. Grossman suggests that innovation is endogenous; the firms that spend in excess of $100 billion on R&D must be doing so for a reason. He also cites the evidence in Baumol that innovations vary across history in response to variation in incentives facing innovators.

Third, Grossman asks whether "formal" R&D is responsible for the bulk of technological progress. The evidence presented by Jones (1995) suggests not: The long-run surge in R&D activity in the postwar period has not been accompanied by equal surges in the growth of per capita output, and the decline in productivity since 1973 does not seem to be explained by declining R&D (Griliches 1988). Perhaps this mismatch of R&D and output growth reflects a focus on the use of "formal" R&D, which may not measure efforts to improve manufacturing processes or organizational structures, or, more generally, to innovate at the margin.

Finally, Grossman asks whether the market-determined level of R&D investment is socially optimal. The answer to this question depends upon the existence of knowledge "spillovers": Knowledge gained from one firm's investment makes research more productive for other firms, while the other firms need not compensate the originating firm for this knowledge. When spillovers exist, the *social* returns to investing, which include the returns to those who did not pay for the investment, exceed the *private* returns. Jorgenson is skeptical of the existence of such spillovers, but Grossman reads the bulk of the empirical evidence as pointing to social returns to R&D investment that are more than twice as large as private returns. Does the presence of excess social returns suggest an investment tax credit or subsidy to foster innovative activity? Not necessarily; as Mansfield (1986) points out, R&D tax credits often encourage firms to relabel existing activities as investment, rather than to undertake new research.

Grossman acknowledges the important contributions of the neoclassical framework, favored by Jorgenson, to growth theory. However, he points out limitations of the model that make it "not well suited for studying innovation": The neoclassical model assumes constant returns to scale and perfect competition. Investment in knowledge, on the other hand, requires large up-front fixed costs that imply *increasing* returns to scale, and pricing in excess of marginal costs to recover high fixed costs, in violation of the assumptions of perfect competition. Thus, Grossman feels, one must study innovation in a setting that allows for imperfect competition, even when this makes policy prescriptions more difficult.

Uncertainty and Technological Change

Nathan Rosenberg examines the relationship between uncertainty, technological change, and economic growth. Rosenberg's approach to the topic is, he admits, anecdotal; but he discusses many of the most important innovations of this century, demonstrating the influence of uncertainty for technologies that have had tremendous economic impact.

Many of Rosenberg's primary conclusions are exemplified in his study of the laser. The laser currently has dozens of applications, from producing CDs to enabling delicate eye surgery, from an essential instrument in chemical research to the rapid carrier of data, voice, and optical information across telecommunications lines. And yet the initial developers of the laser at Bell Labs not only could not foresee these applications, but did not think the invention worthy of a patent application, since "such an invention had no possible relevance to the telephone industry." This lack of foresight was not a malady unique to the telecommunications industry or to potential users of lasers; the same inability to predict the general usefulness of an invention, let alone its particular uses, extends to the developers of the telephone, the computer, the transistor, the jet engine, and the radio.

What categories of uncertainty make it so difficult to foresee the usefulness of innovations? Rosenberg catalogues several. First, new technologies arrive on the scene with characteristics that do not immediately or obviously lend themselves to application. For example, new techniques for visualization in medicine, such as CAT scanners and magnetic resonance imagers (MRIs), were developed before it was known how to interpret their output in a clinically useful fashion. Significant additional research was required to render the innovation not only technically feasible but also usable by doctors and technicians in making diagnoses.

A second class of uncertainty arises when the success of invention A depends on improvements in complementary invention B, which may not exist at the time invention A is introduced. Take, for example, the use of lasers in communications. Only upon the development of fiber optics, and upon understanding how laser light could be transmitted through fiber optic cable, did lasers become a viable communications medium. When the success of the innovation depends upon a system of complementary innovations, as may be the case with computer technology, the length of the gestation period from inception to a full menu of uses may be decades.

A third class of uncertainty arises because many inventions were designed to solve very specific problems. For example, British engineers invented the steam engine in the eighteenth century to pump out flooded mines. The possibility that such an engine could be used in entirely different industries, for transportation or power generation for manufacturing, became evident only after many decades, during which time a sequence of improvements were made to the initial invention.

Finally, Rosenberg identifies uncertainty about the marketability of an invention. As he puts it, inventions need "to pass an economic test, not just a technological one." When Marconi invented the radio, he did not possess David Sarnoff's vision of a new medium "to transmit news, music, and other forms of entertainment and information into every household in the country." Without someone to anticipate and champion the commercial possibilities of the technology, the radio might have gone the way of the buggy whip.

In concluding, Rosenberg draws out the policy implications of the almost overwhelming uncertainty involved in technological innovation. First, he suggests that the increased emphasis on the "relevance" of research to social and economic needs is misplaced; we cannot know which research or development will turn out to be relevant, or relevant to what! For the same reasons, the government should not attempt to support a single technological approach to a problem, or one narrow area of research. These caveats do not necessarily apply to the private sector, however. In the face of uncertainty, Rosenberg asserts, the market will of its own accord encourage individual firms to pursue a wide array of research strategies, which, given uncertainty, is more likely to produce a useful innovation.

Joel Mokyr is largely sympathetic to Rosenberg's characterization of the uncertainty (or perhaps ignorance) facing decision-makers, but he suggests a modest reinterpretation. First, Mokyr posits two levels of uncertainty in technological change, the firm's *micro*-uncertainty, and the economy's *macro*-uncertainty. The former comprises a host of firm-level questions: Can this particular technical problem be solved? Can this firm solve it? Will we arrive at the answer first? Will it sell, or sell profitably? At the macro level, uncertainty involves which technological regime will dominate: nuclear or fossil fuels? Both levels of uncertainty figure prominently in the decisions of potential innovators.

Mokyr poses an analogy between evolutionary biology and technological innovation. The analogy holds in two regards. First, innovations, like mutations, occur at least somewhat randomly, and thus we do not know in advance what the future supply of innovations will look like. The degree of randomness likely differs between biology and technology, as the latter presumably attempts to respond to economic need. However, Mokyr and Rosenberg agree that while the correlation between need and mutation "may not be zero, it is not very high either."

Second, we do not well understand the "laws" that determine whether a particular mutation will be *selected* or not, in the biological case by natural selection, and in the case of technology by the market. Success in many instances depends on luck; Mokyr points out that 70 percent of all new products that make it to the distribution stage disappear again within 12 months. This high mortality rate underscores the poverty of knowledge, even among the innovators themselves, about the laws that determine which innovations will be successful.

Mokyr adds a third "evolutionary" process that is germane to understanding the uncertainty in innovation: the evolution of economic institutions. As Douglass North (1990) has emphasized, institutions evolve in a way that is no more predictable than the evolution of science and technology.

But the situation is even more complex, as the sources not only evolve but *co*evolve. Many institutions—free labor markets, enforced property rights—are good for technological development, whereas others—uncertain property rights, totalitarian government—clearly are not. Modern innovators need to know how the institutional climate will be when they bring their product to market. Will the FDA approve it? Will I get sued? Will it pass environmental restrictions? Only as institutions friendly to innovation evolve with technology will technology succeed.

Mokyr concludes with reference to a final biological/technological debate, between "adaptationists" and "anti-adaptationists." Do technology and living species adapt so that we see only efficient technological and biological outcomes, or do important examples exist of innovations (mutations) that are clearly suboptimal and persistent? Is the dominance of the Qwerty keyboard a result of inefficient lock-in and path-dependence, or do we not properly understand its inherent efficiency? Mokyr declines to take a firm stance on this issue, but notes a difference between the biological and technology versions of the debate. The biological adaptation debate involves a more constrained evolutionary process: A species can adapt or become extinct. Technology is somewhat less constrained; societies can, at least in principle, adopt a completely different technology very rapidly, albeit at significant private and social cost. Does the private benefit to changing technologies cover the social costs of not changing? If not, another role for the government may be to spur such changes when private benefits fall short of total social benefits.

Luc Soete cautions against drawing broad conclusions from the anecdotal evidence presented by Rosenberg. The innovations chosen by Rosenberg may have sparked the interest of historians precisely because they had such unanticipated success; if so, they may not be truly representative. Soete also suggests that sectors vary greatly in the type of uncertainty facing their research efforts. A drug firm that pursues hundreds of leads on a trial and error basis faces a different kind and magnitude of uncertainty from a chip manufacturer that is developing the next generation that will double processing speed.

Soete questions whether omnipresent uncertainty could explain the productivity slowdown. Do the productivity gains that we expect from, for example, information processing technologies, seem to lag their invention because of the difficulties in identifying their most efficient uses? "You ain't seen nothin' yet" is the optimistic buzz-phrase of this explanation.

Soete proposes two other equally plausible explanations of the "missing productivity." The first is the difficulty inherent in measuring the output of information goods and services. As suggested by Nakamura (1995), the failure to properly capture the consumer surplus generated by the vast array of new electronic and communications products recently made available will likely underestimate output growth, perhaps by enough to account for the missing productivity. The second explanation centers on the possibility that the short-term disinflationary monetary policies of the 1980s, which significantly increased real long-term interest rates, may have turned businesses' research focus to short-term R&D with immediate payoffs, at the expense of longer-term, more uncertain research.

Cross-Country Variations in National Economic Growth Rates: The Role of "Technology"

J. Bradford De Long's paper attempts to explain two striking observations about the cross-country distributions of living standards and growth. The first is that the cross-country disparity of per capita real incomes has increased markedly over the past two centuries. The second is that the growth rates of real income in individual countries seem to be converging to the pace that is consistent with their rates of investment and population growth (as documented in the work of Ball, Mankiw, and Romer 1988).

Broadly construed, De Long's explanation works as follows. He notes that the countries that were relatively poor 200 years ago are relatively poor today, and those that were relatively rich 200 years ago are relatively rich today, and that the gap between the rich and the poor is increasing. According to the neoclassical model, if each country had started with somewhat different endowments of labor, capital, and materials but had access to the same technology, then over long spans of time, all countries would approach the same level of real per capita income. The long-run divergence of incomes argues against this simple case. If, however, the rich countries enjoy *amplified* effects of technology improvements on standards of living, while poor countries do not, then we will not observe even a gradual convergence of living standards.

De Long's paper identifies two novel sources of income divergence, each of which rests on a magnified long-run effect of productivity on real per capita income for richer countries. The first source is the strong endogeneity of population growth with respect to productivity and income. Countries with high productivity and thus high real incomes tend to have lower population growth rates. De Long shows that, for the United States, each tripling in real per capita GDP is associated with a 1 percentage point fall in the annual rate of population growth. De Long suggests several explanations for this pattern. More prosperous countries are often more educated countries, and better-educated women demand better birth control; in poor countries, the average number of years of schooling is low, and children are more valuable to production there because they can be put to work at an earlier age. In other words, children in poor countries are "investment goods" rather than "consumption goods," as they are in rich countries. Other things equal, then, a country that experiences rapid growth through increasing productivity will experience lower population growth that will, in turn, raise income per capita.

The second magnification effect arises from the endogeneity of the relative price of capital. Prosperous countries tend to benefit from a low relative price for investment goods. Most wealthy countries have achieved their prosperity largely through attaining high levels of manufacturing productivity. This achievement implies a relatively low price for manufactured goods, including the investment equipment that firms use to produce more goods. In support of the negative correlation between prosperity and the price of capital, De Long notes that the real purchasing power of domestic currency in foreign markets can be as much as eight times higher in rich countries than in poor countries. The disparity in real purchasing power directly reflects the difference between the relative price of easily traded goods, such as physical capital, in richer and poorer countries. This negative correlation between prosperity and the price of capital also magnifies the effects on real incomes of changes in productivity: As productivity and real incomes rise, investment goods become cheaper, and the economy can afford more investment goods for a given pool of savings, thus affording further increases in productivity.

De Long shows that the combined effect of these productivity magnifiers is substantial. Including them implies that the estimated effect of a productivity increase on the steady-state level of output is orders of magnitude larger than simple growth accounting would suggest. These important endogeneities between income, population growth, and physical investment could go a long way toward explaining the extreme divergence in national incomes that we have observed over the past two centuries.

Thus, De Long concludes that technology, broadly defined as differences in productivity, explains much of the disparity in standards of living across countries. He notes, however, that technology, narrowly defined as the possession of the most modern machinery and manufacturing processes by a particular country, explains relatively little of the differences in per capita incomes across countries. He cites work by Clark (1987) that shows remarkable differences in output per hour in cotton textiles across countries in the early twentieth century, even though many of these countries used exactly the same textile machinery. The McKinsey Global Institute's study (1993) of cross-country productivity differences reveals similar puzzles: Japan appears to be 47 percent more productive than the United States in steel manufacture, but 67 percent less productive in food processing. It seems unlikely that Japan is adept at using and refining the best manufacturing procedures for steel manufacture, yet is completely inept at "learning and developing technologies for making frozen fish."

Reacting to De Long's observation concerning the link between income and population growth, **Jeffrey Frankel** points out that "a prime motive in poor countries for having many children is that they provide the only form of insurance against destitution in old age." As a country develops, its financial institutions develop with it, and the increased accessibility of savings instruments can substitute for a high ratio of children to working-age population as a savings plan.

Frankel also observes that De Long's hypothesis about the endogeneity of both population growth and the price of investment goods suggests a timing test: Under De Long's interpretation, one ought to see significant decreases in population growth or increases in investment rates *following* surges in real growth. Frankel finds little evidence in the data for East Asian countries that declines in population growth are more likely to follow peak growth rates than to precede them. Investment rates follow peak growth rates in some cases, perhaps confirming De Long's hypothesis. However, the data also show large increases in investment that predate the peak in growth rates and could, thus, be considered the proximate cause of subsequent growth, contrary to De Long's interpretation.

Frankel ends by noting De Long's omission of a critical determinant of differences in growth across countries: openness to trade and investment. A large body of empirical work finds openness to be an important contributor to growth, even accounting for differences in factor accumulation. The economies that have converged are those that are open, whether across the OECD, across Europe, or within the United States. The reason, according to Frankel, is that "openness is how countries absorb the best technology from the leaders," whether we construe technology narrowly, as in the most up-to-date machinery and equipment, or more broadly, to include managerial and organizational techniques. In addition, openness to trade is part of a self-reinforcing pattern of growth: Countries that open their boundaries to trade grow more, but countries that have grown also tend to lower tariffs and promote trade.

Adam Jaffe presents cross-country evidence supporting the effect of income on population growth. Real per capita income and population growth exhibit a strong negative correlation, with an increase in per capita income from $1,000 to $10,000 associated with a decline in population growth from 2.5 percent per year to 1.5 percent. Of course, the link between income and population growth is partly mechanical: As population grows, holding income constant, per capita income must fall. But Jaffe shows that the strength of the correlation could not arise exclusively from this mechanical relationship. Suppose two countries begin with the same per capita income, but the population of one grows at 1.5 percent while the other grows at 2.5 percent. The low-population-growth country will reach an income 10 times the rapid-population-growth country only after 156 years! It is plausible, therefore, that much of the cross-section variation in income and population growth rates arises because high income causes low population growth, and not vice versa.

Jaffe suggests that the negative relationship between real income and population growth is not continuous. The correlation falls substantially for incomes above the median, and vanishes for countries with per capita incomes above $10,000. Thus, the returns (measured in lower population growth) to higher income appear to cease above this threshold income level. This observation alters De Long's story somewhat. Once the one-time demographic threshold is crossed, no further population growth effect would occur for the rich country.

Jaffe also clarifies the explanation for the observed correlation between income and the price of investment goods. Productivity improvements must (by definition) make goods and services cheaper. Because most of the productivity enhancements of the past century have been concentrated in manufactured goods, the real price of manufactured goods has fallen faster than the real price of services. As investment is likely to draw more heavily on manufactured goods than on services, the relative price of investment goods will also fall as productivity rises. The importance of this observation is that the apparent feedback between income and the price of investment goods can arise from productivity increases in an autarkic country, and thus does not depend upon foreign trade. The correlation between the real purchasing power of domestic currency and growth simply reflects underlying differences in productivity improvements across countries.

Finally, Jaffe questions the usefulness of a debate over which inputs to production should be labeled "technology." Echoing comments made by a number of participants during the conference, Jaffe finds it more useful to expand the list of potential explanations of differences in growth across regions and sectors. He suggests that a deeper understanding of the importance of hardware, software, human capital, ideas, and institutional and market factors in production may help us better explain differences in productivity and growth.

Address: Job Insecurity and Technology

Alan Greenspan's address focuses on human reactions to the structural changes caused by modern computer and telecommunications technologies. Pointing to the paradoxical pervasiveness of insecurity and malaise in a period of extended economic growth, restrained inflation, and a comparatively low layoff rate, he examines the origins of this anxiety and suggests ways of alleviating it.

He sees modern societies as having evolved from a time when the creation of economic value depended on physical brawn and physical product to the present when ideas are the critical input. This accelerating trend has had two important consequences: It has played a major role in changing the distribution of income in this country, and it has created a sense of foreboding in a large part of the work force.

Expanding on the first outcome, Greenspan explains that as ideas have become critical to the creation of economic value, education and intellectual skill have become increasingly important determinants of earned income. Although the supply of college graduates rose with demand in the 1960s and 1970s, by the 1980s the demand for skilled workers was apparently outstripping supply. The seeming result was a rise in the compensation of college graduates relative to that of less-educated individuals. Because the growth in real incomes slowed markedly in the mid 1970s—reflecting a similar (and not fully explicable) slowdown in productivity growth—widening income disparity has meant that parts of the work force have experienced stagnant or falling real incomes and understandably feel rooted to a treadmill.

Greenspan suspects that an even larger share of the work force is suffering from the job insecurity caused by rapid technological change. This group, composed of relatively skilled, experienced, and well-paid individuals who interact closely with our high-tech capital stock, are acutely aware of the speed at which this stock is being radically transformed. As a consequence, they fear that their own job skills may suddenly become obsolete. Greenspan suggests that these fears have led to an extraordinary period of labor peace, with a preference for job security over wage hikes, lengthening labor contracts, and unusually subdued strike activity.

Given widespread recognition of the growing income disparity, labor's acquiescence is somewhat surprising. Still, the relative economic welfare of low-income workers may not have deteriorated as much as the rising disparities in the distribution of income and wealth suggest. For example, recent work by Johnson and Shipp (1996) finds that the rise in consumption inequality since 1981 is only three-quarters as large as the rise in income inequality. Since purchases of consumer durables provide services throughout their useful lifetimes and are more akin to investments, the distribution of consumer durables deserves special attention.

Since 1982, household ownership of consumer durables has grown at an annual average rate of 3.3 percent a year, a slightly faster rate than in the 1960s and 1970s. Moreover, according to data provided by Stephanie Shipp and her colleagues at the Bureau of Labor Statistics, while ownership of consumer durables clearly rises with income, the distribution of ownership rates across income groups for cars and many appliances actually became more equal between 1980 and 1994. By exception, the disparity in ownership rates for personal computers remains large—unfortunately, given that knowledge of computers is linked to economic success.

Stressing that economic security depends on much more than owning selected consumer durables, Greenspan argues that the solution to the malaise created by rapid technological change involves finding ways to enhance skills. Since education has clearly become a lifetime activity, it is fortunate that many companies are beginning to see that human capital development is crucially important to improving profitability and shareholder value. He hopes that this approach will also help to reduce income disparities.

While the twenty-first century is likely to remain just as fast-paced as the recent past, Greenspan concludes, individuals currently entering the work force are used to rapid change and many six-year-olds are computer literate. Thus, as in previous periods of great structural change, the current frictions and uncertainties will diminish as people learn to adapt.

Microeconomic Policy and Technological Change

Reviewing the impact of public policies towards R&D spending, patents, and competition on innovation, **Edwin Mansfield** argues that government has a major influence on the rate of technological change in major industries. He points out that the federal government finances about 35 percent of all U.S. R&D investment and 60 percent of the R&D performed by colleges and universities. He provides two rationales for these expenditures. First, where government is the primary purchaser of public goods, like national defense or space exploration, the government clearly bears primary responsibility for promoting related technological change. In addition, much federal R&D is directed towards basic research because market failures or spillovers could cause private sector investment to fall short of socially optimal levels.

However, it is not self-evident that R&D spending is actually suboptimal. In many oligopolistic markets, product improvement is a major form of competition. As a result, R&D spending might actually exceed socially desirable levels in such industries. In addition, the government currently subsidizes R&D activities through the R&D tax credit and various grant programs. Thus, the government may already have offset any tendency for the economy to underinvest in R&D.

To address this issue, Mansfield reviews empirical estimates of the social rate of return from innovation, a body of work to which he has made major contributions. He starts by showing that the social benefits from an innovation equal the sum of the gains to consumers from the resulting decline in prices and society's resource saving (alternatively, the innovator's profit). Arguing that a high social rate of return signals a productive investment, Mansfield reports that empirical studies consistently find the median social rate of return from innovation to be substantial (the lowest median cited was 56 percent), even when private returns were low or negative.

The gap between the social and private rates of return from innovation provides an important rationale for government support of civilian technology. But, while a remarkable number of independent studies find the gap between marginal social and private rates of return to be sizable, many economists suspect that federal intervention could do more harm than good. Accordingly, Mansfield offers guidelines for public R&D support programs. First, given the huge uncertainty surrounding R&D outcomes, government incentives should remain modest, encourage parallel approaches, and provide information for appraising the desirability of further support. Such programs should not aid declining industries or late-stage development work. Recommending a pluralistic, decentralized approach, Mansfield also suggests that potential users of new technologies play a role in project selection so that public R&D efforts reflect market realities.

Mansfield's paper then reviews the pros and cons of another important instrument of national technology policy, the patent system. Some supporters argue that patent protection provides necessary incentives for innovation and development activities by slowing the introduction of relatively low-risk, low-cost copycat products. Other proponents assert that the patent filing process actually speeds the disclosure and dissemination of new technologies. Critics complain that the patent system creates usually weak but sometimes self-sustaining monopolies that slow the spread of new information. Still others conclude that patents have minimal importance, especially for large corporations; firms keep secret what inventions they can, they say, and patent those they cannot.

Turning again to empirical results, Mansfield reports that while patent protection does not make entry impossible or even unlikely, it does raise the cost of imitation. According to one study by Mansfield, Schwartz, and Wagner (1981), patenting raised the median imitation cost by 11 percent—30 percent in ethical drugs and 7 percent in electronics. Despite widespread skepticism about the value of the patent system, Mansfield acknowledges that few economists would recommend abolishing it, given our limited understanding of its impact.

Mansfield's paper ends with a discussion of the effects of market structure and antitrust policy. He concludes that while market entrants often play an important role in promoting technological change, some R&D activities exhibit economies of scale. Since a complementary mix of firm sizes appears to benefit technological change, public policy should aim to eliminate unnecessary barriers to entry and discourage industrial concentration.

The theme of **Samuel Kortum**'s comments is that the effectiveness of government technology policy depends crucially on the responsiveness of technological change to research effort, and that the evidence about the actual impact of research activity on innovation is weak. Although a vast literature has uncovered a systematic relationship between growth of total factor productivity and research effort (R&D/sales), Kortum points out that these studies provide no evidence concerning the direction of causality in this relationship.

Kortum raises the provocative possibility that technological change may be largely impervious to government incentives—if, for instance, innovation is an exogenous process more dependent on the chance arrival of technological opportunities than on incentives to exploit them—and sets out to show that this idea is not so easy to disprove. To do so, he develops a model in which R&D spending is the means by which firms compete for patent rights to innovations that arise within the economy regardless of the level of research activity. The larger a firm's share of industry spending on R&D, the greater is the probability that it will win patent rights valued at the industry's cost savings from the innovation. If the above model describes the real world, a cross-industry estimation of the impact of R&D effort on total factor productivity will reflect the fact that R&D effort depends on the value of exogenous innovation.

In Kortum's model with exogenous technical change, the private rate of return to R&D is the interest rate, but the social rate of return is −100 percent since the marginal expenditure has no benefit for society. Even careful economists, like Mansfield, who sum all research costs for losing as well as winning firms in calculating the social rate of return on R&D, are likely to find huge social payoffs—erroneously if innovation is actually exogenous. Although Mansfield and his coauthors state that social benefits should be measured only between the date when the innovation occurred and the date when it would have appeared if the innovator had done nothing, Kortum questions the validity of survey work based on hypothetical questions about the timing of competitors' innovations.

To provide additional evidence as to whether innovation is endogenous or exogenous, Kortum recommends careful analysis of the impact of a specific policy change, like the increased patent protection stemming from the 1983 creation of a single appellate court for patent cases. If technological change is actually exogenous, then such a policy shift should have no impact on productivity. By contrast, evidence that the policy action raised productivity would be highly suggestive of endogenous technological change.

Joshua Lerner focuses his comments on Mansfield's policy prescriptions. In particular, he asks whether technology policy should recognize that small firms generate a disproportionately large share of major innovations, since, as Mansfield and others have pointed out, many studies find that start-ups play a big role in applying radical technologies. Although key innovations are usually developed with federal funds at universities or research labs, small firms are often the first to act upon the commercial possibilities. As important examples of this phenomenon, Lerner cites the development of biotechnologies and the Internet. Given the uncertain path of technical developments and the critical role often played by previously unknown firms, Lerner is skeptical of Mansfield's stress on a "proper coupling between technology and the market" and his prescription that federal R&D be directed with the advice of potential users.

Lerner next addresses issues raised by the patent system, particularly the impact of the single court of appeals for patent cases established in 1983. Lerner argues that the new court has produced more pro-patent rulings than the previous system—with the result that large and small firms are putting more effort into seeking new and defending old patent protection. Viewed broadly, Lerner contends, the consequent growth in patent litigation has created a substantial "innovation tax" that falls particularly hard on small firms. In a recent research effort Lerner (1985) has found that patent litigation begun in 1991 will lead to total legal expenditures amounting to more than one-quarter of the private dollars spent on basic research; the indirect costs of this litigation are also substantial. Survey results suggest that these costs are a more important deterrent to development efforts for small firms than for large firms. Accordingly, reforms intended to protect and spur innovation have actually discouraged entry. Lerner is concerned that efforts to make federal research commercially relevant could have the same effect.

Technology in U.S. Manufacturing: The Geographic Dimension

Continuing with a micro perspective, **Jane Sneddon Little** and **Robert K. Triest** explore the process by which advanced technology enters general use. Using relatively new data from the U.S. Census Bureau's Surveys of Manufacturing Technology (SMTs) for 1988 and 1993 (U.S. Bureau of the Census 1989 and 1994), their paper examines variations in the adoption of 17 advanced technologies across the nation and within individual states. The authors consider a variety of plant and locational characteristics that might raise the probability of technology use, but they are particularly interested in whether proximity to firms already using advanced technologies fosters adoption. Proximity to early users might affect adoption decisions by reducing the perceived risk and actual cost of investing in this new equipment.

Little and Triest estimate a set of econometric models that control for the effects of plant, firm, and locational characteristics. As measures of technology diffusion, the authors examine the change in the number of advanced technologies used by SMT establishments between 1988 and 1993, the number of technologies used in 1993, and the probability of adopting a particular technology by specified dates covered by the SMT survey. In each case, the authors first control only for proximity to other users of advanced technologies. They then add in a set of plant and firm characteristics, such as size and industry. As a final step, they include a set of locational characteristics, like educational attainment of the work force, in the group of explanatory variables. In all three estimations, proximity to early users almost always has an economically and statistically significant positive effect on technology adoption, not only when proximity is the only explanatory variable but also when plant characteristics are taken into account. While introducing locational characteristics always reduces the coefficient on proximity, these coefficients still remain positive and statistically significant in the equations for the number of technologies used in 1993 and for the change in number of technologies used. By contrast, for the models estimating the probability of adopting specific technologies over a span of years, the proximity variable generally loses its significance when the geographic variables are added.

Little and Triest conclude that proximity to other users of advanced technologies is associated with higher rates of adoption, even when industry and other plant characteristics are controlled. They find this result noteworthy since, with its well-developed communications networks and national markets for capital goods and skilled workers, the

United States might be expected to approach the limiting case of immediate, costless diffusion of technology. Human capital appears to be an important part of the proximity effect, they speculate, because, among the locational variables, access to a work force with a high school education or some technical training is associated with a higher rate of technology adoption. Some of the remaining proximity effect may reflect the impact of social interactions in spreading technical information.

Although the authors were not able to separate proximity/spillover effects from the impact of educational attainment/university R&D to their satisfaction, they believe that the evidence of uneven technology diffusion warrants further research. Because technology adoption is extremely expensive for individual firms and the nation, gaining a better understanding of this process remains an important goal.

John Haltiwanger's comments on the Little-Triest paper center on his concerns about data and measurement issues and about the appropriate interpretation of their results. Citing recent research by Dunne and Troske (1995), Haltiwanger points out that the answers to the retrospective questions in the 1993 SMT on the timing of technology adoption appear subject to substantial recall bias. Respondents systematically date adoption more recently than was actually the case. As a result, Haltiwanger suggests, the Little-Triest variable measuring the change in the number of technologies used may actually be a better measure of the number of technologies in use in 1993. Thus, although Little and Triest find some evidence of clustering, the timing problems raise questions about the direction of causality and the underlying source of this clustering.[1]

Dunne and Troske's work raises another important issue, Haltiwanger contends. Their 1995 study finds evidence of significant rates of de-adoption for specific technologies. For example, for the matched sample of plants responding to both the 1988 and 1993 SMTs, 39 percent of the establishments using local area networks in 1988 were not using them in 1993. This finding suggests additional measurement problems or the intriguing possibility that firms experiment with new technologies that they eventually decide not to use. If so, a region that is relatively slow to de-adopt should not be labeled "advanced," Haltiwanger suggests.

Haltiwanger then takes up a line of argument similar to that raised by Samuel Kortum: Does the adoption of advanced technologies actually affect outcomes we really care about—the growth of income or

[1] In response to Haltiwanger's comments concerning their use of retrospective data, Little and Triest reran their regressions using the subsample of firms responding to both the 1988 and 1993 SMTs. Relying on current rather than retrospective data on technology use did not change the flavor of their results. If anything, the change strengthens the impression that proximity affects technology adoption. See Little and Triest, footnote 43, in this volume, for details.

employment or productivity? While one might presume such a connection, work by Doms, Dunne, and Troske (1995) suggests that differences in technology use are not particularly meaningful. Although Doms, Dunne, and Troske find that advanced technology use has a significant positive effect on plant-level labor productivity, differences in technology adoption account for only 1 percent of the total variation in labor productivity across plants. Moreover, these authors find no statistically significant link between technology adoption and the growth in plant-level labor productivity. (Perhaps the failure of micro studies to find much connection between the adoption of new technologies and productivity levels or growth should not be so surprising, given our similar inability to find any productivity payoff to vast investments in new technologies at the macro level.)

Alluding to research stressing the dominance of idiosyncratic factors and the importance of the reallocation process steering resources from less to more productive plants, Haltiwanger suggests caution in interpreting empirical results concerning technology diffusion. Seemingly, the growth process is noisy and complex, and the required resource reallocation is time-consuming.

In commenting on the Little-Triest paper, **George Hatsopoulos** provides the perspective of his many years of experience in managing high-technology companies. He interprets proximity as representing local management culture or standard technological practice within a given area. In this context he finds that the authors' conclusions correspond with his own observations.

Hatsopoulos starts by emphasizing the relative importance of diffusion—compared with innovation—in determining a country's technological sophistication. Like John Haltiwanger, he also finds that intangibles like managerial and organizational skills, and labor-management relations, exert an extremely important influence on micro and macro productivity levels.

Turning to Little and Triest's empirical results concerning the impact of proximity on the probability of technology adoption, Hatsopoulos reports that this finding matches his observation that decisions about the use of specific technologies are determined by middle managers and foremen who, in turn, are heavily influenced by prevailing practice at neighboring plants. To illustrate this point, he cites the example of two plants, one in Manchester, England and one in Auburn, Massachusetts. Although the two were making identical products for the paper industry, labor productivity in Manchester was about half that in Auburn. The problem, it turned out, was that managers and workers in Manchester were extremely reluctant to import manufacturing and organizational technologies that headquarters had found useful in the United States but that were uncommon in Britain. Because these workers were very heavily influenced by local practice, Thermo-Electron had a very hard time trying to change their behavior.

Reacting to Little and Triest's finding that plant size has a significant positive impact on technology adoption while firm size does not, Hatsopoulos indicates that these relationships again appear intuitively plausible to him since plant scale must be considered in making technology decisions while access to capital, a firm-level characteristic, has only an indirect impact on local technology choices. Similarly, Hatsopoulos reports that he is not particularly puzzled by the result that access to a work force with a high school education has a greater impact on the probability of technology adoption than does access to workers with a college education. Because he finds the importance of foremen and other middle managers to be of overriding importance in the technology decision, Hatsopoulos finds this result matches his expectations.

MACRO POLICY, INNOVATION, AND LONG-TERM GROWTH: A PANEL DISCUSSION

Martin Baily begins by dissecting potential GDP growth, estimated to be 2.3 percent per year, into its major components: labor inputs, which have been rising about 1.1 percent annually; and labor productivity, which has shown trend growth of 1.1 percent per year since 1973. As Baily points out, while trend labor productivity has fallen from its 2.9 percent average in the 1960-73 period, the explicable part of productivity growth (the part due to capital intensity, education and experience, and R&D) has been remarkably constant at 1.1 percent since 1960. By contrast, the unexplained residual, the productivity "bonus" enjoyed between 1960 and 1973, has entirely disappeared; "We did not know where it came from then, and now we do not know where it has gone." In a related puzzle, the growing gap between the annual earnings of college and of high school graduates is widely attributed to a rising demand for technically skilled workers, but we see no signs of major technological breakthroughs in the productivity numbers. More formally, we see evidence of technological bias in the increased return to education but no evidence of technological change in measured productivity growth.

Turning to policy prescriptions, Baily concludes that current growth rates reflect supply rather than demand constraints and, thus, that the potential role for monetary policy in spurring growth is limited. By contrast, fiscal policy is important: During the 1980s the federal budget deficit was a primary cause of our low rates of saving and investment, which in turn contributed to the deceleration in capital intensity and productivity growth. Thus, reducing the federal deficit remains an important policy goal. A second area for policy action relates to education and training. Although the contribution to productivity growth made by education and experience has risen recently, that increase merely reflects the growing experience of the aging baby boom generation, and the rising return to education suggests that the demand for highly skilled workers continues to outstrip supply. Because Alan Krueger's work (1993) shows that computer skills in particular are linked to higher wages and, presumably, thus, to higher productivity, federal seed money for computer literacy programs might prove especially helpful. Finally, since studies by Edwin Mansfield and others suggest that the social return to private R&D is substantial, Baily concludes that tax incentives for R&D could play a positive role. Moreover, since private R&D appears correlated with prior federal R&D spending, Baily is concerned about congressional proposals to curtail the rate of public non-defense research.

Baily ends by speculating about the unexplained growth bonus enjoyed between 1960 and 1973. Much of that spurt in productivity growth may have resulted from a burst of innovation and a shift from craft to mass production that cannot be repeated. If so, we may simply have to adjust to a world with lower productivity growth and slower growth in average real wages—a world split into winners and losers. Such a world would require attention to policy dimensions such as the provision of safety nets, Baily submits. On the other hand, because measuring output and productivity is extremely difficult, particularly in areas like health care, or in retailing and financial services where convenience is important, output and productivity growth may actually be better than we think. Accordingly, Baily advocates investing in, not starving, our statistical agencies in order to get better data and better policies. Finally, maintaining open economies and deregulating domestic markets provide important incentives to adopting better technologies.

Ralph Gomory addressed his remarks to the impact of economic development in technically backward countries on welfare in the industrialized nations, a topic of great concern to many policymakers. As underdeveloped countries improve their technical capabilities, they become significant contributors to world output, but they also become more effective competitors to established industries in developed nations. What is the net impact on the national welfare of the technically advanced nations? To analyze this issue, Gomory offers a classical Ricardian model of international trade in which the relative efficiencies determining comparative advantage are allowed to vary, as in Gomory and Baumol (1995a).

Gomory sketches a two-country model—or rather a family of two-country models—that assumes single-input linear production functions, Cobb-Douglas utilities, and fixed labor supplies and demand parameters, as well as a fixed number of industries. In equilibrium, both countries actively participate in a given industry *only* if their unit labor costs in that industry are equal. The exercise then calculates, for all possible values of average labor productivity, the equilibrium outcome in terms of national utility and share of world income for each country.

The results suggest opportunities for inherent conflict between the two countries because, even though *world* output is greatest when both countries have similar productivities and split world production 50-50, the best outcome for each one *singly* occurs when it has a large share of world output and income; this point always represents a poor result for the other. As Gomory carefully points out, improvements in productivity in one country (which always increase that country's share of world income) sometimes enhance welfare in both countries; however, in other cases, unilateral improvements in productivity decrease the welfare of the other.

What conditions determine the outcome? Assuming, as in Gomory and Baumol, that efficiency rises in an active industry and decays in a less active industry, the model suggests a natural tendency for national shares of world output to remain close to their original values, while incomes expand as a result of improving efficiencies. However, if one country (generally the lower-wage country) succeeds by policy measures in "capturing" a growing share of world output in a given industry, its welfare improves. Whether or not welfare improves in the second (advanced) country depends on whether the depressing effect of the capture is or is not outweighed by improved efficiencies (via learning-by-doing, for instance) in all other industries. This result contrasts with Ricardo's original insight that trade based on comparative advantage determined by a specific pair of production functions always enhances well-being in both countries.

Abel Mateus's experiences with the Banco de Portugal and the World Bank permit him to examine the impact of macro policies on growth from the perspective of developing as well as developed economies. He suggests that technological progress is a primary determinant of growth in developed countries, whereas in developing countries most growth is due to the accumulation of physical and human capital that incorporates ideas transferred from advanced nations; thus, in these developing countries, outward orientation is complementary to the capital accumulation process.

Mateus points out that in small open economies "miraculous" growth is linked with rapid accumulation of human capital and use of that knowledge to operate physical capital to produce goods near the country's technological frontier. Shifting labor and capital to ever more advanced activities allows learning by doing and augments the accumulation of human capital. Export orientation is essential to such a growth strategy because this approach creates a gap between the mix of goods consumed domestically and the mix of goods produced and by necessity exported to larger, more demanding foreign markets. By contrast, Eastern Europe provides counterexamples of countries where the technology gap is sufficiently huge that trade promotes so much Schumpeterian (creative?) destruction that short-term welfare actually declines. Nevertheless, Mateus argues that these "industrialized" transitional nations must pursue the painful path of institutional change, industrial restructuring, and integration into the world trading system. Moreover, most developing countries, with smaller initial manufacturing sectors, do not face such conflicts; for them, the benefits of trade based on comparative advantage apply even in the short run. The policy implications stemming from Mateus's observations of small open economies include an emphasis on formal education, protection of property rights, and an export-oriented trade stance to promote competition and technology transfer.

Mateus then addresses the impact of free trade in goods and technologies on the developed countries, where these developments have been associated in the 1980s and 1990s with high unemployment rates and stagnant or declining real wages for unskilled workers. After a reminder that present levels of global integration are not unprecedented, he points to the drop in transportation costs and the increase in communication speeds as the truly new elements. Although he sees some evidence supporting Paul Krugman's (1981) hypothesis that these developments will improve the lot of peripheral regions at the expense of the core and Jagdish Bhagwati's finding that comparative advantage has become "kaleidoscopic," moving almost at random across developed countries, he finally concurs with Obstfeld (1994) that financial integration, with investment shifting from lower-return to higher-return projects, can yield substantial welfare gains throughout the world via its effect on output and consumption growth.

Because the profitability of innovation and diffusion depends in part on the macro environment, Mateus then turns to fiscal policy and suggests that a high and rising debt ratio is likely to lower the long-term rate of growth. He cites World Bank findings that a 1 percentage point increase in the government surplus as a percent of GDP raises per capita growth by 0.37 percent and the investment ratio by 0.24 percent. Other research suggests that debt ratios and budget deficits are positively associated with increases in long-term risk premia. Mateus concludes, thus, that the near doubling in gross public debt as a share of GDP between the 1970s and the mid 1990s has had a significant negative impact on European growth rates. Accordingly, Mateus recommends wider use of consumption-based tax systems and a significant cut in the size of the public sector, to be accomplished, in part, through better project and activity evaluations. In addition, Mateus warns, social security systems in most countries are unsustainable.

Mateus ends by reprising his major policy recommendations. First, the emphasis on economic stability, trade liberalization, market-oriented policies, and human capital accumulation long advocated by international organizations appears to be appropriate. Second, the potential for improving world welfare by technology diffusion and portfolio diversification is enormous. Finally, within the developed world, blaming globalization and "social dumping" for current labor market problems is misguided. In Europe, reducing high rates of unemployment requires improving labor market flexibility, while in North America dealing with the plight of unskilled workers awaits more adequate redistributive policies.

Robert Solow expressed relief that the panel was discussing whether macro (not monetary) policy can promote long-term growth; as phrased, the question implies that fiscal policy is available for the task—luckily, since monetary policy cannot possibly address the many goals often assigned to it. Solow then begins his policy recommendations by urging advocates—academics as well as politicians—to stop making inflated claims for their favorite policy tools. The flat tax, a cut in the capital gains tax, and various labor market reforms may or may not be good ideas, but their impact on growth is likely to range from negligible to small—at most. In particular, Solow chides, too many theorists have taken to fabricating powerful policy options by leaping from empirically established links between levels to assumed links between levels and growth rates. For example, while most would agree that the level of human capital affects the level of output, too many go on to assume that a high *level* of schooling will increase the *growth* of human capital, or that a high *level* of R&D will speed the *pace* of innovation. With these assumptions, tax policy can readily be shown to affect the permanent rate of economic growth since it is quite easy to design incentives for schooling or R&D. "But do we really know that an increase in schooling or R&D will generate more than a one-time shift in the level of output?" the self-described spoilsport asks.

This plea for circumspection limits the list of growth-promoting policies severely, Solow admits. Still, he considers certain commonplaces worth repeating. Given how little we know about the links between stocks and growth rates, any policy that raises potential output permanently should be described as contributing to growth—even if the long-term rate of growth remains unchanged. Just shifting the steady-state growth path upward, parallel to itself, is a major feat, he contends.

After warning that the trade-offs between growth and current living standards must be weighed, he emphasizes that anyone choosing growth must favor investment over consumption. Since a pro-saving policy need not be pro-investment (because additional saving may reduce a current account deficit rather than raise investment, say), Solow proposes combining improved incentives to save with policies that shift the composition of demand in favor of investment. Any fiscal stance, he reminds us, can be weighted in favor of investment, with tax-and-subsidy policy an obvious instrument. Similarly, while a given macro posture can be achieved with many combinations of monetary and fiscal ease and tightness, in general growth is efficiently served by mixing relatively tight fiscal policy, to promote national saving, with relatively easy monetary policy, to spur domestic investment.

Solow also endorses a macro strategy that guides total demand toward potential whenever a gap between the two appears—for many reasons, but not least because this policy is growth promoting. He notes in this context that actual demand tends to fall below potential somewhat more often than it exceeds it, and that prospects for weak and fluctuating demand discourage investment. While the impact of modest overheating (particularly on investment volumes) is less clear, he cites consensus views that price stability encourages the most productive allocation of capital. Solow ends by asking, tentatively, if the Fed could usefully conduct open market operations at all maturities, not just at the short end, in order to affect long rates which, presumably, are the most relevant for investment decisions.

Moderator **Richard Cooper** initiated the general discussion by remarking that over the last 50 years, the process of innovation has, for the first time, become institutionalized and by asking the panelists and conferees to consider the price of future growth in terms of current income. Would it have been moral to ask our grandparents to save more in order that we could be even better off, compared with them, than we already are? In response, Robert Solow replied that he would be less concerned about growth if we were better at income redistribution, but, since we find redistribution hard, increasing today's growth is one way to help today's poor children and today's poor countries. Baily and Mateus added that public and private myopia about looming retirement needs requires current policy action to spur saving. Other comments addressed the differential impact of environmental spending on measured productivity and the quality of life, and the need to explore the impact of the transitional costs of technological change on the growth process.

Conclusion

After two decades of research focusing on the source and stabilization of short-run economic fluctuations, the profession has recently returned to considering the determinants of long-run growth. This resurgence in interest arises for several reasons. Many developed economies have seen their average growth rate halved since the mid 1970s, and as yet we have no compelling explanation. Differences across countries in standards of living and in growth rates are large and not obviously shrinking, even as modern technology has been disseminated more widely and educational standards have risen. The welfare implications of these cross-time and cross-country income differences dwarf those that arise from business-cycle fluctuations.

One fruitful vein of research has striven to understand growth from within the neoclassical framework, attributing continued increases in income primarily to investments in physical and human capital. Dale Jorgenson's research constitutes probably the most carefully measured and estimated set of econometric models in the neoclassical tradition. His conclusion is that investment can account for the preponderance of growth. This assessment is important, as it provides a benchmark for the contribution of standard inputs to growth. And yet, as Susanto Basu points out, the neoclassical model ultimately cannot plausibly explain all of the differences in growth that we observe over time and across countries. It seems extremely unlikely that we could have achieved most of our high standard of living today simply by using more and more of the investment goods that were prevalent in the nineteenth century. We could not have arrived at our sophisticated communications-linked, information-processed, efficiently manufactured state simply by using more and more shovels, adding machines, and steam engines. And yet the available data do not reveal a clear relationship between the invention, development, or adoption of new technology and subsequent improvements in productivity or income. Where does this observation leave us? Participants in this conference generally agreed on a few tentative conclusions.

First, it may be helpful to understand the input to production that is neither human nor physical capital not simply as "technology," but as an aggregate of the state of technology, organizational and managerial ability, and "economic culture." These concepts are not easily measured, but given the inability of relatively well-measured constructs to explain the variation in productivity in disaggregated data, we must try to model and measure these intangibles better if we are to understand significant differences in growth and productivity over time and across countries.

Second, most conference participants agree that it is probably beyond our grasp to design policies that we can be confident will spur specific innovations, or even spur innovation generally. The difficulty arises largely from the tremendous amount of uncertainty that surrounds the process of innovation. Given the difficulty in knowing which innovations will succeed, when they will arise, and what complementary innovations they will require to become "useful," policymakers do not possess the foresight to tailor policies to foster specific innovations. Still, most participants agreed that the social returns to innovation exceed the private returns. Although the extent to which private returns spill over into non-appropriable social returns is not clear, most would say such spillovers are likely to be sizable. Thus, the government should play a limited role in promoting R&D.

Finally, two clear insights from our panelists merit special attention as pointers to future research. The first, highlighted by moderator Richard Cooper, is that we assume, as a matter of default, that a higher long-run growth rate is better. In doing so, we are implicitly choosing the multiple by which our descendants' welfare will exceed our own. At a 1 percent rate of annual productivity growth, our grandchildren will on average have 65 percent higher real incomes than we do; at a 2 percent rate they will have nearly triple our real incomes. But in order to attain these increases for our descendants, we must forgo some current consumption. Cooper poses the question: How much better off should our grandchildren be than we are, and at what cost? Robert Solow points out, in response to Cooper's question, that productivity-generated increases in the size of the economic pie may benefit the poor children of today *and* tomorrow. This question lies at the root of the discussions about productivity slowdowns and hoped-for improvements.

The second insight, articulated by Robert Solow, is a reminder that not all improvements in welfare must be measured as changes in the growth rate of the economy. One-time permanent improvements in the *level* of potential output are also valuable and probably much more attainable. The profession may do well to focus more of its attention on policies that could more reliably achieve these less spectacular improvements.

References

The references cited in the Overview can all be found in the papers and discussions, except for the following.

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KEYNOTE ADDRESS: THE NETWORKED BANK

Robert M. Howe*

The financial services industry is moving rapidly into the information age, to which many refer as the networked economy. This economy represents the integration of people and institutions obtaining information, transacting business, and entertaining and educating themselves in a connected world, with electronic networks as the underlying backbone. This electronic backbone supports many interfaces including bank branches, ATMs, noncash kiosks, trading desks, stock exchanges, call centers, remote personal computers, and smart card connections.

The growth rate of the networked economy is explosive. Morgan Stanley forecasts that the number of network users for e-mail, interactive web use, and on-line services will grow from 52 million worldwide in 1995 to over 380 million in the year 2000. They also report that Internet hosts are multiplying at a rate of over 100 percent per year, with nearly 10 million hosts or servers connected in 1996. And, although about half of the Internet activity now is located in the United States, growth rates are high around the world—and the highest in emerging economies such as Eastern Europe, Africa, and the Middle East.

Electronic channels are becoming the standard for all types of transactions, from making airline reservations to checking account balances and paying bills. IBM's *Beyond Computing* publication reports that 55 percent of corporate and information technology executives believe that Internet-related technologies will have the single largest impact on their business of all technology issues in 1996.

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Within five to seven years, you will be able to make any financial transaction over the Internet, in a secure environment. Networks will be pervasive, and everyone will have access to them. In your wallet you will carry a smart card that has the power of a PC. The challenge for every financial institution is to figure out what to do with that power, because it is going to be everywhere. My purpose tonight is to describe my vision of how technology will transform the financial services industry in this networked world—creating the "networked bank." I will begin with a description of the networked bank and an overview of the key technologies that support the networked banking environment. I will then offer strategies for how banks might respond in this new competitive landscape. I will conclude with a summary of the issues that affect the networked bank and may be worth consideration by the Federal Reserve System.

THE NETWORKED BANK

Changes in technology and in consumer behavior have allowed electronic channels and interactive financial services to become a reality. This on-line, electronic banking scenario is defined as the networked bank. Everything in this environment is networked: The customers are connected to the bank and to each other through branches and electronic channels; the bank is networked to other financial and technology product and service providers through alliances and special relationships; the employees of the bank are networked through cross-functional processes and modular teams.

The networked bank can be described further by its three major components. The first and most visible component of the networked bank comprises its *access channels*. Access channels include tellers, ATMs, telephones, screen phones, and PCs, which enter the banks' systems via branches, the ATM network, call centers, and on-line direct banking services. In the past, a bank would have managed its branch and ATM networks as a group of distribution channels and controlled the availability of the bank's products and services. In the networked bank, control of the channels is in the hands of the consumer and of the channel provider, and the channel provider is as likely to be a third party, such as an on-line service provider, as it is to be the financial institution. With the proliferation of electronic channels, consumers will determine when, where, and how they will access their financial services.

The second component of the networked bank is the bank's *customer information and relationship management system*. This system is the bank's data warehouse of customer relationships, product information, and related tools and analytics. For example, the networked bank collects customer preferences and profitability information on a transaction-by-transaction basis, and then uses this information to create new products and to market them selectively to targeted customer segments. The data provide the bank with the capability to offer new value-added services proactively to its customers and thereby to increase its ability to enhance customer relationships and retention. Modeling tools allow the networked bank to understand its most profitable customer segments by product and by access channel. Effective use of this customer relationship information becomes the bank's most valued asset and source of competitive advantage.

The third component of the networked bank is the *core back-office system.* The core banking system represents the bank's operational systems, support for retail and commercial banking functions, systems for subsidiaries or acquisitions, and, perhaps most important, links into other content-providers' systems. The networked bank has the ability to offer a wide variety of products and services, some of which may actually be provided by other firms. For example, a networked bank may ally itself with insurance firms, brokerage firms, travel agents, and retailers to offer a rich mix of financial and nonfinancial services. Therefore, a critical competence of the networked bank is in developing the ability and cultural attributes required to work in a network of alliances.

TECHNOLOGIES

Five major technologies empower the networked bank: human-centric technologies, networks, scalable processors, intelligent agents, and new tools such as object-oriented programming and data mining. IBM Research has forecasted the development of these technologies out over the next 10 years, and it is therefore possible to anticipate some of the challenges and opportunities that these technologies will bring to the networked bank environment.

Human-centric technologies are those that allow people to use computers and related digital technology more easily. In IBM's view, the next 10 years will yield significant breakthroughs that will make computers much more natural, navigational, and easier to use—so much so that virtually everyone will become a user. Many are convinced that within the next five to seven years you are going to be able to talk to your computer. It is not going to reason with you, but you are going to be able to give it commands. The key aspects of these breakthroughs lie in speech recognition, including natural language support so that the computer can understand a normal human voice and vocabulary; 3D graphics and animation for high-quality, realistic images; thin screens that allow the computer to be carried in your pocket or mounted on your living room wall; simultaneous speech translation capability; and pen device support, with handwriting recognition and touch screens. You are not going to have to deal with typing and all the mouse keys that we have today. You will be in command of your computer, and many people who are not users today will become users.

The new human-centric technologies provide financial institutions with the opportunity to enhance their products, improve service levels, and enter new markets. For example, E-Bank in South Africa has launched a highly successful direct banking initiative in which they are providing banking access to the previously unbanked population. E-Bank is doing this through high-function, self-service machines that read a customer's digital image off a smart card and validate his identity with his fingerprint on the ATM for positive authentication.

Network infrastructure and management technologies will also have a profound impact on financial institutions. These technologies support the electronic backbone that provides local, regional, and global connectivity for institutions, corporations, governments, and individuals. In the next decade these technologies not only will drop rapidly in price but also will increase in capability, as broader bandwidth allows the delivery of data, voice, and video images to the desktop. The network infrastructure technologies for personal and local area networks may use wireless transmission such as infrared or radio frequencies for convenience and flexibility in the office or at home, while high-speed commercial networks will use advanced transmission technologies such as asynchronous transfer mode (ATM), which allows simultaneous transmission of data, voice, and images. We are going to deliver full motion video, multimedia voice data to you, to the desktop. Everyone tells me we will never do financial planning at home. But what if, as I do my calculations, I push a button and my banker comes up? He can see the same screen I see, and we have a conversation, then I go back to my model. That is the kind of capability you are going to have, and that is a planning horizon that is real to bankers today.

Network management technologies include the communication servers that route message traffic and perform security roles such as screening for authorized users and transaction access; data and network management systems, which monitor and ensure performance, reliability, and connectivity across internal (intranets) and external sites; and encryption techniques ranging from hardware encoding to public and private keys. One of the major implications of network technologies is that they effectively eliminate national or geographic boundaries by creating a globally connected environment. Networks allow banks—and other players—to extend their reach and establish an electronic presence anywhere in the world, with minimal incremental overhead.

The third relevant technology for the networked bank is *scalable processing capability*. Scalable processing takes advantage of the steep price performance curve on which the chip technology rides. A 1985 Cadillac on the same technology curve would create a 1995 model with some interesting characteristics—it would have a top speed of 230 mph, it would get 2100 miles on a tank of gas, and it would cost $42; the only drawbacks would be that it would weigh 34 pounds and it would be only four feet long.

Examples of scalable processing include smart cards, which can have PC processing and storage capability and can be used for everything ranging from a stored-value electronic purse to multi-function support for all types of financial, medical, and government entitlement systems; radio-frequency identification tags, which allow proactive communications for applications such as inventory control and positive identification; and low-cost PCs or "thin clients" on the network, which reduce the overall electronic access costs to the user and allow better control of application software through the network. At the high end, scalable processing also allows the financial institution to manipulate huge quantities of data for analysis, whether calculating derivatives or data mining for customer marketing campaigns. If I can take a customer data base and combine it with transaction processing capabilities so that I really know what's going on with the customer, I can increase the response in a direct mail campaign from 1 to 2 percent to 4 to 5 percent. Do you have any idea of the economic difference for Land's End, say, or for a financial institution? The economics are staggering, but so are the issues of privacy, of customer "ownership," and of who has the most information.

Scalable processing facilitates all types of new transactions for the networked bank. Smart cards enable us to have new financial instruments and transactions, including e-cash, e-checks, e-credit, e-debit, e-travelers checks, and e-coupons. Network-based applications allow a bank to manage its software centrally and to download functions to consumers as needed, rather than forcing it to maintain thousands of individual copies of software distributed throughout the customer base.

The fourth group of technologies are *intelligent agents*. An intelligent agent is software that does what it is commanded to do—"Go out and find me a low-cost car loan with these payment terms." It consists of rules-based processing, where the agent can follow user-specified rules as well as "learn" from transaction patterns. An intelligent agent can seek, filter, and prioritize information into relevant and customized forms, in a proactive manner. It can perform transactions on the individual's behalf, such as automatically investigating new mortgage options when interest rates change by two points.You are going to be able to sit at home with your intelligent agent and it will go into the electronic network, with millions of servers out there, and screen and prioritize information and bring it back to you. However, the other side of this scenario is that such agents can also cause the increased commoditization of products. In response, a networked bank can develop intelligent agents that act to reintegrate commoditized products and thereby protect the bank's brand while creating value for the consumer.

The final group of technologies for the networked bank are *new tools and techniques for managing data and information*, such as object-oriented programming and data mining. Object-oriented programming has been around for quite some time, although it is finally becoming prevalent with advanced visual development tools and the ability to re-use objects. Object-oriented programming permits faster development cycles and improved time-to-market for new applications.

Data mining is relatively new to the financial services industry, although it has been exploited by retail and mail order companies for micro-market segmentation and targeted marketing campaigns. The data-mining tools and models provide the ability to analyze customer and transaction data and more quickly identify potential new areas of business. However, data mining also exacerbates one of the most pressing societal concerns about the networked economy—that of personal privacy. Thus, the networked bank must manage the privacy of its customers' personal and financial information while effectively mining that information for cross-marketing purposes. The bank has to be careful not to overstep its role of "trusted advisor" and thereby endanger its fiduciary responsibility to the consumer.

Overall Impact—The Five Rules

All of these technologies will affect financial institutions' internal operations and cause a dramatic change in the overall competitive landscape. The networked economy brings exciting new growth opportunities as well as significant threats to the banks.

For example, in the networked economy scenario, it is easy to visualize a full-function, video, on-line service provider that comes into every consumer's home through a high-speed communications network, such as the cable television network. The consumer turns on his "PC-TV" and is confronted with 500 channels from which to choose. The channels include many things: traditional television stations, pay-per-view movies, shopping at the local on-line mall, arts and entertainment, electronic mail and chat groups with other consumers, and even financial services such as electronic bill payment or investment management. Probably at least a dozen financial services channels are being offered, all with close to the same set of products and services.

The issue for the bank is how to differentiate itself in this environment. If the channel is owned and controlled by a third party, it will be very hard for the bank to promote its brand and catch the consumer's attention with unique value-added services. The solution is for the bank to change its strategy and determine how to optimize its presence—and profitability—across all its channels. The bank must adapt to the new rules of competing created by the networked economy.

(1) *Electronic value chains will be established.* Banks will have to form

alliances with other content providers, technology vendors, network infrastructure providers, on-line service providers, and access channel providers, and with their customers. The new electronic value chains will have to match or even exceed the functions of today's physical environment. For example, for e-cash to become an accepted financial instrument, banks will have to establish linkages with each other and with retailers, doctors, post offices, telephone companies—wherever people may want to do an e-cash transaction. The linkages may even extend across state and national boundaries, as in support of travelers check and currency-exchange functions. Standards, security issues, and settlement rules will have to be defined and agreed to by all the parties involved in the electronic value chain.

(2) *Power will shift to the channels and to consumers.* As the consumer becomes more technologically sophisticated and accustomed to accessing on-line services, she will determine which channels to use to access her desired financial services, at her convenience. Banks must provide services on those channels or they risk being invisible to the consumer. The consumer will choose the products, services, and channels she wants, from whichever provider best meets her requirements, with little or no loyalty to a particular financial institution.

(3) *Value chains will disaggregate.* Today, a bank has an integrated operation, with infrastructure (the branch), content (the bank's product), and context (a teller, or the advice you get at the bank). The networked bank must manage its products and brand across a variety of channels. This means that the bank has to understand its product costs and profitability by customer segment and by channel, and be able to provide the right mix of products with the appropriate financial performance. The executional infrastructure may or may not belong to the bank, depending on cost considerations. In addition, the bank must learn how to differentiate its brand when its products are just menu items on a screen. The bank will compete based on the value of its context, the complete value proposition that it offers its customers, not just its individual products.

(4) *Assets will be revalued.* The networked bank's most important asset will shift from being its physical presence—its branches—to its customer information and how it uses that information to create knowledge-based assets. The bank must use the new data-mining tools and electronic transactions effectively to manage its business and to enhance customer relationships.

(5) *New cultures will emerge.* Finally, the networked bank competes with a host of new players with very different business strategies, cost structures, and cultures. The bank has to change its own culture in order to become the type of entrepreneurial and flexible organization required to compete in the on-line, electronic world. The networked bank needs staff with new skills, ranging from Internet Web masters to network security specialists. The bank will also have to learn to operate in an

environment where it does not control all the components, and it must move from a physical, hierarchical organization to a networked, modular organization.

Bank Responses and Strategies

A bank can choose among several strategies in order to compete as a networked bank. One response is to adopt *a customer-centric strategy*. This strategy is based on the ability to leverage the bank's customer data in order to serve each customer with a unique interactive relationship and provide contextual value. The value is created by customizable products and services proactively offered to meet the customer's requirements, which the bank understands from its data-mining and intelligent-agent tools. In the customer-centric strategy, the bank focuses on building a strong interactive relationship with each customer. The bank builds knowledge into its products so that the products are more specific to, and interactive with, each customer. For example, a knowledgeable loan product not only will offer the customer the ability to do "what if" analysis on the type of loan he can afford, but also will custom-build that specific loan for the consumer, based on his criteria. Another attribute of a customer-centric strategy is the development of co-evolved customers. Co-evolution implies that the bank teaches as well as learns from the customer in developing new products and services. This interaction increases the potential for customer intimacy and retention.

A second response for the networked bank is to compete based on *a life-event strategy*. This strategy allows the bank to become the leading provider of integrated products and services for specific life events, such as buying a house, sending children to college, or planning for retirement. In this scenario, the bank groups its products around the particular event and offers an integrated suite of products and services.

Establishing the electronic value chain is critically important to enabling the bank to offer this comprehensive set of products. For example, a retirement planning suite may include a range of products —pensions, trusts, short- and long-term investments; legal services, such as estate planning; financial advice ranging from investment choices to tax considerations; and even related services in areas of health care, retirement care facilities, and travel. The bank becomes the one-stop-shopping source for everything to do with retirement and can provide significant value-added by bundling all these disparate products in a way that is convenient and easy for its customers to use.

Still another aspect of the life-event strategy is the building of communities of like-minded customers. This can be done through affinity products, such as sponsoring a credit/debit card for a local sports team. It can also be done by extending the bank's network to allow its customers to talk to each other. The challenge for the bank is to stay at the forefront in anticipating its customers' requirements and providing world-class proposals for the specific life events. The risk is that much of the product content will move away from the bank—for example, move from financial products to health-care planning, in the retirement scenario—and leave the bank in the position of having developed a new market, only to lose it.

A third major response for the networked bank is to compete with *a commodity strategy*. In this case, the bank achieves its competitive advantage by providing its products across a wide range of channels at the lowest cost. The bank would ally itself with other financial institutions and with on-line service providers for establishing the connection to the customer, and focus its efforts on providing the best product in a particular area, such as mortgages or auto loans.

The commodity bank must be very good at managing its costs, creating innovative products, and establishing a strong group of partnerships. The challenge is to maintain the best product at the lowest cost; otherwise, the bank has a high risk of being disintermediated by other competitors. The bank also has to determine how, or if, it keeps its brand visible in this strategy. The commodity bank may find it advantageous to co-brand or even private-label its product, in order to assure the broadest distribution via other financial institutions.

The Challenges of Risk

One major challenge that we have not thought enough about in the industry is the set of electronic risks that we are going to be faced with every day. Regulators at this conference understand the technological aspects of high-value payments risk thoroughly, and we cannot contribute much there. The problem in the low-value, high-volume payment world is not the risk of any individual transaction going awry, but of the fraud that happens out there.

With the pervasiveness of the Internet and the interconnections of the electronic environment, some people are going to misrepresent themselves and some are going to attack your systems. They are the hackers, who would like to get into Citibank's system just to tell all their friends at the Cyberspace Cafe that they did it. They are the pranksters who want to change the picture on your home page. They are what we call frackers, who steal telephone numbers. (About 10 percent of cellular phone industry transactions go to these thieves, who do not pay for the calls. The nice part is that the cost of a marginal phone call is not too much. Can you imagine what the marginal cost would be in the basic banking industry?) Another group we are increasingly worried about are the Internet vigilantes, who have a point of view about something and want to attack you for not agreeing with them, by attacking your system.

Finally, there are the outright criminals and organized crime groups. I have bank clients whose firewalls are attacked constantly.

The risk that we are all going to have to manage involves all the things that these people are going to do. They are going to eliminate files, they are going to insert viruses, they are going to do spoofing. They are going to imitate others. (One of the things they do is get into an e-mail system and pretend to be the CEO, and send out a lot of messages to people in the company, positive or negative.) We are going to build firewalls, and we are going to have to build increasing controls, because this area of security is going to be really important. Yet banks are going to have to do this in an environment where they must also make it easy to deal with their systems, not just for the customers but for their partners in the electronic world.

Some areas in the security world worry me on a more basic level. In a pervasive electronic environment, what if someone could break the operating system on smart cards, say? Another question relates to the whole world of electronic cash—not a security issue, but one of great concern to banks. What do banks do, in an environment where you can, from a technological standpoint, move money back and forth without it going through the balance sheet of a bank?

Issues for the Federal Reserve System

Finally, I would like to outline the challenges the networked bank represents for all financial institutions and for the overall regulatory system. The major issues are broader than just banking, although the depository institutions most likely will drive much of the change. The issues can be grouped into three areas dealing with the industry structure, the financial products, and the newly empowered consumers.

I. Industry structure
- How will the Internet and other on-line services change the industry as they create new competitors, lower the barriers to entry, and remove national borders?
- What are the risk implications of global electronic financial services?
- What new businesses can the banks enter? What will be the impact of these new businesses on banks' costs, profitability, and risks?
- How does the regulatory environment change when banks are competing against other companies offering similar products, but with very different strategies, cultures, and cost structures?
- How do banks remain viable players in this new competitive environment?

II. Financial products
- How can banks best manage all the new electronic products such as electronic bill payment, e-cash, e-credit, and e-check?
- How are standards (EDI, security, regulatory) determined for these new products?
- What are the real security risks involved, and who is responsible for managing them?
- What new clearing organizations and cash-pooling services will be required for these new products?
- What happens to checks?

III. Consumers
- How will electronic networks change the way in which consumers purchase goods and services?
- How will the consumer be protected when anyone can set up an electronic "bank" and offer bank-like services?
- Who is looking after the consumer's right to privacy?
- How can we ensure equal access and nondiscrimination in the electronic environment?

Banks are about to undertake a series of changes to respond to the electronic world. They will turn to customer-centered strategies, life-events strategies, and others like those I have already described. Make no mistake, the electronic world is going to change the face of the financial world dramatically.

Technology in Growth Theory

Dale W. Jorgenson*

The early 1970s marked the emergence of a rare professional consensus on economic growth, articulated in two strikingly dissimilar books. Simon Kuznets, the greatest of twentieth century empirical economists, summarized his decades of research in *Economic Growth of Nations* (1971). The enormous impact of this research was recognized in the same year by the Royal Swedish Academy of Sciences in awarding the third Bank of Sweden Prize in Economic Sciences in Memory of Alfred Nobel to Kuznets "for his empirically founded interpretation of economic growth which has led to new and deepened insight into the economic and social structure and process of development" (Assar Lindbeck 1992, p. 79).

Robert Solow's book *Growth Theory* (1970), modestly subtitled "An Exposition," contained his 1969 Radcliffe Lectures at the University of Warwick. In these lectures Solow also summarized decades of research, initiated by the theoretical work of Roy Harrod (1939) and Evsey Domar (1946). Solow's seminal role in this research, beginning with his brilliant and pathbreaking essay of 1956, "A Contribution to the Theory of Economic Growth," was recognized, simply and elegantly, by the Royal Swedish Academy of Sciences in awarding Solow the Nobel Prize in Economics in 1987 "for his contributions to the theory of economic growth" (Karl-Goran Maler 1992, p. 191).

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After a quarter of a century, the consensus on economic growth of the early 1970s has collapsed under the weight of a massive accumulation of new empirical evidence, followed by a torrent of novel theoretical insights. The purpose of this paper is to initiate the search for a new empirical and theoretical consensus. Any attempt at this thoroughly daunting task may be premature, since professional interest in growth currently appears to be waxing rather than waning. Moreover, the disparity of views among economists, always looming remarkably large for a discipline that aspires to the status of a science, is greater on growth than most other topics.

The consensus of the early 1970s emerged from a similar period of fractious contention among competing schools of economic thought, and this alone is grounds for cautious optimism. However, I believe it is critically important to understand the strengths and weaknesses of the earlier consensus and how it was dissolved by subsequent theory and evidence. It is also essential to determine whether elements have survived that could serve as a useful point of departure in the search for a new one.

Let me first consider the indubitable strengths of the perspective on growth that emerged victorious over its numerous competitors in the early 1970s. Solow's neoclassical theory of economic growth, especially his analysis of steady states with constant rates of growth, provided conceptual clarity and sophistication. Kuznets generated persuasive empirical support by quantifying the long sweep of historical experience of the United States and 13 other developed economies. He combined this with quantitative comparisons among a wide range of developed and developing economies during the postwar period.

With the benefit of hindsight, the most obvious deficiency of the neoclassical framework of Kuznets and Solow was the lack of a clear connection between the theoretical and the empirical components. This lacuna can be seen most starkly in the total absence of cross-references between the key works of these two great economists. Yet they were working on the same topic, within the same framework, at virtually the same time, and in the very same geographical location—Cambridge, Massachusetts.

Searching for analogies to describe this remarkable coincidence of views on growth, we can think of two celestial bodies on different orbits, momentarily coinciding from our earthbound perspective at a single point in the sky and glowing with dazzling but transitory luminosity. The indelible image of this extraordinary event has been burned into the collective memory of economists, even if the details have long been forgotten. The common perspective that emerged remains the guiding star for subsequent conceptual development and empirical observation.

In the next section I consider challenges to the traditional framework of Kuznets and Solow arising from new techniques for measuring economic welfare and productivity. The elaboration of production theory and the corresponding econometric techniques led to the successful implementation of constant-quality measures of capital and labor inputs and investment goods output. However, it was not until July 11, 1994, that these measures were incorporated into a new official productivity index for the United States by the Bureau of Labor Statistics!

The recent revival of interest in economic growth by the larger community of economists can be dated from Angus Maddison's (1982) updating of Kuznets' (1971) long-term comparisons of economic growth among industrialized countries. This was followed by the successful exploitation of the Penn World Table—created by Irving Kravis, Alan Heston, and Robert Summers (1978)—which provided comparisons among more than 100 developed and developing countries. Exploiting the panel data structure of these comparisons, Nasrul Islam (1995) was able to show that the Solow model is the appropriate point of departure for modeling the endogenous accumulation of tangible assets.

The new developments in economic measurement and modeling summarized in the following section have cleared the way for undertaking the difficult, if unglamorous, task of constructing quantitative models of growth suitable for the analysis of economic policies. Models based on the neoclassical framework of Kuznets and Solow determine growth by exogenous forces, principally spillovers from technological innovations. By contrast, models based on the new framework, described next, determine the great preponderance of economic growth endogenously, through investments in tangible assets and human capital.

Endogenous models of economic growth require concepts of an aggregate production function and a representative consumer that can be implemented econometrically. These concepts imply measurements of welfare and productivity that can best be organized by means of a system of national accounts. The accounts must include production, income and expenditure, capital formation, and wealth accounts, as in the United Nations (1993) *System of National Accounts.* Alternative economic policies can then be ranked by means of equivalent variations in wealth, providing the basis for policy recommendations.

I then describe quantitative models suitable for the analysis of economic policies. Econometric techniques have provided the missing link between the theoretical and empirical components of the consensus of the early 1970s. The development of these techniques was a major achievement of the 1970s and successful applications began to emerge only in the 1980s. These techniques were unavailable when Solow (1970) first articulated the objective of constructing econometric models of growth for the analysis of economic policies.

The growth of tangible assets is endogenous within a Solow (1956, 1970) neoclassical growth model. Kun-Young Yun and I constructed a complete econometric model for postwar U.S. economic growth with this feature in two papers published in 1986. We have used this model to analyze the economic impact of fundamental tax reforms. Subsequently, Mun Ho and I extended this model to incorporate endogenous growth in human capital; we have employed the extended model to analyze the impact of alternative educational policies (1995).

Although endogenous investment in new technology has been a major theme in growth theory for four decades, empirical implementation has foundered on the issue, first identified by Zvi Griliches (1973), of measuring the output of research and development activities. Until this issue has been successfully resolved, a completely endogenous theory of economic growth will remain a chimera, forever tantalizing to the imagination, but far removed from the practical realm of economic policy. The final section assesses the prospects for endogenizing investment in new technology and offers conclusions.

Sources and Uses of Growth

The objective of modeling economic growth is to explain the *sources* and *uses* of economic growth endogenously. National income is the starting point for assessments of the *uses* of economic growth through consumption and saving. The concept of a Measure of Economic Welfare, introduced by William Nordhaus and James Tobin (1972), is the key to augmenting national income to broaden the concepts of consumption and saving. Similarly, gross national product is the starting point for attributing the *sources* of economic growth to investments in tangible assets and human capital, but it could encompass investments in new technology as well.

The allocation of the *sources* of economic growth between investment and productivity is critical for assessing the explanatory power of growth theory. Only substitution between capital and labor inputs resulting from investment in tangible assets is endogenous in Solow's neoclassical model of economic growth. However, substitution among different types of labor inputs is the consequence of investment in human capital, while investment in tangible assets also produces substitution among different types of capital inputs. These were not included in Solow's (1957) model of production.

Productivity growth is *labor-augmenting* or equivalent to an increase in population in the simplest version of the neoclassical growth model. If productivity growth greatly predominates among the sources of economic growth, as indicated by Kuznets (1971) and Solow (1957), most of growth is exogenously determined. Reliance on the Solow residual as an explanatory factor is a powerful indictment of the limitations of the neoclassical framework. This viewpoint was expressed by Moses Abramovitz (1956), who famously characterized productivity growth as a "measure of our ignorance."

The appropriate theoretical framework for endogenous growth is the

Ramsey model of optimal growth introduced by David Cass (1965) and Tjalling Koopmans (1965). A promising start on the empirical implementation of this model was made in my 1967 paper with Griliches. It appeared that 85 percent of U.S. economic growth could be made endogenous; determinants of the remaining 15 percent were left for further investigation, but might be attributable to investments in new technology.[1]

The conclusions of my paper with Griliches were corroborated in two studies I published in 1969 and 1970 with Laurits Christensen. These studies provided a much more detailed implementation of the concept of capital as a factor of production. We utilized a model of the tax structure for corporate capital income that I had developed in a series of papers with Robert Hall (1967, 1969, 1971). Christensen and I extended this model to noncorporate and household capital incomes in order to capture the impact of additional differences in returns to capital due to taxation on substitutions among capital inputs.

In 1973, Christensen and I incorporated estimates of the sources of economic growth into a complete system of U.S. national accounts in our paper, "Measuring Economic Performance in the Private Sector."[2] Our main objective was the construction of internally consistent income, product, and wealth accounts. Separate product and income accounts were integral parts of both the U.S. Income and Product Accounts[3] and the United Nations (1968) *System of National Accounts* designed by Richard Stone.[4] However, neither system included wealth accounts consistent with the income and product accounts.

Christensen and I constructed income, product, and wealth accounts, paralleling the U.S. National Income and Product Accounts, for the period 1929 to 1969. We implemented our vintage accounting system for the United States on an annual basis. The complete system of vintage accounts gave stocks of assets of each vintage and their prices. The stocks were cumulated to obtain asset quantities, providing the perpetual inventory of assets accumulated at different points of time or different vintages employed by Raymond Goldsmith (1955–56; 1962).

The key innovation in our vintage system of accounts was the use of asset pricing equations to link the prices used in evaluating capital stocks

1 See Jorgenson and Griliches (1967), Table IX, p. 272. We also attributed 13 percent of growth to the relative utilization of capital, measured by energy consumption as a proportion of capacity; however, this is inappropriate at the aggregate level, as Edward Denison (1974, p. 56), pointed out. For additional details, see Jorgenson, Frank Gollop, and Barbara Fraumeni (1987), especially pp. 179–81.

2 This paper was presented at the thirty-seventh meeting of the Conference on Research in Income and Wealth, held at Princeton, New Jersey in 1971.

3 See, for example, U.S. Office of Business Economics (1966).

4 The United Nations System of National Accounts (SNA) is summarized by Stone (1984) in his Nobel Prize address. The SNA has been revised in United Nations (1993).

and the rental prices employed in our constant-quality index of capital input. In a prescient paper on the measurement of welfare, Paul Samuelson (1961) had suggested that the link between asset and rental prices was essential for the integration of income and wealth accounting proposed by Irving Fisher (1906).[5] Our system of accounts employed the specific form of this relationship developed in my 1967 paper, "The Theory of Investment Behavior."

Christensen and I distinguished two approaches to the analysis of economic growth. We identified the production account with a production possibility frontier describing technology. The underlying conceptual framework was an extension of the aggregate production function —introduced by Paul Douglas (1948) and developed by Jan Tinbergen (1942) and Solow (1957)—to include two outputs, investment and consumption goods. These two outputs were distinguished in order to incorporate constant-quality indices of investment goods.

We utilized constant-quality indices of capital and labor inputs in allocating the sources of economic growth between investment and productivity. Our constant-quality index of labor input combined different types of hours worked into a constant-quality index of labor input, using methodology Griliches (1960) had developed for U.S. agriculture. This considerably broadened the concept of substitution employed by Solow (1957) and altered, irrevocably, the allocation of economic growth between investment and productivity.[6]

Our constant-quality index of capital combined different types of capital inputs. We identified input prices with rental rates, rather than the asset prices appropriate for the measurement of capital stock. For this purpose we used a model of capital as a factor of production I had introduced in my 1963 article, "Capital Theory and Investment Behavior." This made it possible to incorporate differences in returns due to the tax treatment of different types of capital income.[7]

Our constant-quality measure of investment goods generalized Solow's (1960) concept of embodied technical change. My 1966 paper, "The Embodiment Hypothesis," showed that economic growth could be interpreted, equivalently, as "embodied" in investment or "disembodied" in productivity growth. My 1967 paper with Griliches removed this indeterminacy by introducing constant-quality indices for investment

[5] See Samuelson (1961), especially p. 309.

[6] Constant-quality indices of labor input are discussed in detail by Jorgenson, Gollop, and Fraumeni (1987), Chapters 3 and 8, pp. 69–108 and 261–300, and Jorgenson, Ho, and Fraumeni (1994).

[7] A detailed survey of empirical research on the measurement of capital input is given in my 1996 paper, "Empirical Studies of Depreciation," and Jack Triplett's (1996) paper, "Measuring the Capital Stock: A Review of Concepts and Data Needs," both presented at a meeting of the Conference on Research in Income and Wealth, held at Washington, D.C., in May 1992.

goods.[8] The U.S. Bureau of Economic Analysis (BEA 1986) has now incorporated a constant-quality price index for investment in computers into the U.S. national accounts.[9]

Constant-quality price indices for investment goods of different ages or vintages were developed by Hall (1971). This important innovation made it possible for Charles Hulten and Frank Wykoff (1982) to estimate relative efficiencies by age for all types of tangible assets included in the national accounts, putting the measurement of capital consumption onto a solid empirical foundation. Estimates of capital inputs presented in my 1987 book with Gollop and Fraumeni were based on the Hulten-Wykoff relative efficiencies. The BEA (1995) has incorporated these relative efficiencies into measures of capital consumption in the latest benchmark revision of the U.S. National Income and Product Accounts.[10]

Christensen and I identified the income and expenditure account with a social welfare function. The conceptual framework was provided by the representation of intertemporal preferences employed by Frank Ramsey (1928), Samuelson (1961), Cass (1965), Koopmans (1965), and Nordhaus and Tobin (1972). Following Kuznets (1961), we divided the *uses* of economic growth between current consumption and future consumption through saving. Saving was linked to the asset side of the wealth account through capital accumulation equations for each type of asset. Prices for different vintages were linked to rental prices of capital inputs through a parallel set of capital asset pricing equations.

The separation of production and welfare approaches to economic growth had important implications for the theory. The Ramsey model, so beautifully expounded by Solow (1970), had two separate submodels —one based on producer behavior and the other on consumer behavior. The production account could be linked to the submodel of production and the income and expenditure account to the submodel of consumption. This made it possible, at least in principle, to proceed from the design stage of the theory of economic growth, emphasized by Solow, to

[8] A detailed history of constant-quality price indices is given by Ernst Berndt (1991). Triplett's (1990) contribution to the Jubilee of the Conference on Research in Income and Wealth discusses obstacles to the introduction of these indices into government statistical programs. Robert Gordon (1990) constructed constant-quality indices for all types of producers' durable equipment in the national accounts and Paul Pieper (1989, 1990) gave constant-quality indices for all types of structures.

[9] Rosanne Cole, Y.C. Chen, Joan Barquin-Stolleman, Ellen Dulberger, Nurhan Helvacian, and James Hodge (1986) reported the results of a joint project conducted by BEA and IBM to construct a constant-quality index for computers. Triplett (1986) discussed the economic interpretation of constant-quality price indices in an accompanying article. Ellen Dulberger (1989) presented a more detailed report, while Triplett (1989) gave an extensive survey of empirical research on constant-quality price indices for computers. Allan Young (1989) answered Denison's (1989) objections and reiterated BEA's rationale for introducing a constant-quality price index for computers.

[10] The methodology is described by Fraumeni (1996).

econometric modeling, which he accurately described as "much more difficult and less glamorous."[11]

In summary, the dizzying progress of empirical work on economic growth by 1973 had created an impressive agenda for future research. Christensen and I had established the conceptual foundations for quantitative models of growth suitable for analyzing the impact of policies affecting investment in tangible assets. However, critical tasks, such as construction of constant-quality indices of capital and labor inputs and investment goods output, remained to be accomplished. The final step in this lengthy process was completed only with the benchmark revision of the U.S. National Income and Product Accounts in September 1995!

The Growth Revival

On October 16, 1973, the beginning of the Arab Oil Embargo ushered in a series of sharp increases in world petroleum prices that led to a rapidly deepening recession in industrialized countries, accompanied by a rise in inflation. Since this contradicted one of the fundamental tenets of the reigning Keynesian orthodoxy in macroeconomics, it engendered a shift in the focus of macroeconomic research from economic growth to stagflation. Debates among Keynesians, Old and New, monetarists, and New Classical macroeconomists took center stage, pushing disputes among the proponents of alternative views on economic growth into the background.

In graduate courses in macroeconomics the theory of economic growth was gradually displaced by newer topics, such as rational expectations and policy ineffectiveness. Elementary skills required for growth analysis—national income and product accounting, index number theory, the perpetual inventory method, and intertemporal asset pricing—were no longer essential for beginning researchers and fell into disuse. Even the main points of contention in the rancorous debates over growth in the early 1970s began to fade from the collective memory of economists.

Like a watercourse that encounters a mountain range, the stream of research on endogenous growth continued to flow unabated and unobserved, gathering momentum for its later reemergence into the light of professional debate. When it did erupt in the early 1980s, the initial impulse threatened to wash away the entire agenda that had been laboriously put into place following the canonical formulation of the neoclassical framework in the early 1970s. The renewed thrust toward endogenizing economic growth acquired startling but illusory force by

[11] See Solow (1970), p. 105. He went on to remark, "But it may be what God made graduate students for. Presumably he had something in mind."

channeling most of its energy into a polemical attack on the deficiencies of the "exogenous" theories of growth of Kuznets and Solow.

The flow of new talent into research on economic growth was interrupted for a decade, sapping the high level of intellectual energy that fueled the rapid progress of the early 1970s. The arrival of a new generation of growth economists in the early 1980s signaled a feverish period of discovery and rediscovery that is still under way. This has been followed by a revival of the latent interests of many economists in economic growth after a substantial time lapse. The consequence of this time lapse has been a form of amnesia, familiar to readers who recall Washington Irving's fictional character Rip Van Winkle. To remedy this collective lapse of memory it is essential to bring our story of the dissolution of the neoclassical framework up to date.

We can fix the revival of interest in economic growth by the larger community of economists with some precision at Maddison's (1982) updating and extension of Kuznets' (1971) long-term estimates of the growth of national product for 14 industrialized countries, including the United States. Maddison added Austria and Finland to Kuznets' list and presented growth rates covering periods beginning as early as 1820 and extending through 1979. Maddison (1991, 1995) has extended these estimates through 1992. Attempts to analyze Maddison's data led to the "convergence debate" initiated by Abramovitz (1986) and William Baumol (1986).

Denison (1967) had compared differences in growth rates for national income per capita for the period 1950 to 1962 with differences of levels in 1960 for eight European countries and the United States. He also compared sources of these differences in both growth rates and levels. The eight European countries as a whole were characterized by much more rapid growth and a lower level of national income per capita. However, this association was not monotonic for comparisons between individual countries and the United States. Nonetheless, Denison concluded: "Aside from short-term aberrations Europe should be able to report higher growth rates, at least in national income per person employed, for a long time. Americans should expect this and not be disturbed by it."[12]

Kuznets (1971) provided elaborate comparisons of growth rates for the 14 countries included in his study. Unlike Denison (1967), he did not provide comparisons of levels. Maddison (1982) filled this gap by comparing levels of national product for 16 countries. These comparisons were based on estimates of purchasing power parities by Kravis, Heston,

[12] See Denison (1967), especially Chapter 21, "The Sources of Growth and the Contrast between Europe and the United States," pp. 296–348.

and Summers (1978).[13] These estimates have been updated by successive versions of the Penn World Table.[14] These data have made it possible to reconsider the issue of convergence of productivity levels raised by Denison (1967).

Abramovitz (1986) was the first to take up the challenge of analyzing convergence of productivity levels among Maddison's 16 countries. He found that convergence appeared to characterize the postwar period, while the period before 1914 and the interwar period revealed no tendencies of productivity levels to converge. Baumol (1986) formalized these results by running a regression of growth rate of GDP per hour worked over the period 1870 to 1979 on the 1870 level of GDP per hour worked.[15]

In a notable paper on "Crazy Explanations for the Productivity Slowdown," Paul Romer (1987) derived a version of the growth regression from Solow's (1970) growth model with a Cobb-Douglas production function. An important empirical contribution of the paper was to extend the data set for growth regressions from Maddison's (1982) group of 16 advanced countries to the 115 countries included in the Penn World Table (Mark 3), presented by Robert Summers and Alan Heston (1984). Romer's key finding was that an indirect estimate of the Cobb-Douglas elasticity of output with respect to capital was close to three-quarters. The share of capital in GNP implied by Solow's model was less than half as great, on average.[16]

Gregory Mankiw, David Romer, and David Weil (1992) provided a defense of the neoclassical framework of Kuznets (1971) and Solow (1970). The empirical portion of their study is based on data for 98 countries from the Penn World Table (Mark 4), presented by Summers and Heston (1988). Like Paul Romer (1987), Mankiw, David Romer, and Weil derived a growth equation from the Solow (1970) model; however, they also augmented this model by allowing for investment in human capital.

The results of Mankiw, David Romer, and Weil (1992) produced

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[13] For details see Maddison (1982, pp. 159-168). Purchasing power parities were first measured for industrialized countries by Milton Gilbert and Kravis (1954) and Gilbert et al. (1958).

[14] A complete list through Mark 5 is given by Summers and Heston (1991), while the results of Mark 6 are summarized by the World Bank in the *World Development Report 1993*.

[15] This "growth regression" has spawned a vast literature, summarized by Ross Levine and David Renelt (1992), Baumol (1994), and Robert Barro and Xavier Sala-I-Martin (1994). Much of this literature has been based on successive versions of the Penn World Table.

[16] Unfortunately, this Mark 3 data set did not include capital input. Romer's empirical finding has spawned a substantial theoretical literature, summarized at an early stage by Robert Lucas (1988) and, more recently, by Gene Grossman and Elhanan Helpman (1991, 1994), Romer (1994), and Barro and Sala-I-Martin (1994). Romer's own important contributions to this literature have focused on increasing returns to scale, as in Romer (1986), and spillovers from technological change, as in Romer (1990).

empirical support for the augmented Solow model. There was clear evidence of the convergence predicted by the model; in addition, the estimated Cobb-Douglas elasticity of output with respect to capital was in line with the share of capital in the value of output. The rate of convergence of productivity was too slow to be consistent with the 1970 version of the Solow model, but it is consistent with the augmented version.

Finally, Islam (1995) exploited an important feature of the Summers-Heston (1988) data set overlooked in prior empirical studies. This panel data set contains benchmark comparisons of levels of the national product at five-year intervals, beginning in 1960 and ending in 1985. This made it possible for Islam to test an assumption maintained in growth regressions, such as those of Mankiw, David Romer, and Weil. Their study, like that of Paul Romer (1987), was based on cross sections of growth rates. Both studies assumed identical technologies for all countries included in the Summer-Heston data sets.

Substantial differences in overall levels of productivity among countries have been documented by Denison (1967), my paper with Christensen and Dianne Cummings (1981), and, more recently, my paper with Chrys Dougherty (1996). By introducing econometric methods for panel data, Islam (1995) was able to allow for these differences in technology. He corroborated the finding of Mankiw, David Romer, and Weil (1992) that the elasticity of output with respect to capital input coincided with the share of capital in the value of output. This further undermined the empirical support for the existence of the increasing returns and spillovers analyzed in the theoretical models of Paul Romer (1986, 1990).

In addition, Islam (1995) found that the rate of convergence of productivity among countries in the Summers-Heston (1988) data set was precisely that required to substantiate the *unaugmented* version of the Solow model (1970). In short, "crazy explanations" for the productivity slowdown, like those propounded by Paul Romer (1987, 1994), are not required to explain the complexities of panels of data for advanced and developing countries. Moreover, the model did not require augmentation, as suggested by Mankiw, David Romer, and Weil (1992). However, differences in technology among these countries must be taken into account in econometric modeling of differences in growth rates.

The conclusion from Islam's (1995) research is that the Solow model is an appropriate point of departure for modeling the endogenous accumulation of tangible assets. For this purpose it is not essential to endogenize human capital accumulation as well. The rationale for this key empirical finding is that the transition path to balanced growth equilibrium requires decades after a change in policies, such as tax policies, that affect investment in tangible assets. By comparison, the transition after a change in policies affecting investment in human capital requires as much as a century.

Islam's conclusions are strongly reinforced in two important papers by Charles Jones (1995a, 1995b), testing alternative models of economic growth based on endogenous investment in new technology. Jones (1995a) tests models proposed by Paul Romer (1990), Grossman and Helpman (1991), and Phillippe Aghion and Peter Howitt (1992). This model is based on an endogenous growth rate, proportional to the level of resources devoted to research and development. Jones (1995a) demonstrates that this implication of the model is contradicted by evidence from the advanced countries that conduct the great bulk of research and development. While these countries have steadily increased the resources devoted to research and development, growth rates have been stable or declining.

Jones (1995b) tests models of endogenous investment in new technology proposed by Romer (1986, 1987), Lucas (1988), and Sergio Rebelo (1991), so-called AK models. These models have a growth rate that is proportional to the investment rate; Jones (1995b) shows that there are persistent changes in investment rates for advanced countries, while there are no persistent changes in growth rates. Jones (1995b, p. 519) concludes that "Both AK-style models and the R&D-based models are clearly rejected by this evidence." Jones (1995a) suggests, as an alternative approach, models that make investment in new technology endogenous, by preserving the feature of the Solow model that long-run growth rates are determined by exogenous forces. We consider the obstacles that remain to successful implementation of this approach below.

In summary, the convergence debate provided an excellent medium for the revival of interest in growth. The starting point for this debate was the revival of Kuznets' program for research on long-term trends in the growth of industrialized countries by Maddison (1982, 1991, 1995). As the debate unfolded, the arrival of successive versions of the Penn World Table engaged the interests of new entrants into the field in cross-section variations in patterns of growth. However, a totally novel element appeared in the form of relatively sophisticated econometric techniques. In the work of Islam (1995) these were carefully designed to bring out the substantive importance of cross-section differences in technology. This proved to be decisive in resolving the debate.

Endogenous Growth

Despite substantial progress in endogenizing economic growth over the past two decades, profound differences in policy implications militate against any simple resolution of the debate on the relative importance of investment and productivity. Proponents of income redistribution will not easily abandon the search for a "silver bullet" that will generate economic growth without the necessity of providing incentives for investment in tangible assets and human capital. Advocates of growth strategies based on capital formation will not readily give credence to claims of the importance of external benefits that "spill over" to beneficiaries that are difficult or impossible to identify.

The proposition that investment is a more important source of economic growth than productivity is just as controversial today as it was in 1973. The distinction between substitution and technical change emphasized by Solow (1957) parallels the distinction between investment and productivity as sources of economic growth. However, Solow's definition of investment, like that of Kuznets (1971), was limited to tangible assets. Both specifically excluded investments in human capital by relying on undifferentiated hours of work as a measure of labor input.

Kuznets (1971) and Solow (1957) identified the contribution of tangible assets with increases in the stock, which does not adequately capture substitution among different types of capital inputs. Constant-quality indices of both capital and labor inputs and investment goods output are essential for successful implementation of the production approach to economic growth. By failing to adopt these measurement conventions, Kuznets and Solow attributed almost all of U.S. economic growth to the Solow residual.[17]

To avoid the semantic confusion that pervades popular discussions of economic growth, it is essential to be precise in distinguishing between investment and productivity. Investment is the commitment of current resources in the expectation of future returns and can take a multiplicity of forms. This is the definition introduced by Fisher (1906) and discussed by Samuelson (1961). The distinctive feature of investment as a source of economic growth is that the returns can be internalized by the investor. The most straightforward application of this definition is to investments that create property rights, including rights to transfer the resulting assets and benefit from incomes that accrue to the owners.[18]

Investment in tangible assets provides the most transparent illustration of investment as a source of economic growth. This form of investment creates transferable property rights with returns that can be internalized. However, investment in intangible assets through research and development also creates intellectual property rights that can be transferred through outright sale or royalty arrangements and returns that can be internalized. Private returns to this form of investment—

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[17] The measurement conventions of Kuznets and Solow remain in common use. See, for example, the references given in my 1990 article, "Productivity and Economic Growth," presented at The Jubilee of the Conference on Research in Income and Wealth, held in Washington, D.C., in 1988. For recent examples, see Martin Baily and Gordon (1988), Steven Englander and Axel Mittelstadt (1988), Olivier Blanchard and Stanley Fischer (1989), pp. 2–5, Baily and Charles Schultze (1990), Gordon (1990), Englander and Andrew Gurney (1994), and Lawrence Lau (1996).

[18] Fisher (1906) discusses property rights in Chapter 2, pp. 18–40.

returns that have been internalized—have been studied intensively in the literature surveyed by Griliches (1994, 1995) and Bronwyn Hall (1996).

The seminal contributions of Gary Becker (1993), Fritz Machlup (1962), Jacob Mincer (1974), and Theodore Schultz (1961) have given concrete meaning to the concept of "wealth in its more general sense" employed by Fisher (1906). This notion of wealth includes investments that do not create property rights. For example, a student enrolled in school or a worker participating in a training program can be viewed as an investor. Although these investments do not create assets that can be bought or sold, the returns to higher educational qualifications or better skills in the workplace can be internalized. The contribution of investments in education and training to economic growth can be identified in the same way as for tangible assets.

The mechanism by which tangible investments are translated into economic growth is well understood. For example, an investor in a new industrial facility adds to the supply of assets and generates a stream of rental income. The investment and the income are linked through markets for capital assets and capital services. The income stream can be divided between the increase in capital input and the marginal product of capital or rental price. The increase in capital contributes to output growth in proportion to the marginal product. This is the basis for construction of a constant-quality index of capital input.

Griliches (1973, 1979, 1995) has shown how investments in new technology can be translated into economic growth. An investor in a new product design or process of production adds to the supply of intellectual assets and generates a stream of profits or royalties. The increase in intellectual capital contributes to output growth in proportion to its marginal product in the same way as the acquisition of a tangible asset. However, investments in research and development, unlike those in tangible assets, are frequently internal to the firm, so that separation of the private return between the input of intellectual capital and the marginal product or rental price of this capital is highly problematical. The U.S. Bureau of Labor Statistics (1994) and Griliches have provided estimates of the contribution of these investments to economic growth.

Finally, an individual who completes a course of education or training adds to the supply of people with higher qualifications or skills. The resulting income stream can be decomposed into a rise in labor input and the marginal product of labor or wage rate. The increase in labor contributes to output growth in proportion to the marginal product. This provides the basis for constructing a constant-quality index of labor input. Although no asset markets exist for human capital, investments in human and nonhuman capital have the common feature, pointed out by Fisher (1906), that returns are internalized by the investor.

The defining characteristic of productivity as a source of economic growth is that the incomes generated by higher productivity are external to the economic activities that generate growth. These benefits "spill over" to income recipients not involved in these activities, severing the connection between the creation of growth and the incomes that result. Since the benefits of policies to create externalities cannot be appropriated, these policies typically involve government programs or activities supported through public subsidies. Griliches (1992, 1995) has provided detailed surveys of "spillovers" from investment in research and development.[19]

Publicly supported research and development programs are a leading illustration of policies to stimulate productivity growth. These programs can be conducted by government laboratories or financed by public subsidies to private laboratories. The justification for public financing is most persuasive for aspects of technology that cannot be fully appropriated, such as basic science and generic technology. The benefits of the resulting innovations are external to the economic units conducting the research and development, and these must be carefully distinguished from the private benefits of research and development that can be internalized through the creation of intellectual property rights.

An important obstacle to resolution of the debate over the relative importance of investment and productivity is that it coincides with ongoing disputes about the appropriate role for the public sector. Productivity can be identified with spillovers of benefits that do not provide incentives for actors within the private sector. Advocates of a larger role for the public sector advance the view that these spillovers can be guided into appropriate channels only by an all-wise and beneficent government sector. By contrast, proponents of a smaller government search for means to privatize decisions about investments by decentralizing investment decisions among participants in the private sector of the economy.

Kevin Stiroh and I (1995) have shown that investments in tangible assets are the most important sources of postwar U.S. economic growth. These investments appear on the balance sheets of firms, industries, and the nation as a whole as buildings, equipment, and inventories. The benefits appear on the income statements of these same economic units as profits, rents, and royalties. The BLS (1983) compiled an official constant-quality index of capital input for its initial estimates of total factor productivity, renamed as multifactor productivity.

The BLS retained hours worked as a measure of labor input until July 11, 1994, when it released a new multifactor productivity measure incorporating a constant-quality index of labor input as well as the BEA's (1986) constant-quality index for investment in computers. The final step

[19] Griliches (1992) also gives a list of survey papers on spillovers. Griliches (1979, 1995) has shown how to incorporate spillovers into a growth accounting.

in empirically implementing a constant-quality index of the services of tangible assets was the incorporation of Hulten-Wykoff (1982) relative efficiencies into the U.S. National Income and Product Accounts by the BEA (1995). Four decades of empirical research, initiated by Goldsmith's (1955-56) monumental treatise, *A Study of Saving,* have provided a sound empirical foundation for endogenizing investment in tangible assets.

Stiroh and I have shown that the growth of labor input is second in importance only to capital input as a source of economic growth. Increases in labor incomes have made it possible to measure investments in human capital and assess their contributions to economic growth. In 1989 Fraumeni and I extended the vintage accounting system developed in my 1973 paper with Christensen to incorporate these investments. Our essential idea was to treat individual members of the U.S. population as human assets with "asset prices" given by their lifetime labor incomes. Constant-quality indices of labor input are an essential first step in incorporating investments in human capital into empirical studies of economic growth. We implemented our vintage accounting system for both human and nonhuman capital for the United States on an annual basis for the period 1948 to 1984.

Asset prices for tangible assets can be observed directly from market transactions in investment goods; intertemporal capital asset pricing equations are used to derive rental prices for capital services. For human capital, wage rates correspond to rental prices and can be observed directly from transactions in the labor market. Lifetime labor incomes are derived by applying asset pricing equations to these wage rates. These incomes are analogous to the asset prices used in accounting for tangible assets in the system of vintage accounts I had developed with Christensen (1973).

Fraumeni and I have developed a measure of the output of the U.S. education sector, presented in Jorgenson and Fraumeni (1992b). Our point of departure was that while education is a service industry, its output is investment in human capital. We estimated investment in education from the impact of increases in educational attainment on the lifetime incomes of all individuals enrolled in school. We found that investment in education, measured in this way, is similar in magnitude to the value of working time for all individuals in the labor force. Furthermore, the growth of investment in education during the postwar period exceeded the growth of market labor activities.

Second, we have measured the inputs of the education sector, beginning with the purchased inputs recorded in the outlays of educational institutions, in Jorgenson and Fraumeni (1992a). A major part of the value of the output of educational institutions accrues to students in the form of increases in their lifetime incomes. Treating these increases as compensation for student time, we evaluated this time as an input into the educational process. Given the outlays of educational institutions and the value of student time, we allocated the growth of the education sector to its sources.

An alternative approach, employed by Schultz (1961), Machlup (1962), Nordhaus and Tobin (1972), and many others, is to apply Goldsmith's (1955–56) perpetual inventory method to private and public expenditures on educational services. Unfortunately, this approach has foundered on the absence of a satisfactory measure of the output of the educational sector and the lack of an obvious rationale for capital consumption. The approach fails to satisfy the conditions for integration of income and wealth accounts established by Fisher (1906) and Samuelson (1961).[20]

Given vintage accounts for human and nonhuman capital, Fraumeni and I (1989) have constructed a system of income, product, and wealth accounts, paralleling the system I had developed with Christensen. In these accounts the value of human wealth was more than 10 times the value of nonhuman wealth, while investment in human capital was five times investment in tangible assets. We defined "full" investment in the U.S. economy as the sum of these two types of investment. Similarly, we added the value of nonmarket labor activities to personal consumption expenditures to obtain "full" consumption. Our product measure included these new measures of investment and consumption.

Since our complete accounting system included a production account with "full" measures of capital and labor inputs, we were able to generate a new set of accounts for the *sources* of U.S. economic growth. Our system also included an income and expenditure account with income from labor services in both market and nonmarket activities. We combined this with income from capital services and allocated "full" income between consumption and saving.[21] This provided the basis for a new Measure of Economic Welfare and a set of accounts for the *uses* of U.S. economic growth. Our system was completed by a wealth account containing both human wealth and tangible assets.

We aggregated the growth of education and noneducation sectors of the U.S. economy to obtain a new measure of U.S. economic growth. Combining this with measures of input growth, we obtained a new set of accounts for the *sources* of growth of the U.S. economy. Productivity contributes almost nothing to the growth of the education sector and only a modest proportion to output growth for the economy as a whole. We also obtained a second approximation of the proportion of U.S. economic growth that can be made endogenous. Within a Ramsey model with separate education and noneducation sectors, we find that exogenous productivity growth accounts for only 17 percent of growth.

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[20] For more detailed discussion, see Jorgenson and Fraumeni (1989).

[21] Our terminology follows that of Becker's (1965, 1993) theory of time allocation.

The introduction of endogenous investment in education increases the explanatory power of the Ramsey model of economic growth to 83 percent. However, it is important to emphasize that growth without endogenous investment in education is measured differently. The traditional framework for economic measurement of Kuznets (1971) and Solow (1970) excludes nonmarket activities, such as those that characterize the major portion of investment in education. The intuition is familiar to any teacher, including teachers of economics: What the students do is far more important than what the teachers do, even if the subject matter is the theory of economic growth.

A third approximation to the proportion of growth that could be attributed to investment within an extended Ramsey model results from incorporation of all forms of investment in human capital. This would include education, child rearing, and addition of new members to the population. Fertility could be made endogenous by using the approach of Robert Barro and Becker (1989) and Becker and Barro (1988). Child rearing could be made endogenous by modeling the household as a producing sector along the lines of the model of the educational sector I have outlined above. The results presented by Jorgenson and Fraumeni (1989) show that this would endogenize 86 percent of U.S. economic growth. This is a significant, but not overwhelming, gain in explanatory power for the Ramsey model.

In summary, endogenizing U.S. economic growth at the aggregate level requires a distinction between investment and productivity as sources of growth. There are two important obstacles to empirical implementation of this distinction. First, the distinctive feature of investment as a source of growth is that the returns can be internalized. Decisions can be successfully decentralized to the level of individual investors in human capital and tangible assets. Productivity growth is generated by spillovers that cannot be captured by private investors. Activities generating these spillovers cannot be decentralized and require collective decision-making through the public sector. Successive approximations to the Ramsey model of economic growth increase the proportion of growth that can be attributed to investment, rather than productivity.

Econometric Modeling

We are prepared, at last, for the most difficult and least glamorous part of the task of endogenizing economic growth—constructing quantitative models for the analysis of economic policies. The Ramsey growth model of Cass (1965) and Koopmans (1965) requires the empirical implementation of two highly problematical theoretical constructs, namely, a model of producer behavior based on an aggregate production function and a model of a representative consumer. Each of these abstracts from important aspects of economic reality, but both have important advantages in modeling long-term trends in economic growth.

My 1980 paper on "Accounting for Capital" presented a methodology for aggregating over sectors. The existence of an aggregate production function imposes very stringent conditions on production patterns at the industry level. In addition to value-added functions for each sector, an aggregate production function posits that these functions must be identical. Furthermore, the functions relating sectoral capital and labor inputs to their components must be identical and each component must receive the same price in all sectors.[22]

Although the assumptions required for the existence of an aggregate production function appear to be highly restrictive, Fraumeni and I estimated that errors of aggregation could account for less than 9 percent of aggregate productivity growth.[23] In 1987, Gollop, Fraumeni, and I published updated data on sectoral and aggregate production accounts in our book, *Productivity and U.S. Economic Growth.* We generated the data for sectoral production accounts in a way that avoids the highly restrictive assumptions of the aggregate production function. These data were then compared with those from the aggregate production account to test for the existence of an aggregate production function. We demonstrated that this hypothesis is inconsistent with empirical evidence. However, our revised and updated estimate of errors arising from aggregation over industrial sectors explained less than 3 percent of aggregate productivity growth over the period of our study, 1948 to 1979.[24]

Gollop, Fraumeni, and I also presented statistical tests of the much weaker hypothesis that a value-added function exists for each industrial sector, but this hypothesis was also rejected.[25] The conclusion of our research on production at the sectoral level was that specifications of technology such as the aggregate production function and sectoral valued-added functions result in substantial oversimplifications of the empirical evidence. However, these specifications are useful for particular but limited purposes. For example, sectoral value-added functions are indispensable for aggregating over sectors, while the aggregate production function is a useful simplification for modeling aggregate long-run growth, as originally proposed by Tinbergen (1942).

Sectoral value-added functions were employed by Hall (1988, 1990a)

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[22] A detailed survey of econometric modeling of production is included in my 1986 paper, "Econometric Modeling of Producer Behavior." This is also the focus of Solow's 1967 survey article, "Some Recent Developments in the Theory of Production." The conceptual basis for the existence of an aggregate production function was provided by Robert Hall (1973).

[23] Fraumeni and Jorgenson (1980), Table 2.38, lines 4 and 11.

[24] Jorgenson, Gollop, and Fraumeni (1987), Table 9.5, lines 6 and 11.

[25] Jorgenson, Gollop, and Fraumeni (1987), Table 7.2, pp. 239–41. The existence of an aggregate production function requires *identical* value-added functions for all sectors.

in modeling production at the sectoral level. In measuring capital and labor inputs, he adhered to the traditional framework of Kuznets (1971) and Solow (1970) by identifying labor input with hours worked and capital input with capital stock. He found large, apparently increasing returns to scale in the production of value added.[26] Producer equilibrium under increasing returns requires imperfect competition. However, Susanto Basu and John Fernald (1996) have pointed out that the value-added data employed by Hall are constructed on the basis of assumptions of constant returns to scale and perfect competition.

Basu and Fernald (1996) have employed the strategy for sectoral modeling of production recommended in my book with Gollop and Fraumeni (1987), treating capital, labor, and intermediate inputs symmetrically. They estimate returns to scale for the sectoral output and input data presented in my 1990 paper to be constant. These data include constant-quality measures of capital, labor, and intermediate input. Basu and Fernald (1996) also show that returns to scale in the production of value added are constant, when value added is defined in the same way as in my book with Gollop and Fraumeni and constant-quality measures of capital and labor inputs are employed.

Data for individual firms provide additional support for value-added production functions with constant or even decreasing returns to scale. Estimates incorporating intellectual capital have been surveyed by Griliches (1994, 1995) and Bronwyn Hall (1996).[27] These estimates are now available for many different time periods and several countries. Almost all existing studies employ value-added data for individual firms and provide evidence for constant or decreasing returns to scale. This evidence is further corroborated by an extensive study of plant-level data by Martin Baily, Charles Hulten, and Donald Campbell (1992), providing evidence of constant returns at the level of individual manufacturing plants.

Turning to the task of endogenizing investment in tangible assets and education, we first review the endogenous accumulation of tangible assets. An important objective of the Christensen-Jorgenson (1973) accounting system was to provide the data for econometric modeling of aggregate producer and consumer behavior. In collaboration with Lawrence Lau, Christensen and I introduced an econometric model of producer behavior in 1973. We modeled joint production of consumption and investment goods from inputs of capital and labor services, utilizing data on these outputs and inputs from the aggregate production account.

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[26] Hall (1990a) reports a median degree of returns to scale in value added for 2-digit U.S. manufacturing industries of 2.2!

[27] Bronwyn Hall (1996) gives a list of survey papers.

In 1975 Christensen, Lau, and I constructed an econometric model of a representative consumer behavior. We estimated this model on the basis of data from the aggregate income and expenditure account of the Christensen-Jorgenson (1973) accounting system. We tested and rejected the implications of a model of a representative consumer. Subsequently, Lau, Thomas Stoker, and I (1982) constructed a model of consumer behavior based on exact aggregation over individual consumers that specializes to the representative consumer model for a fixed distribution of total expenditure over the population of consumers.[28]

Yun and I (1986a, 1986b)) constructed an econometric model for postwar U.S. economic growth with endogenous accumulation of tangible assets. Our model of consumer behavior involved endogenous labor-leisure choice, following Tinbergen's (1942) neoclassical econometric model of economic growth. Labor-leisure choice is exogenous in Solow's (1956) neoclassical model. In addition, we employed the Ramsey (1928) representation of intertemporal preferences to model saving-consumption behavior, following Cass (1965) and Koopmans (1965). In Solow's model the saving ratio is exogenous.

The econometric application of Ramsey's model of optimal saving was initiated by Hall (1978), removing the final remaining gap between theoretical and empirical perspectives on economic growth.[29] This occurred only eight years after Solow's (1970) classic exposition of the neoclassical theory of growth! The key to Hall's achievement in 1978 was the introduction of an econometrically tractable concept of "rational expectations," which he successfully combined with Ramsey's theoretical model. Building on Hall's framework, Lars Hansen and Kenneth Singleton (1982, 1983) have tested and rejected the underlying model of a representative consumer.

Yun and I (1990) have revised and updated our econometric model of U.S. economic growth and analyzed the consequences of the Tax Reform Act of 1986. We also considered alternative proposals for fundamental tax reform, including proposals now under consideration by the U.S. Congress, such as consumption-based and income-based value-added taxes. We found that the 1986 Act resulted in a substantial increase in social welfare. However, we also discovered that several of the alternative proposals would have produced substantially higher gains.

The econometric model of U.S. economic growth I developed with Yun (1990, 1991a) provides the starting point for the endogenous growth model of the U.S. economy that I constructed with Ho (1995). While the

[28] A survey of empirical approaches to aggregation is given by Stoker (1993).

[29] Hall's 1978 paper and his subsequent papers on this topic have been reprinted in his 1990 book, *The Rational Consumer*. Hall (1990b) and Angus Deaton (1992) have presented surveys of the literature on econometric modeling of consumer behavior within the Ramsey framework.

model with Yun endogenized capital input, the endogenous growth model also endogenizes investment in human capital. This model includes all of the elements of our Ramsey model of U.S. economic growth. However, the new model also includes a highly schematic model of production for the U.S. educational system.

Our production model includes a production possibility frontier for the noneducation sector that is analogous to the frontier in my papers with Yun (1990, 1991a). The model also includes a production function for the education sector with investment in education as the output. The inputs include capital and labor services as well as purchases of goods and services from the noneducation sector. For both submodels, we allow for exogenous growth of productivity; however, Jorgenson and Fraumeni (1992a) show that this is negligible for the education sector.

Ho and I (1995) have evaluated alternative educational policies through the equivalent variation in wealth associated with each policy. As an *alternative case* we consider an educational policy that would raise the participation rates and policies, keeping taxes and expenditures constant. Presumably, this would result in a lower level of "quality." We also consider an *alternative case* that would retain the *base case* participation rates, but raise "quality" by increasing expenditures on consumption goods and capital and labor services in the education sector and the corresponding taxes. Eric Hanushek (1994) has shown that the second of these alternative policies, substantial improvement in educational quality through increased expenditure, is closely comparable to the actual educational policy pursued during the 1980s.

Ho and I (1995) have shown that increasing participation rates without altering expenditure would produce substantial gains in social welfare. In this sense the "quality" level of the existing educational system is too high to be cost-effective. On the other hand, increasing "quality" with no change in participation rates would result in a sizable loss in social welfare. These results are consistent with the literature on educational production functions surveyed by Hanushek (1986, 1989).[30]

With endogenous accumulation of tangible capital, as in the model I constructed with Yun (1986), almost three-quarters of growth is endogenous. By contrast, the model with endogenous investment in education I constructed with Ho (1995) accounts for 83 percent of growth. By endogenizing fertility behavior and child rearing it would be possible, at least in principle, to add an incremental 3 percentage points to the

[30] Note that the meaning of "production function" in this context is different from the meaning of this term in our model of the education sector. In Hanushek's terminology, the output of the education sector is measured in terms of measures of educational performance, such as graduation rates or test scores. Our terminology is closer to Hanushek's (1994) concept of "value-added" by the educational system. The output of the education system is the addition to the lifetime incomes of all individuals enrolled in school.

explanatory power of the Ramsey model of economic growth. Modeling population growth endogenously is clearly feasible. However, the construction of an econometric model with this feature would require considerable new data development and is best left as an opportunity for future research.

In summary, the endogenous models of growth I constructed with Yun (1986a, 1986b) and Ho (1995) require the econometric implementation of concepts of an aggregate production function and a representative consumer. While each of these concepts has important limitations, both are useful in modeling long-run economic trends. Furthermore, these concepts lead naturally to a substantial increase in the level of sophistication in data generation, integrating investment and capital into a complete system of national accounts.

Conclusion

The key innovation in economic measurement required for endogenizing growth is a wealth account that can be integrated with production and income and expenditure accounts. This encompasses the system of vintage accounts for tangible assets implemented in my work with Christensen (1973) as well as the vintage accounts for human capital I developed with Fraumeni (1989). These incorporate accumulation equations for tangible assets and human capital, together with asset-pricing equations. Both are essential in constructing *endogenous* models of growth to replace the *exogenous* models that emerged from the professional consensus of the early 1970s.

The framework for economic measurement developed in my work with Christensen (1973) and Fraumeni (1989) incorporates the principal features of the United Nations (1993) *System of National Accounts*. This provides a production account for allocating the *sources* of economic growth between investment and growth in productivity. It also includes an income and expenditure account for analyzing the *uses* of economic growth through consumption and saving. Alternative policies are ranked by means of equivalent variations in wealth for the representative consumer.

In principle, investment in new technology could be made endogenous by extending the accounting framework to incorporate investment in R&D. The BEA (1994) has provided a satellite system of accounts for research and development, based on Goldsmith's (1955-56) perpetual inventory method, applied to private and public expenditures. Unfortunately, this is subject to the same limitations as the approach to human capital of Schultz (1961) and Machlup (1962). The BEA satellite system has foundered on the absence of a satisfactory measure of the output of research and development and the lack of an appropriate rationale for capital consumption.

The standard model for investment in new technology, formulated by Griliches (1973), is based on a production function incorporating inputs of services from intellectual capital accumulated through investment in research and development. Intellectual capital is treated as a factor of production in precisely the same way as tangible assets in my work with Christensen (1973). Bronwyn Hall (1993) has developed the implications of this model for the pricing of the services of intellectual capital input and the evaluation of intellectual capital assets.[31]

Griliches (1973) represented the process of research and development by means of a production function that included the services of previous research and development. This captures the notion of "standing on the shoulders of giants," originated by Jacob Schmookler (1966) and elaborated by Riccardo Caballero and Adam Jaffe (1993) and Jones and Williams (1996). Under constant returns to scale, this representation also captures the "congestion externality" modeled by Jones and Williams and by Nancy Stokey (1995). Research and development, leading to investment in intellectual capital, is conducted jointly with production of marketable output, and this poses a formidable obstacle to measuring the output of new intellectual capital.

The model of capital as a factor of production that I first proposed in 1963 has been applied to tangible assets and human capital. However, successful implementation of this model for intellectual capital would require a system of vintage accounts including not only accumulation equations for stocks of accumulated research and development, but also asset pricing equations. These equations are essential for separating the revaluation of intellectual property due to price changes over time from depreciation of this property due to aging. This is required for measuring the quantity of intellectual capital input and its marginal product.

Pricing of intellectual capital is the key issue remaining before investment in new technology can be endogenized in quantitative models for the analysis of alternative economic policies. Bronwyn Hall (1993) has constructed prices for stocks of accumulated intellectual capital from stock market valuations of the assets of individual firms. However, she points out that the high degree of persistence in expenditures on research and development at the firm level has made it virtually impossible to separate the effects of the aging of assets from changes in the value of these assets over time. Her evaluation of intellectual capital is conditional upon a pattern of relative efficiencies imposed on past investments in new technology.

Nonetheless, Hall's pioneering research on pricing of intellectual assets has yielded interesting and valuable insights. For example, the

[31] These implications of the model are also discussed by Charles Jones and John Williams (1996).

gross rate of return in the computer and electronics industry, including depreciation and revaluation of these assets, greatly exceeds that in other industries. This can be rationalized by the fact that revaluation in this industry, as measured by Hall, is large and negative, mirroring the rapid decline in the price of the industry's output. This is evidence for the empirical significance of the process of creative destruction described by Joseph Schumpeter (1942) and modeled by Phillippe Aghion and Peter Howitt (1992), Stokey (1995), and Jones and Williams (1996). Since revaluation enters negatively into the gross rate of return, this rate of return exceeds that for industries with positive revaluations.

Another important result that emerges from Bronwyn Hall's (1996) survey of gross rates of return to research and development is the repeated finding that investment funded by the federal government has a zero private return. Even private firms conducting this research under government contract have been unable to internalize the returns. This has the very important policy implication that public investments in new technology can be justified only by comparisons of the costs and benefits to the government. Measurement of these benefits requires careful case studies like those of civilian space technology by Henry Herzfeld (1985) and commercial aircraft by David Mowery (1985). Grandiose visions of spillovers from public research and development have been exposed as a fleeting mirage.

The final issue that must be resolved in order to complete the endogenization of economic growth is modeling of spillovers. Griliches (1995) has provided a detailed survey of alternative methodologies and results, based on the model he originated in 1979. The essential idea is to include aggregate input of intellectual capital, together with the inputs of individual producers, as a determinant of output. Unfortunately, this requires precisely the same separation of marginal product and capital input for intellectual capital needed for the identification of returns that can be internalized by the individual producer.

Caballero and Richard Lyons (1990, 1992) have attempted to circumvent the problem of measuring intellectual capital by including aggregate output as a determinant of sectoral productivity. However, Basu and Fernald (1995) have shown that the positive results of Caballero and Lyons depend on the same value added data employed by Robert Hall (1988, 1990a). Treating capital, labor, and intermediate inputs symmetrically, as in their research on economies of scale, Basu and Fernald show that the evidence for spillovers evaporates. This leaves open the question of the importance of spillovers from investment in new technology, which must await satisfactory measures of the output of research and development.

An elegant and impressive application of the Griliches (1979) framework for modeling spillovers across international boundaries has been presented by David Coe and Elhanan Helpman (1995). The key idea is to trace the impact of these spillovers through trade in intermediate goods. For each country, the stock of accumulated research and development of its trading partners is weighted by bilateral import shares. However, Wolfgang Keller (1996) has shown that the evidence of spillovers is even more impressive if the bilateral trade shares are assigned randomly, rather than matched with the countries conducting the research and development. Another vision of spillovers can be assigned to the lengthening roll of unproven theoretical hypotheses.

In summary, a great deal has been accomplished, but much remains to be done to complete the endogenization of economic growth. An important feature of recent research, for example, in the seminal papers of Paul Romer (1986, 1987, 1990), has been the linking of theoretical and empirical investigations. This integration need no longer be left to the remarkable coincidence of empirical and theoretical perspectives that led Kuznets (1971) and Solow (1970) to the neoclassical framework. In the absence of a clear and compelling link between the theoretical model and the data generation process, the breakdown of this framework had left economists without a guide to long-run economic policy for two decades.

Fortunately, a new empirical and theoretical consensus on economic growth would require only a relatively modest reinterpretation of the neoclassical framework established by Solow (1956, 1970, 1988), Cass (1965), and Koopmans (1965). However, the traditional framework of economic measurement established by Kuznets (1961, 1971) and imbedded in the U.S. National Income and Product Accounts will have to be augmented considerably. The most important change is a reinterpretation of the concepts of investment and capital to encompass Fisher's (1906) notion of "wealth in its more general sense."

In closing, I must emphasize that my goal has been to provide a new starting point in the search for a consensus on economic growth, rather than to arrive at final conclusions. The new framework I have outlined is intended to be open-ended, permitting a variety of different approaches to investment—in tangible assets, human capital, and new technology. Ample, if carefully delimited, space is available within this framework for endogenizing spillovers, for example, by using the Lindahl-Samuelson theory of public goods. New entrants to the field will continue to find a plethora of opportunities for modeling economic growth.

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DISCUSSION

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Dale Jorgenson has written a provocative and challenging paper based on many years of research on theory and measurement. He takes a position that challenges important elements of both the neoclassical growth theory of the 1960s and 1970s and the "New Growth" theory of the 1980s. He adopts the standard neoclassical framework of an aggregate production function with constant returns to scale, perfect competition, and no externalities or spillovers between firms. On the other hand, he agrees with the basic tenet of New Growth theory that long-run growth rates should be "endogenous"—explained by economic forces—instead of being taken as exogenous to the economic system. In this paper, Jorgenson argues that a slightly augmented version of Robert Solow's (1957) growth-accounting framework is sufficient to explain all of postwar economic growth as the outcome of purposeful investment.[1] In particular, one need not invoke "exogenous technological progress." To understand the ambition of this project, note that Solow found that capital accumulation explained only 12.5 percent of per capita output growth, with the remainder attributed to exogenous changes in technology!

In order to assess the success of Jorgenson's project, I want to ask how well his framework does at explaining three fundamental questions of growth theory.

- Why does per capita income increase over time?

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[1] In Jorgenson's lexicon, "investment" means that all returns are appropriated by the investor, in a model that has perfect competition. Understanding this terminology is important, since the New Growth theory also explains all growth as the outcome of capital accumulation, but must invoke either increasing returns or spillovers to do so.

- Why are some countries rich and others poor?
- Why has economic growth slowed down in developed countries?

The framework that Jorgenson uses leaves him very few degrees of freedom—a virtue in any scientific hypothesis. Thus, his answers to all three questions must be, "Variations in the quality and quantity of investment in a standard neoclassical setting." The setting is that of a standard constant-returns production function for every producer (and therefore for the economy):

$$Y = AF(K, L, T), \tag{1}$$

where K is capital, L is labor, and T stands for technology. As noted, we assume constant returns to scale, perfect competition, and no spillovers. This is the standard setting of growth accounting and productivity measurement using the Solow (1957) residual:

$$\Delta p = \Delta y - \alpha_L \Delta l - (1 - \alpha_L)\Delta k. \tag{2}$$

Lowercase letters represent natural logarithms and α_L is the share of labor income in national income. Under Jorgenson's conditions, Δp is proportional to Δt. To simplify matters, assume that a fixed fraction of national output is devoted to capital accumulation:

$$\Delta K = s_K Y - \delta_K K. \tag{3}$$

So far, everything is standard neoclassical theory. Unlike Solow, however, Jorgenson does not allow for exogenous change in technology. In his framework, "technology" is just knowledge (a shorthand for R&D and other forms of human capital), and knowledge is a form of capital that is accumulated like any other. On the other hand, the New Growth theory, which also treats knowledge as a form of capital, believes that knowledge is special, in the sense that investors cannot fully internalize the benefits from accumulating knowledge. The New Growth theory thus has large spillovers to knowledge accumulation. These two positions can be summed up as special cases of the following general equation:

$$\Delta T = (s_T Y)T^{\phi} - \delta_T T. \tag{4}$$

ϕ indexes the size of knowledge spillovers—the degree to which previous knowledge reduces the cost of accumulating new knowledge. Jorgenson holds that $\phi = 0$; note that in this case equation (4) is an exact analog of equation (3), so there is nothing special about knowledge capital. On the other hand, New Growth theory requires very strong spillovers: At a minimum, it needs $\phi = 1$.

Both of these extreme positions have some unpleasant implications. Jorgenson's position implies that, in the long run, no per capita output growth can occur (since his model has capital accumulation as the only source of growth, but the marginal product of capital is diminishing). This seems to contradict both recent human experience (since the Industrial Revolution) and very long-run experience (the rise in living standards since Neolithic times). On the other hand, the parameters of the New Growth theory imply that the long-run growth rate of per capita output depends on the rate of saving in knowledge. Jones (1995) shows that postwar time series data for the United States and other advanced economies reject this implication.

However, as Jones (1995) points out, a whole range of intermediate positions is possible: We can have $0 < \phi < 1$. An intermediate position of this sort is consistent with many studies that find significant positive spillovers to R&D investment, and with our intuition that something is indeed special about knowledge. It also avoids both the counterfactual implications noted above. The intermediate model predicts that long-run per capita growth will occur, but says that this growth rate is not influenced by policy.

But while I believe that the data do not fully support Jorgenson's answer to the first question, I think his answer is closer to being correct than either the neoclassical model or the New Growth model. In particular, his conclusion—that growth is driven by investment but growth *rates* are not—is robust to adding spillovers of moderate size.

It is in answering the second question, however, that Jorgenson's framework shows greater problems. The recent work of Islam (1995) shows that production functions seem to differ significantly across countries: That is, differences in capital per worker seem insufficient to explain cross-country differences in output per worker. Thus, we need a modification of equation (1):

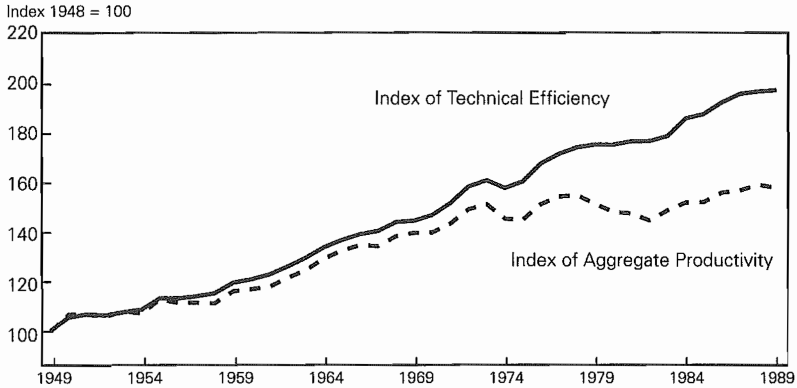
$$Y_i = A_i F(K, L, T), \tag{5}$$

where i indexes "location." What are the economics of "location"? In the context of cross-country growth, it is easy to identify "location" with geography. But in the sense that matters for economics, location means a factor that is relevant for production. Such factors can certainly be country-specific—for example, political and legal institutions—but they probably also have a great deal to do with technology diffusion and infrastructure, factors that can vary even within countries (and sometimes be approximately constant across countries).

These cross-country results suggest that we augment the Jorgenson "Quality, Quantity" paradigm with one other factor: "Quality, Quantity, Location." I conclude by asking whether location in the sense I have defined it might matter for short-run productivity dynamics within countries—for example, the productivity slowdown that has been the focus of much public discussion.

Figure 1

A Comparison of Productivity Growth and Technological Change



Location matters if identical factors of production have different marginal products in different uses. In the context of within-country differences, location might matter if different sectors (firms, industries) have different degrees of market power or different returns to scale, or pay identical workers different wages. Basu and Fernald (1995) discuss these ideas in detail. Their conclusion can be summarized as saying that a gap exists between productivity change and technology change, and this gap comes from factor reallocation:

$$\Delta p = \Delta t + R. \tag{6}$$

Recall that Δp is productivity growth and Δt is technology change. R stands for "reallocation." One implication of equation (6) is that changes in the growth rate of productivity may not represent changes in the growth rate of technology, as most of the discussion surrounding the productivity slowdown assumes. Instead, a change in the growth rate of productivity may represent a change in the allocation of inputs over time. This is an important conjecture to examine, since the policy responses to the two would likely be quite different.

Using the methods of Basu and Fernald (1995), I construct the *R* in equation (6). To allow for a trend break in *R* around the time of the productivity slowdown, I estimate *R* separately over two subsamples: 1949 to 1969, and 1970 to 1989. Subtracting the implied series for *R* from the series for productivity growth defined in equation (2) yields the implied series for technology change. Figure 1 presents the results. As the figure shows, the calculations imply that changes in input allocation accounted for the bulk of the productivity slowdown, with only a small reduction in the growth rate of technology. This calculation is subject to all of the caveats noted by Basu and Fernald (1995), but it is at least suggestive.

To summarize, Dale Jorgenson has written a paper that shows the explanatory power of standard neoclassical theory when combined with careful measurement. For the reasons I have outlined, I think that model will need to be augmented by allowing for small knowledge spillovers and a modest degree of imperfect competition. Nevertheless, the amended model will retain much of the flavor of the neoclassical framework, particularly in the conclusion that economic policy does not determine the rate of long-term growth. However, policy may have an important effect on the *level* of output (and hence welfare), and thus is likely to be far from irrelevant.

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Discussion

Gene M. Grossman*

Despite the title of his paper, Dale Jorgenson devotes relatively few words to elucidating the place of technology in growth theory. Many of what I consider to be the most important questions about technology and growth are not addressed. Therefore, I will devote most of my space to explaining how I would have interpreted the topic "technology in growth theory," while addressing a few comments to the particulars of his paper, in passing.

It seems to me that one could ask four levels of questions about the place and treatment of technology in growth theory. First:

- Is technological progress needed to sustain growth? That is, can and would growth continue indefinitely if more and more of the tangible factors could be accumulated but there were no improvements in the ability to combine these factors in producing final output?

As we now know, and in fact as Bob Solow knew already in 1956, growth can be sustained with an unchanging technology provided there are no long-run diminishing returns to the accumulable factors of production. That is, if as physical and human capital are accumulated indefinitely, their rates of return remain bounded above some minimum level, then growth can and will continue without any technological progress.

While we cannot know for sure whether or not this condition applies, both a priori reasoning and the available econometric evidence suggest

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that it does not. On a priori grounds, it is easy to think of factors that are available in relatively fixed supply that should impart decreasing returns to those that can be accumulated. I am thinking in particular of natural endowments—land, water, minerals, fuels, and the like—but "raw" labor might become another constraining factor at some point. The econometric evidence presented by, for example, Mankiw, Romer, and Weil (1992) points to rather significant diminishing returns to physical and human capital, even if both types of capital accumulate together.

A simple thought experiment might make the issue more concrete. Imagine how the world economy would have evolved if none of the major inventions of the last 200 years had materialized—no steam engine, no electricity, no transistors, no computers, and so on. Would growth have proceeded nonetheless thanks to investments in ever more capital (more field animals and hand instruments?) and continued increases in levels of schooling?

Parenthetically, I would remark that growth accounting, no matter how carefully conducted, cannot shed light on this question. The reason is that growth accounting is just that—an *accounting* procedure, but not a structural model. It is easiest to see the point at the sectoral level, using the approach favored by Jorgenson and his coauthors, which includes intermediate goods as well as capital and labor as factors used in producing gross output. Suppose we observe that output of the automobile industry has doubled, that inputs of steel have doubled, and that steel accounts for 50 percent of the value of a car. Growth accountants would claim that they have "explained" half of the growth of output already; I would claim that they have explained nothing. Knowing that steel inputs have increased does not tell us why output has expanded, or whether it would have expanded under some alternative counterfactual scenario. Rather, steel inputs increased because firms wanted to produce more cars, for some other reason.

Similarly, observing that physical and human capital inputs have expanded does not tell us why growth has occurred, or whether it would have occurred absent technological progress. Individuals invest in these assets in the expectation of making a return, and until we explain the determinants and evolution of that return we have not explained the associated growth. In other words, the statement that investment is more important in the growth process than productivity increases is a meaningless one, unless one believes that investments happen autonomously.

The second question I would ask about the role of technology in growth theory is as follows:

- Is technological progress the result of intentional (economic) activities or not? That is, is it endogenous to the economic system or exogenously determined?

Here again the verdict is still out, but my own view is that a lot of technological progress is endogenous. For one thing, firms in the United States now spend more than 100 billion dollars per year in activities labeled as formal R&D. Presumably, they are being driven to do so by a profit motive, and they believe they are getting something for their money. The more convincing evidence, to me, comes from looking across time and across space. Baumol (1990) provides a compelling account of how the allocation of entrepreneurial effort to innovation has varied across historical epochs and how this variation seems to align closely with the types of incentives confronting these entrepreneurs. And the great variation in productivity levels across regions and countries also seems to relate to the nature of the various economic environments and the rules of the game.

Let me remark briefly on an often-heard comment, which is also implicit in many of the growth accounting exercises: that R&D is too small a percentage of GDP to be an important determinant of technological progress and growth. It is true that an allocation of 2 to 3 percent of output per year, even with high rates of return, can directly account for only a small fraction of aggregate output growth. But again, the accounting perspective is not the correct one. In our 1994 *Journal of Economic Perspectives* article, Elhanan Helpman and I report a simple back-of-the-envelope calculation to show that a small amount of R&D might drive a good deal of growth, once the investments in capital that are undertaken to implement the new innovations are taken into account.

Jorgenson confuses the issue, I feel, when he equates identifying the "sources of growth" with "endogenizing" growth. He believes that it is important to allocate the sources of growth between investment and productivity, and that the part of output expansion that can be accounted for by investment has been endogenized, whereas productivity growth (the residual) remains exogenous. I would rather reserve the words "endogenous growth" for growth that can be traced to its fundamental economic determinants. An accounting procedure that attributes output growth to investment has not endogenized growth, unless the factors that generate incentives for investment are also explained. On the other hand, growth that can be traced to productivity increases might be endogenous, if the productivity increases themselves can be tied convincingly to economic activities.

The third question I would ask is this:

- Is formal R&D responsible for most technological progress?

Here I would guess the answer is "probably not." One negative observation is that made by Charles Jones (1995): Formal R&D, as measured by either the number of scientists and engineers engaged in R&D or business spending on R&D, has been growing steadily and rapidly in the postwar period, while rates of total factor productivity growth and per capita output growth have not (on a related point, see Hall 1993). Also, declining R&D does not seem to explain the productivity slowdown that occurred after 1973 (Griliches 1988). Undoubtedly, many activities contribute to firms' productivities besides their formal R&D. Mansfield (1988) notes that Japanese firms have devoted as much as 40 percent of the cost of developing new products to activities that would be categorized as "process engineering"; for example, to tooling and manufacturing equipment and facilities. Even more informal activities—what the theory literature might designate as "learning by doing"—have been found to be empirically important in many industries. And improvements in the organization of firms and production also contribute significantly to productivity gains.

The theoretical literature on endogenous innovation so far has concentrated on formal R&D. I would guess that this has more to do with what theorists feel they know how to model than it does with any empirical assessment of what is more or less important. I could easily imagine growth theory evolving to a richer specification of the various activities firms undertake to improve their productivity.

The fourth and final question on my list, and the one that seems to interest Jorgenson the most, concerns the normative implications of our models of growth. In particular:

- Is the level of investment in new technologies determined by market forces the socially optimal one? Would welfare or growth rates rise dramatically if we promoted more R&D? And is the R&D tax credit, or another similar subsidy scheme, the appropriate way to do so?

As is well known, the normative questions hinge on the existence or not of positive spillovers in the process of creating knowledge. Griliches (1992) distinguishes two types of spillovers. Rent spillovers arise if innovating firms cannot act as perfectly discriminating monopolists and thereby capture all of the consumer-surplus benefits from their new and better products in the form of increased prices. Knowledge spillovers occur if learning activities undertaken by one set of agents make research more productive for others, and if the latter group does not need to compensate the former for these benefits.

Jorgenson clearly is suspicious of such spillovers. He explains how investments in R&D create "intellectual assets" which yield private returns in the form of profits and royalties. And he notes that an "increase in intellectual capital contributes to output growth in proportion to its marginal product in the same way as the acquisition of a tangible asset." Both of these points are of course correct. But intellectual capital is different from physical capital, certainly in degree if not in kind. Whereas the property rights to physical capital can easily be defined and enforced, the property rights for intellectual capital are notoriously difficult to protect. And whereas physical capital is a "rival input" in the sense that it can only be used in one place at one time, intellectual capital is "nonrival" inasmuch as the same knowledge can be deployed in many places simultaneously. Therefore, while investments in intellectual capital can and do generate private returns, the scope for social returns in excess of private returns far exceeds that for other types of investment.

A myriad of studies have attempted to measure spillovers by examining different firms, industries, and countries, using a variety of case-study and econometric techniques. These studies have been surveyed many times, for example, by Griliches (1992) and Mairesse and Mohnen (1995). The specific findings vary widely, and the many methodological problems would shake one's confidence in any single one of them. Nonetheless, most of the studies find private rates of return in excess of 20 percent and social rates of return more than twice as high as the private rates. Moreover, the estimated rates of return are invariably higher than those found in the same studies for physical capital. All of this leads Griliches to conclude:

> In spite of all these difficulties, there has been a significant number of reasonably well done studies all pointing in the same direction: R&D spillovers are present, their magnitude may be quite large, and social rates of return remain significantly above private rates (1992, p. S43).

Even so, one cannot immediately conclude that there is too little innovation. As Aghion and Howitt (1992) and Grossman and Helpman (1991) have shown, the existence of positive knowledge spillovers from R&D is not sufficient for the conclusion that it would be socially beneficial to allocate greater resources to this activity; in markets with imperfect competition, firms might invest too much in R&D if their private benefits came largely from taking business from their rivals rather than from expanding the size of the social pie. But calibration exercises performed by Stokey (1995) and Jones and Williams (1996) suggest that this caveat probably has more bite in theory than it does in practice.

The question of whether an R&D tax credit or another subsidy is a good way to encourage industrial innovation is a different one entirely. Many observers (for example, Mansfield 1986) believe that an R&D tax credit does as much or more to encourage firms to redefine their activities as R&D as it does to promote greater innovation effort. And even if the government could somehow monitor R&D expenses closely, it is not at all clear that the social return to this sort of learning activity exceeds that for the other things that firms do in their efforts to enhance their productivity.

Jorgenson seems to believe that growth accounting can shed light on the appropriateness of R&D promotion and other similar policy problems. In particular, he associates "spillovers" with the size of the Solow residual. I fail to see this correspondence. There might be a sizable residual in aggregate growth accounting due to, for example, an important component of exogenous technological progress, and yet no spillovers from research activities and no call for (economic) policy intervention in the growth process. Alternatively, the residual might be reasonably small, and yet spillovers large and government intervention very much warranted. The latter could occur if the well-known problems of measuring product quality meant that actual output growth were greater than what is measured, or if a relatively small amount of total factor productivity growth were sufficient to induce a great deal of investment in physical and human capital.

Conclusion

Let me summarize my own feelings about the role of technology in growth theory as follows. First, there is no reason at all to deny or diminish the accomplishments of neoclassical growth theory. Undoubtedly, understanding the incentives for investment are important for understanding growth. But so too, I would argue, is understanding the incentives for innovation, the more so the longer the growth horizon. The neoclassical model, with its built-in assumptions of constant returns to scale and perfect competition, is not well suited for studying innovation. Investments in knowledge are up-front investments that naturally imply increasing returns to scale in production. Firms cover these fixed costs by charging prices in excess of marginal cost. Therefore, there is little choice but to study innovation in a setting that allows for imperfect competition, despite the ambiguities in policy advice that this implies. Growth theory has made some modest progress along these lines in recent years, but much more remains to be done.

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Uncertainty and Technological Change

Nathan Rosenberg*

I would like to begin with two generally accepted propositions: First, technological change is a major ingredient of long-term economic growth, and second, technological change is characterized by a high degree of uncertainty. Understanding the nature of these uncertainties and the obstacles to surmounting them is not a trivial matter. Rather, it goes to the heart of how new technologies are devised, how rapidly they diffuse, the ultimate extent of that diffusion, and their eventual impact on economic performance and welfare.

In view of the great uncertainties attached to the innovation process, it is hardly surprising that innovating firms have, historically, experienced high failure rates. Quite simply, the vast majority of attempts at innovation fail. But to describe the high failure rate associated with past innovation is to tell only a part of the story, and perhaps not the most interesting part. Indeed, I want to suggest that the more intriguing part of the story, with which I will be mainly concerned, has been the inability to anticipate the future impact of successful innovations, even after their technical feasibility has been established. This statement remains valid whether we focus on the steam engine 200 years ago or on the laser within our own lifetimes.

I will suggest that uncertainty is the product of several sources and that it has a number of peculiar characteristics that shape the innovation process and, therefore, the manner in which technological change exer-

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cises its effects on the economy. Since I will be concerned primarily with what has shaped the trajectory and the economic impact of new technologies, my focus will be confined to technologies that have had significant economic consequences.

I should also say at the outset that, while I am not primarily concerned with the recent formal literature on growth theory (specifically The New Growth Theory), I am surprised that that literature has, so far at least, omitted any mention of uncertainty. While the rate of innovation is surely a function of the degree to which investors can appropriate the gains from their innovation, a number of central features of the innovation process revolve around uncertainty. At the very least, when evaluating projects, a risk/return trade-off that reflects the uncertainty attaching to appropriability must be considered. But the kinds of uncertainties that will be identified here go far beyond the issue of appropriability.

One further caveat seems appropriate. The discussion that follows is "anecdotal" in nature. However, the anecdotes have been deliberately selected to include many of the most important innovations of the twentieth century. Thus, if the characterizations offered below stand the test of further scrutiny, the analysis of this paper will have captured distinct features of the innovation process for technologies whose cumulative economic importance has been immense.

It is easy to assume that uncertainties are drastically reduced after the first commercial introduction of a new technology, and Schumpeter offered strong encouragement for making that assumption. His views have proven to be highly influential. In Schumpeter's world, entrepreneurs are compelled to make decisions under circumstances of very limited and poor quality of information. But in that world, the successful completion of an innovation resolves all the ex ante uncertainties. Once invention occurs, the stage is set for imitators, whose actions are responsible for the diffusion of a technology. Perhaps it should be said that the stage is now set for "mere imitators," for Schumpeter was fond of preceding the noun "imitators" with the adjective "mere." The point is one of real substance, and not just linguistic usage. In Schumpeter's view, life is easy for the imitators, because all they need to do is to follow in the footsteps of the entrepreneurs who have led the way, and whose earlier activities have resolved all the big uncertainties.

It is, of course, true that some uncertainties have been reduced at that point. However, after a new technological capability has been established, the questions change and, as we will see, new uncertainties, particularly uncertainties of a specifically economic nature, begin to assert themselves.

The purpose of this paper is to identify and to delineate a number of important aspects of uncertainty as they relate to technological change. These aspects go far beyond those connected with the inventive process alone. In addition, they reflect a set of interrelated forces that are at the heart of the relationship between changes in technology and improvements in economic performance.

Some Historical Perspectives

Consider the laser, an innovation that is certainly one of the most powerful and versatile advances in technology in the twentieth century, and one that is surely still in the early stages of its trajectory of development. Its range of uses in the 30 years since it was invented is truly breathtaking, and would include precision measurement, navigation, and chemical research. It is also essential for the high-quality reproduction of music in compact discs (CDs). It has become the instrument of choice in a range of surgical procedures, including extraordinarily delicate eye surgery, where it is used to repair detached retinas, and gynecological surgery, where it now provides a simpler and less painful method for removal of certain tumors. It is extensively employed in gallbladder surgery. The pages of this manuscript were originally printed by a laser (Hewlett Packard laser jet printer). It is widely used throughout industry, including textiles, where it is employed to cut cloth to desired shapes, and metallurgy and composite materials, where it performs similar functions. The opening sentence in an article appearing in *The New York Times* in April 1996 stated: "Lawrence Livermore Laboratory, builder of lasers powerful enough to shoot down missiles or ignite miniature hydrogen bombs, has created a portable laser that is said to be able to obliterate graffiti from walls and statues at lightning speed."

But perhaps no single application of the laser has been more profound than its impact on telecommunications where, together with fiber optics, it is revolutionizing transmission. The best transatlantic telephone cable in 1966 could carry simultaneously only 138 conversations between Europe and North America. The first fiber optic cable, installed in 1988, could carry 40,000. The fiber optic cables being installed in the early 1990s can carry nearly 1.5 million conversations (Wriston 1992, pp. 43–44). And yet it is reported that the patent lawyers at Bell Labs were initially unwilling even to apply for a patent on the laser, on the grounds that such an invention had no possible relevance to the telephone industry. In the words of Charles Townes, who subsequently won a Nobel Prize for his research on the laser, "Bell's patent department at first refused to patent our amplifier or oscillator for optical frequencies because, it was explained, optical waves had never been of any importance to communications and hence the invention had little bearing on Bell System interests" (Townes 1968, p. 701).

Let me cite some further major historical instances where the common theme is the remarkable inability, at least from a later perspective, to foresee the uses to which new technologies would soon be put. Western Union, the telegraph company, was offered the opportunity to purchase Bell's 1876 telephone patent for a mere $100,000, but turned it down. In fact, "Western Union was willing to withdraw from the telephone field in 1879 in exchange for Bell's promise to keep out of the telegraph business." But if the proprietors of the old communications technology were myopic, so too was the patent holder of the new technology. Alexander Graham Bell's 1876 patent did not mention a new technology at all. Rather, it bore the glaringly misleading title "Improvements in Telegraphy" (Brock 1982, p. 90).

Marconi, who invented the radio, anticipated that it would be used primarily to communicate between two points where communication by wire was impossible—as in ship-to-ship or ship-to-shore communication. (To this day the British call the instrument the "wireless," precisely reflecting Marconi's early conceptualization.) Moreover, the radio in its early days was thought to be of potential use only for private communication: that is, point-to-point communication, rather like the telephone, and not at all for communicating to a large audience of listeners. Surprising as it may seem to us today, the inventor of the radio did not think of it as an instrument for broadcasting. Marconi, in fact, had a conception of the market for radio that was the precise opposite of the one that actually developed. He visualized the users of his invention as steamship companies, newspapers, and navies that required directional, point-to-point communication—"narrowcasting" rather than broadcasting. The radio should therefore be capable of transmitting over great distances, but the messages should be private, not public (Douglas 1987, p. 34).

The failure of societal imagination was widespread. According to one authority: "When broadcasting was first proposed . . . a man who was later to become one of the most distinguished leaders of the industry announced that it was very difficult to see uses for public broadcasting. About the only regular use he could think of was the broadcasting of Sunday sermons, because that is the only occasion when one man regularly addresses a mass public" (Martin 1977, p. 11).

The wireless telephone, when it became feasible in the second decade of the twentieth century, was thought of in precisely the same terms as the wireless radio. J.J. Carty, who was chief engineer of the New York Telephone Company, stated in 1915, "The results of long-distance tests show clearly that the function of the wireless telephone is primarily to reach inaccessible places where wires cannot be strung. It will act mainly as an extension of the wire system and a feeder to it" (Maclaurin 1949, pp. 92–93).

The computer, in 1949, was thought to be of potential use only for rapid calculation in a few scientific research or data processing contexts. The notion of a large potential market was rejected by no less a person than Thomas Watson, Sr., at the time the president of IBM. The prevailing view before 1950 was that world demand probably could be satisfied by just a few computers (Ceruzzi 1987, pp. 188–93).

The invention of the transistor, certainly one of the greatest inventions of the twentieth century, was not announced on the front page of *The New York Times*, as might have been expected, when it was made public in December 1947. On the contrary, it was a small item buried deep in the newspaper's inside pages, in a regular weekly column titled "News of Radio." It was suggested there that the device might be used to develop better hearing aids for the deaf, but nothing more.

This listing of failures to anticipate future uses and larger markets for new technologies could be expanded almost without limit. We could, if we liked, amuse ourselves indefinitely at the failure of earlier generations to see the obvious, as we see it today. But that would be a mistaken conceit. For reasons that I propose to examine, I am not particularly optimistic that our ability to overcome the ex ante uncertainties connected with the uses of new technologies is likely to improve drastically. If I am right, a more useful issue to explore is what incentives, institutions, and policies are more likely to lead to a swifter resolution of these uncertainties.

Much of the difficulty, I suggest, is connected to the fact that new technologies typically come into the world in a very primitive condition. Their eventual uses turn upon an extended improvement process that vastly expands their practical applications. Thomas Watson, Sr., was not necessarily far off the mark when he concluded that the future market for the computer was extremely limited, *if one thinks of the computer in the form in which it existed immediately after the Second World War*. The first electronic digital computer, the ENIAC, contained no less than 18,000 vacuum tubes and filled a huge room. (It was more than 100 feet long.) Any device that has to rely on the simultaneous working of 18,000 vacuum tubes is bound to be notoriously unreliable. The failure in prediction was a failure to anticipate the demand for computers after they had been made very much smaller, cheaper, and more reliable, and when their performance characteristics, especially their calculating speed, had been improved by many orders of magnitude. That is to say, the failure was the inability to anticipate the trajectory of future improvements and the economic consequences of those improvements.

If space permitted, the history of commercial aviation could be told in similar terms, as could the history of many other innovations. With respect to the introduction of the jet engine, in particular, the failure to anticipate the importance of future improvements occurred even at the most eminent scientific levels. In 1940, a committee of the National Academy of Sciences was formed to evaluate the prospects for developing a gas turbine for aircraft. The committee concluded that such a turbine was quite impractical because it would have to weigh 15 pounds for each horsepower delivered, whereas existing internal combustion engines weighed only slightly over one pound for each horsepower delivered. In fact, within a year the British were operating a gas turbine that weighed a mere four-tenths of one pound per horsepower (U.S. Navy, Bureau of Ships 1941, p. 10).

This is an appropriate place at which to make a very simple, but nonetheless fundamental observation: Most R&D expenditures are devoted to product improvement. According to McGraw-Hill annual surveys over a number of years, the great bulk of R&D (around 80 percent) is devoted to improving products that already exist, rather than to the invention of new products. Thus, it is incorrect to think of R&D expenditures as committed to the search for breakthrough innovations of the Schumpeterian type. On the contrary, the great bulk of these expenditures need to be thought of as exhibiting strongly path-dependent characteristics. Their main goal is to improve upon the performance of technologies that have been inherited from the past.

A moment's reflection suggests that this should not be surprising. The telephone has been around for more than a hundred years, but only recently has its performance been significantly enhanced by facsimile transmission, electronic mail (e-mail), voice mail, data transfer, on-line services, mobile phones, conference calls, and "800" numbers. The automobile and the airplane are each more than 90 years old, the camera is 150 years old, and the Fourdrinier machine, which is the mainstay of the papermaking industry today, was patented during the Napoleonic Wars. Clearly the improvement process deserves far more attention than is suggested by Schumpeter's frequent recourse to the derisory term "mere imitators." Equally clearly, a world in which most R&D expenditures are devoted to improving upon technologies that already exist is also a world in which technological change can hardly be characterized as exogenous.

So far it has been suggested, by citing important historical cases, that uncertainty plays a role in technological change that goes far beyond the uncertainty associated with technological feasibility alone. Indeed, the uncertainty associated with the eventual uses of the laser or the computer might, more appropriately, be characterized as "ignorance" rather than as "uncertainty." That is to say, along any particular dimension of uncertainty, decisionmakers do not have access to an even marginally informative probability distribution with respect to potential outcomes. It is not difficult to demonstrate that ignorance plays a large part in the process of technological change! However, rather than arguing over the differences between Arrovian and Knightian uncertainty, the next section of this paper will outline a number of important dimensions along which uncertainty plays a role in the rate and direction of inventive activity and diffusion. Taken together, we have very little information, *even retrospectively,* about the relationships among these different dimensions. If uncertainty exists along more than one dimension, and the decisionmaker does not have information about the joint distribution of all the relevant random variables, then we have little reason to believe that a "rational" decision is possible or that a well-defined "optimal" investment or adoption strategy will be found.

The Dimensions of Uncertainty

Why is it so difficult to foresee the impact of even technologically practicable inventions? Much of the relevant literature emphasizes the huge uncertainty associated with the question: "Will it work?" This is clearly a major source of uncertainty, but the fixation upon workability has served to distract attention from several other, more subtle and overlapping sources. We turn now to a consideration of these sources.

Ex Ante Uncertainty about Improvements and Uses

It is not only that new technologies come into the world in a very primitive condition; they often do so with properties and characteristics whose usefulness cannot be immediately appreciated. It is inherently difficult to identify uses for new technologies. The laser (Light Amplification by Stimulated Emission of Radiation) represents, at one level, simply a light beam formed by the excitation of atoms at high energy levels. It has turned out that laser action can occur with a wide range of materials, including gases, liquids, and solids. The uses to which this capability has been put have been growing for 30 years, as suggested earlier, and will doubtless continue to grow for a long time, just as it took many decades to explore the uses to which electricity could be put after Faraday discovered the principles of electromagnetic induction in 1831.[1]

An essential aspect was that neither the laser nor electricity represented an obvious substitute for anything that already existed. Neither had a clearly defined antecedent. Rather, each technology was a newly discovered phenomenon that was the outcome of pure scientific research.[2]

In the field of medical diagnostics it has frequently happened that, after some new visualization technology has been developed, it has taken

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[1] It is recorded that a skeptical MP turned up at Faraday's laboratory shortly after his discovery of electromagnetic induction and asked him in a rather supercilious tone what it was good for. Faraday is supposed to have replied: "Sir, I do not know what it is good for. But of one thing I am quite certain: someday you will tax it."

[2] In fact, Einstein had already worked out the pure science underlying laser action in 1916, in a paper on stimulated emission. From the point of view of the history of science, it might be said that there was "nothing new" when laser technology was developed some 45 years later, although a Nobel Prize was awarded for the achievement. From the point of view of technological change and its economic and social impact, the development of the laser was of course a major event.

a long time to learn how to translate the new observational capability into clinically useful terms. This has been the case with respect to CAT scanners, magnetic resonance imaging (MRI), and most recently echocardiography. Often a great deal of time-consuming additional research has been required before it was possible to make a reliable, clinically helpful interpretation of what was already being visualized in terms of the diagnosis of a disease condition in the heart, lungs, or brain.

This is presently the case with respect to PET—positron emission tomography. PET scanners are powerful tools for providing a quantitative analysis of certain physiological functions, unlike CAT and MRI, which are valuable for anatomical observation. Thus, it has great potential for providing useful information on the effectiveness, for example, of drug therapy for the treatment of various diseases, such as brain tumors. But, quite aside from the huge cost of this technology, its clinical application in such fields as neurology, cardiology, and oncology has so far been limited by the continuing difficulties of translating observations and measurements of physiological functions into specific, meaningful clinical interpretations.

A related point can be made in the currently burgeoning field of medical innovation. The inherent complexity of the human body and, perhaps equally important, the heterogeneity of human bodies, have rendered it extremely difficult to tease out cause–effect relationships, even in the case of medications that have been widely used for long periods of time. Aspirin (acetylsalicylic acid), probably the world's most widely used drug, has been in use for very nearly a century, but only in the last couple of years has its efficacy been established for reducing the incidence of heart attacks as a consequence of its blood-thinning properties.

Although the discovery of negative side effects has received far more public attention, the discovery of unexpected beneficial new uses for old pharmaceutical products is a common, and often serendipitous, experience. Another significant case in point has been the applications of andrenergic beta-blocking drugs, one of the more significant medical innovations of our time. These compounds were originally introduced for the treatment of two cardiovascular indications, arrythmias and angina pectoris. Today they are used in the treatment of more than 20 diverse conditions, largely as a result of new uses that were uncovered after they had been introduced into cardiology. These include such noncardiac indications as gastrointestinal bleeding, hypertension, and alcoholism (Gelijns 1991, pp. 121 and 269). Similar experiences could be related with respect to AZT (currently employed in the treatment of AIDS patients), oral contraceptives, RU-486, streptokinase, alpha interferon, and Prozac. More generally, the widespread "off-label" uses of many drugs provide a good indication of the pervasiveness of ex ante uncertainty in medical innovation.

The Need for Complementary Technologies

Second, the impact of an innovation depends not only on improvements of the invention, but also upon improvements that take place in complementary inventions. For the lawyers at Bell Labs to have had some appreciation of the laser's importance for telephone communication, they would have required some sense of fiber optic technology and the ways in which the two—lasers and fiber optics—might be combined. The laser was of no particular use in telephone transmission without the availability of fiber optics. Telephone transmission is being transformed today by the *combined* potential of these two technologies. Optical fiber did in fact exist in its own rather primitive form in the early 1960s, when the first lasers were developed, but not in a form that could accommodate the requirements of telephone transmission. In fact, it is interesting to note that an excellent book on the telecommunications industry, published as recently as 1981, provides no discussion whatsoever of this new fiber optic technology (Brock 1982). As is often the case, it took a number of years for some of the attractive properties of fiber optics technology to become apparent: the lack of electromagnetic interference, the conservation of heat and electricity, and the enormous expansion in bandwidth that fiber optics can provide—the last feature a consequence of the fact that the light spectrum is approximately 1,000 times wider than the radio spectrum.

The general point is that the impact of invention A will often depend upon invention B, and invention B may not yet exist. But perhaps a more useful formulation is to say that inventions will often give rise to a search for complementary inventions. An important impact of invention A is to increase the demand for invention B. The declining price of electricity, after the introduction of the dynamo in the early 1880s, stimulated the search for technologies that could exploit this unique form of energy. But the time frame over which such complementary innovations could be developed turned out to vary considerably. The search gave rise almost instantly to a burgeoning electrochemical industry, employing electrolytic techniques (aluminum), but a much longer period of time was required before the development of the complementary electric motor that was to become ubiquitous in the twentieth century.

Similarly, a main reason for the modest future prospects that were being predicted for the computer in the late 1940s was that transistors had not yet been incorporated into the computers of the day. The introductions of the transistor, and later integrated circuits, into computers were, of course, momentous events that transformed the computer industry. Indeed, in one of the most remarkable technological achievements of the twentieth century, the integrated circuit eventually *became* a computer with the advent of the microprocessor in 1970. The world would be a far different place today if computers were still made using vacuum tubes.

The need to develop complementary technologies may have had a great deal to do in the last couple of decades with the apparent failure of computer technology to raise the level of productivity growth in the United States above its recent rather dismal levels. Robert Solow has made the observation that we see computers everywhere today except in the productivity statistics. But it appears to be typical of truly major innovations that they take a long time to absorb. The historical experience with respect to the introduction of electricity offers many earlier parallels. If we date the beginning of the electric age in the early 1880s (dynamos), it was fully 40 years—into the 1920s—before the electrification of factories began to show up in terms of significant measured productivity growth (Du Boff 1967; Devine 1983; Schurr 1990).

Major new technological regimes take many years before they replace an established technology. Partly the delay is due to having to develop numerous components of a larger technological system, an issue that will be addressed shortly. Restructuring a factory around an electric power source, in place of the earlier steam engine or water power, commonly required a complete redesign and restructuring of a factory facility. It represented, among other things, a revolution in the principles of factory organization. The layout of the machinery in the factory now had far more flexibility than it did with the old power sources. Learning how best to exploit a new, highly versatile power source with entirely different methods of power transmission inside the plant involved decades of experimentation and learning. Indeed, such technological innovations commonly require significant organizational changes as well. (The glacial pace at which organizational changes often take place may have a great deal to do with Solow's complaint about the failure of computers to be reflected in the productivity statistics.)

Moreover, firms that had huge investments in manufacturing plants, with long productive lives still ahead of them, naturally were reluctant to discard a facility that was still perfectly usable. As a result, if we ask who the early adopters of electricity were in the first 20 years of the twentieth century, it turns out that they were mainly new industries that were setting up production facilities for the first time; that is, producers of "tobacco, fabricated metals, transportation equipment and electrical machinery itself." In the older, established industries, the introduction of electric power had to await the "physical depreciation of durable factory structures," and the "obsolescence of older-vintage industrial plants sited in urban core areas" (David 1990, p. 357).

The general point is that a radical new technology such as a computer must necessarily have a very long gestation period before its characteristics and opportunities are well understood and can be thoroughly exploited. In 1910 only 25 percent of U.S. factories used electric power. But 20 years later the figure had risen to 75 percent. History suggests that we should not be terribly surprised. Yet if we date the beginning of the modern computer—a much more complex general purpose technology than electricity—from the invention of the microprocessor in 1970, we are still only a quarter century into the computer age. It took some 40 years or so before electric power came to play a dominating role in manufacturing. History strongly suggests that technological revolutions are never completed overnight. If this is correct, it should be a source of optimism. The great economic benefits of the computer may still lie before us!

Innovations as Components of a Technological System

As a closely connected point, major technological innovations often constitute entirely new technological systems. But it is difficult in the extreme to conceptualize an entirely new system. Thus, thinking about new technologies is likely to be severely handicapped by the tendency to view them in terms of the old technologies that they eventually replace. Time and again, contemporaries of a new technology are found to have thought about it as a mere supplement that would offset certain inherent limitations of an existing technology. In the 1830s and 1840s, railroads were thought of merely as feeders into the existing canal system, to be constructed in places where the terrain had rendered canals inherently impractical (Fogel 1964). This is precisely the same difficulty that later was encountered by the radio. Similarly, the telephone was originally conceptualized as primarily a business instrument, like the telegraph, to be used to exchange very specific messages, such as the terms of a prospective contractual agreement. This may of course explain why Bell's telephone patent was, as mentioned earlier, titled "Improvements in Telegraphy."

It is characteristic of a system that performance improvements in one part are of only limited significance without simultaneous improvements in other parts. In this sense, technological systems may be thought of as comprising clusters of complementary inventions. Improvements in power generation can have only a limited impact on the delivered cost of electricity until improvements are made in the transmission network and the cost of transporting electricity over long distances. This need for further innovation in complementary activities is an important reason why even apparently spectacular breakthroughs usually have only a slowly rising productivity curve flowing from them. Within technological systems, therefore, major improvements in productivity seldom flow from single technological innovations, however significant they may appear to be. At the same time, the *cumulative* effects of large numbers of improvements within a technological system eventually may be immense.

Unanticipated Applications

An additional and historically very important reason why it has been so difficult to foresee the uses of a new technology is that many major inventions had their origins in the attempt to solve very specific and often very narrowly defined problems. However, it is common that once a solution has been found, it turns out to have significant applications in totally unanticipated contexts. That is to say, much of the impact of new technologies is realized through intersectoral flows. Inventions have very serendipitous life histories (Rosenberg 1976a).

The steam engine, for example, was invented in the eighteenth century specifically as a device for pumping water out of flooded mines. In fact it was, for a long time, regarded exclusively as a pump. A succession of improvements later rendered it a feasible source of power for textile factories, iron mills, and an expanding array of industrial establishments. In the course of the early nineteenth century, the steam engine became a generalizable source of power and had major applications in transportation—railroads, steamships, and steamboats. In fact, before the Civil War, the main use of the steam engine in the United States was not in manufacturing but in transportation. Later in the nineteenth century the steam engine was, for a time, used to produce a new and even more generalizable source of power—electricity—which in turn satisfied innumerable final uses to which steam power itself was not directly applicable. Finally, the steam turbine displaced the steam engine in the generation of electric power, and the special features of electricity—its ease of transmission over long distances, the capacity for making power available in "fractionalized" units, and the far greater flexibility of electricity-powered equipment—sounded the eventual death knell of the steam engine itself.

Major innovations such as the steam engine, once they have been established, have the effect of inducing further innovations and investments over a wide frontier. Indeed, the ability to induce such further innovations and investments is a reasonably good definition of what constitutes a major innovation. It is a useful way of distinguishing between technological advances that are merely invested with great novelty from advances that have the potential for a major economic impact. But this also highlights the difficulties in *foreseeing* the eventual impact, since that will depend on the size and the direction of these future complementary innovations and associated investments.

The life history of the steam engine was shaped by forces that could hardly have been foreseen by British inventors who were working on ways of removing water from increasingly flooded coal mines in the eighteenth century. Nevertheless, the very existence of the steam engine, once its operating principles had been thoroughly understood, served as a powerful stimulus to other inventions.

Impacts on Other Industries

I have been stressing here that innovations often arise as solutions to highly specific problems in a particular industry, and that their subsequent interindustry flow is bound to be highly uncertain. This is because the uses of a new technology in a quite different industrial context are especially difficult to anticipate. Moreover, in some cases a new technological capability may have multiple points of impact on another industry.

Consider the impact of the computer upon the air transportation industry. I would suggest that the changing performance of commercial air transportation has been at least as much influenced by the application of the computer to new uses in this industry as by the R&D spending that has taken place within air transportation itself.

- Supercomputers now perform a good deal of fundamental aerodynamic research, including much—but not all—of the research that was formerly performed in wind tunnels.
- Computers have been a major source of cost reduction in the design of specific components of the aircraft, such as the wing. They played an important role in the wing designs of the Boeing 747, 757, and 767, as well as the Airbus 310.
- Computers are now responsible for much of the activity that takes place in the cockpit, including of course the automatic pilot.
- Computers, together with weather satellites, which routinely determine the shifting location of high-altitude jet streams, are now widely used in determining optimal flight paths. The fuel savings for the world commercial airline industry is probably well in excess of $1 billion per year. (Note that this is yet another important case of the economic impact of a technology, the computer, depending upon a complementary technology that was only developed many years later, weather satellites.)
- Computers and computer networks are at the heart of the present worldwide ticketing and seating reservation system.
- Computer simulation is now the preferred method of instruction in teaching neophytes how to fly.
- The computer, together with radar, has become absolutely central to the operation of the air traffic control system, which would be difficult to conceive without it.

One important implication of this discussion is that R&D spending tends to be highly concentrated in a small number of industries. However, each of these few industries needs to be regarded as a locus of research activity that generates new technologies that may be widely diffused throughout the entire economy. Historically, a small number of industries have played this role in especially crucial ways: steam engines, electricity, machine tools, computers, transistors, and so on. This reinforces the earlier suggestion that we may even *define* a major—or breakthrough—innovation as one that establishes a new framework for the working out of incremental innovations. In this sense, incremental innovations are the natural complements of breakthrough innovations. Breakthrough innovations, in turn, have often provided the basis for the emergence of entirely new industries.

The Identification of Needs

The final constraint is rather less precise than the rest but, I believe, it is no less important. That is, the ultimate impact of some new technological capability is not just a matter of technical feasibility or improved technical performance; rather, it is a matter of identifying certain specific categories of human needs and catering to them in novel or cost-effective ways. New technologies need to pass an economic test, not just a technological one. Thus, the Concorde is a spectacular success in terms of flight performance, but it has proved to be a financial disaster, costing British and French taxpayers the equivalent of several billions of dollars.

Ultimately, what is often needed is not just technical expertise but the exercise of imagination. Understanding the technical basis for wireless communication, which Marconi did, was a very different matter from anticipating how the device might be used to enlarge the human experience. Marconi had no sense of this. On the other hand, an uneducated Russian immigrant, David Sarnoff, had a lively vision of how the new technology might be used to transmit news, music, and other forms of entertainment and information into every household (and eventually automobile) in the country. Sarnoff, in brief, appreciated the commercial possibilities of the new technology. Sarnoff's vision eventually prevailed, under his leadership of RCA after the First World War (Bilby 1985).

Similarly, Howard Aiken, a Harvard physics instructor who was a great pioneer in the early development of the computer, continued to think of it in the narrow context in which its early development took place—that is, purely as a device for solving esoteric scientific problems. As late as 1956 he stated: "if it should ever turn out that the basic logics of a machine designed for the numerical solution of differential equations coincide with the logics of a machine intended to make bills for a department store, I would regard this as the most amazing coincidence that I have ever encountered" (Ceruzzi 1987, p. 197). That is, of course, precisely how it turned out, but it was hardly a coincidence. A technology originally invented for one specific purpose—the numerical solution of large sets of differential equations—could readily be redesigned to solve problems in entirely different contexts, such as department store billing procedures. But it obviously was not obvious!

The essential point, of course, is that social change or economic impact is not something that can be extrapolated out of a piece of hardware. New technologies, rather, need to be conceived of as building blocks. Their eventual impact will depend on what is subsequently designed and constructed with them. New technologies are unrealized potentials that may take a very large number of eventual shapes. What shapes they actually take will depend on the ability to visualize how they might be employed *in new contexts*. Sony's development of the Walkman is a brilliant example of how an existing technological capability, involving batteries, magnetic tapes, and earphones, could be recombined to create an entirely new product that could provide entertainment in contexts where it previously could not be delivered—where, indeed, no one had even *thought* of delivering it—for example, to walkers or even joggers. To be sure, the product required a great deal of engineering redesign of existing components, but the real breakthrough was the identification, by Akio Morita, of a market opportunity that previously had not been identified.

Although many Americans continue to believe that the VCR was an American invention, that is simply an unsupportable perception. The American pioneers in this field, RCA and Ampex, gave up long before a truly usable product had been developed. Matsushita and Sony, on the other hand, made thousands of small improvements in design and manufacturing after the American firms had essentially left the field. These developments were closely connected to another point. A crucial step forward in the development of the VCR was the realization that a potential mass market existed in households if certain performance characteristics, especially the product's storage capacity, could be sufficiently expanded. Although the initial American conception of the VCR had been of a capital good to be used by television stations, some American as well as Japanese developers were aware of the much larger home market possibilities. The crucial difference seems to have been the Japanese confidence, based upon their own manufacturing experience, that they could achieve the necessary cost reductions and performance improvements. The rapid transformation of the VCR into one of Japan's largest export products was therefore an achievement of both imagination and justified confidence in their engineering capabilities (Rosenbloom and Cusumano 1987).

The limited view once held by Americans of the potential for the VCR bears some parallels with the disdain of the mainframe computer makers toward the personal computer as it began to emerge about 15 years ago. It was then fashionable to dismiss the PC as a mere "hacker's toy," with no real prospects in the business world and therefore no serious threat to the economic future of mainframes (*The New York Times* 1994).

Reviving Old Technologies, or Killing Them Off?

My analysis has focused upon barriers to the exploitation of new technologies. But in highly competitive societies with strong incentives to innovation, those incentives apply to improving old technologies as well as to inventing new ones. In fact, innovations often appear to induce vigorous and imaginative responses on the part of firms that find themselves confronted with close substitutes for their traditional products. It is not at all uncommon to find that the competitive pressure resulting from a new technology leads to an accelerated improvement in the old technology. Some of the greatest improvements in wooden sailing ships took place between 1850 and 1880, just after the introduction of the iron hull steamship and the compound steam engines that were to displace sailing ships by the beginning of the twentieth century. These innovations included drastic improvements in hull design that allowed greater speed, more cargo in proportion to the tonnage of the ship and, above all, the introduction of labor-saving machinery that reduced crew requirements by no less than two-thirds. Similarly, the greatest improvements in gas lamps used for interior lighting occurred shortly *after* the introduction of the incandescent electric light bulb (Rosenberg 1976b). More recently, soon after the introduction of coronary angioplasty, a potential substitute for coronary bypass surgery, substantial improvements were made in the "old" surgical procedure. In each case, of course, the timing may have been coincidental.

A major feature of the postwar telecommunications industry is that research has increased the capabilities of the already installed transmission system, in addition to leading to the development of new and more productive technologies. Every major transmission system—a pair of wires, coaxial cables, microwaves, satellites, fiber optics—has been subject to extensive later improvements in message-carrying capabilities, often with only relatively minor modification of the existing transmission technology. In some cases, order-of-magnitude increases have occurred in the message-carrying capability of an existing channel, such as a 3/8th inch coaxial cable, and such productivity improvements have frequently led to the postponement of the introduction of new generations of transmission technologies. For example, time-division multiplexing allowed an existing pair of wires to carry 24 voice channels or more, rather than the single channel that it originally carried. The same pattern is observed in fiber optics technology. When AT&T began field trials with fiber optics in the mid 1970s, information was transmitted at 45 megabytes per second. By the early 1990s, the standard for new fiber cables had reached 565 megabytes per second, with reliable sources predicting capacities of nearly 1,000 megabytes per second in the near future.

But it is not only the case that the introduction of new technologies often has to await the availability of complementary technologies and that, in the meantime, established technologies may achieve renewed competitive vigor through continual improvements. New technologies may also turn out to be substitutes rather than complements for existing ones, thus drastically shortening the life expectancy of technologies that once seemed to warrant distinctly bullish expectations. The future prospects for communication satellites declined quite unexpectedly during the 1980s with the introduction of fiber optics and the huge and reliable expansion of channel capacity that they brought with them. In turn, fiber optics, whose first significant application was in medical diagnostics in the early 1960s, may now be approaching the beginning of the end of its useful life. Fiber optic endoscopes had made possible a huge improvement in minimally invasive techniques for visualizing the gastrointestinal tract. Recently, new sensors from the realm of electronics, charged couple devices (CCDs), have begun to provide images with a resolution and degree of detail that could not possibly be provided by fiber optic devices. The CT scanner, certainly one of the great diagnostic breakthroughs of the twentieth century, is giving way to an even more powerful diagnostic capability—MRI. Uncertainties of this sort impart a large element of risk to long-term investments in expensive new technologies. The competitive process that eventually resolves these uncertainties is not the traditional textbook competition among producers of a homogeneous product, each seeking to deliver the same product to market at a lower cost. Rather, it is a competition among different technologies, a process that Schumpeter appropriately described as "creative destruction." Thus, it is no paradox to say that one of the greatest uncertainties confronting new technologies is the invention of yet newer ones.

The simultaneous advance in new technology, along with the substantial upgrading of old technology, underlines the pervasive uncertainty confronting industrial decisionmakers in a world of rapid technological change. One would have to be very optimistic, as well as naive, to think that some intellectual paradigm can be developed to handle all the relevant variables in some neat and systematic way. But it may be plausible to believe that a more rigorous analysis of the issues raised here may lead to considerable improvement in the way we think about the innovation process.

We can now return to the initial point: The lack of knowledge about the relationships between these different dimensions of uncertainty precludes us from understanding the total effect of uncertainty upon technological change. For example, two dimensions of uncertainty, discussed above, concern the refinement of complementary technologies and the potential for any technology to form the core of a new technological system. Even at the simplest level, it is difficult to be precise about the interaction between these different effects. The existence and refinement of complementary technologies may exercise a coercive and conservative effect, forcing the novel technology to be placed inside the current "system." Alternatively, however, complementary technologies may be exactly what is necessary for the practical realization of an entirely new system. My point is not to decide one way or the other on these issues; instead, it is to argue that a research program that neglects these interactions may be missing a very large part of how uncertainty has shaped the rate and direction of technological change and, by extension, the historical growth experience.

Concluding Observations

It is not part of my warrant to offer any policy recommendations. However, a few closing observations may be in order. The research community is currently being exhorted with increasing force to unfurl the flag of "relevance" to social and economic needs. The burden of much that has been said here is that frequently we simply do not *know* what new findings may turn out to be relevant, or to what particular *realm* of human activity that relevance may eventually apply. Indeed, I have been staking the broad claim that a pervasive uncertainty characterizes not only basic research, where it is generally acknowledged, but the realm of product design and new product development as well—the D of R&D. Consequently, early precommitment to any specific, large-scale technology project, as opposed to a more limited, sequential decision-making approach, is likely to be hazardous—that is, wasteful. Evidence for this assertion abounds in such government-sponsored projects as weapons procurement, the space program, research on the development of an artificial heart, and synthetic fuels.

The pervasiveness of uncertainty suggests that the government ordinarily should resist the temptation to play the role of a champion of any one technological alternative, such as nuclear power, or any narrowly concentrated focus of research support, such as the "War on Cancer." Rather, it would seem to make a great deal of sense to manage a deliberately diversified research portfolio, a portfolio that is likely to illuminate a range of alternatives in the event of a reordering of social or economic priorities or the unexpected failure of any single, major research thrust. Government policy ought to open many windows and provide the private sector with financial incentives to explore the technological landscape that can only be faintly discerned from those windows. Thus, my criticism of the federal government's postwar energy policy is not that it made a major commitment to nuclear power that subsequently turned out to be problem-ridden. A more appropriate criticism is aimed at the single-mindedness of the focus on nuclear power that led to a comparative neglect of many other alternatives, including not only alternative energy sources but improvements in the efficiency of energy utilization.

The situation with respect to the private sector is obviously different. Private firms may normally be expected to allocate their R&D funds in ways that they hope will turn out to be relevant. Private firms are very much aware that they confront huge uncertainties in the marketplace, and they are capable of making their own assessments and placing their "bets" accordingly. Bad bets are, of course, common, indeed so common that it is tempting to conclude that the manner in which competing firms pursue innovation is a very wasteful process. Such a characterization would be appropriate were it not for a single point: uncertainty. In fact, a considerable virtue of the marketplace is that, in the face of huge ex ante uncertainties concerning the uses of new technological capabilities, it encourages exploration along a wide variety of alternative paths. This is especially desirable in the early stages, when uncertainties are particularly high and when individuals with differences of opinion (often based upon differences in access to information) need to be encouraged to pursue their own hunches or intuitions. Indeed, it is important that this point be stated more affirmatively: The achievement of technological progress, in the face of numerous uncertainties, *requires* such ex ante differences of opinion.

Finally, a further considerable virtue of the marketplace is that it also provides strong incentives to terminate, quickly and unsentimentally, directions of research whose once rosy prospects have been unexpectedly dimmed by the availability of new data, by some change in the economic environment, or by a restructuring of social or political priorities. For a country that currently supports more than 700 federal laboratories with a total annual budget of over $23 billion, more than half of which is devoted to weapons development or other defense-related purposes, that is no small virtue.

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DISCUSSION

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Anyone can have fun collecting technological predictions that did not materialize. Time and again, learned scientists and skilled engineers have been caught predicting with Lord Kelvin that most things that can be invented already have been and that diminishing returns to innovation have set in. Inventions that we know now to have been of momentous importance were more often than not thought to be minor curiosa.[1] Nathan Rosenberg, in his stimulating and entertaining paper, thinks that in part it is a "failure of social imagination" that accounts for these erroneous predictions. I am not sure what a social imagination is, but clearly some writers, from Roger Bacon to Jules Verne to more contemporary science fiction writers, did not suffer from a lack of imagination. It is just that the worlds they imagined and the worlds that eventually materialized subsequently overlap very little.

If there is one technology that preoccupies and fascinates our current world, it must be decentralized information and communication. *That* was not what most people who imagined at all half a century ago foresaw. They believed that by this time space travel would be common—it is not. Many of them feared total control by a central government that had access to incredible technologies allowing them to manipulate people beyond anyone's wildest nightmares. Such totalitarianism has not come about. Kurt Vonnegut's nightmarish world in *Player Piano,* in which labor-saving technological change has made labor redundant, has not

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[1] One of the more entertaining examples was *The New York Times* prediction in 1939 that "Television will never be a serious competitor for radio, because people must sit and keep their eyes glued on a screen; the average American family hasn't time for it." Cited in *The Economist,* July 5th, 1996, p. 15.

arrived. In fact, we seem to be working harder than ever before, if Juliet Schor is to be believed. It is not, I submit, lack of imagination, but the simple fact that imagination had it mostly wrong. We are today the future of the 1950s, but—with some exceptions—we are not what futurologists of that time thought we were going to be. The Talmud had it right when it sighed that "since our second temple was destroyed, the art of prophesy was given to the fools."

Rosenberg distinguishes in his paper between "uncertainty" and "ignorance." Decision-makers do not have access to an even marginally informative probability distribution, he says, so ignorance is perhaps a more suitable concept than uncertainty. The uncertainty of technological change is one that society cannot hedge against and cannot diversify away (although, of course, individual firms engaged in R&D can). The question is why technological change is so difficult to predict and so difficult to understand, and Rosenberg gives some very good answers. My own answers may seem on the surface different from his, but at second glance will turn out to be more or less a reformulation rather than an alternative.

To start off, technological change involves two levels of uncertainty. One is the firm's *micro*problem: Will a particular line of research pay off? That question can be decomposed into a whole host of subquestions that compound each other: Can this technical problem be solved at all? Can *we* solve it? Can we do so before anyone else does? Will it sell, and at what price? The other level is the economy's *macro*problem: What kind of technological *regime* will emerge as dominant? Will it be using digital or analog computers? Western antibiotics or Chinese herbal treatments? Fixed-wing aircraft or dirigibles? Nuclear or fossil fuels? Boiled potatoes or oatmeal porridge? This is the kind of uncertainty that historians have to deal with when they wish to explain why a society's production techniques developed in one direction but not another, but it is also hugely relevant for decision-makers at the micro level.

Mutation and Natural Selection

The lack of predictability is not the curse of the economics of technological change alone. Evolutionary biology, too, is incapable of making accurate predictions.[2] Instead, biologists depend largely on the paleontologists and their fossil bones to tell them about the facts of evolution. No biologist has ever witnessed a speciation event. We know that speciation occurred, of course, from our past record, but speciation cannot be predicted, or even recognized when we see it. The concept only makes sense in view of the past. The reason why biologists cannot predict

[2] For more details on this analogy, see Mokyr (1991 and 1996).

is fairly obvious: Mutations occur at random. The raw materials from which natural selection has to choose have no systematic component. Direction is imparted to the system exclusively by the selection process, an ex post mechanism. Moreover, the selection mechanism picks new life forms by well-defined criteria, yet we rarely understand these criteria sufficiently beyond saying that they increase fitness, a rather circular argument.

Indeed, it is now well understood that many seemingly favorable mutations will disappear, for a variety of reasons. To be picked, a mutation may have to increase fitness, but the reverse clearly does *not* hold. In any case, we are a long shot away from making conditional predictions on what *will* happen. This does not mean we know nothing at all: We can make negative conditional predictions such as "If an insect weighing 300 pounds emerges by some implausible mutation, it will not survive." But narrowing the bands of the possible does not amount to prediction. The uncertainty thus comes in twice: We do not know what the supply of innovations will look like, nor do we know with certainty which ones will be picked for retention.

What does all this have to do with technological change? Social and cultural processes have increasingly been thought of in evolutionary terms (Campbell 1960; Cavalli-Sforza 1986). That is not to say that they resemble in all their details the mechanism we now think of as the neo-Darwinian orthodoxy in evolutionary biology. In the living world, because mutations occur as a result of random processes and are orthogonal to the "needs" of the organism, they are far more than likely to be either detrimental or neutral. Only in the rarest of cases will a mutation turn out to increase fitness. In other evolutionary processes, that is not necessarily so. Moreover, in biological evolution, parentage is either single- or biparental. In cultural and social processes, the analog of genomes can be acquired from many sources. Acquired characteristics are retained and passed on to other generations. And so on—the differences are quite substantial. All the same, many of us find it useful to think of technological change as an evolutionary process. Innovations occur and are passed through selective filters. Whether natural or not, the idea of *selection*, in one philosopher's catchy phrase, "Darwin's dangerous idea," is often thought to be central in explaining why things are what they are (Dennett 1995).

While cultural evolution (of which technological evolution is a special case) thus differs from what Darwinian dogma holds for biology, the idea of directed selection imposed upon an exogenous and stochastic supply of innovations seems to be a powerful notion. Predictability depends on the correlation between need and mutation. Rosenberg implies that while such a correlation may not be zero, it is not very high either. "Necessity" is neither a sufficient nor a necessary condition for an innovation to emerge. Needs remain unsatisfied despite frantic scrambling for a technological fix; at other times, as in the case of the Walkman cited by Rosenberg, the need may have emerged after the invention became feasible or turned out to be quite different than originally intended. What he is looking at is something that biologists have called "exaptation" following a term proposed by Gould and Vrba (1982): A trait may arise resulting from one set of selective pressures and then end up being used in an entirely different capacity.

Predicting the supply of innovation is thus an extremely risky venture. To make things worse, as noted, the selective filters are only very imperfectly understood. Why do some inventions succeed and others fail? It would be nice if we had a one-to-one mapping of "fitness" defined in some way (say, firm profitability) to the adoption of inventions. But we know better: Complementarities, frequency dependency, the fortuitous presence or absence of a crucial factor, the energy and single-mindedness of one individual (as in the case of Admiral Hyman Rickover and the heavy-water nuclear reactor), and other factors mean that contingency and luck will continue to play a role. Seventy percent of all new products that get through the first layer of filters and actually make it to the supermarket shelves disappear again in their first 12 months. If prediction were easy, such errors would not occur.

In short, then, two sources of uncertainty compound each other in technological history: one concerns which novelties emerged at all, the other which novelties that somehow emerged made it to the marketplace and survived. To repeat, this does not mean that we are *totally* ignorant, but that by and large the techniques that we end up using were not inevitable. Many artifacts and techniques actually in use are no more inexorable than the peacock or the platypus. Technological history, very much like natural history, is ridden by what we may call *bounded contingency*. The history of science is similarly the result of blind variation and selective retention, as a long series of distinguished historians of science from Donald Campbell to David Hull have been arguing. Some scientific advances are of course obvious, given what precedes them. The more we learn about how science developed, however, the more we start to understand how Kuhn's great paradigms often evolved as the result of political power plays and a directionality imparted upon science by the ways scientists made a living, not their internal logic. Science, in short, is no more predictable than technology.

The third leg of our triad of evolutionary processes is the changes in economic institutions. Douglass North, the guru of institutional analysis, has long called upon us to propose an evolutionary theory of institutions (North 1990). None has emerged so far. Perhaps this is because, unlike other cultural systems such as science and language, the intuition of what an innovation is, is less clearly defined. To be sure, institutional innovations, such as the emergence of modern stock markets, indentured servitude, or fee simple, have occurred, but institutional change seems to be less about innovation and selection than about adaptation and the emergence of certain conventions and coalitions that have a vague interpretation of Nash equilibria. All the same, it is fair to say that whatever process one envisages here, it would be foolhardy to construct models that predict what institutions are going to emerge in the future. Even if we could somehow specify the "demand" side, we do not always get the institutions we need and surely do not always need the institutions we have. Here too, history dictates what we can and cannot do. Present institutions are a Markov chain: the sum of all past changes plus an epsilon. Of course, sudden innovation is possible, and societies at times overthrow their institutional structure and pick another—but their choice is usually limited to what others have done before. Only a few times in history did a few societies have a true revolution (in that they set up a new set of institutions not previously tried by anyone else), usually with disastrous results.

The Coevolution of Technology, Science, and Institutions

Now that we have depicted history as these three evolutionary and unpredictable processes moving side by side, we can add another layer to Rosenberg's questions about predictability. The point is that technology, science, and institutions do not only evolve, they *co*-evolve. The path that technology can take is not only conditioned by its own past, its luck, and its selection mechanism, it is also conditioned by the unpredictable path of science and institutions. What is more, its evolution feeds back into the evolution of the other two. Such feedback could be positive, negative, or a mixture of the two. Many volumes have been written about how science and technology interact, and Rosenberg's ideas imply that even if the course of technology were entirely deterministic, we still could not predict its future. The same is true for institutions. Some institutions are conducive to technological change, such as choice in education, free labor markets, well-enforced property rights, intellectual tolerance, and political pluralism. Others are clearly detrimental, such as uncertain property rights, strong conservative labor unions, totalitarian government, and excessive conformism and deference to the achievements of past generations. Most have ambiguous effects, such as patent systems, religion, and democratic government. What is certain is that technology depends for its development on what is happening to institutions. If we cannot predict the one, we cannot predict the other.

One example of the coevolution of institutions and technology is especially relevant. I have repeatedly maintained that the success of technological progress depended not only on the marketplace and complementarities but also on the continuous struggle between those who want technological change and those who, for one reason or another, do not (Mokyr 1994). Inventions often encounter resistance, either from entrenched interests who stand to lose from the new technique or think they will, or from groups and individuals who, for one reason or another, do not approve of the invention. This is a source of uncertainty that Rosenberg does not mention, but not one to be glossed over. From the hapless Roman glassmaker who, according to Tacitus, claimed to have invented unbreakable glass and was assassinated for his troubles by the evil Emperor Tiberius, to a modern bioengineering company that has to cope with the likes of Jeremy Rifkin, animal rights advocates, and greedy lawyers anxious to skim off rents through product liability suits, innovators have had to deal with Luddites in all forms and shapes.

In addition, then, to the normal questions an inventor asks himself such as "Will it work?" and "Will I be the first one?" are the questions "What will my neighbors say?"and "Will the FDA approve it?" and "Could somebody sue me for product liability?" In some cases, such as the French inventor of the sewing machine, Barthélemy Thimonnier, and the English inventor of the flying shuttle, John Kay, the neighbors were unhappy to the point of burning down their workshops and forcing them into flight. Precisely because such resistance always takes the form of non-market mechanisms, the evolution of institutions friendly to new technology is crucial. It is this coevolution that is responsible for the relatively short duration of periods of rapid technological development. While technological and institutional development often aid and abet each other, leading to rapid technological change, institutions soon change and bring the process to a halt.

Rosenberg's policy recommendation, which is a call to "Let a hundred flowers bloom," seems to me very much in the traditions of evolutionary thinking, even if he does not acknowledge this: The process of innovation, he concludes wistfully, is inevitably inefficient and wasteful because of uncertainty. Yet this seems to me to miss the point that all evolutionary creativity is by necessity incredibly wasteful: Think of all the millions of mutations that go to waste before one is fixed. Think of the species that have gone extinct over the past 600 millions of years of multicellular life. In technological change, we may not even want to call this "wasteful" since the process itself cannot be made efficient. If it were, it would lose much or all of its creativity. Uncertainty is neither the *cause* of this inefficiency nor its *effect*. Rather, both are the results of the evolutionary dynamic at work here.

This coevolutionary dynamic is especially important if we are to understand the following sentences of Rosenberg's: "The existence and refinement of complementary technologies may exercise a coercive and conservative effect, forcing the novel technology to be placed inside the current 'system.' Alternatively, however, complementary technologies may be exactly what is necessary for the practical realization of an entirely new system." This seems to link in neatly with the current thinking on the dynamic behavior of evolutionary systems that are at the edge of chaos, to use Murray Gell-Mann's phrase (1994). They are neither in the purely conservative area in which all change is immediately absorbed in the existing system and any innovation is immediately frozen and absorbed in local equilibria, nor in the chaotic region in which minor change immediately causes a total disruption of everything and in which nothing ever returns to a predictable state. Instead, in this region of self-organizing complexity exist a finite number of equilibria in which the system can settle down, and while we cannot predict which one will be chosen, the choice is not totally random.

This is the kind of behavior that "new evolutionists" like Stuart Kauffman (1995) are trying to bring to bear on evolution. Economic history should take notice. Technological change may be one of these "supracritical" processes in history. For thousands of years, technological change occurred in a variety of societies, always to run out of steam and see the economy revert back to a steady state. The Industrial Revolution meant that all of a sudden technological change became the norm rather than the exception. At that stage, as Kauffman puts it, technology moved into the supracritical region, and "all bets are off." This is a pithy way of summarizing Rosenberg's main point.

OPTIMALITY AND ADAPTATION

Finally, a debate among evolutionary biologists is highly relevant to Rosenberg's paper here, because it is mirrored in debates among social scientists interested in technological change. This is the debate between adaptationists and anti-adaptationists. The former basically maintain that evolution gets it right and that every trait that survives the harsh filters of natural selection has a purpose and a function. This is not quite equivalent to the "Panglossian" view that everything evolves into an optimum optimorum, but it does mean that there are no outcomes that are obvious and persistent errors. Gould and Lewontin's classic "Spandrels of San Marco" paper (1979) was a frontal assault on the "adaptationist program," as they called it.

In economic history we have similar debates: On the one hand we have Paul David (1986), Brian Arthur (1989), and others pointing to classic cases of lock-in as a result of path dependence, coordination failures, and externalities; on the other hand we have the standard neoclassical approach that maintains that if you observe a highly inefficient outcome such as the Qwerty keyboard you have not looked hard enough or you are overestimating the degree of inefficiency, as Liebowitz and Margolis (1990) have argued. The neoclassical view would not rule out contingency altogether, but it would confine it to more or less equivalent outcomes and deny that in the long run, chance and history could lead to persistent inefficient outcomes. If the internal combustion engine beat out electrical and steam cars, this view suggests, it is because it simply was better.

Rather than take a position on this debate—and Rosenberg must speak for himself—I think it is important to emphasize how and why technology here differs from living beings. A species that finds itself in drastically less favorable circumstances has to adapt in some way or it is likely to go extinct. It can adjust only if some members of the species have the genetic information that contains the raw materials necessary to adapt. If this is not the case, extinction is likely. In technological choice, adaptation is less constrained, since societies can adopt a completely different technology wholesale—at a cost. These costs are both private and social, involving at times quite radical adaptation. Think of societies that after millennia of use have to abandon the camel and the oxen and get used to the jeep and the tractor. What is interesting in this context is to investigate whether the private capturable benefits are sufficient to cover the costs. Without that, there may be another role for the government, but it is unclear whether the political environment will produce this correction. That, too, is a source of uncertainty.

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Discussion

Luc L.G. Soete*

As one has come to expect when reading Nathan Rosenberg's papers and books, his detailed analysis of the history of new technologies provides invaluable insights into the surprising ways the inventors themselves originally thought these innovations would affect particular activities. It is as if the level of inventors' creativity were somehow inversely related to their level of imagination with respect to possible applications of their inventions. In other words, a future remains for us economists and other creative social scientists!

Through the many cases detailed in Rosenberg's paper, one gets a strong impression of the predominance of widespread uncertainty in technological change. Five dimensions of uncertainty are emphasized:

1) the inherent difficulty of identifying uses for a new technology, given the often primitive condition in which it first appears;

2) the crucial dependence on improvements through complementary inventions, often in sectors where potential users are to be found;

3) the systemic features of such complementary improvements when society is confronted with entirely new technological systems;

4) the inventor's tendency to aim new technology at a narrow problem-solving task, thereby foreclosing possible applications in other, unanticipated contexts; and

5) the need for technological novelty to pass the test of cost-effectiveness: the economic test.

The author concludes, "New technologies are unrealized potentials that may take a very large number of eventual shapes." Hence, he

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strongly argues, governments should refrain from promoting any one technological alternative (the example of nuclear energy is given) or focusing on specific research support (he cites the example of the "War on Cancer"). Rather, "government policy ought to open many windows and provide the private sector with financial incentives to explore the technological landscape that can only be faintly discerned from those windows."

I am of course impressed with the variety of cases described by the author. While Rosenberg admits in his typical understated way that the evidence presented is "anecdotal," he nevertheless claims that the anecdotes have been so selected as to include many of the most important innovations of the twentieth century. I am, with my limited knowledge, tempted to agree, but first I would like to see a more rigorous and complete description of what could be reasonably called "major" (at what time, though, and on what basis?) new technologies over the past two centuries. Could it not be that precisely because of their unanticipated impacts, one tends to focus on just those technologies that turned out to have economic and social impacts so unexpected that they aroused the interest of historians? In other words, is the anecdotal evidence indeed just "anecdotal," that is, of little general value?

Second, is there not much more to be said about some kinds of sectoral or technological uncertainty associated with research? Surely, the uncertainties in new drug research are of a different nature from the uncertainties in designing a next generation of chips. In the first case, a much larger degree of uncertainty seems to be linked to the often "trial and error" nature of the research involved; in the second case, the research often appears to be progressing along a relatively straightforward engineering trajectory—with attempts at miniaturization, say, or use of alternative materials (see, for example, Moore's Law). Would it not then be reasonable to assume that the uncertainties in the latter case are much less uncertain, and much more the type detailed by experts in the field, like Robert Howe of IBM with respect to the future intelligent assistant, the potential impact of electronic networking on banking, and the commodification of financial services?

Third, and as indicated in the introduction to this session, is there not also evidence that these uncertainties might be different over time and might even display some cyclical characteristics, depending on the particular phase of the economy? Beginning some 15 years ago, Rosenberg and I have both taken part in a long-standing discussion with a German colleague, Gerhard Mensch, about the possible "clustering" of major new technologies in periods of depression (the Mensch claim) or recovery (our claim). Again, I would argue that beyond the particular long-term aspects of that debate, it has some significant features that could shed light on the way the aggregate performance of the economy might influence technological risks and uncertainties.

Let me elaborate somewhat on this point, in light of the paper by Dale Jorgenson as well. The "productivity paradox," highlighted in Rosenberg's paper, is illustrated for the G-7 countries in Figures 1 and 2 in a very approximate way. Productivity growth fell steadily in the G-7 countries over the past 30 years to about half the level of the late 1960s. (Productivity growth is measured in Figure 1 as GDP per man-hour for the aggregate G-7 and smoothed over 11-year averages; an even more rapidly declining picture would be obtained using growth in Total Factor Productivity.) This decline in productivity growth contrasts sharply with the increase in business expenditures on research and development over the 1970s and 1980s, as illustrated in Figure 2. It also contrasts sharply with the increase in the share of total private R&D funding in most OECD countries, which has also risen steeply over the same period.

In explaining this paradox, Nathan Rosenberg, along with many others including myself, emphasizes the numerous uncertainties and difficulties involved in identifying the efficient use of a set of relatively pervasive technologies, such as information and communication technologies. And again, while I am very sympathetic to this view and the optimism it gives rise to—"You ain't seen nothin' yet: The future is still going to bring us the major benefits of these new technologies!"—alternative explanations are possible, two of which I would like to highlight here.

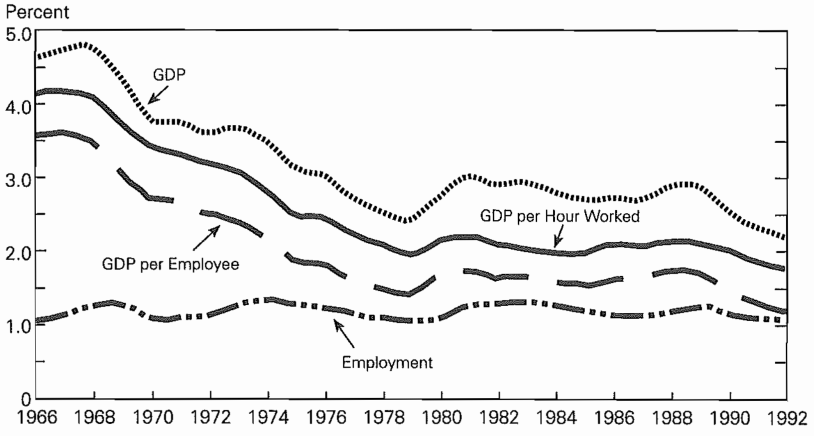
The first one focuses on aggregate measurement issues and the likelihood that, increasingly, we are mismeasuring output in a large number of information goods and services. This explanation has been raised by many authors, and I will not elaborate on it here (for more detail, see Soete 1996). I would just insist, as has Nakamura (1995), that our failure to include "consumer surplus" in real output measures is likely to have led us to greatly underestimate output growth, by much more than we may have corrected through the use of techniques like hedonic pricing. My guesstimate is that Nakamura, with his assessment of a 2 to 3 percent per year overestimation of inflation, is probably nearer the mark than the Boskin report.[1] My own back-of-the-envelope calculation for Europe would suggest that 2 to 3 percent is a reasonable estimate of the overestimation bias there as well.

The second explanation focuses on the interaction between short-term macroeconomic policies and long-term incentives for investment in research and development, possibly the core question at this conference. The crucial question is whether one unexpected side effect of the monetary policies of the 1980s, which were aimed at reducing inflation,

[1] "Toward a More Accurate Measure of the Cost of Living." Interim Report to the Senate Finance Committee from the Advisory Committee to Study the Consumer Price Index, September 15, 1995.

Figure 1

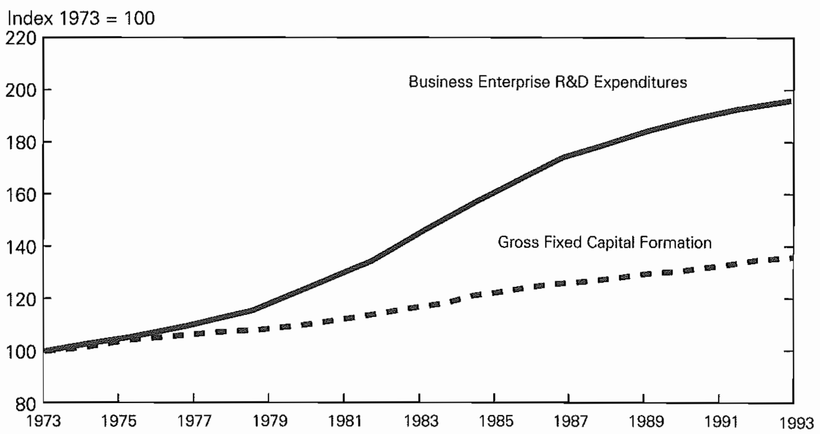
GDP, Employment, and Productivity Trend Growth in G-7 Countries[a]



[a]Smoothed trend derived using centered 11-year moving averages.
Source: OECD 1996.

Figure 2

Investment Levels in G-7 Countries[a]

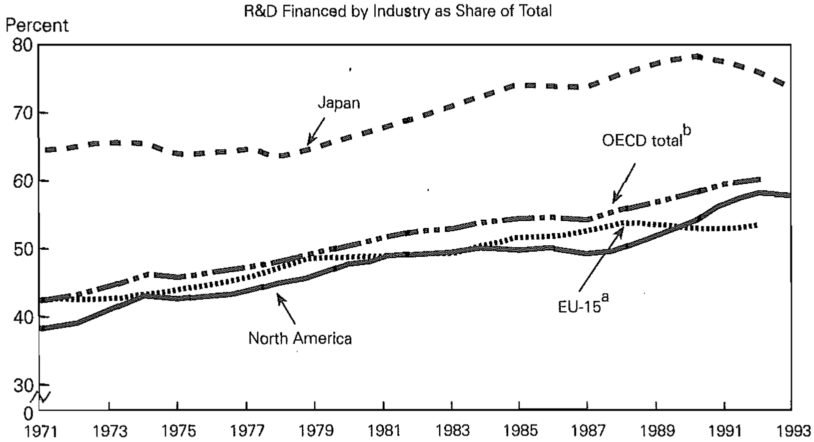


[a]11-year moving averages.
Source: OECD 1996.

Figure 3

Research Effort in the Business Sector

R&D Financed by Industry as Share of Total



[a] EU-15 excludes Greece and Luxembourg in the 1971-80 period.
[b] OECD total includes EU-15, North America, Japan, Iceland, and Norway.
Source: OECD 1996.

has been a significant shift in the nature of research and development. In the 1980s and 1990s, real long-term interest rates turned positive and became, in the postwar context, extremely high. Among other things, the rise signaled the burden on capital markets posed by excessive government deficits in some of the major OECD countries, as well as by the growing capital needs of an expanding group of newly industrializing countries. As is illustrated in Figure 3, the 1980s were also a period of "crowding-in" of private R&D investment.

My claim would be that the short-term monetary policies of the 1980s led to a focus on short-term R&D, with a much stronger emphasis on product differentiation and relatively immediate private returns. In other words, short-term monetary policies could well have resulted in a pernicious decline in long-term potential growth, as high real interest rates shifted private firms' investment incentives to research of an immediate, short-term nature at the expense of longer-term, more uncertain efforts.

High real interest rates lead to an intensified focus on the present. Hence, more long-term, risky, and uncertain activities will often be eliminated from the research portfolio. Indirect evidence for such a trend, I would claim, can be found in the business literature on R&D and innovation management. This literature describes, in quite some detail, how R&D activities in many firms gradually became "streamlined" into business units' R&D centers. Strategic, "free" R&D had to become increasingly "legitimized" and was dramatically reduced over a very short period. As has been highlighted in consultancy reports, many large firms cut their strategic independent R&D dramatically: Hoechst, for example, from 75 percent to 25 percent of total R&D.

The result has been, as emphasized by authors in the innovation management area, that the R&D manager has become much more directly controlled by business unit managers, who are more aware of the immediate pressures for results. As Arnold (1992) put it: "Being close to the customer encourages incremental development and rarely inspires breakthroughs, simply because customers tend to have an evolutionary view of their need and rarely support a visionary spark." Similarly, a recent Arthur D. Little survey of European R&D managers points to the way "R&D functions are going through a quiet revolution, driven by intensifying competition and shorter product life cycles. They are becoming more closely linked to other parts of the business; researchers are becoming more aware of business economics and the needs of consumers." As one manager put it: "We have short-term profit and loss pressures which do not allow us to focus on long-term visions."[2] This case evidence fits well the aggregate trend and the resulting shift in the nature of R&D, described above.

To conclude, let me question the relevance of some of the historical analogies in this area. Can we really say, with anything more than faith, that as it took 40 years for electricity to produce efficiency benefits, the same must be true for current information and communication technologies? Surely the world has changed a great deal, and the technologies are by and large not comparable in their impact. The price decline linked to information processing reportedly already exceeds by a full percentage point the limited price effects of electricity. As Triplett (1994) has pointed out in a critique of an historical analogy made by Paul David (1990) between the computer and the dynamo, any simple diffusion model would tell you that the rate of diffusion of computer technology should be much more rapid than that of the dynamo. In other words, as time passes, productivity growth remains low; yet we are witnessing the introduction of ever more powerful information and communication equipment all around us, while technologists, economists, bankers, and policymakers herald the benefits of these new technologies. I am becoming more and more suspicious of explanations predicting the likely benefits to come on the basis of historical analogy. The future is not what it used to be, still less what historians today believe the past was like.

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[2] See further Houlder, V. "Quiet Revolution." *Financial Times*, March 26, 1996, p. 10.

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CROSS-COUNTRY VARIATIONS IN NATIONAL ECONOMIC GROWTH RATES: THE ROLE OF "TECHNOLOGY"

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I want to praise "technology" as *the* important factor in the relative growth performance of the nation-states' economies. I want to argue that the conventional wisdom substantially understates the role of differences in total factor productivity in explaining differentials across nation-state economies in GDP per capita. "Technology" in this sense is *more* important, because of the strong endogeneity of population growth and investment rates. Rich economies are economies in which children are much more "consumption" than "investment" goods; these economies have completed their demographic transitions to a régime of low fertility and low population growth. Thus, an economy that initially finds itself with a small advantage in total factor productivity will see that advantage magnified into a larger advantage in output per capita, as it converges to a steady-state growth path with lower population growth and a higher capital-output ratio.

Similarly, a rich economy is one in which the price of capital goods is relatively low: In a rich economy, a given share of national product saved translates into a greater real investment effort than if the economy had the world's average relative price structure. This channel magnifies differences in total factor productivity into larger differences in output per capita, working through the steady-state capital-output ratio.

Researchers in economic growth have been puzzled by the apparent combination of "conditional convergence" with absolute divergence. Economies appear to be moving toward their individual steady-state

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growth paths by about 2 percent per year, yet the spread of relative output per capita levels across the world continues to increase.

A naive interpretation of this pattern would suggest that, at some time in the past, nation-states' savings and population growth rates—and thus their levels of output per capita—were closer together than they are now; that some shock drove savings and population growth rates apart; and that since then the world's distribution of relative incomes has diverged as economies have traversed toward their steady-state growth paths. But what was this shock that drove savings and population growth rates apart? The evolution of the world's cross-country distribution of income and productivity is much more understandable once one recognizes the endogeneity of factor accumulation, and the fact that relatively poor countries have low investment rates and high rates of population growth in large part *because* they are relatively poor.

But I also have a caveat: In another sense, I want to bury "technology." Robert Solow's (1957) seminal article is entitled "Technical Change and the Aggregate Production Function." Certainly since 1957, and perhaps before, economists have used "technical change" and "technology" as shorthand ways of referring to shifts in the aggregate production function. Yet much of the difference seen across nations in aggregate total factor productivity has little to do with *technology*—in the sense of knowledge of the internal combustion engine, continuous-casting, the freeze-drying process, or anything that would be recognizable in a model like that of Caballero and Jaffe (1993). *Technology* properly so-called is the ultimate source of our enormous material wealth today relative to our counterparts of a century or so ago: Economic growth over the past century in the United States is *built* on our knowledge of the internal combustion engine, continuous-casting, freeze-drying, and all of our other technologies. Yet differences across nation-states in total factor productivity seem to be related tenuously, or not at all, to *technology*.

Robert Solow may not have done us a big favor when he convinced us to call shifts in the aggregate production function "technical change"; his doing so may not have helped economists to think clear thoughts over the past 40 years.

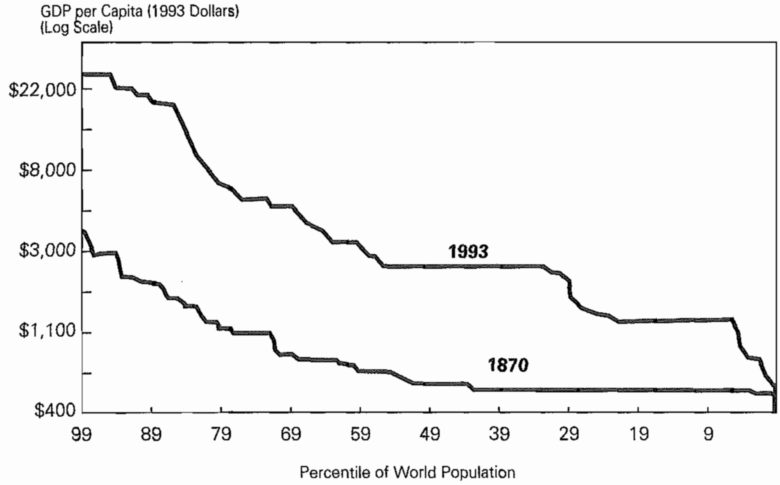
Divergence

As best we can determine from badly flawed data, the economic history of the past century and a quarter is a history not of "convergence" but of "divergence": The different countries and peoples of the world have not drawn closer together in relative living standards, but have drifted further apart.

Figure 1 shows the distribution of world real GDP per capita—by percentage of world population, not by nation-state—in 1993 and in 1870, as best as it can be estimated. The 1993 estimates of real GDP per capita

Figure 1

World Distributions of per Capita GDP, 1870 and 1993 (Purchasing Power Parity Concept)



are purchasing-power-parity estimates, measured in the "international dollar" concept that pegs U.S. GDP per capita to its current-dollar value, but attempts to use the relative price structure not of the advanced industrial economies but of the "world average" economy. They are taken from the 1995 *World Development Report*. The 1870 estimates of real GDP per capita are my own extensions and modifications of those found in Maddison's (1995) *Monitoring the World Economy*; by and large they are constructed by "backcasting" individual, nation-specific estimates of growth rates of real GDP per capita.

Thus, a very large number of caveats must be attached to Figure 1:

- Because estimates of 1870 GDP per capita are "backcast," errors in estimating 1993 GDP per capita are necessarily included in estimates of 1870 GDP per capita as well.
- The individual, nation-specific estimates of growth rates underlying the backcasting are of widely variable quality; they do not use the same methodology.
- Most of the nation-states of today's world did not exist in 1870. Estimates for 1870 cover roughly the same area that the nation-state occupies now.
- Figure 1 suppresses all variability in productivity and real GDP

per capita *inside* nation-states: Everyone in China in 1993 is assumed to have the 1993 real GDP per capita of $2,330 estimated using the purchasing-power-parity concept.

- Estimates even for 1993 are very uncertain for developing countries. This applies especially to China which, as the World Bank team politely puts it in a footnote, has a GDP per capita estimate that is "subject to more than the usual margin of error."
- The entire enterprise of computing levels of real GDP per capita using the purchasing-power-parity concept may be seriously biased; it may fail to incorporate appropriate allowances for quality differences between products produced in industrialized and in developing economies. Certainly, purchasing-power-parity estimates made in the 1980s of relative living standards east and west of the Iron Curtain appear, in retrospect, to have wildly exaggerated the levels of productivity and material wealth in the former Soviet Union's sphere of influence.[1]
- Estimates of growth in real GDP per capita between 1870 and 1993 are unlikely to incorporate adequately changes in quality and in the scope of products that are produced. The thought experiment that underlies constant-dollar, cross-time comparisons implicitly involves taking the output produced at a particular date, moving it across time to the base year, and selling it in the base year at the base year's market prices. But suppose you gave me $2,763—the estimate of U.S. GDP per capita in 1870—and told me "By the way, you can only spend this sum on products that existed in 1870 and at the quality levels that were produced then." Under these stringent restrictions on what I could purchase, I might well value that sum as worth much less than $2,763 in today's dollars.
- Figure 1—plotting approximate GDP per capita by percentile of the world's population—looks significantly different in some respects from Figure 2, which plots GDP per capita in 1870 and 1993 by percentile of the world's number of nation-states. Nation-state-based calculations show a nearly uniform distribution of log GDP per capita levels over the observed range, especially for 1993. Population-based calculations show a non-uniform distribution with a pronounced upper tail: The difference, of course, springs from the two very large populations of the nation-states China and India, which are now and were in 1870 relatively poor.

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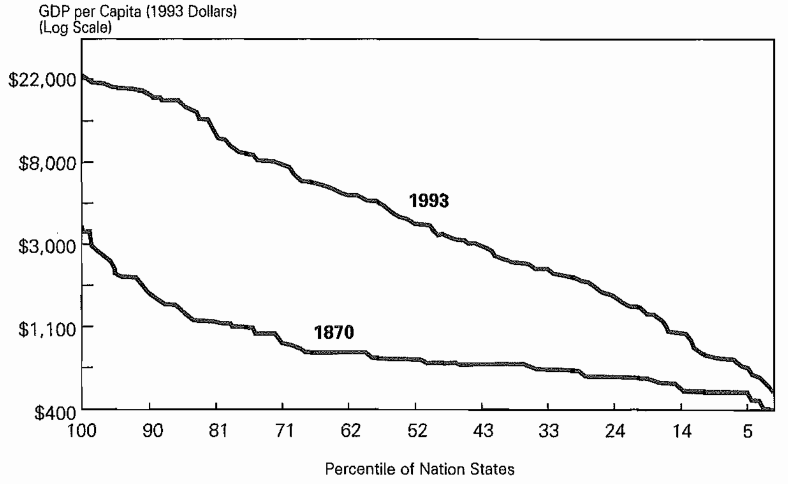
[1] Current exchange rate-based calculations of relative productivity levels and living standards show differences an order of magnitude greater than do purchasing power parity-based calculations; it may be that in some senses the exchange rate-based calculations are more informative.

Figure 2

1870 and 1993 Distributions of GDP per Capita, by Nation-State (Purchasing Power Parity Concept)



Nevertheless, Figure 1 is the best we can do at present. What are the principal lessons of Figure 1? I believe that there are three. The first is the extraordinary pace of real economic growth over the past century. The highest level of GDP per capita attained in 1993 (for the United States) was some $24,470 in 1993-level international dollars; the highest attained in 1870 (for Australia) was some $4,108 in 1993-level international dollars. Using this particular metric, the United States today is some six times as wealthy in a material-product, real-income sense as was Australia in 1870 (and some nine times as well off as was the United States in 1870).[2]

I stress that this pace of growth is not only very fast but also extraordinarily faster than in any previous century that we know of. If 1870–1993 growth were simply a continuation of pre-1870 growth trends,

[2] This pace of real economic growth would be further magnified if the argument turned out to be correct that measured growth in the GDP accounts fails to capture much of the growth in real income that takes form of improvements in the quality and variety of commodities. Such factors *might* lead standard estimates to understate "true" economic growth over the past century by a factor of two or three. See, for example, Nordhaus (1994). On the other hand, Simon Kuznets (1963) argued that the constant-dollar, current-base-year calculations of real GDP that he designed were the most appropriate ones: that we should use the yardstick of the present to assess the past.

then in 1600 the richest economy in the world would have had a real GDP per capita level of some $110 a year—far too low to support human life.[3]

The twentieth century (extended back to 1870) has seen at least a sixfold multiplication of real GDP per capita at the leading edge of the world's economies; the previous century and a quarter had seen perhaps a doubling during the period of the classical Industrial Revolution (Crafts 1985; Mokyr 1985). But before that? Perhaps the most prosperous economy of the mid eighteenth century (probably the Netherlands) held a 50-percent edge over the most prosperous economy of the mid fifteenth century (probably the city-states of northern Italy). But perhaps not.

And looking more than 500 years into the past, it is hard to see any significant advance in living standards or average productivity levels. Human populations appear to have been in a near-Malthusian equilibrium, in which population growth quickly removes the margin for any significant increase in living standards (Kremer 1993; Livi-Bacci 1992; Malthus 1798). It is not clear that a French peasant of the seventeenth century was any better off than an Athenian peasant of the fourth century B.C.

The second important lesson of Figure 1 is the extremely uneven pace of economic growth over the past century. Because the relatively poor economies of the world have not yet completed their demographic transitions to a régime of relatively low fertility, the poorest economies have had the fastest-growing populations over the past century. International migration has not proceeded at a particularly fast pace. Thus, the distribution of economic growth appears more uneven and less widely distributed in Figure 1, which plots GDP per capita by percentile of the world's population, than in Figure 2, which plots GDP per capita by nation-state.

But in both figures, the line plotting the world's economic growth has rotated clockwise about the bottom right corner. The richest economies today have some six to nine times the GDP per capita of their counterparts in 1870; the median economy today has perhaps four times the GDP per capita of its counterpart in 1870; the poorest economies are little advanced over their counterparts of 1870.

To put this another way, the strong economic growth of the past century—the rise in the geometric average of output per capita in the world from some $760 to some $3,150 in 1993 international dollars per year—has been accompanied by a substantial increase in variance as well. In 1870, the standard deviation of log GDP per capita across the world's population was some 0.53; today it is 1.00. The range from one standard deviation below to one standard deviation above the mean in

[3] A point made by Kuznets (1963), and expanded on in considerable depth by Pritchett (1994).

log GDP per capita took up the interval from $450 to $1,310 international dollars in 1870; the same interval runs from $1,160 to $8,510 international dollars today.

The third lesson is that by and large the economies that were rich in relative terms in 1870 are rich in relative terms today, and the economies that were poor in relative terms in 1870 are poor in relative terms today (Figure 3). Barro and Sala-i-Martin (1995) draw a distinction between what they call σ-divergence and β-divergence. They call "σ-divergence" the case where the variance of a distribution grows despite a tendency for any given element to revert toward the mean over time; they call "β-divergence" the case where the variance of the distribution would continue to widen even in the absence of all shocks—when there is no systematic regression toward the mean.

The world since 1870 has exhibited not only σ-divergence but also β-divergence: The world's distribution has a greater spread today because there has been a systematic tendency for the relatively rich economics to grow faster than the relatively poor, and not because shocks to individual nation-states' GDP per capita levels have dominated regression to the mean. Table 1 documents this by reporting simple regressions of nation-states' log GDP per capita levels in 1993 on the level of 1870. If two economies' log GDP per capita levels were separated by an amount X in 1870, they were separated by 1.542(X) in 1993.

The degree of β-divergence is slightly attenuated when continent dummies are added to the right-hand side. The continent dummies have the standard pattern: strongly positive for North America, strongly negative for Africa. More interesting, perhaps, is some evidence that GDP per capita levels have tended to converge over the past century and a quarter, if attention is confined to those economies that were in the richer half of the sample in 1870.[4]

The fact that the distribution of income and productivity levels across nation states has been diverging goes oddly with a large number of studies (see Cogley and Spiegel 1996; Mankiw, Romer, and Weil 1992) that find evidence for "conditional convergence": Gaps between an economy's aggregate income and productivity level, and the level corresponding to the steady-state growth path predicted by its investment and population growth rates, shrink over time by some 2 to 3 percent per year.

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[4] Williamson (1996) and Taylor and Williamson (1994) point to the factors—largely international migration, increasing trade, and thus converging factor and commodity prices—making for "convergence" among relatively well-off economies before World War I. Dowrick and Nguyen (1989) point to similar factors and document similar "convergence" within the club of relatively rich OECD economies after World War II. Lewis (1978) attempts to account for the failure of relatively poor economies to industrialize before and after World War I.

Figure 3A

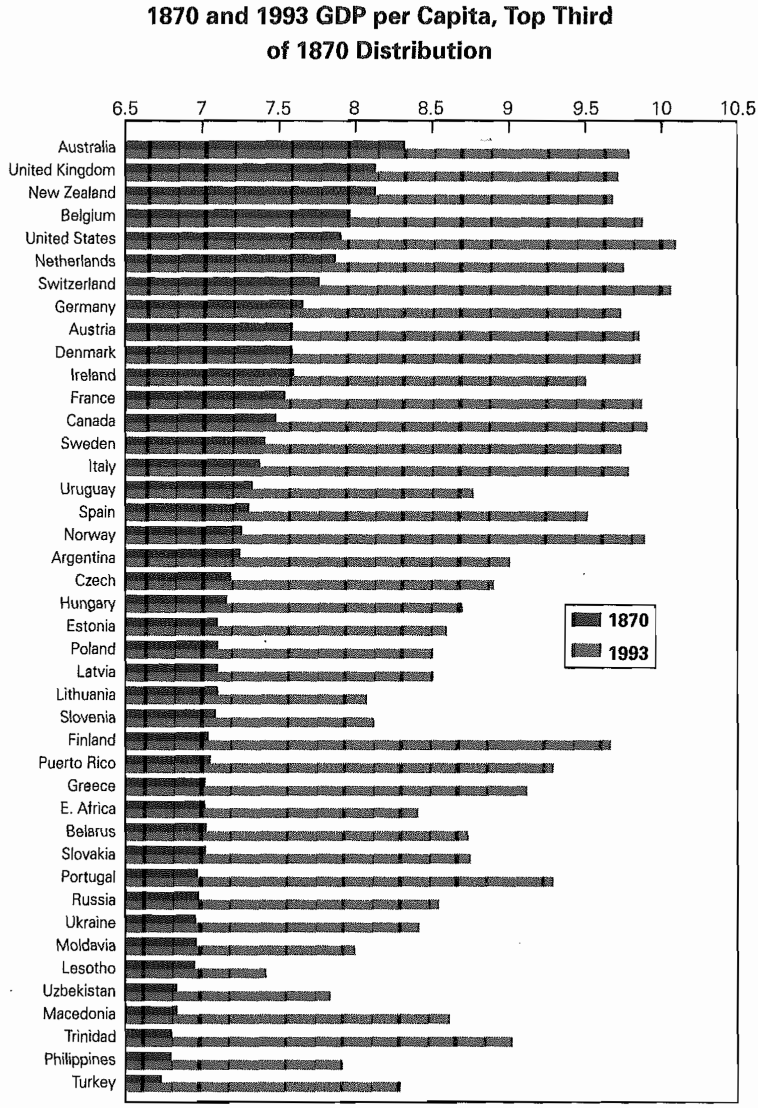

1870 and 1993 GDP per Capita, Top Third
of 1870 Distribution
6.5
7
7.5
8
8.5
9
9.5
10
10.5
Australia
United Kingdom
New Zealand
Belgium
United States
Netherlands
Switzerland
Germany
Austria
Denmark
Ireland
France
Canada
Sweden
Italy
Uruguay
Spain
Norway
Argentina
Czech
Hungary
Estonia
Poland
Latvia
Lithuania
Slovenia
Finland
Puerto Rico
Greece
E. Africa
Belarus
Slovakia
Portugal
Russia
Ukraine
Moldavia
Lesotho
Uzbekistan
Macedonia
Trinidad
Philippines
Turkey
1870
1993

Figure 3B

1870 and 1993 GDP per Capita, Middle Third of 1870 Distribution

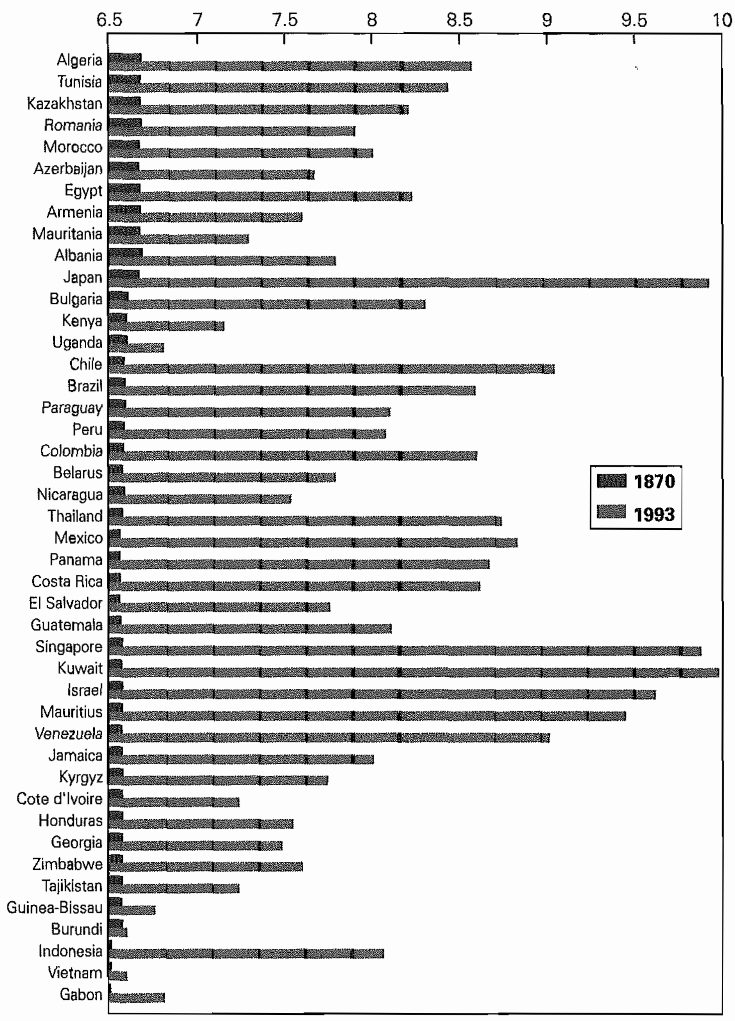
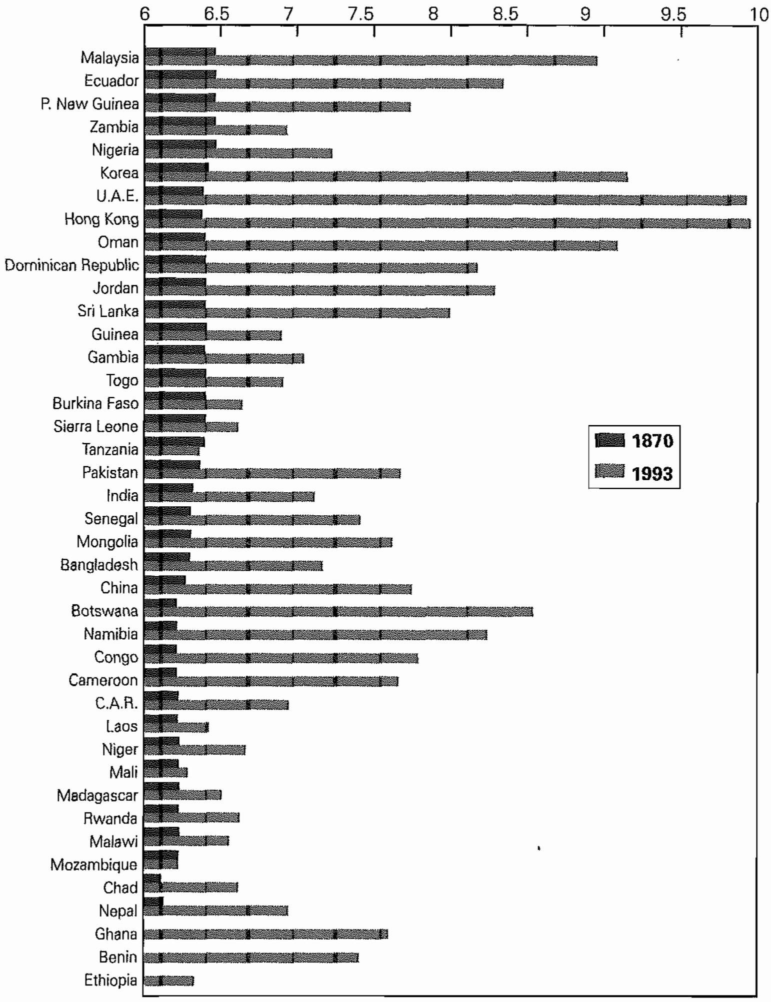


Figure 3C

1870 and 1993 GDP per Capita, Bottom Third[a] of 1870 Distribution



[a]Note change in scale from Figures 3a and 3b.

Table 1
Simple Convergence Regressions, 1870 and 1993

	Log 1870 GDP per Capita	With Continent Dummies		R^2
Full Sample	1.542 (.145)			.689
		Full Sample	1.316 (.197)	.753
		North America	.501 (.381)	
		South America	.174 (.252)	
		Asia	.208 (.225)	
		Africa	−.592 (.226)	
Richer Half	.620 .126			.533
Poorer Half	1.252 (.305)			.466

ENDOGENOUS FACTOR ACCUMULATION

Conditional Convergence

Barro (1991) and Mankiw, Romer, and Weil (1992) were among the first to stress the existence of *conditional convergence* in the post-World War II growth rates of a cross section of nation-state economies. Mankiw (1995) interprets this finding as indicating that the straightforward Solow growth model is working better and better as time passes: It is becoming more and more the case that differences across nations in relative levels of GDP per capita are reflections of the differences in steady-state capital intensity implied by their rates of factor accumulation and population growth.

Yet the appearance of conditional convergence—a coefficient of between −2 and −3 percent per year when the growth rate is regressed on the difference between an economy's initial level of GDP per capita and the steady-state level implied by its investment and population growth rates—fits oddly with the fact, documented in the previous section, of unconditional divergence. How can economies be traversing toward their steady states *and* at the same time be drawing further and further apart in relative GDP per capita levels?

A naive interpretation of this pattern would suggest that at some time in the past, nation-states' savings and population growth rates must have been much more closely bunched together than they are today. This would mean that at that time, economies' steady-state and actual levels of output per capita also were bunched together more closely than they are today, and that some economic shock or series of shocks has since driven their respective savings and population growth rates apart. Thus, the world's relative distribution of incomes has diverged since, as the world's relative economies have traversed toward their now distantly separated paths of steady-state growth.

But this naive interpretation has a central problem: What was this shock that drove savings and population growth rates apart? The principal candidate would be the Industrial Revolution. But the Industrial Revolution saw not a fall but a sharp rise in population growth rates in the most heavily affected economies (Livi-Bacci 1992). And today very little is left of Rostow's (1957) bold hypothesis that the key to the Industrial Revolution was a sharp rise in investment as a share of national product (Crafts 1985; Mokyr 1985). The shifts in investment and in population growth rates brought about by the Industrial Revolution did not occur in the directions that would support such an interpretation.

Other candidates for a shock sharp enough to drive economies' investment and population growth rates away from one another simply are absent. The overwhelming bulk of the divergence in GDP per capita over the past century and a quarter has been due to the uneven spread of the Industrial Revolution, and to differences in relative national rates of growth in total factor productivity. But why, then, the finding of conditional convergence, and the strong positive association of per capita levels of GDP with investment rates and the negative association with population growth rates?

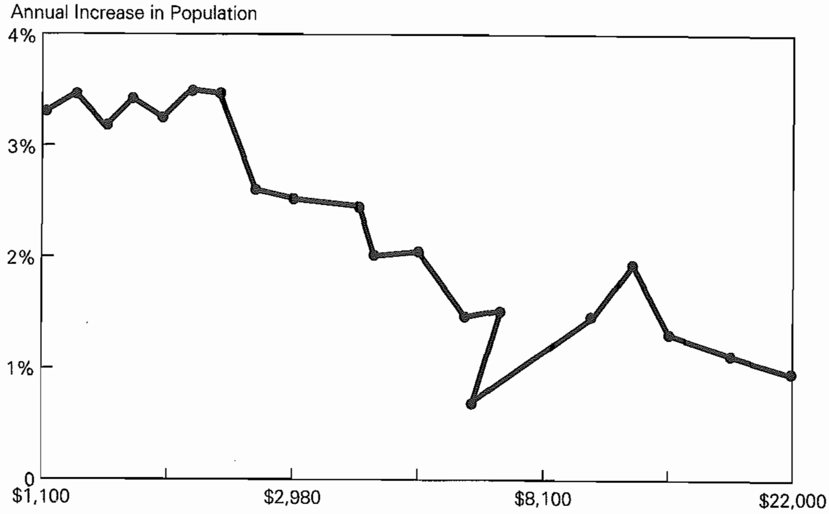
Population Growth and the Demographic Transition

One reason is the endogeneity of population growth. Sometime between the fifteenth and the eighteenth centuries, the human race passed through what we all hope was its last "Malthusian" episode, in which rising population and limited agricultural resources led to nutritional deficits, higher than average mortality, and population stagnation. Since then, the pace of productivity improvement in agriculture has kept ahead of agricultural resource scarcity and the population growth that has carried the world's population from one to six billion, so far. Nutrition has been relatively high by historical standards, natural fertility high as well, and natural mortality low.

In the past, the richest human populations appear to have also seen the fastest population growth. But, starting perhaps in eighteenth century France, a new pattern began to emerge, in which increases in GDP per capita led not to greater fertility and faster population growth but to

Figure 4

U.S. Population Growth and GDP per Capita, 1790 - Present



lower fertility and slower population growth. The number of girls born per potential mother fell, and population growth rates slowed.

Figure 4 shows this pattern at work in the United States over the past two centuries: As GDP per capita has grown, the rate of natural increase of the U.S. population has fallen steadily. Once U.S. GDP per capita grew beyond $2,000 or so (1993 dollars), fertility began to drop sharply enough to offset the declines in mortality that accompanied better medical care and rising material prosperity. The rate of population growth, excluding net immigration, is now little over 1 percent per year—far below the 3.5 percent per year in natural population increase seen in the first half-century of the Republic.

The pattern of rising material prosperity and falling natural population increase has had only one significant interruption in the United States in the past two centuries. The Great Depression of the 1930s saw a very sharp fall in childbearing and a reduction in natural population growth to only 0.7 percent per year. In what Richard Easterlin (1982) sees as a delayed response to the Great Depression that balanced out the birth deficit of the 1930s, births rose in the 1950s "baby boom" to a level not seen since the nineteenth century.

The pattern of increasing material wealth and slowing population growth seen in the United States is completely typical of the pattern followed so far by all nations that have successfully industrialized. Each tripling of GDP per capita has been associated with an approximately 1 percentage point fall in the annual rate of natural population increase.

To my knowledge, no one has ever argued that falling population growth in the United States has any sources other than our increasing material prosperity and the changes in social and economic organization that have followed from it. A richer country has more literate women, and literate women—worldwide—are very interested in effective birth control. In a poorer country, the average level of education is low and children can be put to work at a relatively early age, thus augmenting the production resources of the household. In a richer country, the average level of education is high and children are a major drain on household cash flow for nearly two decades.

Children in relatively poor, low-productivity economies are much like an "investment" good: They are a way to augment the economic resources of the household in a time span of a decade or so. By contrast, children in relatively rich, high-productivity economies are more like a "consumption" good. Thus, we would expect to see—and we do see—a substantial correlation between high GDP per capita and low population growth, arising not so much because low population growth leads to a higher steady-state capital-output ratio but because of the demographic transition: the changes in fertility that have so far been experienced in every single industrialized economy.

The Relative Price of Investment Goods

Begin with the large divergence between purchasing power parity and current exchange rate measures of relative levels of GDP per capita. The spread between the highest and lowest levels of GDP per capita today, using current exchange rate-based measures, is a factor of 400; the spread between the highest and lowest GDP per capita levels, using purchasing power parity-based measures, is a factor of 50. If the purchasing power parity-based measures are correct, real exchange rates vary by a factor of eight between relatively rich and relatively poor economies. And the log GDP per capita level accounts for 80 percent of the cross-country variation in this measure of the real exchange rate, with each 1 percent rise in GDP per capita associated with a 0.34 percent rise in the real exchange rate (Figure 5).

Real exchange rates make the prices of traded manufactured goods roughly the same in the different nation-states of the world, putting to one side over- or undervaluations produced by macroeconomic conditions, tariffs and other trade barriers, and desired international investment flows. Thus, the eightfold difference in real exchange rates between

Figure 5

Log Real Exchange Rate, and Log GDP per Worker

relatively rich and relatively poor economies is a reflection of an approximately eightfold difference in the price of easily traded manufactured goods: Relative to the average basket of goods and prices on which the "international dollar" measure is based, the real price of traded manufactures in relatively rich countries is only one-eighth the real price in relatively poor countries.

This should come as no surprise. The world's most industrialized and prosperous economies are the most industrialized and prosperous because they have attained very high levels of manufacturing productivity. Their productivity advantage in unskilled service industries is much lower than that in capital- and technology-intensive manufactured goods. And a low relative price of technologically sophisticated manufactured goods has important consequences for nation-states' relative investment rates. In the United States today, machinery and equipment account for one-half of all investment spending; in developing economies—where machinery and equipment, especially imported machinery and equipment, are much more expensive—they typically account for a much greater share of total investment spending (Jones 1994; De Long and Summers 1991).

Table 2
Consequences for National Investment of Relative Poverty and a High Price of Capital Goods

Level of Real Exchange Rate-Based GDP per Capita	Price Level of Machinery	Nominal Savings Share of GDP (Percent)	Real Investment Share of GDP (Percent)
$24,000	100	20.0	20.0
$ 6,000	160	20.0	15.4
$ 1,500	257	20.0	11.2
$ 375	411	20.0	7.8
$ 95	659	20.0	5.3

Consider the implications of a higher relative price of capital goods for a developing economy attempting to invest in a balanced mix of machinery and structures. There is no consistent trend in the relative price of structures across economies: Rich economies can use bulldozers to dig foundations, but poor economies can use large numbers of low-paid unskilled workers to dig foundations. But the higher relative price of machinery capital in developing countries makes it more and more expensive to maintain a balanced mix: The poorer a country, the lower is the real investment share of GDP that corresponds to any given nominal savings share of GDP.

Table 2 shows the consequences—the gap between nominal savings and real investment shares of GDP—that follow from the high relative price of machinery and equipment in poor countries that wish to maintain a balanced mix of investment in structures and equipment. For a country at the level of the world's poorest today—with a level of real exchange rate-based GDP per capita of some $95 a year—saving 20 percent of national product produces a real investment share (measured using the "international dollar" measure) of only some 5 percent of national product.

In fact, poor economies do *not* maintain balanced mixes of structures and equipment capital: They cannot afford to do so, and so they economize substantially on machinery and equipment. Thus, here are two additional channels by which relative poverty is a cause of slow growth. First, relative poverty is the source of a high real price of capital, a low rate of real investment corresponding to any given nominal savings effort, and a low steady-state ratio of capital to output. Second, to the extent that machinery and equipment are investments with social products that significantly exceed the profits earned by investors (see De Long and Summers 1991), the price of structures in relatively poor developing economies leads them to economize on exactly the wrong kinds of capital investment.

The Implications

The standard Solow (1956) and Swan (1956) growth model, written in per worker terms and expressed in logs, contains the production function:

$$\ln(y) = \alpha \ln(k) + \tau, \tag{1}$$

where y is output per worker, k is capital per worker, α is the capital share in the production function, and τ is the log of total factor productivity. If the economy has a constant investment rate I, a constant population growth rate n, and labor efficiency growth and depreciation rates g and δ, then in a steady state at any point in time, output per worker will be given by:

$$\ln(y) = \frac{\alpha}{1-\alpha}(\ln(I) - \ln(n + g + \delta)) + \frac{\tau}{1-\alpha}. \tag{2}$$

Suppose, however, that we take account of the feedback from GDP per capita levels on population growth rates:

$$\ln(n + g + \delta) = -\phi \ln(y) + \nu \tag{3}$$

where n is that portion of $\ln(n + g + \delta)$ not accounted for by the combination of the dependence of population growth on output and the background rates of labor efficiency growth and depreciation. The pattern of demographic evolution from the U.S. historical experience suggests that the parameter ϕ is, over the relevant range, approximately equal to 0.2.

And suppose we take account of the feedback from GDP per capita levels to the real investment share:

$$\ln(I) = \ln(s) - \ln(p_k) = \ln(s) + \theta \ln(y) - \eta, \tag{4}$$

where s is the economy's nominal savings share, ρ_k is the real price of capital goods, η is the deviation of the price of capital goods from what would have been predicted given the level of real output, and θ—the elasticity of capital goods prices with respect to output—is roughly equal to 0.3 over the range relevant for developing economies.

Combining (2), (3), and (4) produces an expression for the steady-state level of output, allowing for the endogeneity of population growth rates as a result of the demographic transition and for the dependence of the relative price of investment on output per worker:

$$\ln(y) = \frac{\alpha \ln(s) - \alpha\eta - \alpha\nu + \tau}{1 - \alpha - \alpha\theta - \alpha\phi}. \tag{5}$$

Table 3
Consequences for Steady State of Endogenous Population Growth and Capital Goods Prices

Capital Share α	Denominator of Equation (5)	Effect of s, g, η	Effect of Total Factor Productivity
.20	.70	.29	1.43
.40	.40	1.00	2.50
.60	.10	6.00	10.00
.67	.00	∞	∞

Equation (5) allows us to calculate, for various possible values for the share α of produced capital goods in the production function and for the chosen values of ϕ and θ, the impact on the level of the steady-state growth path of a shift in the exogenous component of savings, capital goods prices, population growth, or total factor productivity. Because they enter symmetrically into equation (5), the effects of the first three are the same.

Table 3 reports that—with a share of produced factor inputs in the production function of 0.4—a 1 percent increase in the savings rate (or a 1 percent fall in the exogenous component of capital goods prices) carries with it a 1 percent increase in the steady-state level of output. But a 1 percent increase in total factor productivity raises the steady-state level of output by fully 2.5 percent. Growth-accounting decompositions would, if applied to such an economy, attribute only 1 percent of the higher level of output to higher total factor productivity—*less than two-fifths* of the total effect. The growth accounting decomposition is not wrong, but incomplete: To the extent that the higher capital stock is a result of higher total factor productivity reducing the relative price of capital, and to the extent that higher total factor productivity pushes an economy further along its demographic transition to low population growth, exogenous shifts in total factor productivity have effects that are orders of magnitude greater than growth accounting procedures suggest, even without any powerful externalities in the production function.

Equally interesting, perhaps, is the case in which there *are* externalities to investment—whether in infrastructure, in research and development, in human capital, or in machinery and equipment—and in which the true capital share α in the production function is substantially greater than the 0.4 found in the usual specifications of the Solow model. The true capital share cannot get as high as 0.67 without triggering explosive paths for output per capita, in which very small boosts to total factor productivity set in motion patterns of population growth reduction and investment increase that converge to no steady state at all, but simply grow until the log-linear approximations in equations (3) and (4) break down.

It is difficult to look at the cross-country pattern of growth over the past century without thinking that the determinants of the steady-state growth paths toward which countries converge must be nearly singular. What differences between Canada and Argentina in 1870 would have led anyone to forecast their now more than two and one-half-fold difference in GDP per capita? Or the twentyfold gap between Taiwan and India? Recognizing the endogeneity of the demographic transition and of investment has the potential to help us understand why the economic history of the past century and a quarter has proceeded as it did, without requiring assumptions of external effects that seem perhaps implausibly large.

The endogeneity of the demographic transition, and of investment, also helps make sense of the odd combination of global divergence together with "conditional convergence." To the extent that relatively low productivity today is a cause of an economy's attraction to a low steady-state growth path, it is less necessary to look for shocks in the past that both pushed economies away from their long-run growth paths and pushed economies' GDP per capita levels together, if we want to account for the evolution of the world's distribution of income.

Caveat

But I still have one important caveat: Do we really want to refer to shifts in the aggregate production function as "technical change" and "technology"? Much of the difference seen across nations in aggregate total factor productivity seems to have little to do with *technology* per se.

Consider Greg Clark's (1987) excellent study of productivity in the cotton textile industry circa 1910. Table 4 reports some of Clark's calculations, most strikingly the sevenfold difference in labor productivity found between mills in the United States and cotton mills in the region of China near Shanghai.

Table 4
International Productivity in Cotton Textiles, circa 1910

Country	Output per Worker-Hour	Staffing Levels (Machines per Worker)
United States	1.78	2.97
England	1.33	2.04
Austria	.60	1.24
Italy	.59	.88
Japan	.33	.53
India	.28	.50
China	.25	.48

Source: Clark (1987).

The most striking thing about this sevenfold differential—the point of Clark's article—is that all of these mills used the same *technology*, if that word has any meaning. Japanese, Chinese, and Indian cotton mills had no local source of capital goods, so they bought and imported textile machinery made in the same machine shops near Liverpool that British manufacturers used. The United States produced its own textile machinery; Belgium, France, Germany, and Austria produced textile machinery as well. But everyone else imported capital goods—and in many cases, according to Clark, paid British mechanics to assemble and install it as well.

Yet with the same *technology*—the same machinery, the same production process, the same automated transformation of raw materials by metal and chemistry into final product—Clark found differences in labor productivity that reached three-to-one even when comparing the United States to Italy, a country with a very long history of textile production.

The key to the differences in labor productivity is found in the last column of Table 4: staffing levels. In the United States, one operative took care of three machines. In China, two operatives took care of one machine. Add this sixfold differences in staffing levels to the perhaps 15 percent lower output per machine-hour near Shanghai to obtain an arithmetic explanation of the sevenfold difference in output per worker.

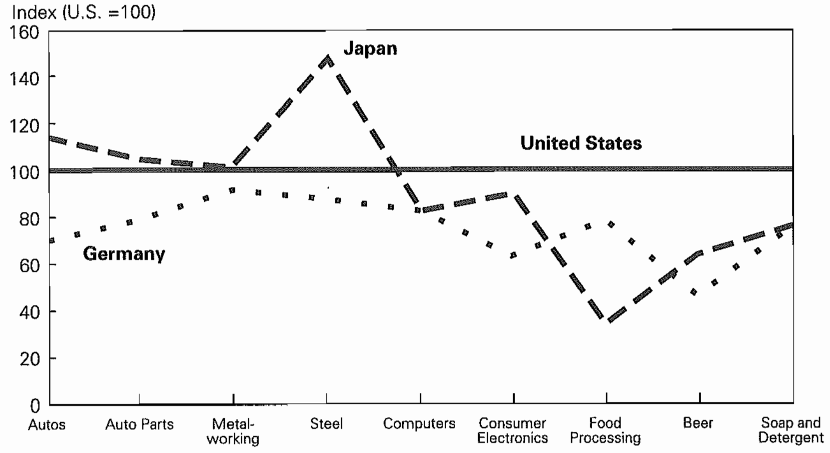
Since Clark wrote his article, a cottage industry has sprung up to try to explain how all of these textile mills could still be operating on the same production function. Perhaps the extra workers in the Asian mills were substituting for a poorer quality of raw materials? After all, poorer-quality raw materials would lead to more breaks, snarls, and machine stoppages that would have to be corrected. Perhaps the extra workers in the Asian mills allowed machines to run faster? Perhaps the extra workers allowed the machines to run with less downtime? Not one of the attempts to establish that these textile mills were working on the same production function, with Asian mills getting increased output (or diminished other inputs) in return for their higher staffing levels, has been convincing. The turn-of-the-last-century cotton textile industry did exhibit very large differences in productivity across countries, yes. But the differences are not readily attributable to differences in anything I would call *technology*.

Or consider the McKinsey Global Institute's (1993) study of manufacturing productivity in the United States, Germany, and Japan—a study carried out with the assistance of Martin Baily and Robert Solow. As best they could estimate, Japanese manufacturing productivity in 1990 varied from 33 percent of the U.S. level in food processing to 147 percent of the U.S. level in steel. German manufacturing productivity varied from 43 percent of the U.S. level in beer to 91 percent of the U.S. level in metalworking (Figure 6).

If we are going to attribute these productivity differences to differ-

Figure 6

Relative Labor Productivities by Industry, 1990



Source: McKinsey Global Institute (1993).

ences in *technology*, it is hard to understand how Japanese businesses can be so successful at learning and developing technologies for making automobile parts, and so inept at learning and developing technologies for freezing fish. True differences in technology surely are a greater factor in comparisons between countries further apart in the world distribution of GDP per capita than Germany, Japan, and the United States: Developing economies do use last generation's or even last century's procedures and practices because they cannot afford the capital goods that embody today's, because they do not have the mechanics to maintain today's, or because they have different factor price structures that make it more costly to use today's best practice. But even identical technologies can yield very different productivities. A lot more is going on.

Conclusion

Thus, the moral of this paper is that "technology" is both more important and less important a factor in accounting for relative national levels of prosperity than the conventional wisdom suggests. *Technology*—in the sense of differences in total factor productivity—is *more* important because of the strong endogeneity of population growth and capital investment rates. Countries that are rich have low rates of population growth: They have completed their demographic transitions to a régime in which fertility is relatively low and their children have become more "consumption" than "investment" goods. Countries that are rich also have relatively low prices of capital goods—a given share of national product saved implies a higher ratio of investment to GDP. Hence, being rich tends to make a nation-state's capital-output ratio high.

Thus, small differences in total factor productivity can translate into large differences in productivity levels and living standards, once the feedback from a richer economy to higher investment and lower population growth rates is taken into account. Studies examining the impact of total factor productivity differences on output per capita that hold savings and population growth rates constant understate the true long-run impact of raising total factor productivity.

On the other hand, *technology*—in the sense of knowledge of the internal combustion engine, continuous-casting, or freeze-drying—is much less important in accounting for differences across nations. Many differences in total factor productivity are related tenuously, or not at all, to differences in technology. All of the textile factories at the turn of the last century were equipped with the same or similar machines, many of them from the same machine shops in Lowell, Massachusetts or Manchester, Lancashire.

This should not be taken to imply that *technology* per se is unimportant in long-run economic growth. It is very important in those particular industries that are near the active edge of technological expansion and intensive in research and development. Indeed, better technology today is the sole important reason why we today have six to 20 times the standard of living of our predecessors in 1870. But it has much less to do with the sources of aggregate productivity differences across nations.

The last wave of research on aggregate growth theory called forth an effort, by Abramovitz (1956, 1986) and Denison (1967) among others, to try to decompose aggregate total factor productivity differences into more interesting and meaningful components. It is too bad that the current wave of research on aggregate growth has failed to generate a corresponding effort.

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DISCUSSION

Jeffrey A. Frankel*

Upon my first reading of J. Bradford De Long's paper, my reaction was to be impressed with its clarity and convinced by its basic arguments. He takes on some big ideas regarding the statistical record of cross-country growth rates, and he provokes the reader into new and useful thoughts. I expected, at most, to be pointing out some missing references that are relevant to the central point, the endogeneity of investment and other standard determinants of growth. Upon further thought, I remain impressed by his clarity and stimulated by his ideas, but no longer so convinced of all his conclusions.

The basic starting point is an apparent paradox. On the one hand, countries' income levels have failed to converge over time. In fact, the inequality among nations has actually increased by most standard measures. On the other hand, when we condition on the standard determinants of growth such as investment and population growth, we find a tendency for inequality to diminish—the finding now known as conditional convergence (Barro and Sala-i-Martin 1992; Mankiw, Romer, and Weil 1992). There is no contradiction here, but an interesting pair of major trends remain to be explained. It would be nice to be able to fold them into a single explanation. How can this be done?

De Long's explanation is elegant in its simplicity. Initial differences in technology, for example, Britain's Industrial Revolution, have become increasingly magnified with the passage of time because of two channels. First, higher income levels lead to less rapid population growth. Popu-

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lation growth is, in turn, a standard negative determinant of GNP per capita in the neoclassical growth model of Solow (not to mention in earlier contributions going back to Malthus). The reason is that higher population growth means that more of investment is used up equipping workers with the already existing level of capital, and less is left over to raise the capital/labor ratio. Second, higher income levels lead to lower relative prices of capital goods, so that a given saving rate buys more real investment. Through both channels, the initial divergence in incomes becomes self-reinforcing.

My response falls into several parts. First, I will recall previous authors who have made similar points, together with some additional ways that the standard determinants of growth could in theory be endogenous. Then, I will discuss some empirical evidence: on convergence itself, on the timing of increases in investment, and on what causes some countries to converge and others not.

Doctrinal History

Both the endogeneity of investment and the endogeneity of population growth are points that are long-known and well-known. Perhaps they are better known in the development literature than in the growth literature. In the case of investment, the specific channel mentioned by De Long, via the relative price of capital goods, is new, so far as I know. But many have noted that saving (and therefore investment) might change as income rises.

One possible channel comes out of the same demographic transition described by De Long: A lower ratio of children to working-age population implies a higher saving rate, according to the life-cycle hypothesis (Mason 1987; Leff 1969). Other possible effects have been suggested as well. The development process is often accompanied by the growth of more sophisticated financial systems, as well as pension plans and social security systems. This evolution can lead not only to more saving and investment, but also to lower population growth, since a prime motive in poor countries for having many children is that they provide the only form of insurance against destitution in old age.[1] Investment in human capital is often greater in rich countries than in poor countries, perhaps because education is a superior good.

I would like to add another effect to the list. The growth literature often falls into the habit of speaking of national saving and investment interchangeably. But the two differ; the difference is net foreign borrowing. Countries undergoing rapid growth often find foreign capital increasingly available, perhaps even to a greater extent than they would

[1] For citations on all these points, see Hammer (1985) or Kelley (1988, pp. 1706–07).

like, as some emerging market countries found in the 1990s. The increased ease of international financing of investment is another way that this key determinant of growth can be endogenous.

Some effects can also go the other way. Not everyone agrees that population growth has a clear negative effect on income per capita. A longer life span leads to an increased ratio of elderly to working-age population, which in turn results in a fall in saving, according to the life-cycle hypothesis. Another effect is symmetric to De Long's effect on the price of capital goods. As he points out, countries as they grow tend to undergo a real appreciation of their currency, and thus an increase in their relative price of nontraded goods and services, versus traded goods. But just as this means cheaper capital goods, it also means more expensive education. Thus, a given saving rate buys less real investment in human capital (as parents of today's students are well aware). I would not argue that either of these two effects dominates the ones that work to reinforce growth, though someone else might.

Perhaps the most important precedent for De Long's argument is research by Richard Nelson.[2] He argued precisely that, because population growth and saving could be endogenous, a takeoff in growth could become self-sustaining. The alternative was what he called a "low-level equilibrium trap," in which a country is unable to achieve growth until it gets its population growth down and its saving rate up, but is unable to get its population growth down and its saving rate up until it achieves growth. This sort of model leads directly to De Long's worldwide divergence.

Before I leave the subject of doctrinal history, I want to make a comment on De Long's characterization of technology. He says, on the one hand, that shifts in total factor productivity are more important than sometimes thought, in that they, rather than added inputs per capita, form the origin of the self-sustaining takeoff. But, on the other hand, he says that Solow's labeling such shifts as technology "may not have helped economists think clear thoughts over the past 40 years." I do not believe Bob Solow needs me to defend him, and in any case I am sure that no lack of respect for his contributions in this area was meant. Nevertheless, I thought I would recall the relevant two sentences from Solow (1957): "I am using the phrase 'technical change' as a shorthand expression for *any kind of shift* in the production function. Thus slowdowns, speedups, improvements in the education of the labor force, and all sorts of things will appear as 'technical change.'" From the start, there has been plenty of awareness that the Solow residual was only "a measure of our ignorance," and that it could be influenced by managerial practices, government-induced distortions, cultural factors, and a hundred other

[2] Nelson (1956 and 1960, p. 378); see also Jones (1976, p. 88).

aspects of how countries organize their economies, as easily as by the mastery of the internal combustion engine or the freeze-drying process.

Empirical Evidence

Now I will turn to empirical observation. The divergence in per capita incomes that De Long identifies is striking, but this generalization is a bit too sweeping and unqualified. Some of the most important trends over the postwar period are obscured.

In 1870, the self-evident generalization would have been that Europe and European-settled regions had achieved remarkable growth and other regions had not. In the middle of this century, the picture did not look very different, with a few exceptions: Japan had industrialized, while Latin America had fallen behind (most dramatically Argentina and Uruguay, which in 1870 had been as rich as Norway, as one can see from De Long's interesting Figure 3a). But when numerous colonies gained their independence in the 1950s and 1960s, the great hopes that many had for their rapid economic development were based on theory, on politics, on hope—on anything but historical experience. By 1980, those hopes had been dashed. It seemed that countries developed if and only if they were European (with Japan the only major exception).

Now, at last, this situation has suddenly changed. A group of East Asian nations, led by the four tigers, have joined the class of industrialized countries. On a per capita basis, Hong Kong and Singapore are now richer than Canada, France, the United Kingdom, and many other industrial countries. At the same time, a group of European nations, led by the former Soviet Union, have joined the class of less-developed countries.

On an aggregate basis, the U.S. share of Gross World Product has declined from almost one-half after World War II to less than one-fourth. China has surpassed Japan and Germany, in terms of total GDP. India has surpassed France, Italy, and Britain. Brazil and Mexico have surpassed Canada. Indonesia has surpassed Spain. Korea and Thailand have surpassed Australia. If the criterion were economic size, three of these countries would have a greater claim to be in the G-7 than does Canada, as would others within the foreseeable future.[3]

Why, then, does De Long find divergence rather than convergence? Romer (1986, 1989), Sala-i-Martin (1995), and others find the same. (This result has been an important stimulus to the recent surge in growth theory.) But still others conclude the opposite. For instance, Baumol

[3] Frankel (1996). These comparisons are on a Purchasing Power Parity basis. If one does the comparison on the basis of current exchange rates, then the Third World countries do not rank as high.

(1986), Dowrick and Nguyen (1989), and others see convergence among developed countries.[4] De Long (1988), in a earlier paper, attributed this finding to sample selection bias. That critique was convincing. Nevertheless, a number of authors have found convergence within groups of countries, such as Europe, or within groups of regions within countries, such as states of the United States, prefectures of Japan, or provinces within other countries. These findings are not due to sample selection bias. Sala-i-Martin describes them as another kind of "conditional convergence," conditioning now on a class of countries or regions, rather than on factor accumulation or other determinants of growth.

I think we have to go at least one cut deeper than simply looking at the variance across all countries. We have to consider which kinds of countries have converged and which kinds have not. Clearly, most East Asian countries have done well, while most African countries have not. Indeed, this last is an understatement. Some Asian countries have virtually completed convergence with European levels of development, while most African countries have made no progress in this regard at all. Why is this?

The large empirical literature on cross-country growth comparisons has found many explanations. The most robust are definitely the rates of investment in physical and human capital, which are high in East Asia. (Population growth shows up much less consistently.) Indeed, Young (1995) and his popularizer Krugman (1994) have startled many people with their claims that factor accumulation explains most or all of the superior performance of the Newly Industrialized Economies of East Asia. Little is left to be attributed to technical change or total factor productivity growth, whether interpreted as technology or Confucianism.

For present purposes, the key question is whether the high rates of investment in East Asia were a cause of the takeoffs of the high-performing economies, as is most often assumed traditionally, or whether they merely resulted from and amplified the high growth rates once they were already under way, as De Long argues (and the same for lower rates of population growth). Both channels that De Long mentions should require time to occur—certainly the demographic transition takes time, and so I think does the process of bidding up the price of nontraded

[4] Helpman (1987), in a different context (the connection between income and trade, discussed below) and with a different measure, found that the dispersion of incomes has fallen over the postwar period. That calculation, like Baumol's, was on a sample of developed countries, but Hummels and Levinsohn (1995) reproduced the result on a sample of developing countries. While difference in sample may play a role, the major explanation for this finding is probably that these authors are looking at countries' total GDPs, while the growth literature works with countries' per capita GDPs. The demographic transition says that rich countries have lower population growth than middle-income countries, so the distribution across countries could become more equal over time for total incomes, even as it becomes less equal for per capita incomes.

goods and services relative to internationally traded capital goods. Thus, one can look to see whether the changes occurred early in the takeoff process, supporting the traditional interpretation, or followed it, supporting De Long's interpretation. The one thing that seems to me missing from this paper is such an attempt to test the timing from the data.

I have plotted the investment rates and population growth rates of the East Asian countries over the past 30 to 40 years, the time span of their takeoffs.[5] (See the Figures, in the Appendix.) Most cases show very little evidence of population growth declining more in the aftermath of the peak in growth rates than it did before. Perhaps most of these countries will complete their demographic transitions in the future, but they have not yet done so. Investment rates show much more evidence of favorable changes after the peak in growth rates. However, they also show large increases in investment that pre-date the peak in growth rates, and these appear to be likely candidates for the cause of the takeoff, contrary to the De Long hypothesis. Perhaps the point about endogeneity of investment rates and self-reinforcing growth is correct, and yet the point about the initial takeoff being due more to exogenous technology than to exogenous investment differences is incorrect. More systematic analysis is needed.

Concluding Remarks

This discussion leaves out many other determinants of growth. I cannot end my comment without calling attention to one of them: openness to trade and investment. Many studies have found that openness, in addition to factor accumulation, is an important determinant of growth. Furthermore, this relationship survives accusations of simultaneity that have been frequently leveled against it, analogously to the point about the endogeneity of investment (Frankel and Romer 1996; Frankel, Romer, and Cyrus 1995). The countries that have converged are those that are open. This observation can explain convergence within the OECD, within Europe, within the United States, and within other countries. It is also part of the success of the East Asian countries. Openness is how countries absorb the best technology from the leaders, whether it is technology in the technological sense, or in more general organizational, managerial, and cultural senses. (See, for example, Grossman and Helpman 1991.)

Openness, by the way, is another self-reinforcing mechanism. While trade promotes growth, without question growth also promotes trade.

[5] This is a more compressed time span than that in which the transition of the industrialized countries occurred. But the time taken by the East Asian tigers to double their incomes has been only about 10 years, whereas it originally took the United States 47 years to do so (from 1839), and the United Kingdom 58 years (from 1780).

Countries tend to lower tariffs, for example, as they become richer. Trade has made East Asia today a powerful, self-sustaining growth area. The trade is the result (as is well-known) of pro-trade policies and also (I would argue) of the proximity of the East Asian countries to each other. At their takeoff stages, they were dependent on the North American market for trade. In the 1990s, however, they have continued to chug along on their own, even when the United States and Japan were in recession—another example of self-reinforcing growth.

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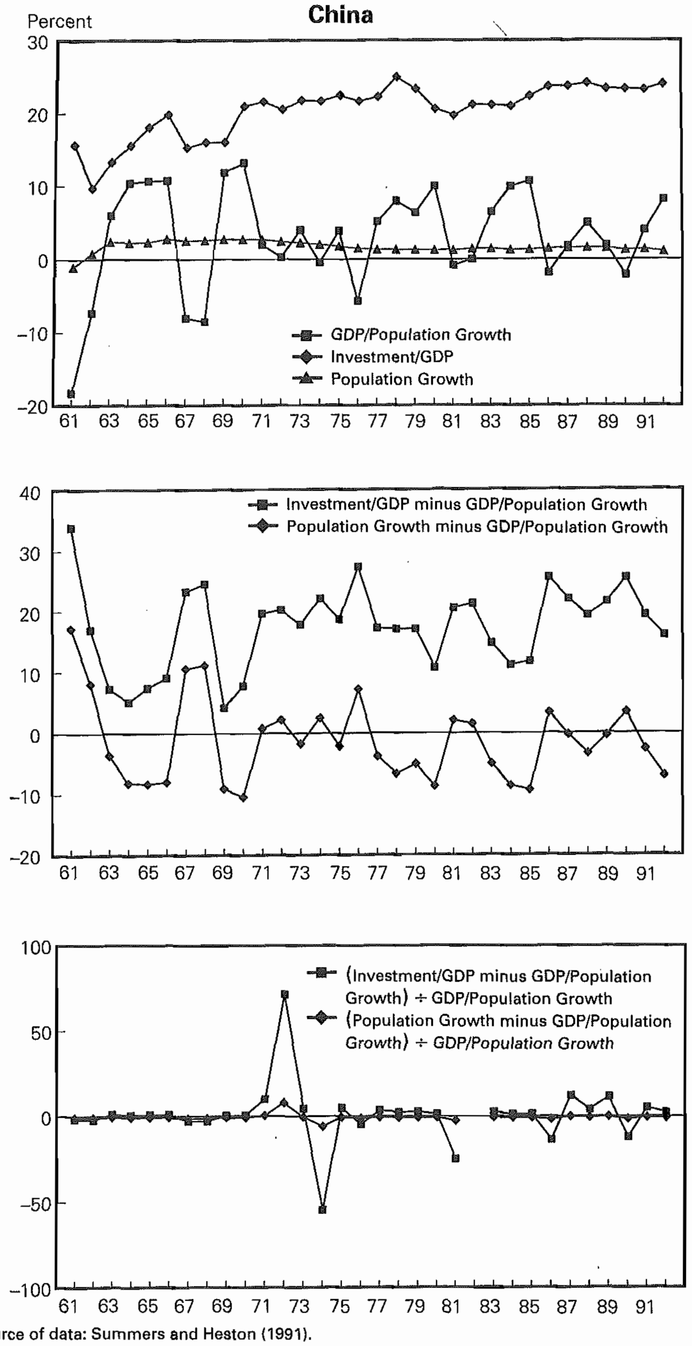
Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

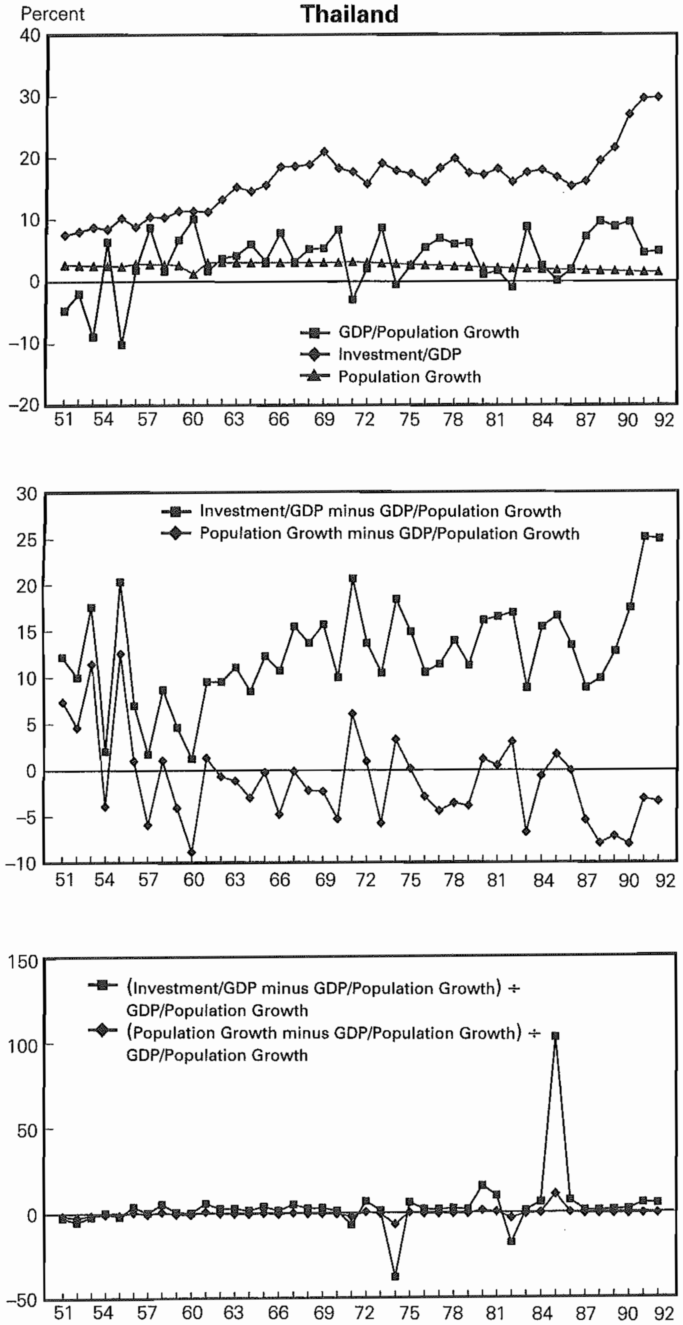
Figure 1
China



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

Figure 2
Thailand



Source of data: Summers and Heston (1991).

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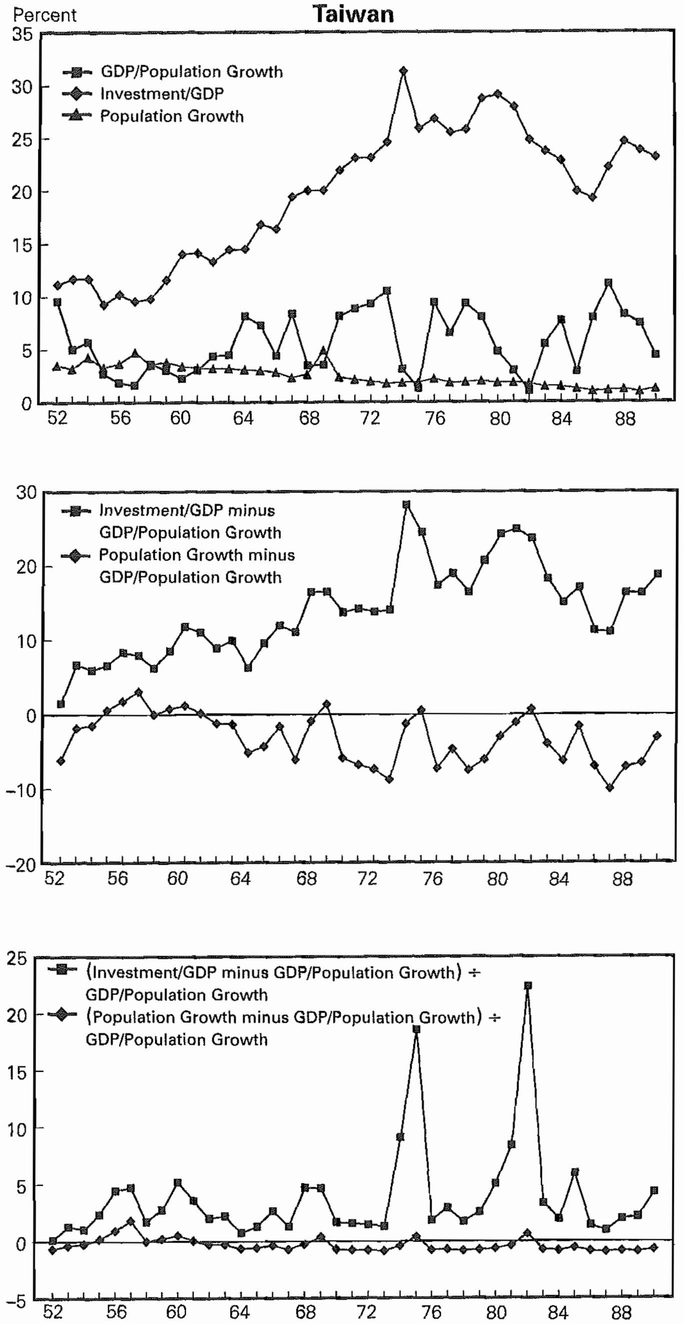
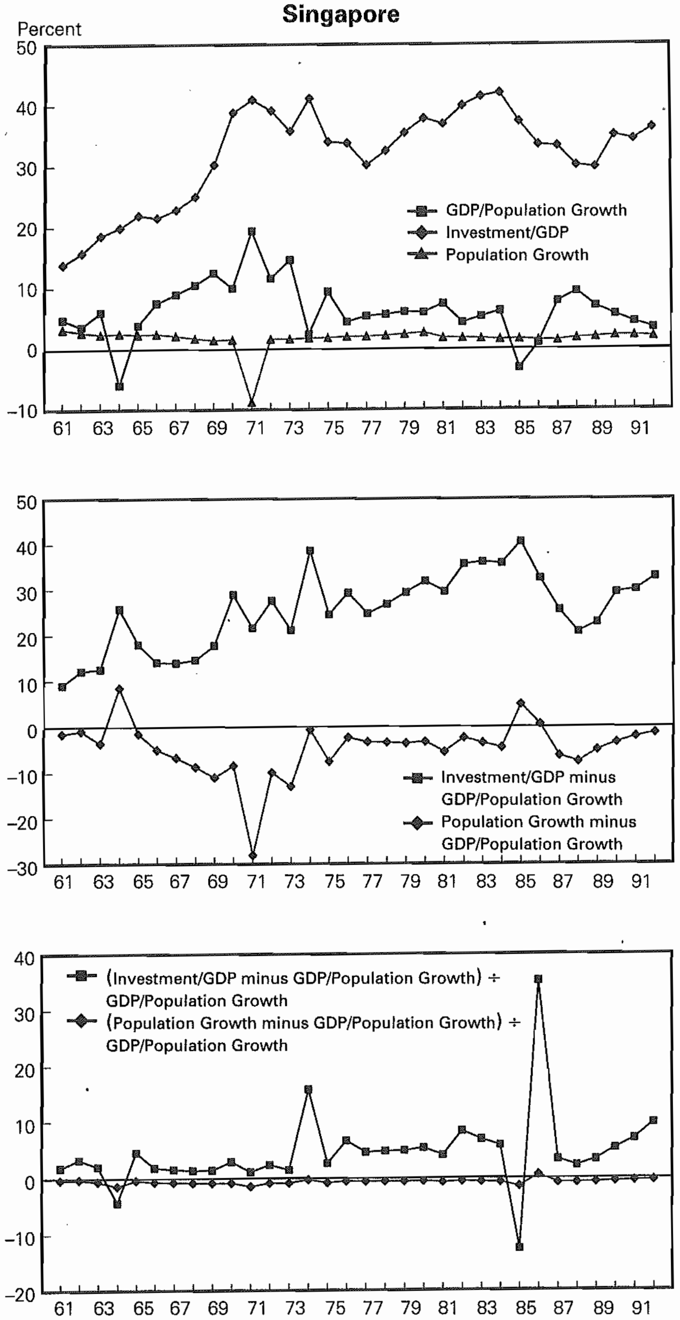
Figure 3
Taiwan



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

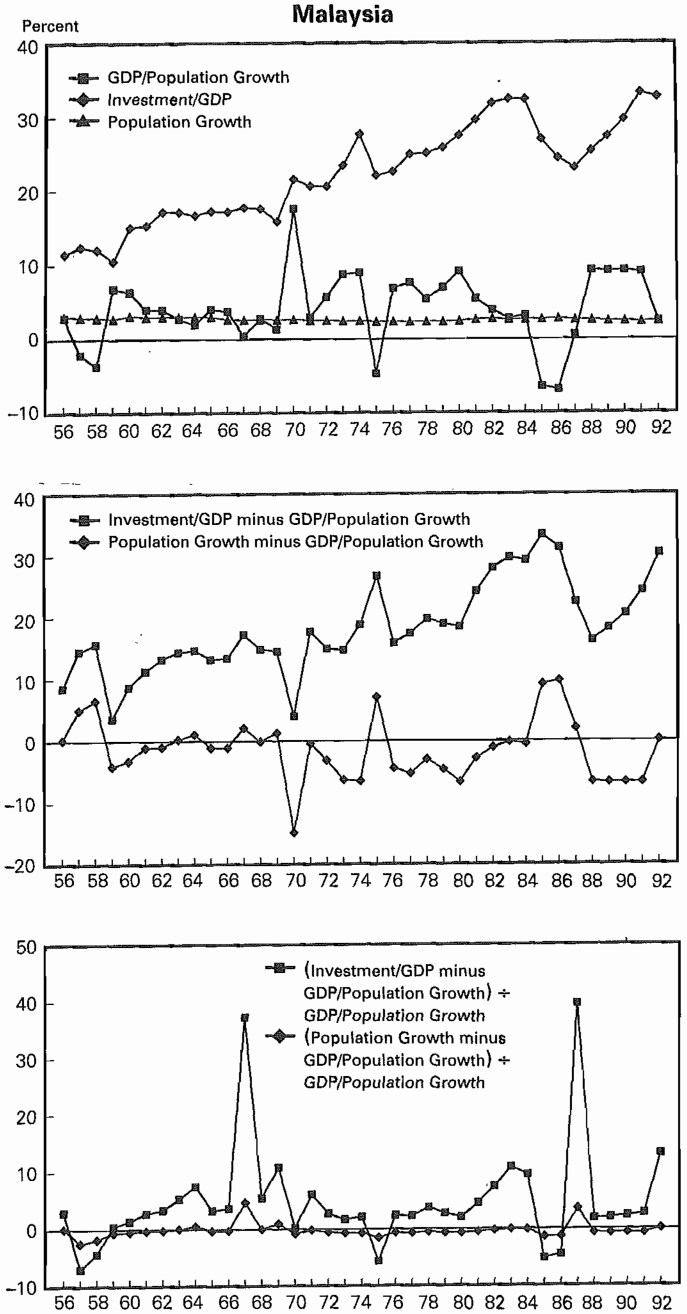
Figure 4
Singapore



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

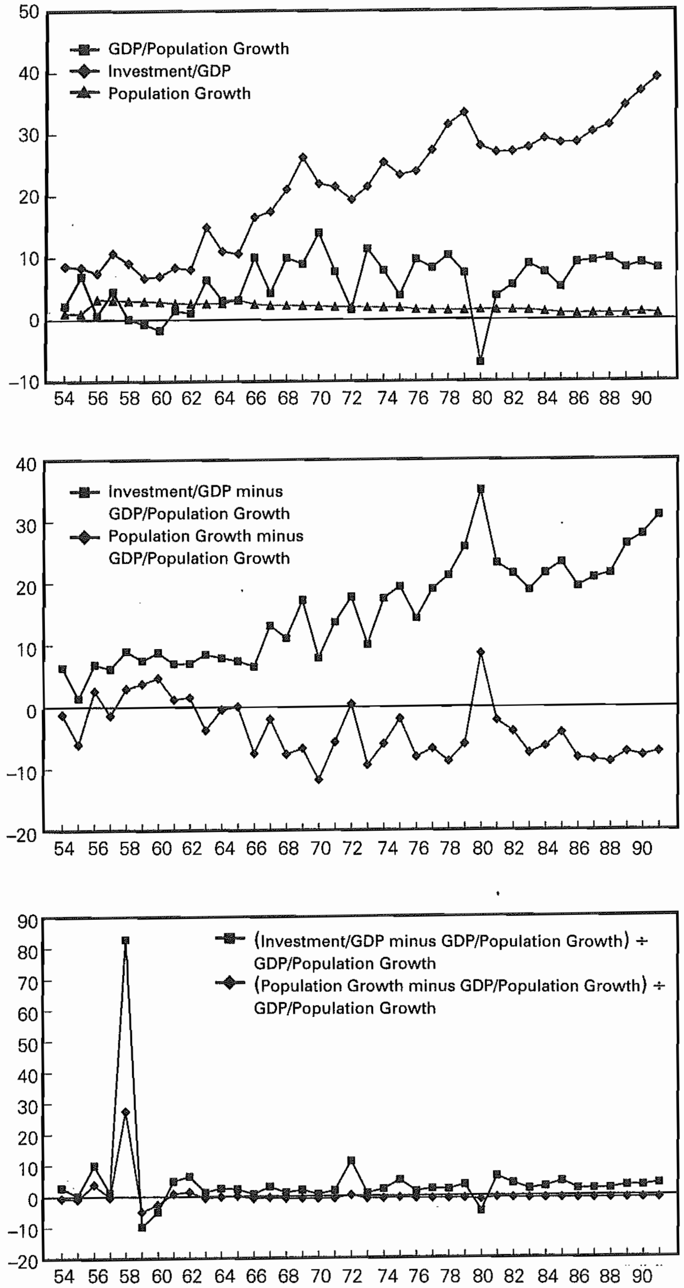
Figure 5
Malaysia



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

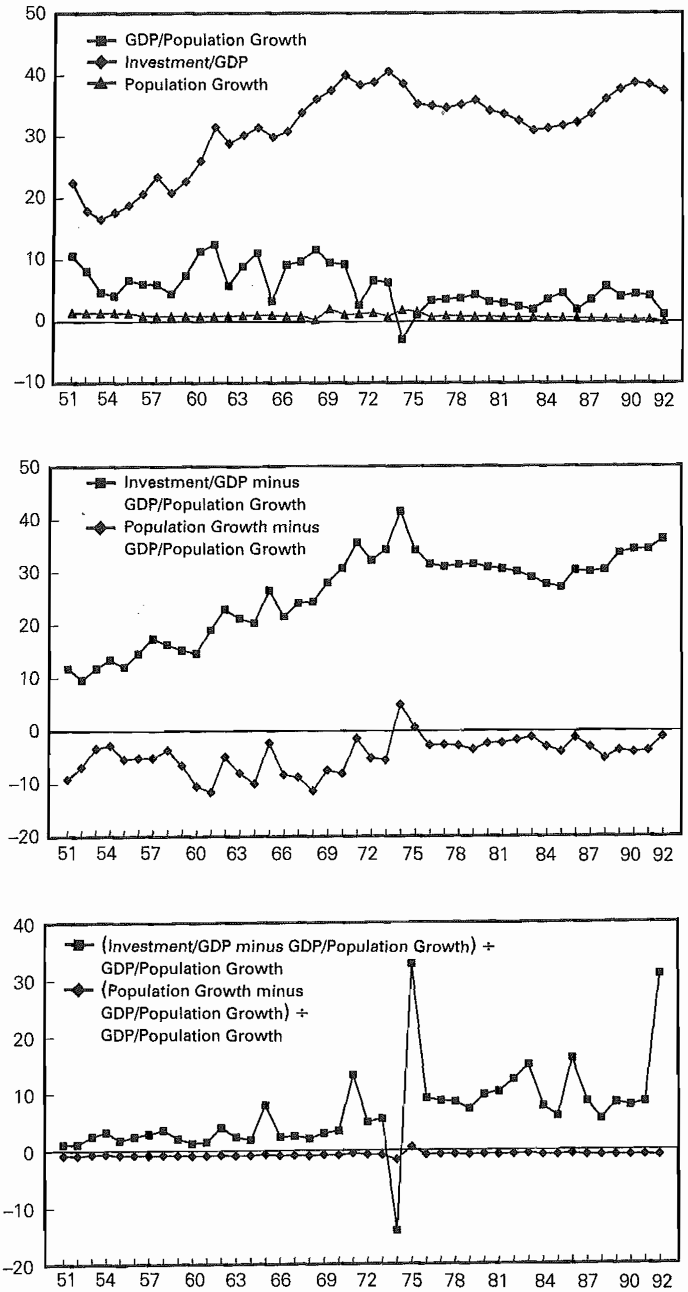
Figure 6
South Korea



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

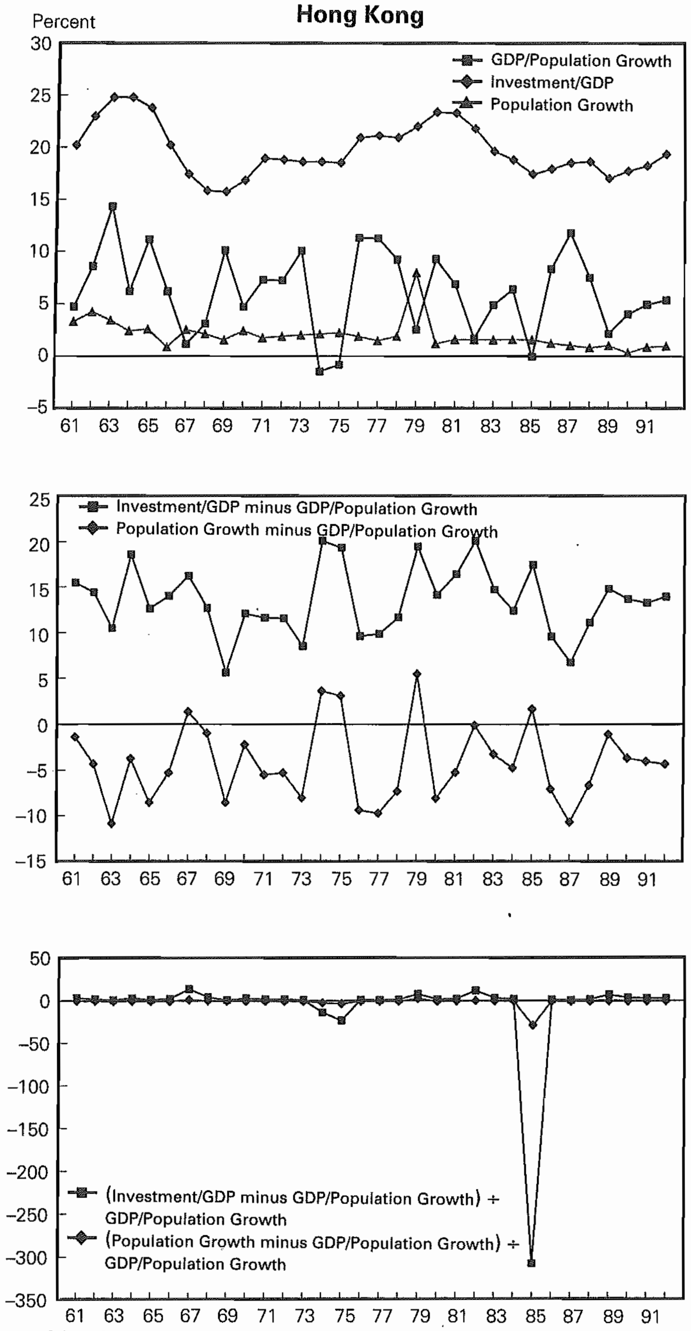
Figure 7
Japan



Source of data: Summers and Heston (1991).

Appendix: Does Investment Rise Before, or After, the Growth Takeoff?

Figure 8
Hong Kong



Source of data: Summers and Heston (1991).

DISCUSSION

Adam B. Jaffe*

This paper by J. Bradford De Long provides a clear and provocative overview of a number of issues related to long-run trends in economic growth. The paper makes five important points. First, the historical record provides us with the task of reconciling the fact that income per capita has been diverging across nations (unconditional divergence) at the same time that countries individually appear to be converging towards the steady-state income levels implied by their savings and population growth rates (conditional convergence). Second, population growth rates are endogenous, tending to decline as per capita income rises. Third, the real price of investment goods is also endogenous, and tending to decline as income rises. Fourth, both of these "positive feedback" effects amplify the impact of differences in productivity across countries. And fifth, such productivity differences are not determined solely, or perhaps even primarily, by "technology" as that term is normally defined.

There is much that I agree with in this presentation, at least qualitatively. In my comment, I wish to make three points that bear primarily on the interpretation and implications of these findings. First, I believe that the evidence for the *qualitative* endogeneity of population growth and the real price of investment goods is compelling. These phenomena undoubtedly are important in understanding the historical record, particularly the dramatic failure of *some* of the world's underdeveloped countries to grow. Second, it is less clear that modeling these phenomena as continuous functions, and analyzing their effects in the steady state, is the most useful approach. The change in population

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growth, particularly, is more likely to behave as a one-time transition, its occurrence facilitated by high income. Finally, I would put aside the semantic question of which shifters of the aggregate production function ought to be labeled "technology" and which "not technology." But I would endorse the charge to disaggregate the different sources of such shifts and to understand how economic incentives and effects differ for different sources of productivity improvements.

The Case for Qualitative Endogeneity Is Compelling

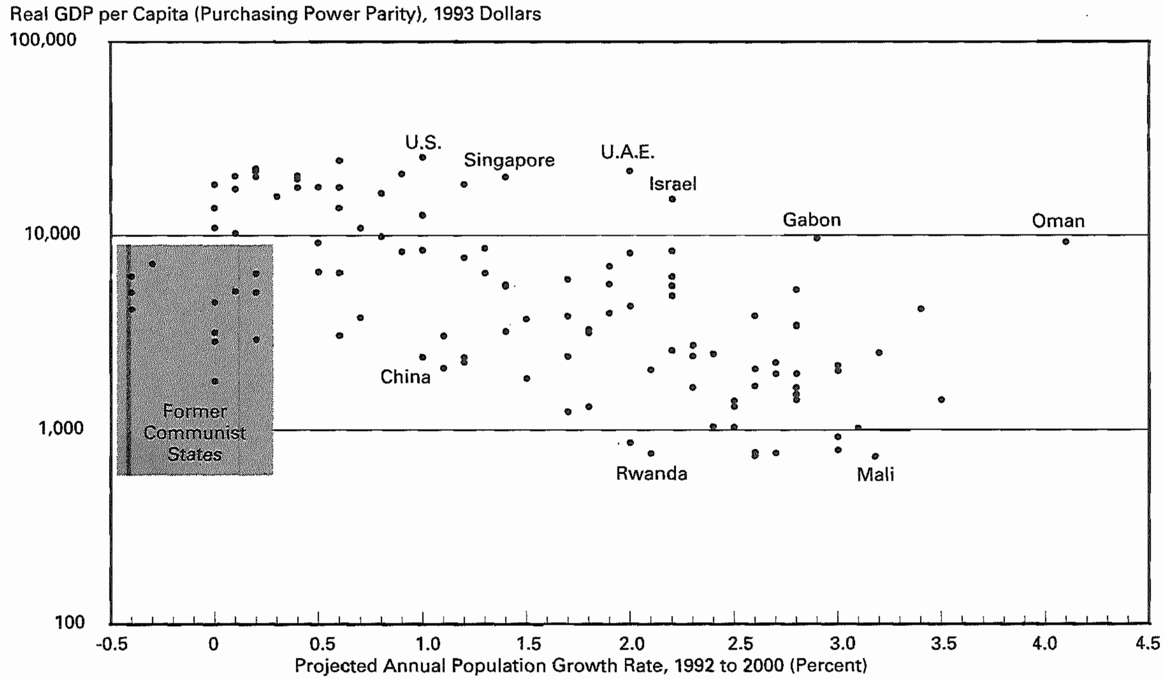
De Long's paper makes the case for the effect of income on population growth primarily by reference to the historical record in the United States. This case can be augmented by the cross-sectional evidence presented in my Figure 1. This plot shows a strong negative relationship between the log of purchasing power parity (PPP) per capita income and the rate of population growth. The simple correlation coefficient between the two series is about −0.6, and a regression line implies that an increase in income from $1,000 to $10,000 per capita is associated with a decline in population growth from about 2.5 percent per year to about 1.5 percent per year. Of course, causality runs in both directions here. But the magnitude of the relationship makes it implausible that it is due entirely to high population growth leading to low income per head. If two countries started out at the same income level, but one had population growth of 1.5 percent and one had population growth of 2.5 percent, it would take 156 years for the per capita income of the less fertile country to reach 10 times that of the other, all else equal. Hence, the cross-section evidence supports the proposition that the countries in the lower right-hand corner of the scatter have high rates of population growth *because* they have low income, to a significant extent.

My acceptance of the effect of income on the price of investment goods has a theoretical rather than an empirical basis. By definition, improvements in productivity make goods and services cheaper (in real terms) than they used to be. It is clear that productivity improvements over the last century have been disproportionately concentrated in manufactured goods, for which the application of non-animal energy and techniques of mass production have dramatically increased output.[1] This means that the real price of manufactured goods has fallen faster than the real price of services. If investment draws on manufactured goods more

[1] The true *extent* of the concentration of productivity improvements in manufacturing is difficult to determine, because output of the service sector is so hard to measure. But the direction of the bias is not in doubt.

Figure 1

The Relationship between per Capita Income and Population Growth



than it draws on services, then it has to be the case that the relative price of investment goods falls as productivity rises.

Note that this positive feedback mechanism, and its resulting implications for unconditional divergence, do not depend on international trade. Completely autarkic economies would enjoy the same positive feedback as productivity rose, and this positive feedback would amplify income differences resulting from productivity differences. The real exchange rate figures provided in De Long's paper are the manifestation of the underlying disproportionate rates of productivity improvement, not the cause.

Feedback Effects Are Not Smooth or Continuous

Referring back to Figure 1, the correlation between log income and population growth falls to -0.3 if only countries above the median income (about \$3,000) are considered. For countries above \$10,000 (the income level where the regression line crosses the U.S. population growth rate of 1 percent), the correlation is actually $+0.15$, though this positive correlation is not significantly different from zero. Thus, among the approximately 30 countries with income at least as high as Slovenia or Korea, there appears to be no further depressing effect of income increases on population growth. Hence, rather than a function $\phi \ln(y)$ as modeled by De Long, it would seem more appropriate to think of a demographic transition that countries must traverse, reducing their population growth rate from something like 2.5 percent per year to something like 1 percent or less. With the exception of small, natural resource-rich countries and countries with high immigration rates, all wealthy countries have made this transition. Rising income helps in making this transition, but it is clearly not a necessary condition, as demonstrated by the important examples of China and the other formerly Communist states.[2]

This one-time demographic transition has different steady-state implications than the model analyzed by De Long. Essentially, two classes of steady states exist, one class in which the demographic transition has been made, and one class in which it has not. The two classes will have very different levels of per capita income, but within classes the amplification effect described by De Long for differences in initial productivity levels will not operate. One way to think of it may be that higher productivity increases the *probability* of making the demographic transition, rather than increasing steady-state income per se.

This suggests that the endogeneity of population growth was more

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[2] Interestingly, very few countries that have achieved population growth of 1 percent or less are not *either* high-income or once-Communist.

important historically than it will be prospectively. While it clearly helps us in understanding what happened in the United States over the past century and what will happen to the countries of sub-Saharan Africa over the next several decades, it is apparently irrelevant to understanding what will happen in China or the former Soviet Union.

Finally, understanding that income affects population growth, and probably does so in a highly nonlinear way, has implications for the econometric specification of the conditional convergence regressions that De Long discusses. Accepting the population growth rate as a nonlinear function of income suggests that the conditional convergence regressions have to be estimated as part of some kind of nonlinear system of equations.

Sources of Differences in Total Factor Productivity Across Time and Space

I do not think that it is productive to engage in extended debate regarding which factors that shift production functions ought to be labeled technology and which ought to be labeled something else. What I do think is productive is to recognize that production functions differ for several distinct reasons, and with different implications for economic analysis. My personal list would look something like this:

- *Hardware*: technology embodied in equipment;
- *Software*: technology embodied in digital programs, training manuals, textbooks, and other places where knowledge is encoded in ways that can be read by others;
- *Human capital*: skills that can be taught, or acquired through learning by doing;
- *Ideas*: knowledge carried by humans in their minds that cannot be or is not encoded in software;
- *Institutional and market factors*: political, legal, and social forces that affect efficiency;
- *Idiosyncrasies*: everything else.

These shifters of the production function differ in the nature of incentives that surround their creation and in the economic forces that govern their spread. For example, ideas are *nonrival* in use, meaning that their use in one context does not deplete them. Software also is largely nonrival, equipment is less so, and human capital is largely rival. This means that their contribution to output is likely to be characterized by increasing returns to scale, with implications for growth as captured in the new growth theory models.

Another important characteristic is the extent to which factors are *excludable*, meaning that it is possible to prevent people who do not pay for them from using them. Human capital is mostly excludable, but hardware and software are only partially so. This means that their creation produces spillovers, implying that their contribution to output and hence growth exceeds their returns to their creators. Finally, hardware and software are largely portable and tradable, facilitating their diffusion around the world; human capital and ideas are much less so. By identifying and analyzing these distinct categories, we can begin to understand the economic forces driving productivity improvement and hence growth.

ADDRESS: JOB INSECURITY AND TECHNOLOGY

Alan Greenspan*

I regret that I was unable to join you for the earlier portions of this conference. I know that you have had some important explorations of the process through which technology contributes to economic growth. What I would like to do in this session is perhaps augment these discussions by shifting gears a bit. I would like to focus on the question of how people *perceive* the benefits of recent technological change.

Today a truly puzzling phenomenon confronts the American economy: I refer to the pervasiveness of job insecurity in the context of an economic recovery that has been running for more than five years, inflation that has been contained, and a layoff rate that is historically quite low. Yet, in the face of all this seemingly good news, a sense persists that something is fundamentally wrong. This afternoon I want to try to explain where I believe the insecurity is coming from and, I hope, raise some suggestions as to how it might be assuaged.

The issue, as best I can judge, appears to be rooted in one of those rare, perhaps once-in-a-century events—a structural technological advance. The advent of the transistor and the integrated circuit and, as a consequence, the emergence of modern computer, telecommunication, and satellite technologies have fundamentally changed the structure of the American economy. Since the beginning of the Industrial Revolution, our economy and, to only a slightly lesser degree, the economies of our industrial trading partners have been progressing toward a regime in which abstract ideas and concepts are the dominant element in the creation of economic value. A hundred years ago, physical brawn was critical to value-added determination. People who personally could lift

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rolled sheet steel and help haul it from one part of the plant to another performed an activity that was valuable in the marketplace. Today, several generations later, the structure of production has become, to a remarkable degree, idea-determined.

On the output side, at the turn of the twentieth century, we produced steel, industrial chemicals, and heavy fabrics in abundance; what impressed was the very size and bulk of the productive facilities and the output itself. Today, the products that we find remarkable are those that are lighter, smaller, and in some cases, almost invisible. Our radios used to be activated by large vacuum tubes; today we have pocket-sized transistors to perform the same function. Thin fiber optic cables have replaced huge tonnages of copper wire. In the past, buildings were so over-structured and sturdy that, when their time for replacement arrived, demolition was a Herculean task. Owing to conceptual advances in metallurgy, engineering, and architectural design, we now can enclose as much or more space with fewer materials.

Indeed, such advances have created an overall national output whose physical weight probably is only modestly greater than that of whatever we produced a hundred years ago. Real GDP, that is, price-adjusted value added, of course is much higher today; and by far, ideas account for the difference. That trend will doubtless continue because idea creation is irreversible. Knowledge, once acquired, does not disappear.

If anything, this process has accelerated in recent years, and that acceleration seems to have had two important side effects. First, it has had a major influence on the distribution of income in this country; and second, a related but different concept, it has imparted a degree of insecurity, uncertainty, and even fear to a vast segment of jobholders. The consequence of both effects, as I will explain shortly, has been to create a sense that something in the economy is awry, which is wholly at odds with what the macroeconomic data seemingly imply—economic success, tranquility, and progress.

The roots of this puzzling situation go back a few decades. As ideas became especially valuable relative to physical activity in the creation of value added, education and intellectual skill became increasingly major determinants of income. Throughout the 1960s and 1970s, the rapid rise in the number of college graduates apparently kept the supply of educated workers moving up with the demand. However, by the latter 1970s and into the 1980s, demand seemed to have outstripped supply; the apparent consequence was a fairly pronounced rise in compensation going to college graduates relative to the compensation going to those who had only high school diplomas. A similar disparity of earnings developed between those who had graduated from high school and those who had dropped out.

After the mid 1970s, productivity slowed quite markedly, for reasons that are not wholly apparent, and so did average real incomes. As a consequence, the widening disparity also means that a not insignificant portion of our work force—primarily those whose work involves less conceptual activities—has been experiencing either stagnant or falling real incomes in the past 10 or 15 years. A substantial number of these people understandably feel that they have been on a treadmill and are barely able to make ends meet from their incomes. That feeling has engendered significant concerns about economic and financial well-being among this part of our work force.

I suspect that other concerns affect an even larger group—composed of those who have average-or-above incomes and have been employed in their current jobs for a number of years. These are the people with higher skills, who interact closely day by day with the high-tech part of our capital stock. Because that stock, reflecting computer and telecommunications-based technologies, is turning over very rapidly, the involved workers have a high degree of uncertainty and insecurity about their jobs. As one affected employee commented to a *Wall Street Journal* reporter a couple of weeks ago, "Is . . . somebody getting ready to change my whole life for me?"[1] These workers perceive the job skills that they have acquired through high school or college to be increasingly open to competitive challenge. One must wonder how highly skilled, turn-of-the-century telegraphers felt with the onset of the telephone or the skilled buggy-whip craftsman with the advent of the automobile. Today, large numbers of people have become so demonstrably insecure about whether their skills will still be relevant in, say, five years that they fear for their jobs.

This insecurity is evidenced by the fact that they have increasingly forgone wage hikes for job security. As a consequence, the past few years have been a period of extraordinary labor peace. In fact, 1995 had the lowest strike record for a half-century. Moreover, labor contracts, which historically almost never extended beyond 36 months, are now sometimes going out five and six years as people try to lock in job security, often willing to forgo significant wage increases in the process.

This sense of job insecurity is so deep that many workers are truly scared. Some fear that their skills will no longer be appropriate for the future. Some fear their ability to make ends meet in the future. Many appear truly concerned about a prospective decline in their standard of living.

This development is startling considering the overall state of the economy suggested by the macroeconomic data. It is certainly the case that growth in average real income has slowed and that the disparity in real incomes has widened. After reaching a postwar low in the late 1960s,

[1] *Wall Street Journal*, May 16, 1996, page A:16.

income disparities, as measured by Gini coefficients, climbed steadily through 1994—the most recent year for which data are available. Moreover, disparities in the distribution of wealth (net wealth) as measured by the Federal Reserve's Survey of Consumer Finances also widened significantly between the surveys taken in 1963 and 1992, with much of that increase in Gini coefficients occurring during the 1980s. Doubtless, that disparity has widened further in recent years in the wake of major increases in stock and bond prices. But the notion that the economic well-being of the lower-income segments of our work force has deteriorated as much as might be suggested by the widening disparities in the income and wealth statistics is open to question.

I say this because there is a surprising difference between trends in the dispersion of holdings of *claims* to goods and services (that is, income and wealth) and trends in the dispersion of actual consumption, which is, of course, the ultimate determinant of material or economic well-being. Put another way, well-being is determined by things people consume, either directly from their incomes and accumulated savings or indirectly from the stock of household goods they already own—automobiles, telephones, TVS, VCRs, and so forth, not to mention the homes themselves. And disparities in consumption and ownership of hard goods do not appear to have widened nearly as much as income disparities.

I do not wish to disparage income as a partial antidote to insecurity. Nevertheless, some aspects of economic well-being may be more accurately discerned by examining consumption.

A number of researchers have compared trends in the distribution of consumption with the distribution of income. Many of these studies rely on data from the Consumer Expenditure Survey that the Bureau of Labor Statistics conducts, and much of the analytical research on distributional issues has been carried out by BLS economists. A recent study by David Johnson and Stephanie Shipp of the BLS finds that "income inequality is more volatile than consumption and the level is about 30 percent more than that of consumption inequality."[2]

These findings are not surprising. As is well known, consumers tend to maintain their levels of consumption in the face of temporary changes in income. Variations in asset holdings and debt buffer changes in income. In short, consumption patterns tend to look more like patterns in income that has been averaged over several years, rather than the one-year convention of our statistics.

But, besides finding differences in the levels of consumption and income inequality, Johnson and Shipp find differences in the inequality

[2] David Johnson and Stephanie Shipp, "Changing Inequality in the U.S. from 1980–1994: A Consumption Viewpoint," manuscript, U.S. Bureau of Labor Statistics, January 1996, and U.S. Department of Labor, *Report on the American Workforce*, 1995.

Table 1
Gini Coefficients for Consumption and Income[a]

Year	Consumption	Income
1980	.291	.365
1981	.286	.369
1982	.299	.380
1983	.298	.382
1984	.307	.383
1985	.315	.389
1986	.326	.392
1987	.322	.393
1988	.320	.395
1989	.325	.401
1990	.325	.396
1991	.321	.397
1992	.331	.403
1993	.321	.429
1994	.317	.426

[a] Based on annual average data.

Source: Consumption data are from the *Consumer Expenditure Survey*, U.S. Bureau of Labor Statistics. Income data are from the U.S. Bureau of the Census.

trends. In particular, although consumption inequality has increased, on average, since 1981, the rise has been only three-fourths as large as that of income inequality (Table 1).

An evaluation that views consumption not in terms of outlays but, rather, in terms of the flow of services that comes from purchases, indicates an additional qualification. The reason, of course, for examining the flow of services from spending, and not just current-period spending alone, is that while outlays for food and haircuts, for example, are consumed immediately, a television set that is purchased today provides entertainment over its entire service life. Thus, unless ownership of household appliances and other consumer durables is brought into the evaluation, the story of the dispersion of material well-being is incomplete.

What do the numbers show? During the 1960s and 1970s, the real net stock of consumer durables per household increased an average of 3.1 percent per year. The average growth rate has slowed slightly since then—to a pace of 2.5 percent—but all of that slowing occurred during the recessions of 1980 and 1981–82. Indeed, since 1982 households have been adding to their stock of durables at an annual rate per household of 3.3 percent—slightly faster than in the 1960s and 1970s.[3]

[3] The growth rate of the net stock of owner-occupied housing (measured in 1992 dollars) per household was 2.3 percent annually from 1959 to 1979; 1.3 percent from 1979 to 1994; and 1.8 percent from 1982 to 1994.

Table 2
"Gini Coefficients" for Ownership Rates of Selected Consumer Durables
By income decile

	1980	1994
Microwave ovens	.28	.08
Dishwashers	.29	.22
Clothes dryers	.17	.12
Garbage disposals	.26	.19
Motor vehicles	.09	.07
Freezers	.06	.07
Clothes washers	.08	.09
Refrigerators	.01	.01
Stoves	.01	.01

Source: Based on tabulations from the *Consumer Expenditure Survey*, U.S. Bureau of Labor Statistics. See the technical note for a discussion of the method used to calculate the "Gini coefficients."

Moreover, we have apparently not had a widening disparity in holdings of hard assets like the one that appears in the income and wealth data. Stephanie Shipp and her colleagues in the Division of Consumer Expenditure Surveys at the BLS generously provided the Board's staff with detailed tabulations of the ownership of consumer goods and vehicles by income decile. To be sure, these data show that ownership rates for consumer durables clearly rise with income. But the data also show that for motor vehicles and a number of appliances—for example, dishwashers, clothes dryers, microwave ovens, and even garbage disposals—the distribution of ownership rates by income decile moved toward greater *equality* between 1980 and 1994 (Table 2).[4]

For some consumer goods we are moving toward greater equality because the proportion of households with access to these items is moving close to saturation. For example, nearly all poor families have access to a refrigerator, stove, and color TV. In addition, three-fourths of poor households have telephones, and nearly two-thirds have microwave ovens and VCRs.[5]

These encouraging findings are not without qualification, however. As an example, for personal computers, which nowadays are critical for economic success, the disparity in ownership rates is quite large—around 10 percent for lower-income households in 1994 compared with more than 50 percent for the highest-income decile. And, even when most families own a durable good or vehicle, the number owned by the low-

[4] The calculation of the measure of distributional inequality used to support this statement is described in the attached technical note.

[5] Some of these data are taken from Kathleen Short and Martina Shea, "Beyond Poverty, Extended Measures of Well-Being: 1992," U.S. Bureau of the Census, *Current Population Reports*, P70-50RV, November 1995.

Table 3
"Gini Coefficients" for Number of Units Owned Per Household of Selected Consumer Durables
By income decile

	1984	1994
Microwave ovens	.24	.08
Dishwashers	.27	.21
Clothes dryers	.15	.12
Garbage disposals	.23	.19
Motor vehicles	.14	.13
Freezers	.06	.07
Clothes washers	.08	.09
Refrigerators	.03	.02
Stoves	.03	.02

Source: Based on tabulations from the *Consumer Expenditure Survey*, U.S. Bureau of Labor Statistics. See the technical note for a discussion of the method used to calculate the "Gini coefficients."

income group typically is less than that owned by the upper-income groups. For example, in 1994 lower-income families owned slightly more than one color television set, on average, whereas high-income families tended to own more than two. The figures for motor vehicles are similar—slightly under one per household at the lower end of the income distribution and slightly more than two at the upper end. Nonetheless, even though the inequality in the number of units owned per household is often greater than that in the ownership rate, the degree of inequality measured on this basis narrowed between 1984 and 1994 in a manner similar to the shifts for ownership rates (compare Tables 2 and 3).[6]

But, even if the number of hard assets per family were the same for rich and poor, it is not evident how much this would assuage the current deep-seated sense of insecurity that pervades such a large segment of our work force. Clearly, there is more to economic security than owning consumer durables. In fact, the very forces that load our households with every sort of gadget come from an economy that apparently is changing too quickly for many Americans to absorb readily. Accelerated change fosters fear in all walks of life. It is a rational human response to such an imperative.

Finding a solution to such insecurity is not simple. If job insecurity is largely a fear of skill obsolescence, real or imagined, some way must be found to enhance skills. People who believe that their skills are up-to-date and readily marketable do not inordinately fear job layoffs.

Bolstered by signals from the marketplace, education clearly is

[6] Collection of data in the Consumer Expenditure Survey on the average number of units owned per household did not begin until 1984.

increasingly becoming a lifetime activity. Resting on one's skills as the world rapidly goes by will only intensify a sense of job insecurity. Ongoing schooling and training are becoming ever more relevant for the average worker.

Fortunately, developing human capital is rapidly being perceived by many corporations as adding to shareholder value. If ideas are increasingly the factor that engenders value added, then training and education are crucial to the expansion of company value added and profitability.

As a consequence, corporate universities are emerging as a growth industry in this country. A significant and expanding number of companies require that employees attend class, say, twice a week, at company expense, to augment their on-the-job techniques. Moreover, there is a growing peripheral industry whose basic product is the training of company employees in the latest technologies. Such trends should decidedly be encouraged. Hopefully, in that environment, efforts to increase the competitive skills of workers in the lower half of the income distribution will succeed in narrowing income disparities.

At this point it is unclear whether the particular current surge of technology is peaking and will eventually slow down or whether we are in its early stages. Much of this surge may well represent more wheel-spinning than real increases in production, as our subdued national productivity data suggest. Nathan Rosenberg in his paper for this conference points out that organizational changes and further development of complementary technologies likely will be required before we see the productivity payoff to computer technology. If so, as the infrastructure of the economy finally adjusts itself to the new semiconductor-based revolution, the rapid changes are likely to finally become more evident in increased measured productivity and growth.

In any event, a new world is emerging. The twenty-first century will be different—much more rapidly paced and changing than any of us who have been around for a while have experienced in our lifetimes. There will be a different America out there. Fortunately, job insecurity does not appear to be a problem for a 21-year-old who has experienced nothing else, and even less for a six-year-old who seems to be far more computer literate than grandfather.

As a consequence, with the inexorable turnover of the population, people will adjust. When we go through a period of transition, inevitable symptoms of friction, uncertainty, and fear arise. They will pass.

TECHNICAL NOTE

The raw data on the ownership rates of consumer durables by income decile are not in a form that can be used directly to calculate standard measures of inequality (for example, Gini coefficients or mean log deviations). However, William Cleveland of the Board's staff suggested a transformation of the raw data that allows one to calculate a measure of inequality that looks like a Gini coefficient. This note describes the procedure.

The first step is to transform the raw data into a discrete probability distribution. In the case of ownership rates for consumer durables, the calculation for a given consumer good is:

$$p_i = r_i / \sum_{i=1}^{10} r_i \tag{1}$$

where p_i is the fraction of all households that own the consumer good who are in income decile i, and r_i is the actual ownership rate for the i^{th} decile. By construction, the sum of the p_i's is equal to one. For goods that have ownership rates that are relatively equal across deciles (regardless of the level of the ownership rate), these probability distributions are fairly flat, with values of P_i close to 0.1. For goods that are more concentrated among the affluent households, the probability distributions tend to rise across income deciles.

The next step is to take the probability distributions and create cumulative probability distributions (CPD) (for example, the value of the CPD for the second decile equals $P_1 + P_2$). The CPDs look like Lorenz curves. The standard formula for the Gini coefficient is then used to construct a measure of the degree of inequality implied by the CPDs.[7] These are shown in Table 2.

The calculation of "Gini coefficients" for the average number of units owned per household in each income decile (u_i) is the same, except u_i is substituted for r_i in equation (1). These "Gini coefficients" are shown in Table 3.

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[7] The "Gini coefficient" is defined as one minus twice the area under the CPD. Although this statistic looks like a Gini coefficient, it does not have all the properties of a true Gini coefficient. For example, a true Gini coefficient must fall between zero and one; but the "Gini coefficient" calculated here could have turned out to be negative if, say, poor people had owned more microwave ovens than rich people.

Microeconomic Policy and Technological Change

Edwin Mansfield*

My assigned topic is the question: Can policymakers spur or deter technological change? The question is to be addressed from a micro perspective, by examining policies regarding research and development (R&D), patents, and competition. Since there is no point in keeping the reader in suspense, I shall argue that government policy plays a major role in influencing the rate of technological change in many important industries.

The paper begins by looking at the salient features of federal support of R&D activities in the private sector of the economy. The next two sections take up the rationale for federal support of R&D and then consider whether, on a priori grounds, it is possible to say with any reasonable degree of certainty that underinvestment in R&D occurs in particular parts of the private sector.

Measures of the social benefits from new technology are then taken up, with particular emphasis on the social rate of return from investments in new technology. The gap between social and private rates of return from investments in new technology is also discussed. Building on the previous results, I then put forth five guidelines regarding public policy toward civilian technology. These guidelines are not new, but I believe that they are just as applicable today as they were when first presented 20 years ago. The final sections of the paper take up the patent system and antitrust policy, two areas continually subject to attention and controversy.

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*Professor of Economics and Director of the Center for Economics and Technology, University of Pennsylvania. This paper draws freely on the author's papers listed in the references, as well as on his previous reports to government agencies. Most of this work has been supported by grants from the National Science Foundation.

Federal Support for R&D

Expenditures in the United States for R&D in 1995 totaled $171 billion, of which about 35 percent was financed by the federal government (National Science Foundation 1995b). Federal R&D expenditures are concentrated heavily in a relatively few areas. In 1996, almost $38 billion was spent on defense R&D and almost $8 billion on space R&D. Health R&D accounted for over $11 billion. Other areas with significant amounts of federally financed R&D were energy, environmental protection, transportation, agriculture, and education. The federal government also spent a considerable amount on the general advancement of science and technology (National Science Foundation 1995a).

Much of the federal R&D takes place outside government laboratories. In 1995, the Department of Defense performed about one-fourth of its R&D in government laboratories; most of the remainder was carried out by industrial firms. Similarly, NASA did about one-quarter of its R&D in government laboratories, while industry performed much of the rest. On the other hand, the Department of Energy undertook about one-half of its R&D in federally funded centers like Oak Ridge, Sandia, Brookhaven, and Los Alamos, some of which are administered by private firms, some by universities and other nonprofit institutions. Still other agencies, like the Department of Agriculture and the Department of Commerce, carried out most of their R&D in their own laboratories.

Industries also exhibit substantial differences in the extent to which their R&D is financed by the federal government. As shown in Table 1, in 1992 the federal government financed about 40 percent of the R&D in transportation and computer programming, the industries with the largest shares of federally financed R&D. In the chemical, petroleum, primary metals, and food industries, among others, the percentage of total R&D that is federally financed is much smaller.

Finally, our nation's colleges and universities are heavily dependent upon the federal government for R&D funds. About 60 percent of the R&D carried out by the colleges and universities is financed by the federal government. Table 2 lists the 30 universities that received the most federal support for R&D in 1993 and the amount each received. As would be expected, the leading research-oriented universities, such as MIT, Harvard, Cornell, Michigan, and Stanford, ranked among the highest. In 1990, the 100 universities and colleges at the top of this list received about 85 percent of the total federal obligations to colleges and universities.

Rationale for Federal Support of R&D

The rationale for federal support of R&D varies from one area to another. Many areas with relatively large amounts of federally financed R&D are intended to provide new or improved technology for public

Table 1
Funds for R&D Performance, by Industry and Source, 1992
Millions of Dollars

Industry	Industry Financed	Federally Financed	Total
Total	96,654	24,660	121,314
Food	1,371	0	1,371
Tobacco	40	0	40
Textiles	190	[a]	[a]
Apparel	69	[a]	[a]
Lumber	[a]	0	[a]
Furniture	168	[a]	[a]
Paper	1,191	[a]	[a]
Printing	[a]	[a]	290
Chemicals	16,420	[a]	16,711
Petroleum	2,330	9	2,339
Rubber	1,337	[a]	[a]
Leather	[a]	0	[a]
Stone, Clay, and Glass	479	[a]	[a]
Primary Metals	542	[a]	555
Fabricated Metal Products	764	293	1,057
Machinery	14,073	1,062	15,135
Electrical Equipment	9,689	3,857	13,546
Transportation	15,726	10,738	26,484
Instruments	7,426	2,226	9,652
Miscellaneous Manufacturing	322	[a]	[a]
Communication Services	4,131	[a]	[a]
Electric and Gas	309	[a]	[a]
Computer Programming	3,889	2,774	6,663
Hospitals and Medical Laboratories	424	191	615
Research, Development, and Testing	8,286	1,381	9,667
Other Manufacturing	7,172	257	7,429

[a] Data withheld to avoid disclosing operations of individual companies.

Source: National Science Foundation, *Research and Development in Industry, 1992*. (Washington, DC: National Science Foundation, 1995.)

sector functions. Defense and space exploration, for example, are public goods; it is inefficient (and often impossible) to deny their benefits to a citizen who is unwilling to pay the price. The government is the sole or principal purchaser of the equipment used to produce such goods; and since it has primary responsibility for their production, it must also take primary responsibility for the promotion of technological change in relevant areas. Although much of the R&D of this type is performed by private firms, its primary objective is to promote technological change not in the private sector but in the public sector. While some beneficial spillover to private industry may occur, it is likely to be much less than if the funds were spent directly on private sector problems.

Table 2
Federally Financed R&D Expenditures in Science and Engineering at the 30 Colleges and Universities Receiving the Largest Amounts, 1993

Rank and University	Millions of Dollars	Rank and University	Millions of Dollars
1 Johns Hopkins	674	16 Penn State	160
2 Washington	269	17 California, Berkeley	156
3 MIT	267	18 Southern California	150
4 Stanford	254	19 Pittsburgh	142
5 Michigan	250	20 Illinois	141
6 California, San Diego	243	21 Texas	139
7 Wisconsin	214	22 Colorado	139
8 California, San Francisco	210	23 Duke	136
9 Cornell	195	24 North Carolina	131
10 California, Los Angeles	189	25 Rochester	131
11 Columbia	183	26 Washington (St. Louis)	129
12 Harvard	182	27 Texas A & M	123
13 Minnesota	175	28 Arizona	113
14 Pennsylvania	174	29 Ohio State	109
15 Yale	169	30 California, Davis	105

Source: National Science Foundation, *Academic Science and Engineering R&D Expenditures, Fiscal Year 1993*, NSF 95-332.

Another rationale for large federally financed R&D expenditures is the presence of some form of market failure. The fact that farms are relatively small productive units has been used to justify federally financed R&D for agriculture, for example. Further, some federally financed R&D is directed toward the general advance of science and technology. Such expenditures seem justified because the private sector will almost certainly invest less than is socially optimal in basic research. This underinvestment occurs because the results of such research are unpredictable and usually of little direct value to the firm supporting the research, although potentially of great value to society as a whole.[1]

Are Existing Federal Programs Adequate?

Economic theory has been used to analyze whether existing federal programs supporting civilian technology are likely to be adequate. Because it is often difficult for firms to appropriate the benefits that society receives from new technology, private investors may tend to devote too few resources to its development. In particular, the more competition there is and the more basic the information, the less appro-

[1] See Alic, Branscomb, Brooks, Carter, and Epstein (1992); Cohen and Noll (1994); Eads (1974); Grossman and Helpman (1991); and Mansfield and Lee (forthcoming).

priable the new technology is likely to be. Also, firms may invest too little in inherently risky R&D efforts, because many seem to be risk averse and have only limited and imperfect ways to shift these risks.

Moreover, particular kinds of R&D may be characterized by economies of scale that prevent small organizations from undertaking them efficiently. This argument seems much more applicable to development than to research, however. While firms may have to be of a certain minimum scale to do many kinds of R&D effectively, this scale may be a relatively small share of the market. In fact, small firms have been responsible for many important innovations, while many big firms have concentrated on more minor product improvement innovations. Nonetheless, it is often argued that some industries are so fragmented, they cannot do the proper amount of R&D.

Despite the relevance of the preceding arguments, they by no means prove that there is at present any underinvestment in civilian technology. For one thing, these arguments generally assume that markets are perfectly competitive, whereas in fact many important markets are oligopolistic. In oligopolistic markets, many economists believe that firms often stress product improvement as a form of rivalry, rather than direct price competition. Because of tacit agreement among the firms, product improvement may even be the principal form of rivalry, with the result that more may be spent on R&D than is socially optimal. This is not, however, a proposition that is easy to prove or disprove.

Another reason why there may be no underinvestment in civilian technology is that the government is already intervening in a large number of ways to support civilian R&D. For example, a tax credit has been granted for R&D and the National Institute of Standards and Technology's Advanced Technology Program has awarded hundreds of millions of dollars in grants. Sematech (the Semiconductor Manufacturing Technology Corporation) has received federal subsidies of $100 million a year, and in industries like aircraft, a host of government influences promote R&D and technological change. It is not obvious, on a priori grounds, thus, that the government has not already offset whatever latent underinvestments existed in R&D.

Going a step further, Partha Dasgupta and Joseph Stiglitz (1980) have questioned whether on balance there is any reason for supposing that a market economy results in too low a level of investment in R&D. They conclude that the fact that only a relatively few firms are engaged in R&D does not show that a market economy contains too little R&D activity, and that the pressures of competition may result in excessive speed in research.[2]

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[2] See Arrow (1962); Cohen and Noll (1991); Dasgupta and Stiglitz (1980); Mansfield (1996), and Romer (1990).

Measuring Social Benefits from New Technology

Because pure theory cannot tell us whether underinvestment in R&D exists in the private sector (and if so, where it is most severe), let us turn to the available empirical studies of the returns from R&D of various types. Of course, measuring the social benefits from new technology presents a variety of problems. Any innovation, particularly a major one, has effects on many firms and industries, and obviously it is difficult to evaluate each one and sum them up properly. Nonetheless, economists have devised techniques that should provide at least rough estimates of the social rate of return from particular innovations, assuming that the innovations can be regarded as basically resource-saving in nature.

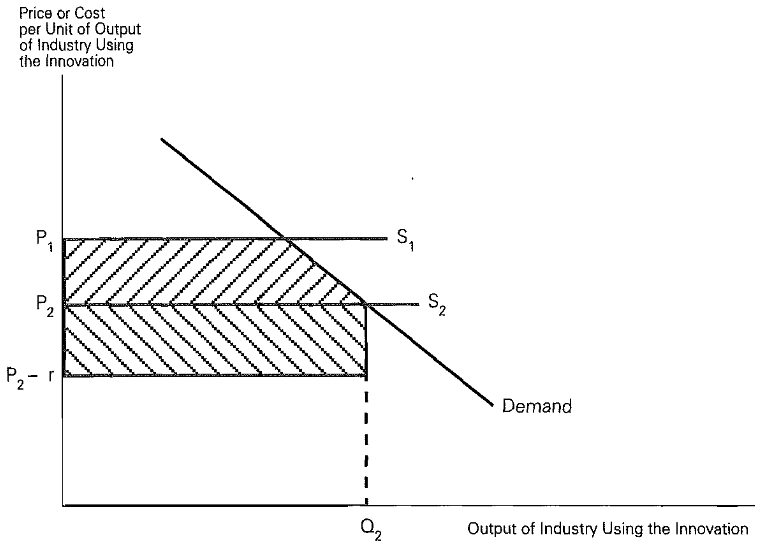
Consider a new product (used by firms) that can shift the supply curve of the industry using the new product. How far downward this supply curve will shift depends on the pricing policy of the innovator. Assume that the innovator decides to set a price for its new product that yields a profit to the innovator equal to r dollars per unit of output of the industry using the innovation (for example, r dollars per appliance, in the case of a new type of metal used by the appliance industry). Also, assume that the industry using the innovation is competitive, that its demand curve is as shown in Figure 1, and that its supply curve is horizontal in the relevant range. In particular, suppose that, before the advent of the innovation, this supply curve was S_1 in Figure 1, and the price charged by the industry using the innovation was P_1. After the advent of the innovation, this supply curve is S_2, and the price is P_2.

The social benefits from the innovation can be measured by the sum of the two shaded areas in Figure 1. The upper shaded area is the consumer surplus due to the lower price (P_2 rather than P_1) stemming from the use of the innovation. Also, a resource saving occurs, along with a corresponding gain in output elsewhere in the economy, because the resource costs of producing the good using the innovation—including the resource costs of producing the innovation—are less than P_2Q_2. Instead, they are P_2Q_2 minus the innovator's profits from the innovation, the latter being merely a transfer from the makers of the good using the innovation to the innovator. Thus, in addition to the consumer surplus arising from the price cut, a resource saving occurs, amounting to the innovator's profits.

In many cases, two adjustments must be made in this estimate, which corresponds with the lower shaded area in Figure 1. First, if the innovation replaces another product, the resource saving described in the previous paragraph does not equal the innovator's profits from the innovation, but these profits less those that would have been made (by the innovator or other firms) if the innovation had not taken place and the displaced product had been employed instead. This lesser amount is the proper measure of the resource saving. Second, if other firms imitate

Figure 1

Social Benefit from New Product



the innovator and begin selling the innovation to the industry that employs it, their profits from the sale of the innovation must be added to those of the innovator to get a complete measure of the extent of the resource saving caused by the innovation.

One also can measure the social benefits from new products used by individuals rather than firms, and from new processes. But since the principles involved are much the same as those described above, we will not present the measurement procedures here (see Mansfield et al. 1977a, 1977b).

Social Rates of Return

By a social rate of return, we mean the interest rate received by society as a whole from an investment. To economists, the social rate of return from investments in new technology is important, since it measures the payoff to society from these investments. A high social rate of return indicates that society's resources are being employed effectively and that more resources should be devoted to such investments, if the rate of return stays high. In a series of papers, I have tried to describe the many difficulties in measuring and interpreting the social rate of return.[3] They are numerous and important, but until something better comes along, estimates of this sort are likely to continue to be used.

Although earlier efforts to measure the social rates of return from such investments had been made in agriculture, the first attempt to measure the social rate of return from investments in industrial innovations was published in 1977. The innovations that were included in the study took place in a variety of industries, including primary metals, machine tools, industrial controls, construction, drilling, paper, thread, heating equipment, electronics, chemicals, and household cleaners. They occurred in firms of quite different sizes. Most of them were of average or routine importance, not major breakthroughs. While the sample could not be viewed as randomly chosen, we found no obvious sign that it was biased toward very profitable innovations (socially or privately) or relatively unprofitable ones. The findings indicated that the median social rate of return from the investment in these innovations was 56 percent, a very high figure (Mansfield et al. 1977a, 1977b).

It is important to recognize that this sample was not confined to "winners." We went to considerable trouble to get as representative a sample as possible. The innovations were chosen at random from those carried out recently by the cooperating firms. A very substantial number turned out to have low or negative private returns. (One interesting finding was that the social rate of return tended to be very high for these "losers" as well as for the "winners".) One of the contributions of this study, in our opinion, was that it included a broader and more representative sample than any in the past. To extend this sample and replicate the analysis, the National Science Foundation commissioned two studies, one by Robert R. Nathan Associates (1978) and one by Foster Associates (1978). Their results, like ours, indicate that the median social rate of return tends to be very high. Based on its sample of 20 innovations, Nathan Associates found the median social rate of return to be 70 percent. Foster Associates, based on its sample of 20 innovations, found the median social rate of return to be 99 percent.

More recently, Manuel Trajtenberg (1990) estimated that the social rate of return to R&D in the field of CT scanners in medical technology was about 270 percent. As he is careful to point out, the interpretation of the gains as social depends on the motives underlying the behavior of hospitals when choosing medical technologies. Also, as in the example of hybrid corn, which Zvi Griliches (1958) studied, a high rate of return

[3] For example, see Mansfield (1991a, 1991b, 1992, 1995d) and Nadiri (1993).

would be expected because the innovation was known in advance to be a gusher, not a dry hole. But bearing these things in mind, Trajtenberg's results certainly are consistent with the proposition that the social rate of return from investments in new technology tends to be high.

In sum, practically all of the studies carried out to date indicate that the average social rate of return from industrial R&D is very high. Moreover, the marginal social rate of return also seems high, generally in the neighborhood of 30 to 50 percent. As I have pointed out elsewhere, a variety of very important problems and limitations are inherent in each of these studies.[4] Certainly, they are very frail reeds on which to base policy conclusions. But recognizing this fact, it nonetheless is remarkable that so many independent studies, based on so many types of data, result in so consistent a set of conclusions.

The Relationship between Social and Private Returns

The gap between social and private rates of return from investments in new technology is of great importance. A major rationale for government support of civilian technology is that some R&D projects have social rates of return far in excess of their private rates of return. What determines the gap (if it exists) between the social and private rates of return? One relevant factor is the market structure of the innovator's industry. If the innovator is faced with a highly competitive environment, it is less likely to be able to appropriate a large proportion of the social benefits than if it has a secure monopoly position or is part of a tight oligopoly. Of course, the extent to which the innovator is subjected to competition, and how rapidly, may depend on whether the innovation is patented. Another consideration of at least equal importance is how expensive it is for potential competitors to "invent around" the innovator's patents, if they exist, and to obtain the equipment needed to begin producing the new product (or using the new process). In some cases, like Du Pont's nylon, it would have been extremely difficult to imitate the innovation (legally). In other cases, a potential competitor could obtain and begin producing a "me-too" product (or using a "me-too" process) at relatively little cost.

Another factor that economists have emphasized as a determinant of the size of the gap between social and private rates of return is whether the innovation is major or minor. According to R.C.O. Matthews (1973), the "degree of appropriability is likely to be less . . . in major innovations than in minor ones" since major innovations are more likely, in his view, to be imitated quickly. Similarly, on the basis of a model stressing the

[4] For example, see Mansfield (1991b).

indivisibility of information, Kenneth Arrow (1962) concluded that "the inventor obtains the entire realized social benefit of moderately cost-reducing inventions but not of more radical inventions."

Still another consideration sometimes cited is whether the innovation is a new product or a new process. Thus, Matthews hypothesized that the degree of appropriability might be less for process innovations than for product innovations. On the other hand, Richard Nelson, Merton Peck, and Edward Kalachek (1967) stressed that new processes can often be kept secret and that it frequently is difficult for one firm to find out what processes another firm is using.[5] This idea, of course, suggests that the gap between social and private rates of return might be greater for products than for processes.

Although most of these hypotheses seem quite plausible, they unfortunately have been subjected to just one systematic empirical test, which was based on data for only about 20 innovations (Mansfield et al. 1977a, 1977b). The results seem to support the hypotheses that the gap between social and private rates of return tends to be greater for more important innovations and for innovations that can be imitated relatively cheaply by competitors. Apparently, when the cost of imitating the innovation is held constant, it makes little or no difference whether the innovation is patented—which seems reasonable, because whether or not a patent exists is of relevance largely (perhaps only) because of its effects on the costs of imitation. It is worth noting that this simple model can explain about two-thirds of the observed variation in this gap among the product innovations in our sample. However, at the same time, it is important to bear in mind the small size (and age) of the sample.

Public Policy toward Civilian Technology

For about 25 years, a number of economists have warned that the United States may be underinvesting in civilian technology. Among other things, these economists point out that the marginal social rates of return from investments in civilian technology have been very high, both in agriculture and in industry, according to practically every study carried out. Of course, each of these studies has a number of limitations, but overall their conclusions are remarkably consistent.

The government can stimulate additional R&D in the private sector in a variety of ways—by tax credits, R&D contracts and grants, expanded work in government laboratories, altered regulatory policies, and prizes. Although many economists suspect that underinvestment exists in certain areas of civilian technology, at the same time some voice concern that the federal government, in trying to improve matters, could do more

[5] See Nelson, Peck, and Kalachek (1967) and also Nelson (1959).

harm than good.[6] In this regard, the following five guidelines may be of use.

First, a program to stimulate R&D in the private sector should be characterized by flexibility, small-scale probes, and parallel approaches. In view of the relatively small amount of information available and the great uncertainties involved, the research should be organized, at least in part, to provide information concerning the possible returns from a larger program. On the basis of the information that results, a more informed judgment could be made concerning the desirability of increased or, for that matter, perhaps decreased amounts of government support for R&D in the private sector.

Second, any temptation to focus the program on economically beleaguered industries should be rejected. The fact that an industry is in trouble, or that it is declining, or that it has difficulty competing with foreign firms is, by itself, no justification for additional R&D. More R&D may not have much payoff there or, even if it does, the additional resources may have a bigger payoff elsewhere in the economy. It is important to recall the circumstances under which the government is justified in augmenting private R&D. Practically all economists would agree that such augmentation is justifiable only if the private costs and benefits derived from R&D do not adequately reflect the social costs and benefits. But many industries show little or no evidence of a serious discrepancy of this sort between private and social costs and benefits. Indeed, some industries may spend too much, from society's point of view, on R&D.

Third, except in the most unusual cases, the government should avoid getting involved in the later stages of development work. In general, this is an area where firms are far more adept than government agencies. While situations may exist where development costs are so high that private industry cannot obtain the necessary resources, or where it is so important to our national security or well-being that a particular technology be developed that the government must step in, such cases do not arise very often. Instead, the available evidence indicates that, when governments become involved in what is essentially commercial development, they are not very successful at it.

Fourth, in any selective government program to increase support for civilian technology, it is vitally important that a proper coupling occur between technology and the market. In choosing areas and projects for support, the government should be sensitive to market demand. To the extent that it is feasible, potential users of new technology should play a

[6] See U.S. Congress, Office of Technology Assessment (1995); Eisner, Albert, and Sullivan (1986); Council of Economic Advisers (1994); and U.S. General Accounting Office (1996).

role in project selection. Information transfer and communication between the generators and the potential users of new technology are essential, if the innovation is to be successfully applied. As evidence of the importance of this guideline, studies show that a sound coupling of technology and marketing is one of the characteristics most significant in distinguishing firms that are relatively successful innovators from those that are not (Freeman 1973).

Fifth, in formulating any such program, it is important to recognize the advantages of pluralism and decentralized decision-making. If the experience of the last 30 years has taught us anything, it has taught us how difficult it is to plan technological development. Technological change, particularly of a major or radical sort, is marked by great uncertainty. It is difficult to predict which of a number of alternative projects will turn out best, and very important concepts and ideas come from unexpected sources. It would be a mistake for a program of this sort to rely too heavily on centralized planning. Moreover, it would be a mistake if the government attempted to carry out work that private industry can do better or more efficiently.

The Patent System

One of the major instruments of national policy regarding technology is the patent system. Since the Congress passed the original patent act in 1790, the arguments used to justify the existence of the patent laws have not changed very much. First, these laws are regarded as an important incentive to induce the inventor to put in the work required to produce an invention. Particularly in the case of the individual inventor, it is claimed that patent protection is a strong incentive. Second, patents are regarded as a necessary incentive to induce firms to carry out the further work and make the necessary investment in pilot plants and other items that are required to bring the invention to commercial use. If an invention became public property when made, why should a firm incur the costs and risks involved in experimenting with a new process or product? Another firm could watch, take no risks, and duplicate the process or product if it were successful. Third, it is argued that, because of the patent laws, inventions are disclosed earlier than otherwise; as a consequence, other inventions are facilitated by the earlier dissemination of the information.

Not all economists agree that the patent system is beneficial. A patent represents a monopoly right, although it is often a very weak one. Critics of the patent system stress the social costs arising from the monopoly. They point out that, after a new process or product has been discovered, it may cost little or nothing for other persons who could make use of this knowledge to acquire it. (However, the cost of technology transfer frequently is substantial.) The patent gives the inventor the right to charge a price for the use of the information, with the result that the knowledge is used less widely than is socially optimal. Critics also point out that patents have been used to create monopoly positions that were sustained by other means after the original patents had expired; they cite as examples the aluminum, shoe machinery, and plate glass industries. Further, the cross-licensing of patents often has been used by firms as a vehicle for joint monopolistic exploitation of their market.

Critics also question the extent of the social gains arising from the system. They point out that the patent system was designed for the individual inventor, but that over the years most research and development has become institutionalized. They assert that patents are not really important as incentives to the large corporation, since it cannot afford to fall behind in the technological race, regardless of whether or not it receives a patent. They also assert that, because of long lead times, most of the innovative profits from some types of innovations can be obtained before imitators can enter the market. Also, they say that firms keep secret what inventions they can, and patent those they cannot.

Patents are much more important in some industries than in others.[7] Among a random sample of 100 U.S. firms from 12 industries (excluding very small firms), patent protection was judged to be essential for the development or introduction of 30 percent or more of the inventions in only two industries—pharmaceuticals and chemicals. In another three industries (petroleum, machinery, and fabricated metal products), patent protection was estimated to be essential for the development and introduction of 10 to 20 percent of their inventions. In the remaining seven industries (electrical equipment, office equipment, motor vehicles, instruments, primary metals, rubber, and textiles), patent protection was judged to be of much more limited importance (Mansfield 1986). According to another study, product patents were regarded as much more important by the drug and organic chemical industries than by most others, and process patents were regarded as most important by the drug and chemical industries (Levin, Klevorick, Nelson, and Winter 1987).

Without question, the patent system enables innovators to appropriate a larger portion of the social benefits from their innovations than would be the case without it, but patents may not be very effective in this regard. Contrary to popular opinion, patent protection does not make market entry by imitators impossible, or even unlikely. Within four years of their introduction, 60 percent of the patented successful innovations included in one study had been imitated. Nonetheless, patent protection generally increases the cost (to the imitator) of imitation. According to Mansfield, Schwartz, and Wagner (1981), the median estimated increase in imitation cost was 11 percent. Patents had the biggest impact on

[7] See Mansfield (1995a, 1995b, 1995c, 1986); Ordover (1991), and Scotchmer (1991).

imitation costs in the ethical drug industry, a finding that helps to explain why patents are regarded as more important in ethical drugs than elsewhere. (The median increase in imitation cost was about 30 percent in ethical drugs, in contrast to about 10 percent in chemicals and about 7 percent in electronics and machinery.)

Do the benefits derived from the patent system outweigh its costs? Like many broad issues of public policy, the facts are too incomplete and too contaminated by value judgments to permit a clear-cut, quantitative estimate of the effects of the patent system. Nonetheless, few leading economists, if any, favor abolition of the patent system. Even those who publish their agnosticism with respect to the system's effects admit that it would be irresponsible, on the basis of our present knowledge, to recommend abolishing it.

Technological Change and Antitrust Policy

Finally, a considerable amount has been written by economists concerning the effects of market structure and antitrust policy on the rate of technological change. Although we are far from having final or complete answers, the following generalizations seem warranted, based on the available evidence.

The role of the small firm is very important at the stage of invention and the initial, relatively inexpensive stages of R&D. Studies indicate that small firms and independent inventors play a large, perhaps a disproportionately large, role in conceiving major new ideas and important inventions. Further, although full-scale development often requires more resources than small firms command, the investment required for development and innovation is seldom so great or so risky that only the largest firms in an industry can undertake the innovating or the developing. Studies of the drug, coal, petroleum, and steel industries indicate that, in all of these industries, the firms that carried out the most innovations, relative to their size, were not the biggest firms. However, in the chemical industry, the largest firm was the most innovative relative to its size.[8]

A variety of surveys have been made of the empirical evidence regarding the most favorable conditions for industrial innovation. Wesley Cohen and Richard Levin (1989) conclude that "[T]he effects of firm size and concentration on innovation, if they exist at all, do not appear to be important." Others come to essentially the same conclusion, although threshold effects are recognized. F.M. Scherer (1992) summarizes the situation as follows:

[8] See Acs and Audretsch (1990); Jewkes, Sawers, and Stillerman (1970); Hall (1993); von Hippel (1988); Hirshleifer (1973); and Kamien and Schwartz (1982).

> Even though idea-rich small firms originate a disproportionate share of innovations, most small enterprises are not particularly innovative. Large companies may carry their new technologies to a higher degree of perfection than small firms, and . . . they may excel at certain kinds of innovative activities. But neither giant company size nor a high degree of seller concentration appears necessary to maintain a vigorous pace of technological advance. Keeping markets open to new entrants with novel ideas—a notion closer to the Schumpeterian vision of 1912 than to his 1942 view—seems a more important condition for progress.

Two other points should be noted. First, new firms and firms entering new markets play a very important role in the process of technological change. Existing firms can be surprisingly impervious to new ideas, and one way that their mistakes and inertia can be overcome in our economy is through the entry of new firms. Second, economists generally agree that the ideal market structure from the point of view of promoting technological change is one characterized by a mixture of firm sizes. Complementarities or interdependencies exist among firms of various sizes. A division of labor often occurs, with smaller firms focusing on areas requiring sophistication and flexibility and catering to specialized needs, and bigger firms focusing on areas requiring larger production, marketing, or technological resources.

Thus, the available evidence does not indicate that we must permit very great concentration of American industry in order to achieve rapid technological change and the rapid adoption of new techniques. Instead, it seems to suggest that public policy should try to eliminate unnecessary barriers to entry and to promote competition in American industry.

Conclusions

Without question, government policy has a major impact on the rate of technological change. The federal government supports about 35 percent of the research and development in the United States, the impact being greatest in defense, space, and health. But the effects extend far beyond these areas. In terms of dollar support, the federal government (particularly the National Science Foundation, the Department of Defense, and the National Institutes of Health) provided about two-thirds of the funding for academic researchers cited by the information processing, electronics, chemical, instruments, pharmaceutical, metals, and petroleum industries as having made significant contributions to innovations in these industries during the 1980s (Mansfield 1995d).

Controversy has been continual over the past 35 years with regard to the proper role of the federal government in supporting civilian technology. Since pure theory cannot provide unambiguous guidance, a variety of empirical studies have been carried out. The results, while subject to many limitations, seem to indicate that the social rate of return from R&D

is very high, generally about 30 to 50 percent. Also, some evidence has been found that the gap between social and private rates of return tends to be greater for more important innovations and for innovations that can be imitated relatively cheaply by competitors.

There seems to be considerable reason to pursue small-scale efforts to shed light on the desirability of increased support for various types of civilian technology. However, such efforts hold many potential pitfalls. In particular, the temptation to focus programs on economically beleaguered industries should be resisted; the government should avoid getting involved in the later stages of development work; a proper coupling should occur between technology and the marketplace; and it is important to recognize the advantages of pluralism and decentralized decision-making.

In recent years, the federal government has set in motion a variety of technology programs, including the National Institute of Standards and Technology's Advanced Technology Program, which has devoted hundreds of millions of dollars to projects aimed at the development and commercialization of technologies with high potential payoff. Given the controversy over this program in the Congress, the need for more and better information concerning the social rate of return from the resources allocated to this program is obvious. It seems doubtful that estimates based on forecasted data at the beginning of projects will be very accurate, but with updating as commercialization and diffusion occur, valuable information can be obtained concerning social rates of return, as well as the size of forecast errors and how one can devise and use early estimates in a civilian technology program of this sort.[9]

The patent system also remains a topic of considerable controversy. Except for a relatively narrow slice of the economy, in particular pharmaceuticals and chemicals, patents tend to be of secondary importance. However, few leading economists, if any, favor abolition of the patent system. Indeed, one of the interesting developments in recent years has been a growing recognition that the strength or weakness of a country's system of intellectual property protection seems to have a substantial effect, particularly in high-technology industries, on the kinds of technology transferred by foreign firms to that country. Also, this factor seems to influence the composition and extent of U.S. foreign direct investment, although the size of the effects seems to differ greatly from industry to industry.[10]

Economists have shown a keen and continuing interest in the effects of antitrust policy on technological change. In general, the effects of firm size and industrial concentration on the rate of innovation do not appear

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[9] See Mansfield (1995b).

[10] See Mansfield (1995a, 1995c) and Lee and Mansfield (1996).

to be of major consequence. Complementarities and interdependencies are found among firms of varying sizes. Accordingly, most analysts agree that we should try to eliminate unnecessary barriers to entry and to promote competition in American industry, since achieving rapid technological change and the rapid adoption of new techniques does not require a high level of industrial concentration.

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Discussion

Samuel S. Kortum*

Edwin Mansfield has made an enormous contribution to our understanding of the economics of technological change. His papers are distinctively direct. To learn about the excess social return to innovation, Mansfield et al. (1977) collected detailed information on a sample of innovations and calculated, for each one, the social and private return. The median social rate of return was over 50 percent, roughly twice the median private return. To learn what patents do, Mansfield, Schwartz, and Wagner (1981) asked firms how patenting an innovation affected the cost and time required for a competitor to imitate it. Patenting raised the cost of imitation on average 10 percent, yet most patented innovations were imitated within four years anyway. To learn about the international transfer of technology, Mansfield and Romeo (1980) asked U.S.-based firms how many years elapsed between the introduction of a new technology in the United States and its transfer to an overseas subsidiary. The mean lag was six years for subsidiaries in developed countries and 10 years for subsidiaries in developing countries. Because direct evidence of this sort is all too rare, I keep Mansfield's articles handy.

In the current paper, Mansfield examines the question: Can policymakers spur or deter technological change? Mansfield conducts an informed review of the different government practices that could potentially influence the rate of technological change: research performed by government, research funded by government, research subsidized by government, patent protection, and antitrust policy. He surveys the arguments for a government role in promoting research and suggests

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some guidelines for government intervention. Mansfield concludes: Yes, "government policy has a major impact on the rate of technological change."

At first glance his conclusion appears obvious. How could the federal government—performing 10 percent of U.S. R&D, directly funding 35 percent of it (NSF 1995), and giving it special tax treatment—not have a major impact on technological change? There are two possibilities. First, government policies may have had little effect on incentives to perform research. Second, technological change may not be very responsive to incentives. For example, the rate of technological change may have more to do with the arrival of technological opportunities than with the number of researchers attempting to exploit them. Perhaps, as Francis Bacon put it, "Time is the greatest innovator."[1]

I will use an economic model to show that this second possibility is not so easy to debunk. The logic is simple. Innovations will have value as long as they cannot be freely imitated. Researchers will therefore compete for innovations whether or not R&D effort, on the margin, leads to new discoveries. Thus, a world in which R&D is simply a way of dividing the pie will be difficult to distinguish from a world in which the marginal R&D expenditure leads to innovations that would not otherwise have occurred.

Before launching into this argument, I offer a note of caution. The fact that a model of exogenous technological change is difficult to reject does not imply that it is correct. Nonetheless, formulating it will serve to highlight where our understanding of technological change is weak, and hence where our policy advice is shaky.

Endogenous R&D—Exogenous Technological Change

To be credible, a model of exogenous technological change must fit some basic facts related to R&D and its correlation with other economic variables. A simple model of perfect competition can be rejected because it will not account for any private investment in R&D.

A good starting point instead is Arrow (1962): The owner of a patented process innovation licenses it to producers in a competitive industry in return for a royalty payment.[2] Suppose that the demand for industry output, at price p, is simply $y = S/p$, where S is a demand shifter (equal to the value of industry sales). At a point in time, unit production

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[1] Bacon is quoted by Merton (1961, p. 349) in an essay on multiples in science (the multiple discovery of the same thing).

[2] This is also an interpretation of the framework described in the section of Mansfield's paper entitled "Measuring Social Benefit from New Technology," under the special case where the innovator has all the bargaining power, so that $P_2 = P_1$.

cost is a constant c. It follows that the royalty rate for a process innovation is the reduction in unit cost it makes possible.

Arrow's model of the incentive to innovate says nothing about where innovations come from. In the spirit of Bacon, assume that time generates one opportunity for a process innovation each year. An innovation, if developed and adopted, leads to a fixed percentage reduction in unit cost, as in the quality ladders model of Grossman and Helpman (1991). For example, if unit cost is c_{t-1} in year $t-1$, then after the year t innovation is adopted the unit cost falls to $c_t = \frac{c_{t-1}}{1+\gamma}$. The parameter $\gamma > 0$ can be thought of as the 'size' of an innovation. Suppose for simplicity that patent protection applies only to the state-of-the-art process at any point in time. Competition will result in zero royalties for all but the most recent innovation. The royalty rate in year t will therefore be $c_{t-1} - c_t = \gamma c_t$. Under perfect competition, the industry price in year t is the sum of unit production cost and the royalty rate, $p_t = (1 + \gamma)c_t$. The total royalty received by the owner of the patent on the innovation adopted in year t is therefore

$$V_t = (\gamma c_t)y_t = \frac{\gamma}{1+\gamma} p_t y_t = \frac{\gamma}{1+\gamma} S.$$

In what sense is technological change exogenous? Suppose that an innovative opportunity can be developed by a researcher at a cost of d, and would then be adopted the following year. Which researcher is 'first to invent' and hence able to patent the innovation? After committing to R&D investments of d, each researcher will develop the invention at some time during the year. Who is first to invent is determined by chance; if there are n researchers, they each face a $1/n$ chance of being first.[3] With free entry into research, and ignoring the integer problem, n should satisfy $d = \frac{1}{n}\frac{V}{1+r}$, where r is the interest rate. It is assumed throughout that the parameters satisfy $\frac{\gamma S}{d(1+\gamma)(1+r)} \geq 2$ (so that $n \geq 2$), and hence each innovation will be developed with or without the help of the last researcher. Annual R&D expenditures in the industry are given by

[3] This model of research is a special case of Tandon (1983). Notice that multiple 'discoveries' of the same thing (multiples) generally will occur. Merton (1963) argues that multiples are ubiquitous, but he envisions a more sophisticated model in which more parallel research increases the probability of someone making a discovery. He suggests that there is an optimal amount of redundancy in research, being "that amount which will approximate a maximum probability of achieving the wanted outcome but not so great an amount that the last increment will fail appreciably to enlarge that probability" (p. 380). These concepts are formalized in the general case of Tandon's model.

$$R = nd = \frac{V}{1+r} = \frac{\gamma S}{(1+r)(1+\gamma)}.$$

The model accounts for private R&D even though (for $R \geq d$) technological change is unrelated to R&D.[4]

Can This Model Fit the Facts?

To convince someone of the importance of R&D in determining the course of technological change, it is natural to point to the vast literature on R&D and productivity surveyed in BLS (1989). Econometric studies have uncovered a systematic relationship between the growth of total factor productivity (TFP) and research intensity (the R&D–sales ratio). Unfortunately, these results do not provide convincing evidence against a model, such as the one laid out above, in which technological change is essentially exogenous.

To see this, assume that the model above held in each of $i = 1, \ldots,$ N industries. Industries might differ according to the value of sales S_i and the size of innovations γ_i. TFP growth in industry i is simply γ_i. Research intensity (RI) in industry i is $R_i/S_i = \frac{\gamma_i}{(1+r)(1+\gamma_i)}$. This leads to the equation,

$$TFP_i \approx \frac{(1+r)RI_i}{1-(1+r)RI_i} \approx (1+r)RI_i,$$

where the approximation is adequate for the small values of research intensity that are actually observed. Even though technological change is exogenous, one would get a slope coefficient of $1 + r$ by regressing TFP growth on R&D intensity across the N industries.[5]

This identification problem has been articulated by Griliches (1995, p. 80):

> one may wind up reporting something as an estimate of the effect of R&D on output which may be mostly a reflection of the effect of output on R&D rather than vice versa.

[4] Note that the last researcher's efforts provide no benefit to society. To my knowledge, Barzel (1968) was the first to present a model in which competition could lead to excessive R&D.

[5] The uncharacteristically large coefficient $(1 + r)$ implied by this model—econometric estimates are closer to 0.3 (Griliches 1995, Table 3.3)—is a result of the simplifying assumption that a new innovation arrives each year, hence there is only one year to recoup R&D expenses.

The model above simply illustrates an extreme example of this conundrum.

I now turn to Mansfield's approach, in earlier work, of directly measuring the rate of return to innovations. In the world described by the simple model of exogenous technological change, the private (internal) rate of return to research is r and the marginal social rate of return to research is -100 percent (that is, the marginal expenditure on research has a cost but confers no benefit to society). What would one conclude by collecting data on innovations? The naive economist, collecting data only from the firm that patents the innovation, would calculate an extraordinarily high social and private rate of return on the winner's small investment in research. A more sophisticated economist would count as expenditure all the research costs of the losing firms as well as the winner. In this way, the private rate of return to research would be calculated correctly as equal to the market return r. (This is exactly the condition that determines the equilibrium level of R&D for the industry.) But the marginal social rate of return would be calculated incorrectly as being greater than r, since the social benefits of the innovation extend indefinitely. The mistake in this calculation is that the social benefit should not be attributed to the marginal expenditure on research.

In principle, Mansfield and his collaborators (1977) would not have been fooled by this problem. As they clearly state,

> we calculated the social benefits only during the period between the date when the innovation occurred and the date when it would have appeared if the innovator had done nothing.

In the world of exogenous technological change described by the model, Mansfield would correctly conclude that each innovation would have occurred even if the innovator had done no research. Nonetheless, one worries that such calculations, based on survey evidence, are sensitive to answers by the innovating firm to hypothetical questions about its competitors. Just as the econometric approach has shortcomings, in practice the direct approach is also very difficult to get right.

Government Policies

It is useful to work through several policies toward research in the framework of the model above, even though each policy will, by assumption, have no effect on technological change. First, consider research performed by the government. Suppose that a government researcher acts like a private researcher, attempting to lay claim to a new innovation but then making it available to producers in return for a royalty. In that case, if government research in the industry is less than the equilibrium level of research, government research simply crowds out private research and the total level of research is unchanged by the government intervention.

A government subsidy of research will work somewhat differently. A 10 percent subsidy will lead researchers to raise their gross-of-subsidy expenditures by 10 percent so that their net-of-subsidy expenditures are left unchanged. Thus, the research subsidy will be successful at raising research activity, although it will not alter the rate of technological change.

A policy of strengthening patent protection can also be analyzed with this model. Let θ index the strength of patent protection: With probability θ, patent protection prevents imitation for exactly one year, otherwise imitation is immediate despite patent protection. Under this generalization of the model, equilibrium R&D is $R = \frac{\theta\gamma S}{(1+r)(1+\gamma)}$. It is increasing in the strength of patent protection, as is R&D intensity.[6] In this model, strengthening patent protection raises R&D and lowers consumer surplus (since goods are less frequently supplied at marginal cost) but has no effect on technological change.

CONCLUSION

The government's ability to spur technological change depends ultimately on the responsiveness of technological change to research efforts. But not much evidence is available about the true elasticity of technological change with respect to research effort. A model of endogenous R&D and exogenous technological change (in which the true elasticity is zero) is surprisingly hard to reject. Mansfield's own calculations of the social return to research stand up well to this scrutiny but, as he admits, "Certainly, they are very frail reeds on which to base policy conclusions."

I conclude on a more optimistic note. An econometric analysis of a specific policy change could provide key evidence on the issue of how technological change responds to research. Take, for example, the increased protection that patents have received since the Congress, in 1982, created the Court of Appeals of the Federal Circuit. An unprecedented

[6] The model needs to be slightly enriched in order for the strength of patent protection to influence the fraction of innovations that are patented. Suppose that γ is drawn from a known distribution F after R&D decisions are made but before the patenting decision is made. For simplicity assume that unpatented innovations are imitated immediately. If patenting has a cost, then innovations whose size is below some threshold will not be protected (the R&D equation must also be modified to reflect this option value of patenting). If the strength of patent protection increases relative to the cost of patenting, then the fraction of innovations that are patented will rise. A model of this sort is used by Eaton and Kortum (1996) to infer patterns of international technology diffusion from patterns of international patenting.

burst of patenting activity in the United States resulted; nothing like it had been seen in the past 70 years.

It may be difficult to conclude much from the aggregate time series, but this policy change is likely to have hit different industries differently. Both Mansfield, Schwartz, and Wagner (1981) and Levin et al. (1987) report great variation across industries in the importance of patents. One would expect to see research intensity rise by more in those industries in which patents are an important means of appropriating the fruits of R&D. If technological change is exogenous, then variation in R&D intensity generated by a change in policy would have no impact on productivity. Hence, if industry-level productivity has responded in a systematic way to policy-induced changes in research intensity, this would be persuasive evidence of government's ability to influence technological change.

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Discussion

Joshua Lerner*

Edwin Mansfield's thoughtful review of the literature on the economics of technological change raises a variety of interesting issues, far too many to address in a few pages. Consequently I will focus my discussion on the section that I found most challenging and thought-provoking—his prescriptions for policymakers, in the section "Public Policy toward Civilian Technology." In particular, my discussion revisits these recommendations with a particular question in mind: Should public technology policy be affected by the fact that a disproportionate number of radical innovations are generated by small firms? Viewing his policy prescriptions through these lenses may help enrich the discussion.

The Important Role of New Entrants

As Mansfield observes in a later section, "Technological Change and Antitrust Policy," one of the empirical regularities emerging from studies of technological innovation is the role played by new entrants. From the pioneering study of Jewkes, Sawers, and Stillerman (1958), Acs and Audretsch (1988), and other works, economists have gradually realized that these young firms often play a key role in identifying where new technologies can be applied to meet technological needs, and in rapidly introducing products. (These patterns are also predicted in several models of technological competition, many of which are reviewed in Reinganum 1989.) While several studies suggest that established firms

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have a substantial advantage in incremental innovation, small firms appear to generate a disproportionate share of radical breakthroughs.

The 1990s have seen several dramatic illustrations of this pattern. Two potentially revolutionary areas of technological innovation—biotechnology and the Internet—were pioneered by smaller entrants, typically backed by venture capital investors. Neither established drug companies nor mainframe computer manufacturers were pioneers in developing these technologies. By and large, small firms did not invent the key genetic engineering techniques or the Internet protocols. Rather, the bulk of the enabling technologies were developed with federal funds at academic institutions and research laboratories. It was the small entrants who were the first to seize upon the commercial opportunities. In some cases, these new firms—utilizing the capital, expertise, and contacts provided by their venture capital investors—established themselves as market leaders. In other instances, they were acquired by larger corporations or entered into licensing arrangements with such concerns.

These patterns can only be expected to occur more frequently in coming years. The pool of venture capital has expanded eightfold (in inflation-adjusted dollars) since 1978, vastly increasing the resources available for young technology-based firms. While the share of venture resources going to seed and early-stage firms (as opposed to expansions or buyouts of already profitable concerns) dipped in the mid 1980s, in recent years an increasing share of venture capital disbursements has gone to early-stage firms. Meanwhile, National Science Foundation tabulations suggest that the share of total industrial R&D spending accounted for by major corporations has fallen considerably.[1]

Innovation and the Market Test

How should these patterns affect the design of U.S. technology policy? While Professor Mansfield thoughtfully lays out five criteria for the assessment of technology programs, I believe that one of these might be rethought in light of these patterns, and that an additional consideration might be added.

First, given this pattern of innovation, I am somewhat skeptical of his claim that "it is vitally important that a proper coupling occur between

[1] Data on venture capital fund-raising and disbursements are available in the various publications of Venture Economics and VentureOne. Recent data on research and development expenditures by firms of different sizes are available in National Science Board (1996). It is still important to point out that disbursements by venture capital funds (which go for a wide variety of purposes in addition to R&D, such as capital expenditures and salaries) are vastly smaller than R&D performed by major American corporations. In fact, in the years 1970 through 1994, total annual disbursements of the venture capital industry never exceeded the R&D expenditures of *either* IBM or General Motors.

technology and the market." Mansfield argues that the federal government's technological investments should be made in conjunction with potential users. Given the unexpected nature of many of the radical discoveries and the critical role of previously unknown entrants, this approach seems problematic—perhaps even counterproductive.

Consider what would have been the fate of the Department of Defense's funding of the development of the Internet during the 1960s, or the National Institutes of Health's funding of genetic engineering research during the early 1970s, had federal program officers been required to obtain agreement that these technologies were commercially relevant from executives in the research departments of the major computer and pharmaceutical companies (or, even more improbably, had they been required to obtain matching funds from these organizations). This research would have never been undertaken had it not been motivated by the agencies' missions of providing a strong national defense and better health. To add such a market test would likely harm federal officials' ability to fund very long-run research.

Addressing Threats to New Entrants

Second, if new entrants are playing a vital role in introducing radical innovations, addressing several threats to their future development should be a priority. The area that I believe deserves particular attention relates to intellectual property protection, particularly patents. The U.S. patent system has undergone a profound shift over the past 15 years. The strength of patent protection has been dramatically bolstered, and both large and small firms are devoting considerably more effort to seeking patent protection and defending their patents in the courts. Many in the patent community—officials of the U.S. Patent and Trademark Office, the patent bar, and corporate patent staff—have welcomed these changes. But viewed more broadly, the reforms of the patent system and the consequent growth of patent litigation have created a substantial "innovation tax" that afflicts some of America's most important and creative small firms.[2]

Almost all formal disputes involving issued patents are tried within the federal judicial system. The initial litigation must be undertaken in a district court. Prior to 1982, appeals of patent cases were heard in the

[2] One question raised by this argument is, if these obstacles are important, why has the share of R&D expenditures being undertaken by small firms substantially increased in recent years? The rapid pace of change in many facets of information and communications technology may have created more opportunities for newer organizations. Many observers have noted the difficulties that established organizations have had in responding to rapid technological change: for one example, see Jensen's (1993) discussion of the "major inefficiencies [that exist] in the R&D spending decisions of a substantial number of firms."

appellate courts of the various circuits, which differed considerably in their interpretation of patent law. Because few appeals of patent cases were heard by the Supreme Court, substantial differences persisted, leading to widespread "forum shopping" by litigants.

In 1982, the U.S. Congress established a centralized appellate court for patent cases, the Court of Appeals for the Federal Circuit (CAFC). As Robert Merges (1992) observes:

> While the CAFC was ostensibly formed strictly to unify patent doctrine, it was no doubt hoped by some (and expected by others) that the new court would make subtle alterations in the doctrinal fabric, with an eye to enhancing the patent system. To judge by results, that is exactly what happened.

The CAFC's rulings have been more "pro-patent" than those of the previous courts. For instance, the circuit courts had affirmed 62 percent of district court findings of patent infringement in the three decades prior to the creation of the CAFC, while the CAFC in its first eight years affirmed 90 percent of such decisions (Koenig 1980; Harmon 1991).

The strengthening of patent law has not gone unnoticed by corporations. Over the past decade, the number of patents awarded to U.S. corporations has increased by 50 percent. Furthermore, the willingness of firms to litigate patents has increased considerably. The number of patent suits instituted in the federal courts increased from 795 in 1981 to 1553 in 1993; adversarial proceedings within the U.S. Patent and Trademark Office increased from 246 in 1980 to 684 in 1992 (Administrative Office, various years; U.S. Department of Commerce, various years). My recent analysis of litigation by firms based in Middlesex County, Massachusetts, suggests that six suits related to intellectual property are filed for every 100 patent awards to corporations.

These suits lead to significant expenditures by firms. Based on historical costs, I estimate that patent litigation begun in 1991 will lead to total legal expenditures (in 1991 dollars) of over $1 billion, a substantial amount relative to the $3.7 billion spent by U.S. firms on basic research in 1991. (These findings are summarized in Lerner 1995.) Litigation also leads to substantial indirect costs. The discovery process is likely to require the alleged infringer to produce extensive documentation, involve time-consuming depositions from employees, and generate unfavorable publicity. The firm's officers and directors may also be held individually liable.

As firms have realized the value of their patent positions, they have begun reviewing their stockpiles of issued patents. Several companies, including Texas Instruments, Intel, Wang Laboratories, and Digital Equipment, have established groups that approach rivals to demand royalties on old patent awards. In many cases, they have been successful in extracting license agreements or past royalties. For instance, Texas

Instruments is estimated to have netted $257 million in 1991 from patent licenses and settlements resulting from their general counsel's aggressive enforcement policy (Rosen 1992).

Particularly striking, practitioner accounts suggest, has been the growth of litigation—and threats of litigation—between large and small firms.[3] This trend is disturbing. While litigation is clearly a necessary mechanism to defend property rights, the proliferation of such suits may lead to transfers of financial resources from some of the youngest and most innovative firms to more established, better capitalized concerns. Even if the target firm believes that it does not infringe, it may choose to settle rather than fight. It may be unable to raise the capital to finance a protracted court battle, or it may believe that the publicity associated with the litigation will depress the valuation of its equity.

In addition, these small firms may reduce or alter their investment in R&D. For instance, a 1990 survey of 376 firms found that the time and expense of intellectual property litigation was a major factor in the decision whether to pursue an innovation for almost twice as many firms with under 500 employees as for larger businesses (Koen 1990). These claims are also supported by my study (1995) of the patenting behavior of new biotechnology firms that have varying litigation costs. I showed that firms with high litigation costs are less likely to patent in subclasses with many other awards, particularly those of firms with low litigation costs.

These effects have been particularly pernicious in emerging industries. Chronically strained for resources, U.S. Patent and Trademark Office officials are unlikely to assign many patent examiners to emerging technologies in advance of a wave of applications. As patent applications begin flowing in, the U.S. Patent and Trademark Office frequently finds the retention of the few examiners skilled in the new technologies difficult. Companies are likely to hire away all but the least able examiners. These examiners are valuable not only for their knowledge of the examination procedure in the new technology, but also for their understanding of what other patent applications are in process but not yet awarded. (U.S. patent applications are held confidential until time of award.) Many of the examinations in emerging technologies are, as a result, performed under severe time pressures by inexperienced examiners. Consequently, awards of patents in several critical new technologies have been delayed and highly inconsistent. These ambiguities have created ample opportunities for firms that seek to aggressively litigate their patent awards. The clearest examples of this problem are to be found in the biotechnology and software industries.

[3] Several examples are discussed in Chu (1992). Examples include the dispute between Cetus Corporation and New England Biolabs regarding the taq DNA polymerase and that between Texas Instruments and LSI Logic regarding semiconductor technology.

Conclusion

In conclusion, I concur in large part with Mansfield's thoughtful and well-reasoned policy recommendations. My main concern is that we avoid taking steps in the name of increasing competitiveness that actually interfere with the workings of the American system of innovation. The 1982 reforms of the patent litigation process have had exactly this sort of unintended consequence; and I fear that any efforts to make federal research more commercially relevant will do likewise.

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Technology Diffusion in U.S. Manufacturing: The Geographic Dimension

Jane Sneddon Little and Robert K. Triest*

"Technology" is a key determinant of growth, but economists frequently leave its components jumbled together in Rosenberg's black box. In neoclassical models, we let the residuals represent technology and, waving our hands, treat technical progress as "manna from heaven." And, while the endogenous growth approach explicitly seeks to model the production of technology, the customary use of R&D spending to represent technological change has serious drawbacks. Not all R&D spending is equally productive, for instance, and a significant portion relates to the invention of new consumer products (product innovation). While product innovation may well influence national or regional business cycles and improve consumer welfare, this type of innovation generally has fairly minor effects on factor productivity. By contrast, the invention of new types of capital equipment or new production methods (process innovation) *is* a key determinant of the production frontier. After all, the state of scientific and technical knowledge sets the limits. Nevertheless, the invention of new capital equipment or manufacturing methods represents just one step in the evolution of prevailing production procedures.

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A second critically important determinant of dominant manufacturing practice is the manner in which state-of-the-art technology enters general use. If the speed, intensity, and uniformity with which advanced technologies are adopted vary across nations and regions, these differences will affect the extent to which (or the pace at which) long-term growth rates converge. Views about the ease and pace of technology diffusion differ. Boyan Jovanovic (1995) suggests, for example, that the repetitive process by which each adopting firm learns about and incorporates a new technology into its operations generally consumes a larger share of national income than innovation itself.[1] By contrast, in neoclassical models, the acquisition of frontier technology occurs without delay or cost.

If the neoclassical assumption applies anywhere, that place is surely the United States, given the flow of labor, capital, and information among the U.S. states. Yet, Barro and Sala-i-Martin (1991) and others have found that per capita output converges at a 2 to 3 percent annual rate across the U.S. states, a pace far too slow to conform to neoclassical predictions for a closed, much less an open, economy.[2] While Barro, Mankiw, and Sala-i-Martin (1995) explain this surprisingly slow convergence by incorporating differences in human capital and a requirement that investment in human capital be financed locally, variations in technology adoption might also play a role. Thus, examining actual patterns in technology use across the U.S. states could be informative. Moreover, identifying any environmental characteristics that impede or accelerate technological diffusion would improve our understanding of the growth process and could have useful policy implications.

Accordingly, this paper explores the geographic dimension of technology diffusion in U.S. manufacturing. Using relatively new data from the Census Bureau's Surveys of Manufacturing Technology (SMTs) for 1988 and 1993, it examines variations in the adoption of 17 advanced technologies across the nation and within individual U.S. states.[3] It asks, in particular, whether proximity to firms already using high-tech equip-

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[1] Similarly, Lucas (1993) concludes that a key characteristic distinguishing fast-growing developing countries from slow-growth ones is an ability to adopt increasingly sophisticated production methods and to move along successive learning curves. He suggests that openness to trade supports such an ability.

[2] Cogley and Spiegel (1996) reconfirm this finding using time-series methods and Monte Carlo techniques to improve the precision of the estimates. While Barro and Sala-i-Martin found a somewhat faster rate of convergence (4.6 percent annually) for manufacturing output, this pace remains slow for a neoclassical world with capital mobility.

[3] The SMT covers the use of the 17 advanced technologies listed and described in Appendix 1 at firms with 20 or more employees in the fabricated metals, industrial machinery and equipment, electronic and other electric equipment, transportation equipment, and instruments and related products industries (SIC codes 34-38).

ment fosters adoption, but it also seeks to distinguish other plant and locational characteristics linked to increased probability of technology use.

The paper is organized as follows. The first section discusses why technology use might be expected to vary by geographic area. It distinguishes the influence of locational characteristics, like the availability of skilled workers, from the impact of proximity to other high-tech users. It also points to reasons, like the prevalence of multi-establishment firms, why technology use might be remarkably evenly distributed in the United States. The next section describes the SMT and other Census data bases used in the study, while the third discusses the use of the SMT for geographical analysis and presents some summary tables and maps. The fourth section presents the econometric models used to examine the speed of technology adoption between 1988 and 1993. While this analysis focuses on the impact of proximity to other technology users on the speed of adoption, the models also control for plant and geographic characteristics. The final section offers conclusions.

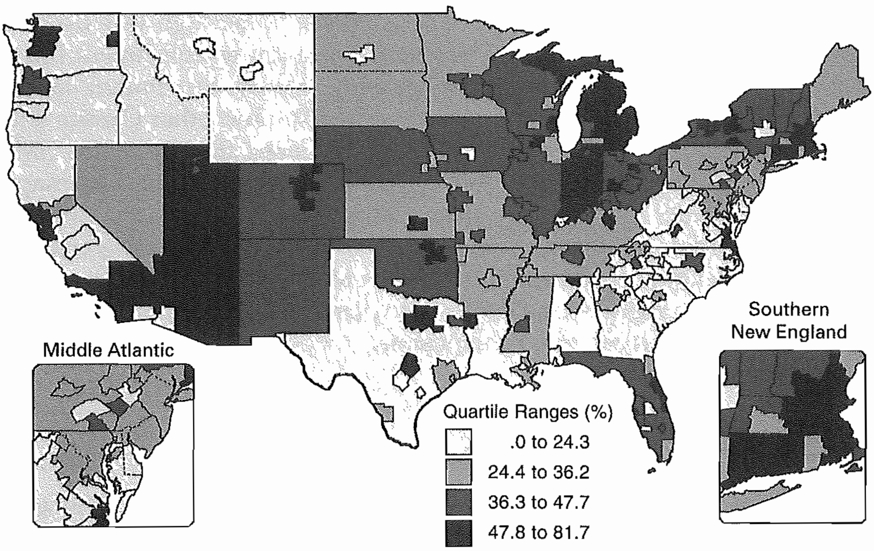
WHY GEOGRAPHY MIGHT MATTER

The use of advanced technologies could vary considerably by state and region for many reasons, such as differences in access to skilled labor or industrial concentration and in the applicability of technologies across industries. As might be expected, for instance, given the auto firms' reputation for close ties to their suppliers, the SMT for 1993 shows that almost one-fourth of the establishments in transportation use intercompany computer networks to link plants with suppliers and customers, whereas only 15 percent of industrial machinery plants have adopted this technology. Similarly, since electronics firms have successfully adapted pick-and-place robots to set chips on semiconductors, the electronics industry reports the greatest use of this equipment; by contrast, transportation plants are the heaviest users of "other" robots.

To illustrate the differences in industrial concentration across the nation, Map 1 shows the share of manufacturing employment in each metropolitan and broader non-metro area[4] accounted for by firms with 20 or more workers in SICs 34 through 38 (the SMT sample population), while Table 1 shows how the use of the 17 advanced technologies examined in the SMT varies across these industries. Map 2 depicts regional variations in the educational attainment of the labor pool, presumably an important locational consideration.

[4] For reasons discussed below, we combine non-metropolitan areas within a state into "quasi-MSAs" (QMSAs); in some cases, QMSAs include small metro counties or combine non-metro areas across state borders.

Map 1
Share of Manufacturing Employment in Establishments with 20+ Employees, SICs 34 to 38, 1987



Note: Regions are MSAs and QMSAs, defined in the text.
Source: U.S. Bureau of the Census, *County and City Data Book, 1994.*

Yet another explanation for regional differences in technology use may be that many of the advanced technologies covered by the SMT, particularly those linked to flexible manufacturing, are especially useful to firms with varied output and short production runs, since this equipment reduces down times and set-up costs. But branch plants with standardized output and long production runs and plants making a variety of innovative or niche products tend to locate in different areas. For branch plants, minimizing labor costs and transportation to mass markets may be crucial, whereas plants producing customized items or prototypes may require a more highly skilled labor force or frequent contact with product designers at headquarters.

These variations in the applicability of technologies, combined with a clustering of plants by industry or stage of product cycle, may explain some geographic differences in technology use; however, these explanations are distinct from the possible impact of proximity to other plants

Table 1
Share of Establishments Using Selected Manufacturing Technologies in 1993, by Industry
Percent

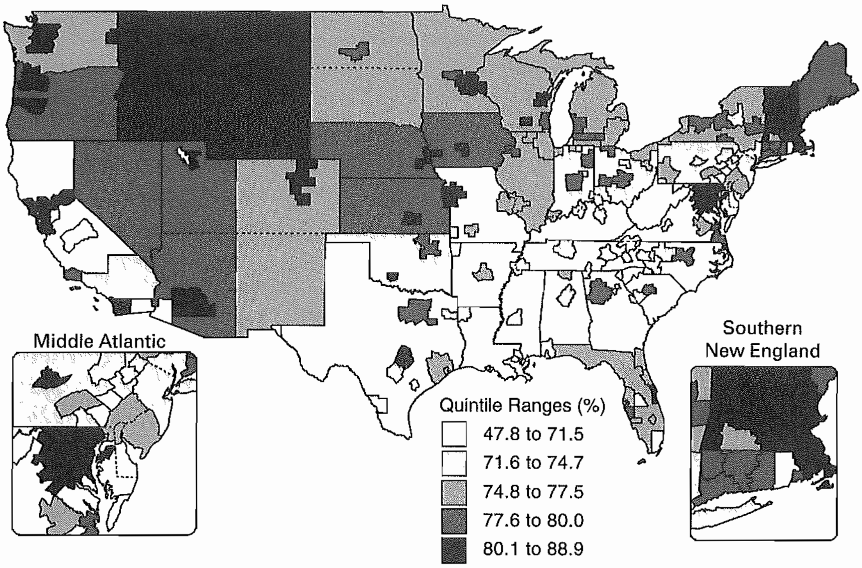
Technology	Fabricated Metals	Industrial Machinery	Electronic and Other Electrical Equipment	Transportation Equipment	Instruments and Related Products
Design & Engineering					
CAD or CAE	46.5	64.1	64.2	53.9	65.5
CAD to Control Machines	19.3	34.8	21.5	25.5	18.5
CAD Used in Procurement	7.0	11.6	16.1	9.6	16.1
Fabrication/Matching Assembly					
Flexible Manufacturing Cells/Systems	9.5	11.8	17.0	15.5	14.2
NC or CNC Machines	40.4	61.9	34.5	44.1	35.1
Materials Working Lasers	3.4	4.3	7.8	5.4	6.3
Pick-and-Place Robots	6.6	5.4	15.2	10.1	11.7
Other Robots	3.8	3.6	5.3	11.7	3.8
Automated Material Handling					
Automatic Storage/ Retrieval	1.2	2.3	3.8	3.8	4.8
Automatic Guided Vehicle Systems	.3	1.1	1.7	2.2	1.5
Sensor-Based Inspection/Testing					
For Incoming or In-Process Materials	8.1	8.1	11.8	15.6	11.7
For Final Product	9.6	10.6	17.5	16.2	14.7
Communication and Control					
LAN for Technical Data	20.1	29.4	37.1	28.0	40.7
LAN for Factory Use	14.5	21.0	30.5	23.9	30.0
Intercompany Computer Network	16.7	15.4	21.9	23.4	15.3
Programmable Controllers	30.2	29.0	30.7	30.7	29.8
Computers Used to Control Factory Floor	20.2	28.1	33.2	26.8	29.0

See Appendix for descriptions of technologies.

Source: U.S. Bureau of the Census, *Manufacturing Technology: Prevalence and Plans for Use 1993*, SMT (93)-3, U.S. Government Printing Office, Washington, D.C., 1994.

using advanced technologies. Why might nearness to plants already using high-tech equipment exert an independent effect on adoption decisions? Because early adopters "infect" other firms. Or, more precisely, because closeness to plants already using advanced technologies is likely to reduce the perceived risk and actual cost of investing in this

Map 2
Share of Population Age 25+ with High School Diploma or Higher, 1990



Note: Regions are MSAs and QMSAs, defined in the text.
Source: U.S. Bureau of the Census, *County and City Data Book, 1994.*

new equipment.[5] A firm incorporating new technology into its production function faces significant costs. Management must learn about a technology, assess the costs and benefits of this often lumpy investment for its own operations, look for the best vendor, adjust the plant's manufacturing operations to accommodate the new equipment, and possibly modify the new equipment to fit the plant's needs. The adoption costs also include a loss of human capital acquired in using the old equipment and reduced productivity while employees work their way down a new learning curve.

Proximity to firms already using a new technology is likely to reduce the apparent riskiness and other costs of investing in this new equipment because it permits process engineers and management staff to observe the equipment in operation at nearby facilities and to discuss the

[5] Aizenman (1995) demonstrates that uncertainty acts as an implicit tax on new activities.

advantages and disadvantages of its use. These neighbors may also have helpful advice about specific vendors, and about problems encountered in introducing the equipment onto the shop floor.[6] Because adopting advanced technologies usually requires changing manufacturing procedures—possibly even the plant layout—the process generally requires considerable engineering input. Accordingly, location near a pool of engineers experienced in using this equipment could cut adoption costs. Similarly, access to a pool of production workers with knowledge of these technologies could also lessen the required investment in human capital. As a final external economy, a cluster of plants using advanced technologies might draw firms supplying support services and parts.[7] In other words, all the Marshallian agglomeration economies pertain.

On the other hand, several forces could be operating to dilute the impact of proximity and promote an even distribution of technology across the United States. First, equipment vendors promote their wares nationwide in business media and at trade shows. Vendors actively try to eliminate any technological backwaters they can find. In addition, many plants are part of a multi-establishment firm and benefit from experience with new technologies at related facilities. Then too, defense contractors and subcontractors are generally required to use many of the technologies covered by the SMT. While many areas are considerably more dependent on defense work than others, these requirements are actually intended to encourage technology diffusion as well as to ensure the quality of military procurement (Rees, Briggs, and Oakey 1984; Knudsen, Jacobs, Conway, and Blake 1994). Finally, several of the technologies covered by the SMT have been available long enough to allow their adoption wherever they are relevant. In particular, numerically controlled (NC) machines, which are not distinguished from computer numerically controlled machines (CNC) on the SMT questionnaire, have been widely used for decades.

Existing evidence on the impact of proximity on technology use is slim. In a recent *American Economic Review* article, Ciccone and Hall (1996) found that productivity is positively associated with employment density across states, a result consistent with the hypothesis that proximity to users spurs technology adoption. More directly relevant is work by or cited by Nadiri (1993), who finds evidence of large externalities from R&D activities and suggests that the spillovers could occur via intra- or inter-industry channels, customer-supplier relations, or geographic location. In addition, Jaffe, Trajtenberg, and Henderson (1993) and Jaffe

[6] As Nooteboom (1993) and Wozniak (1993) point out, informal contacts and chance meetings may be particularly important in the case of small, single-establishment firms and early adopters.

[7] Alternatively, a cluster of firms using advanced technologies may grow up around manufacturers of high-tech equipment—machine tool makers or software developers, for instance. See Assembly of Engineering (1981).

(1995) use patent citations to trace significant spillovers from local patenting activity. They find that, excluding self-referrals, patent citations are two to six times more likely to occur within the same SMSA and two times more likely to occur within the same state, compared with the results for a control group. Similarly, Audretsch and Feldman (1996) find that product innovation clusters even when they control for concentration in production activity. But, as mentioned earlier, invention differs from adoption.

Maintaining this distinction, another body of work has found that location in a metropolitan area promotes product innovation but not necessarily process innovation or advanced technology use. Davelaar and Nijkamp (1989), for example, examined the generation of product and process innovation among Dutch manufacturers and found that location in highly urban areas was important to product but not to process innovation. Similarly, Harrison, Kelley, and Gant (1996) studied the adoption of programmable automation among U.S. metalworking firms and concluded that the likelihood of adoption was significantly associated with location in metropolitan suburbs and edge cities rather than in an urban core or rural area. They also found no association with proximity to clusters of firms in the same industry. Moreover, Rees, Briggs, and Oakey (1984) noted evidence of regional contagion in the use of NC and CNC machines for small plants or single-establishment firms, but not for their entire sample. They attributed the positive impact of location in the North Central region to this area's history as the center of the machine tool industry. Finally, in a study on the use of advanced manufacturing technologies in Canada, based on a Canadian version of the SMT, McFetridge (1992) noted that establishments in Quebec and Ontario were somewhat more likely to adopt some technologies than were plants in the Atlantic or western parts of the country.

The limited amount of econometric work on the role of geography in the adoption process undoubtedly reflects the lack of a comprehensive micro-level data base with a direct measure of technology use. With the exception of McFetridge, all of the studies cited in the preceding paragraph were based on comparatively small, one-time surveys. As the 1993 SMT summary publication points out, "information on technology use was in great demand and short supply" until the late 1980s (U.S. Bureau of the Census 1994). But, starting in 1988, the Surveys of Manufacturing Technology improved the situation dramatically.

What We Have Learned from the SMT to Date

The SMTs and the data bases linked to them provide a wealth of information to researchers interested in technology, growth, and productivity issues. These surveys are designed to obtain a reliable reading on the use of 17 advanced technologies in five groups (design and engineering; fabrication/machining and assembly; automated materials handling;

automated sensor-based inspection and testing equipment; and communications and control) at establishments with 20 or more employees in SIC codes 34 to 38.[8] The first survey, conducted in 1988, was based on 10,526 establishments representing a universe of 39,556, while a follow-on survey, done in 1993, was based on 8,336 units representing 42,991 establishments (accounting for over 40 percent of employment and value added in the 1987 *Census of Manufactures*).[9] The samples were stratified by 3-digit SIC code and three employment-size groups (20–99; 100–499; and 500 and above) and drawn from the 1987 *Census of Manufactures* by simple random sampling within strata.[10] Within each stratum, thus, each establishment had an equal chance of being selected. The establishment count for each cell in the summary publications (and this paper) is a simple weighted estimate, where the establishment weights are the inverse of the sampling fraction.[11]

Tables 2 and 3 present summary data drawn from the 1993 SMT. Table 2 shows the number of establishments and the percentage using at least one and at least five advanced technologies, broken down by industry, size, age, manufacturing process, and whether or not the plant produces to military specification. This summary table immediately suggests that technology use increases with plant size (but not necessarily with age) and is greatest at establishments that combine fabrication and assembly work and that produce to military specification.

Table 3 shows the percent of establishments using each of the 17 technologies and when they first adopted them. As the table suggests, the usage rates vary considerably from highs of 59 percent for computer-aided design and engineering and 47 percent for numerically and computer numerically controlled machines to lows of less than 3 percent for automated materials handling equipment. It is also clear that most of the machining, materials handling, and inspection technologies were introduced by the largest share of users before 1988, whereas most of the computer-aided design and engineering and communication and control technologies were introduced between 1988 and 1991. Only in the case of

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[8] Appendix 1 lists and describes the 17 technologies. The industries covered by SIC codes 34 to 38 include: fabricated metal products; industrial machinery and equipment; electronic and other electric equipment; transportation equipment; and instruments and related products.

[9] An SMT survey conducted in 1991, "Manufacturing Technology: Factors Affecting Adoption," was not designed to follow up the 1988 survey; it does not cover one of the technology groups included in the 1988 and 1993 surveys (communications and control), and it asks a different set of questions. Issues covered concern factors affecting the decision to adopt, intensity of use, time required to achieve full operation, barriers and benefits to adoption, and problems encountered with technology use.

[10] In some sparsely inhabited cells, the entire population was surveyed.

[11] In this paper, the weights are normalized within each area by a region-specific normalization factor. Accordingly, weighted data should not be biased by differences in probability of sample inclusion across strata. See Appendix 2 for further discussion.

Table 2
Manufacturing Technology Use in 1993, by Establishment Characteristic

Characteristic	Number of Establishments	Using at Least 1 Technology (%)	Using at Least 5 Technologies (%)
All Establishments	42,991	75.0	29.1
Industry			
Fabricated Metals	13,190	67.1	22.3
Industrial Machinery	14,231	81.5	30.2
Electronic & Other Electrical Equipment	7,472	78.8	35.6
Transportation Equipment	4,110	68.7	33.2
Instruments	3,988	78.0	31.1
Employment Size			
20 to 99	30,502	69.1	18.3
100 to 499	10,321	89.3	50.3
500 & over	2,168	90.6	80.2
Age of Plants (years)			
Less than 5	4,893	82.9	23.4
5 to 15	13,722	81.2	30.9
16 to 30	11,303	83.4	32.6
Over 30	9,310	80.3	36.7
Not Specified	3,763	4.1	.5
Manufacturing Process			
Fabrication/Machining	6,795	80.3	26.9
Assembly	6,388	79.9	26.9
Both	23,393	85.7	36.6
Neither	2,577	56.3	13.4
Not Specified	3,838	5.3	1.1
Products Made to Military Specification			
Yes	14,112	88.9	39.5
No	22,214	78.4	28.0
Don't Know	2,939	73.9	23.6
Not Specified	3,726	3.3	.4

Source: U.S. Bureau of the Census, *Manufacturing Technology: Prevalence and Plans for Use 1993*, SMT (93)-3, U.S. Government Printing Office, Washington, D.C., 1994, Table 1, pp. 5–6.

intercompany computer networks linking plants with suppliers, subcontractors, and customers were adoption rates increasing in the most recent period. Moreover, and surprisingly perhaps, the use of robots other than pick-and-place, automated material handling systems, and programmable controllers actually declined between 1988 and 1993. As McGuckin, Streitwieser, and Doms (1995) suggest, technology may be an "experience good" involving much trial and error. In addition, some establishments

Table 3
Share of Establishments Using Selected Technologies in 1993, by Time of Adoption
Percent

Technology	Establishments Using in 1993	Adopting in Past 2 Years	Adopting in Past 2 to 5 Years	Adopting 5+ Years Ago
Design & Engineering				
CAD or CAE	58.8	12.4	26.2	19.4
CAD to Control Machines	25.6	5.9	10.9	8.4
CAD Used in Procurement	11.3	3.8	4.8	2.3
Fabrication/Machining				
Flexible Manufacturing Cells/Systems	12.7	3.9	4.7	3.8
NC or CNC Machines	46.9	4.4	11.7	29.6
Materials Working Lasers	5.0	1.5	1.3	2.0
Pick-and-Place Robots	8.6	1.9	3.0	3.4
Other Robots	4.8	.9	1.8	1.9
Automated Material Handling				
Automatic Storage/Retrieval	2.6	.5	.9	1.1
Automatic Guided Vehicle Systems	1.1	.2	.4	.5
Sensor-Based Inspection/Testing				
For Incoming or In-Process Materials	9.9	2.4	3.5	3.6
For Final Product	12.5	3.0	4.3	4.7
Communication and Control				
LAN for Technical Data	29.3	10.0	12.0	6.0
LAN for Factory Use	22.1	7.8	8.2	5.3
Intercompany Computer Network	17.9	7.4	6.1	3.6
Programmable Controllers	30.4	5.2	10.2	13.4
Computers Used to Control Factory Floor	26.9	7.1	10.0	8.6

See Appendix for descriptions of technologies.

Source: U.S. Bureau of the Census, *Manufacturing Technology: Prevalence and Plans for Use 1993*, SMT (93)-3, U.S. Government Printing Office, Washington, D.C., 1994.

may be eliminating some of the older technologies as they gradually update their facilities—replacing programmable controllers, say, with CAD/CAM systems. (See Beede and Young (1996) on possible technology ladders within the SMT group.)

To add to the researcher's cornucopia, the plant-specific data on technology use from the SMT can be matched with information in the Longitudinal Research Database (LRD) to trace individual establishments covered by the Annual Surveys and Censuses of Manufactures over time.[12] The SMT can also be linked to the Worker-Employer Characteristics Database (WECD), not used in this paper, which matches employee data for individuals filling out the long form for the 1990 Census of Population with establishment-level data from the Census of Manufactures. Finally, firm identifiers allow linking individual establishments to the appropriate firm.[13]

Studies based on the SMT and related data bases have already addressed a number of important issues. (See Alexander (1994) for a survey of this work.) For instance, Dunne (1994) finds that use of advanced technologies rises with plant size but is relatively uncorrelated with age, a result supporting the use of models that allow firms to upgrade their capital base. Dunne and Schmitz (1995) use the SMT to examine the large wage premium associated with large employer size, a link that has intrigued researchers for some time. They find that technically advanced plants pay higher wages and employ a greater fraction of non-production (presumably more highly skilled) workers; they also conclude that use of advanced technologies accounts for a significant part of the size-wage premium.[14] Noting that use of advanced technologies has been positively linked to measures of plant performance like productivity, sales and employment growth, and survival rates, McGuckin, Streitwieser, and Doms (1995) conclude that the primary explanation for these cross-section relationships is that well-managed plants adopt new technologies, not that these technologies clearly improve plant performance. Similarly, Doms, Dunne, and Troske (1995) find that technologically advanced plants employ a larger share of highly skilled and highly paid[15] workers both before and after adopting high-tech equipment. While adopting new technologies may increase the demand for skilled workers, they could not find much correlation between the change in plant-level skill mix and technology use.[16,17]

[12] The LRD contains linked data on 300,000 to 400,000 individual manufacturing plants covered by the Census of Manufactures from 1963 on. It also contains linked data from Annual Survey of Manufactures samples starting with 1972.

[13] Access to these confidential establishment- and firm-level data bases requires affiliation with the Census Bureau's Center for Economic Studies and careful attention to their disclosure procedures.

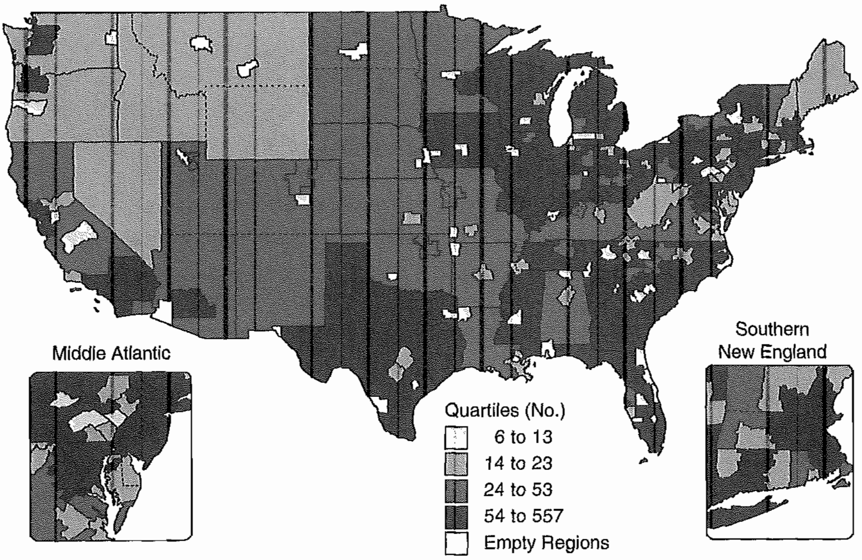
[14] Reilly (1995) draws a similar conclusion about the impact of computer use on the size-wage premium. See also, Davis and Haltiwanger (1991) who, using the LRD and the WECD, find continuously expanding size-wage differentials after 1967. They also attribute rising wage inequality in the United States to skill-biased technical change.

[15] Doms, Dunne, and Troske (1995) find that including quality measures from the WECD mutes but does not eliminate the wage premium associated with use of advanced technologies.

[16] Their study was based on a relatively small sample of plants answering both the 1988 and 1993 SMTs and linked to the WECD.

[17] Sheffrin and Triest (1995) suggest methods for determining the direction of causality in growth models.

Map 3
Number of Observations in 1993 SMT, by QMSA



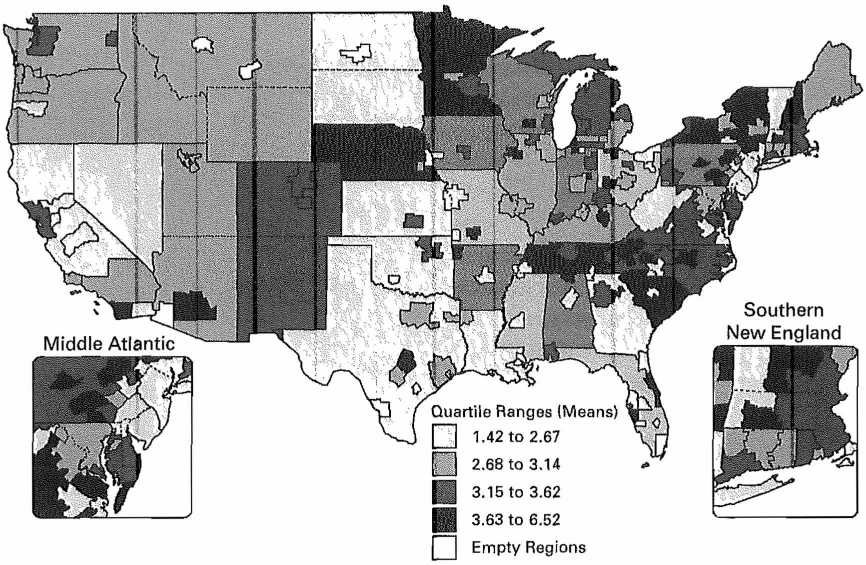
Note: Regions are MSAs and QMSAs, defined in the text.
Source: U.S. Bureau of the Census, Survey of Manufacturing Technology, 1993.

USING THE SMT TO EXPLORE GEOGRAPHIC ISSUES

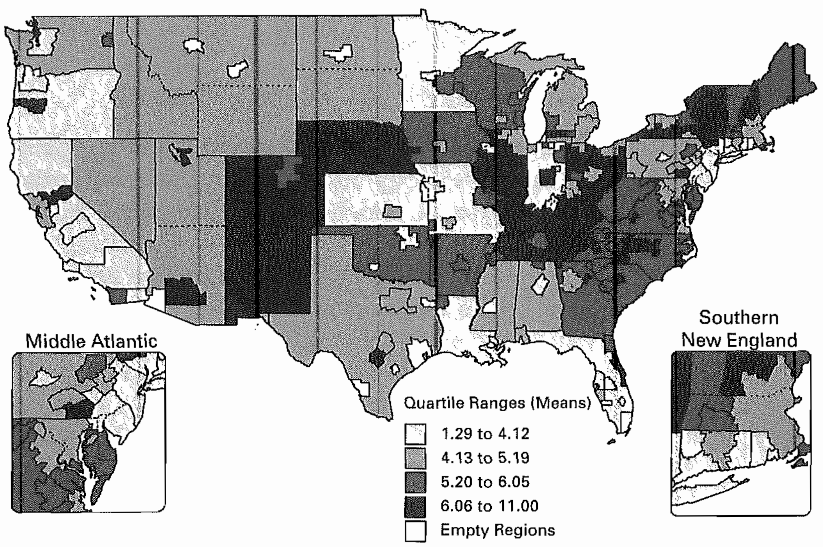
To date, studies based on the SMT have not examined the impact of locational characteristics on technology use, although several authors note that their statistical analysis has included dummies for the nine Census regions (in addition to industry dummies).[18] Accordingly, an extremely important issue becomes defining the appropriate geographic unit for analysis. Over how big an area should the educational attainment of the labor force or proximity to other technology users be measured, for example? Clearly, states often incorporate more than one labor market, and many are too large to be relevant to the issue of proximity. However, in most non-urban (and many urban) counties caught in the SMT net, the SMT sample size is too small to allow meaningful analysis or to meet disclosure constraints. Accordingly, we chose to focus on metropolitan statistical areas (CMSAs and MSAs) and a construct that combines all

[18] Although some papers mention that the regional dummies were statistically significant as a group, they generally do not provide results for the individual regions.

Map 4
Mean Number of Technologies Used, 1988 [a]



Map 5
Mean Number of Technologies Used, 1993 [a]



[a] Based on weighted data.
Note: Regions are MSAs and CMSAs, defined in the text.
Source: U.S. Bureau of the Census, Survey of Manufacturing Technology, 1988 and 1993.

the non-metro counties in a state (a construct called quasi- or QMSAs).[19] Even then, some 150 MSAs or QMSAs did not meet Census disclosure requirements or our own analytic criteria. In these cases, we merged small-sample MSAs with an adjacent QMSA and small-sample QMSAs with similar rural areas across a state border. As a result, we ended with 154 MSA/QMSAs, none of which had fewer than 6 observations in 1988 or 1993.[20] Map 3 shows the location of the well and less well sampled regions for 1993, while Appendix 3 shows the distribution of QMSAs by number of observations contained. Both suggest that the QMSAs with few observations are located in areas with little manufacturing activity and represent a small part of the information available for analysis.

Maps 4 through 7 provide a first visual impression of the variations in technology use across the nation and of how that usage changed between 1988 and 1993. Three caveats are in order. First, these maps do not account for differences in industry mix, plant size, or other characteristics known to influence technology adoption. In addition, in areas with small samples, chance variation may have produced misleading results. Finally, the maps relate only to technology use by establishments in SICs 34 to 38; they tell us nothing about technology use in chemicals or plastics, for instance, or in business or financial services.

To start with one broad measure of technology use, Maps 4 and 5 show the mean number of technologies used by establishments in the SMT population in 1988 and 1993, by QMSA.[21] Unfortunately, the SMTs for 1988 and 1993 provide little information on the intensity with which these technologies are used.[22] However, using the 1991 SMT, which asks about the share of operations dependent on advanced technologies, Doms, Dunne, and Roberts (1995) found that number of technologies used is positively correlated with intensity of use and that number used is a good proxy for intensity. Still, it should be noted that some technologies, like "other" robots and automated materials handling systems, appear to be relevant only to a small number of large plants in a couple of industries. More important, some of these technologies are substitutes; thus, plants are likely to use both only when they are experimenting or shifting from one to another.

One impression emerging from the maps is that technology diffusion

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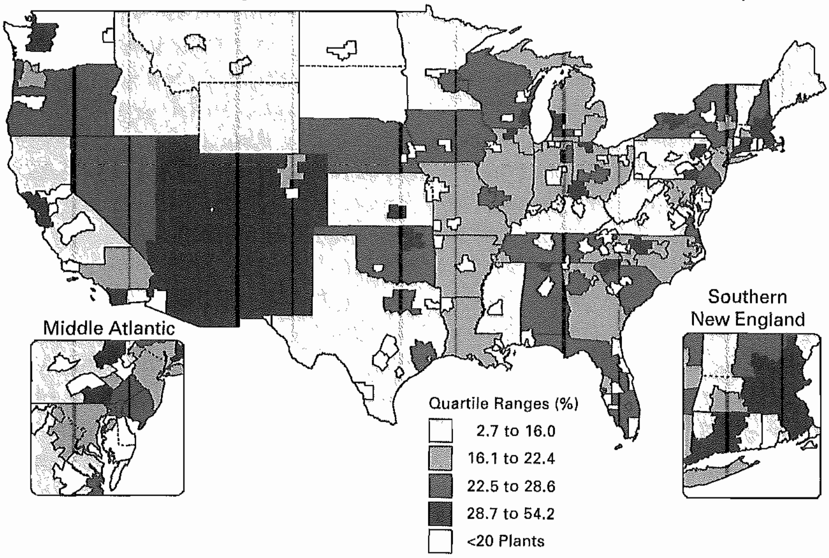
[19] Jaffe, Trajtenberg, and Henderson (1993) used a similar construct which they called "phantom" SMSAs.

[20] In mapping the use of individual technologies, we also dropped all MSA/QMSAs with fewer than 20 observations to meet disclosure requirements and analytic criteria.

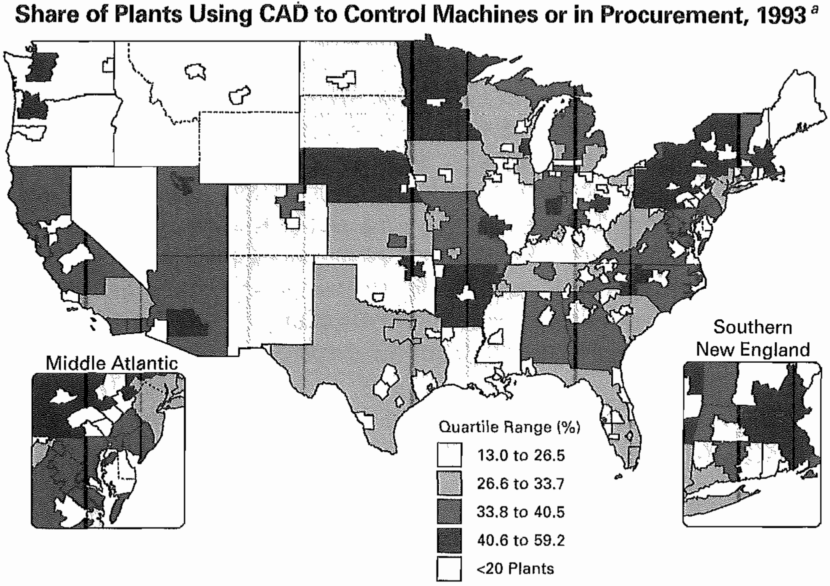
[21] It is important to note that the data displayed in the maps are weighted using SMT weights normalized by region-specific factors. See Appendix 2 for further discussion of the need to use weighted data and other weighting issues.

[22] Although the 1993 SMT does ask about the number of workstations involved—where that question is relevant—it provides no basis for comparing actual with potential use.

Map 6
Share of Plants Using CAD to Control Machines or in Procurement, 1988[a]



Map 7
Share of Plants Using CAD to Control Machines or in Procurement, 1993[a]



[a] Based on weighted data.
Note: Regions are MSAs and QMSAs, defined in the text.
Source: U.S. Bureau of the Census, Survey of Manufacturing Technology, 1988 and 1993.

Table 4
Technology Use, by Beale Code
Weighted Data

		Beale Code									
		Metro				Urban				Rural	
Item		0	1	2	3	4	5	6	7	8	9
Mean Number of	1988	3.0	3.0	3.2	3.2	3.3	4.2	3.1	3.1	2.4	2.6
Technologies	1993	3.5	3.9	3.6	3.9	3.9	4.1	4.1	3.7	3.0	3.7
Share of Establishments Using (%)											
At least five	1988	25.1	24.6	28.0	27.1	31.8	41.3	25.9	26.0	15.3	19.1
technologies	1993	31.0	37.0	32.3	35.2	35.4	45.3	40.4	36.0	32.1	38.0
CAD or CAE alone	1988	43.3	48.6	47.7	43.8	40.7	55.9	40.3	39.2	42.9	42.9
	1993	64.4	66.4	62.8	66.4	66.4	64.7	69.0	65.4	56.4	68.2
CAD used to control machines and/or in	1988	19.0	14.4	21.2	17.0	12.9	23.1	16.7	15.4	14.5	9.3
procurement	1993	35.8	41.4	31.3	31.5	32.7	37.7	30.8	25.7	26.7	41.2
LAN for factory use and/or intercompany	1988	26.2	27.4	27.9	30.3	32.8	39.9	35.3	34.6	25.7	26.5
computer networks	1993	33.2	40,8	35.7	37.4	30.3	42.5	40.2	38.1	25.8	38.6

Source: U.S. Bureau of the Census, Survey of Manufacturing Technology, 1988 and 1993.

between 1988 and 1993 was rapid and widespread; unusually intense technology use measured by 1988 criteria ranks only as lowest-quartile use by 1993. Nevertheless, the maps also indicate that the share of plants making above-average use of advanced technologies in any given period varies considerably across regions and within states. In 1988, relatively high-tech use within the SMT population was concentrated in parts of New York and New England, Virginia, South Carolina, Tennessee, Minnesota, Nebraska, and isolated metro regions dotted about the country. However, many metro areas, particularly in the East, appear as islands of relatively light technology use. By 1993 (Map 5), areas of intense technology use occur in parts of New York-New England, an arc of states that happen to be popular with foreign auto companies and their suppliers (Ohio, Illinois, Kentucky, and Tennessee), and a cluster formed by New Mexico, Colorado, and Nebraska. Some contiguous states in New England, the South Atlantic, the East North, and the West South Central regions also exhibit above-average adoption. On the whole, the pattern of technology use appears less scattered in 1993 than in 1988.

Maps 6 and 7 show the share of SMT establishments that had adopted a specific pair of relatively new technologies, CAD for controlling machines or for procurement. Again, these technologies spread rapidly in the sample period, with above-average use in 1988 subsumed into the lowest quartile by 1993. In the earlier period, the most intense use of CAD beyond design and engineering work occurred in a scattering of metro areas, including the Boston-Worcester-Lawrence and the Seattle-Tacoma-Bremerton CMSAs, as well as the southern Mountain states. By 1993, the heaviest use had spread through most of the Mid-Atlantic, along with Minnesota, Nebraska, and Arkansas. Again, metro regions (with more than 20 observations) do not appear to be at a disadvantage compared with surrounding areas. Interestingly, areas using large numbers of technologies in 1993 (Ohio, Kentucky, Tennessee, and Illinois, for instance) did not exhibit widespread adoption of these new CAD technologies, while West Coast areas, with low mean numbers, showed above-average use of extended CAD.

Because the maps (and, indeed, the construction of QMSAs) blur the distinctions between urban, suburban, and rural counties, Table 4 provides information similar to that covered by the maps for nine types of counties, running from urban core to rural as classified by the Beale codes.[23,24] For 1988 this table appears to confirm Harrison, Kelley, and Gant's (1996) conclusions that technology use peaks in urban counties outside of metropolitan areas (Beale Codes 4 and 5), at least for broad measures of technology use. The data suggest relatively limited technology use in core metro or completely rural areas. However, even in 1988, the pattern is less clear in the case of the newer CAD and LAN technologies. By 1993, moreover, the distinction between total technology use in metro and smaller urban counties seems less pronounced, possibly because the use of CAD and LAN technologies rose relatively fast in metro areas. This pattern raises a question as to whether new manufacturing technologies, which are comparatively inexpensive and reduce the relative cost of short production runs, may be particularly well-suited to the often small facilities located in metro areas.

Econometric Analysis of Technology Adoption

The maps just discussed suggest considerable variation in the use of technologies across and within states and regions. However, as discussed above, the maps are subject to several limitations, and we are reluctant to draw conclusions based solely on them. In order to investigate the

[23] The 1993 urban-rural continuum codes, first developed in 1975 and updated by Calvin Beale, provide a classification scheme that distinguishes metropolitan counties by size and status as core or fringe counties and nonmetro counties by degree of urbanization and proximity to metro areas. These codes reflect population density, commuting patterns, and metro influence generally. See specific definitions in Appendix 4.

[24] Again, the data in the table are not adjusted for differences in industry mix or other determinants of technology adoption. In addition, outside of the metro areas, the number of observations falls off sharply.

regional aspects of technology diffusion more systematically, thus, we estimate a set of econometric models that allow us to control for the effects of plant, firm, and QMSA characteristics. Data for this exercise come from the 1988 and 1993 SMTs; details of our sample construction procedures, along with variable definitions and descriptive statistics, are provided in Appendix 4.

The first measure of technology adoption examined is the change in the number of advanced technologies used by SMT establishments between 1988 and 1993. For each of the 17 technologies covered by the SMT, establishments reported whether they had adopted the technology within the past two years, in the last two to five years, or more than five years ago. With this information, we can calculate the increase in the number of technologies used between 1988 and 1993 for each plant.[25]

As Figure 1 shows, a large share of the sample establishments either did not increase the number of technologies used, or added only one or two new technologies between 1988 and 1993. Accordingly, we have chosen a negative binomial specification for the conditional distribution of the change in the number of technologies used (since the negative binomial is appropriate for data concentrated at small, non-negative integer values).[26] In the negative binomial regression analysis, the natural logarithm of the expected increase in the number of technologies adopted is specified to be a linear function of various conditioning variables.

In our first specification, shown in the left-most column in Table 5, we control only for proximity to other users of advanced manufacturing technologies.[27] Our proximity measure is the natural logarithm of the mean number of advanced technologies used within the establishment's QMSA in 1988 (based on data from the 1988 SMT). Since large establishments seem likely to have a greater impact on neighbors' technology use than do small ones, we weighted each establishment by its total employ-

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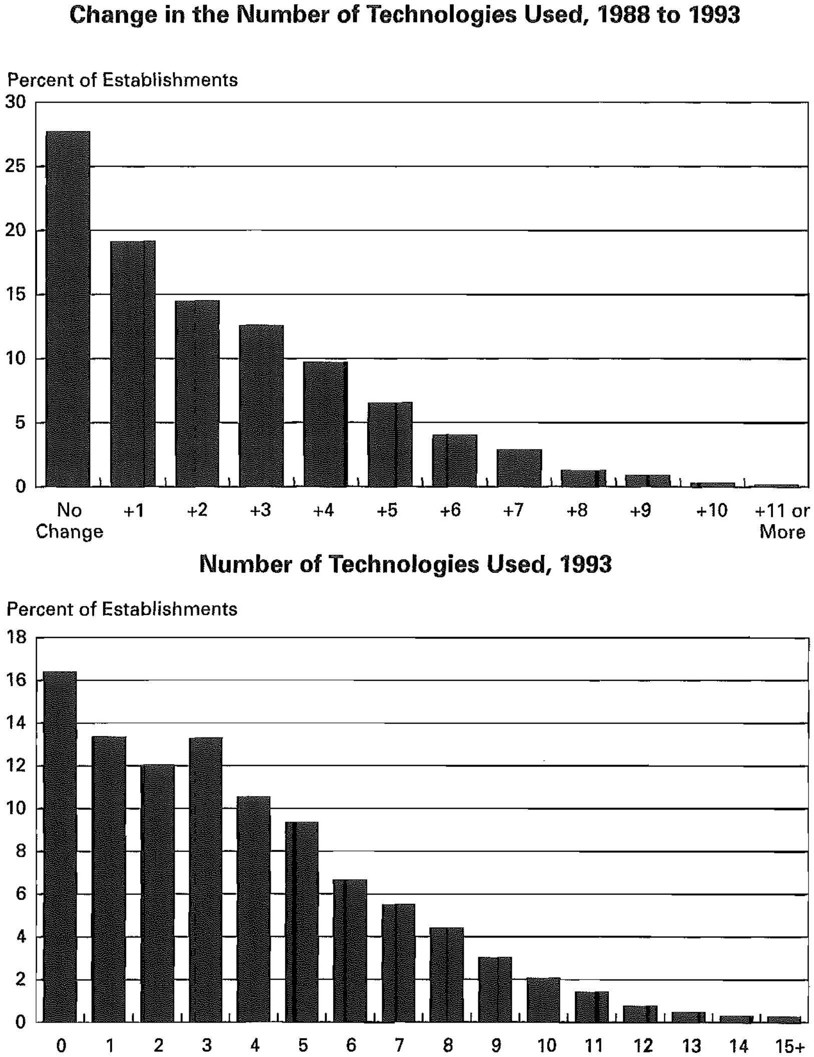
[25] The count of technologies used in 1993 is based on a series of questions asking whether each technology is "currently used in operations," while the count of technologies used in 1988 is based on the questions asking whether each technology was used "more than 5 years ago." Less than 0.2 percent of our sample observations reported using more technologies in 1988 than in 1993. For these observations, the change in the number of technologies used variable was set equal to zero. In addition, establishments less than 5 years old (based on the answer to a question inquiring whether the establishment had been manufacturing products at the current location for "less than 5 years," "5 to 10 years," "16 to 30 years," or "over 30 years") were droppped from the sample, since they could not have adopted any technologies more than 5 years ago.

[26] Hausman, Hall, and Griliches (1984) and Cameron and Trivedi (1986) provide expositions of count data models, including the negative binomial regression specification.

The contributions to the log-likelihood function were weighted by the SMT sample weights in estimating the regressions.

[27] The "ln(dispersion parameter)" coefficient indicates whether the dispersion in the count data is greater than would be expected under a Poisson data-generating process. The dispersion parameter would equal zero (and its natural log $-\infty$) in a Poisson specification.

Figure 1



Source: Authors' calculations, using 1993 Survey of Manufacturing Technology.

Table 5
Results from Negative Binomial Regressions

	Change in Number of Technologies Used, 1988 to 1993			Number of Technologies Used, 1993		
Independent Variable	Coefficient (Std. Error)	Coefficient[a] (Std. Error)	Coefficient[a] (Std. Error)	Coefficient (Std. Error)	Coefficient[a] (Std. Error)	Coefficient[a] (Std. Error)
LN (PROXIMITY)	.226	.190	.105	.236	.182	.096
	(.051)	(.046)	(.051)	(.044)	(.035)	(.038)
LN (TECH USE_{88})		−.137	−.142			
		(.020)	(.020)			
MULTI-EST		.171	.131		.333	.301
		(.236)	(.236)		(.175)	(.174)
LN (EST SIZE)		.953	.942		.684	.680
		(.074)	(.074)		(.054)	(.054)
[LN (EST SIZE)]^2		−.061	−.060		−.033	−.033
		(.007)	(.007)		(.005)	(.005)
LN (FIRM SIZE)		−.036	−.028		−.088	.005
		(.063)	(.063)		(.047)	(.046)
[LN (FIRM SIZE)]^2		.004	.004		.008	.008
		(.004)	(.004)		(.003)	(.003)
MILITARY SPEC		.168	.163		.175	.171
		(.026)	(.026)		(.019)	(.019)
FABRICATION		.253	.257		.304	.304
		(.039)	(.039)		(.030)	(.030)
NO FABRIC/NO ASSM		−.299	−.296		−.206	−.202
		(.070)	(.070)		(.054)	(.054)
FOREIGN OWN		.123	.132		.114	.120
		(.042)	(.236)		(.031)	(.031)
AGE 16–30		−.111	−.112		−.068	−.068
		(.028)	(.028)		(.021)	(.021)
AGE >30		−.226	−.240		−.148	−.157
		(.031)	(.031)		(.023)	(.023)
HIGH SCHOOL+			1.875			1.597
			(.315)			(.237)
BA+			.449			.594
			(.370)			(.278)
RD_{1990}			−.022			.060
			(.075)			(.052)
$BEALE_{12}$			−.070			−.037
			(.032)			(.024)
$BEALE_{35}$			−.022			.013
			(.047)			(.035)
$BEALE_{69}$			−.043			−.019
			(.050)			(.037)
CONSTANT	.391	−.287	−3.781	.859	−2.027	−2.850
	(.097)	(.224)	(.282)	(.083)	(.167)	(.211)
ln (dispersion parameter)	−.402	−.995	−1.012	−.608	−1.676	−1.700
	(.035)	(.048)	(.048)	(.030)	(.053)	(.054)
Observations	6,214	6,214	6,214	6,214	6,214	6,214
Log Likelihood	−12,423	−11,706	−11,686	−14,861	−13,511	−13,485

[a]Indicates that specification also included 25 industry dummy variables. See Appendix 5 for criteria used for dropping observations. Source: Authors' calculations, using 1993 Survey of Manufacturing Technology.

ment in calculating the proximity measure.[28] The proximity coefficient can be interpreted as the elasticity of the expected change in technology use with respect to prior technology use by other firms in the same area. The elasticity is sizable, 0.23, and reasonably precisely estimated. Thus, the number of advanced technologies adopted by plants between 1988 and 1993 is estimated to be an increasing function of the level of technology use by nearby plants in the base year.

This estimate is consistent with proximity to other users of advanced technology being an important determinant of adoption, but this result could also be driven by more general agglomeration economies that lead similar firms (with similar needs for technology) to cluster geographically. To explore this hypothesis, we next added a set of establishment and firm characteristics to the model. Estimates from this specification are shown in the second column in Table 5; in addition to the variables shown, 25 industry dummy variables were also included in the estimation.[29]

Surprisingly, the inclusion of the establishment and firm characteristics has relatively little impact on the size of the estimated proximity effect. Apparently, in other words, the impact of proximity to high-tech neighbors on nearby plants' technology adoption decisions is not simply a matter of similar firms clustering together.

Turning to the establishment characteristics, the estimated coefficients on these variables generally conform with our expectations. The natural log of the number of technologies used by the firm in 1988 is negative and precisely estimated.[30] Firms that were already heavy users of technology tended to adopt comparatively few additional technologies, while firms that were less technologically intensive in 1988 most likely chose to adopt a greater number of new technologies in order to stay competitive.[31]

As in previous work, employment size is found to be an important predictor of technology adoption. The coefficient on the natural log of

[28] Some plants were included in both the 1988 and 1993 SMT samples; in addition, the parents of 1993 SMT establishments sometimes owned other plants within the same QMSA that were also included in the 1988 sample. To avoid having our proximity measure capture intra-firm or lagged plant effects, for each 1993 SMT establishment we calculated the proximity measure excluding other plants owned by the same firm (as of 1992) as well as the establishment itself. SMT sample weights (normalized to average 1 within each QMSA) were used in computing the proximity measure.

[29] The industry groups represented by the dummy variables were created by merging two or three similar 3-digit industries. Details are provided in the list of SIC groups in Appendix 4.

[30] Since a non-trivial number of establishments used none of the advanced technologies in 1988, one was added to the number of technologies used before taking logs.

[31] An alternative, more mechanical, explanation is that since the SMT only asked about 17 specific technologies, the higher the initial number of technologies, the smaller the maximum possible increase.

the employment size variable can be interpreted as the elasticity of the increase in the number of technologies used with respect to the number of employees. This elasticity is nearly 1 for small plants, but the negative coefficient on the quadratic term suggests that the elasticity decreases with plant size.

Why should we expect a positive relationship between technology adoption and employment size? Some explanations focus on there being a minimum plant scale associated with efficient utilization of given technologies. Other explanations relate to both firm and plant size. Economists have long pointed out, for instance, that large firms reap economies of scale in technology adoption because they can spread fixed costs, like the required R&D or the risk of failed implementation, over a larger sales base. While the expected returns to adoption are proportional to size, many of the costs are not. (See Babbage 1835, cited in Rosenberg 1994; Mansfield 1963; Keefe 1991; Nooteboom 1993; and Wozniak 1987, 1993.) In addition, large firms or plants may also encounter more frequent opportunities to make sometimes lumpy capital investments[32] (Rose and Joskow 1988) or to experiment. Large firms may also have relatively ready access to capital and a sophisticated R&D network.

In an attempt to sort out the relative importance of firm and plant size, we include firm employment as a measure of capital access and, possibly, R&D sophistication for multi-establishment firms.[33] Surprisingly, when we control for establishment employment, firm size appears to have relatively little effect on technology adoption. The indicator variable for multi-plant firms is positive but has a standard error more than twice its size.[34] The coefficients for the natural log of firm manufacturing employment and for the square of the log (both of which are interacted with the multi-plant dummy variable) are small and statistically insignificant. These results strongly suggest that plant size, rather than firm size, affects the speed of technology adoption.

As expected, the indicator variables for fabrication activity (FABRICATION) and defense-related production (MILITARY SPEC) are both positive and statistically significant, while the dummy variable indicating that a plant is engaged in neither assembly nor fabrication (NO

[32] While investment in CAD/CAM or LAN equipment might appear to be less lumpy than investment in flexible machining cells or automated materials handling systems, say, adoption of CAM or LAN systems requires developing a new system of organization and control, an expensive proposition, as Mowery (1988) points out.

[33] Our firm size variable captures only employment in establishments appearing in the 1992 Census of Manufactures. Employment in the non-manufacturing facilities belonging to parents of SMT establishments is not included in this measure.

[34] "Multi-plant" was defined to include firms with more than one plant appearing in the 1992 Census of Manufactures. Firms with a single manufacturing plant and other non-manufacturing facilities would not be classified as multi-plant by this definition.

FABRIC/NO ASSM) is negative and significant. Like production to military specification, foreign ownership (FOREIGN OWN) also has a significant positive association with technology use. This result is consistent with foreign direct investment theory linking investment activity with technological sophistication. By contrast, the coefficients on the plant age dummy variables suggest that older plants are slower to take up new technologies.

While the specification just discussed shows that the proximity effect remains largely intact after conditioning on plant characteristics, it does not address whether proximity is capturing spillover effects or is instead serving as a proxy for regional characteristics, like educational attainment, that facilitate technology adoption. We investigate this question in the third specification shown in Table 5, in which several QMSA characteristics are added to the model.

Although the size of the proximity elasticity drops to 0.105 when the QMSA variables are added to the model, it remains both economically and statistically significant. Among the QMSA variables added are two measures of the educational attainment of the labor force (the share of the adult population with a high school diploma but less than a B.A. and the share with a four-year college degree or more) since much previous research has documented a link between technology use and the education of the managers or workers at the facility with the new equipment or process. (See Bartel and Lichtenberg 1987; Doms, Dunne and Troske 1995; Nelson and Phelps 1966; and Wozniak 1987, 1993.) In addition, in the 1991 SMT, cost of education and training and lack of skilled labor were among the major impediments to technology adoption cited by respondents foreseeing barriers.[35]

The variable measuring the fraction of the adult population with a high school diploma but less than a B.A. (HIGH SCHOOL+) has a large, positive, and statistically highly significant coefficient. However, a similar variable measuring the share of the adult population with at least a four-year college degree (BA+) usually has a relatively small, positive, sometimes statistically significant coefficient. These combined results suggest that college graduates are associated with more technology adoption than high school dropouts but have a less favorable impact than high school graduates who did not complete a four-year college. We expected to find that access to a work force with at least a high school education would be associated with technology adoption, but we find the BA+ coefficient puzzling. One possible explanation is that

[35] Somewhat less than half of the respondents anticipated barriers to acquiring equipment in any of the four technology groups covered. For those who foresaw difficulties, the top problems (out of 12 possibilities) were always cost of equipment and cost of software, generally followed by cost of training, lack of benefit, and lack of skilled work force.

manufacturers need educated workers but do not wish to pay production workers the college wage premium. Thus, the most attractive labor pool may contain a large share of individuals with a high school education or post-secondary technical training but not a four-year college degree. Or, professional workers may move in a national labor market. In addition, technologies could vary in their requirements for educated workers.[36] Finally, the BA+ variable may be picking up the effects of omitted QMSA characteristics like land prices and quality-adjusted labor costs.[37]

Because local firms benefit from proximity to research universities —by hiring graduates or faculty consultants, conducting joint research, attending seminars, and the like—the geographic variables also include university R&D spending per worker by QMSA (RD_{1990}).[38] Previous research has shown that proximity to major research universities has spillover effects in the case of patenting activity. Recently, moreover, many universities have strengthened their links to local industry through increased efforts to commercialize university inventions or through technology transfer programs. (See Bania, Eberts, and Fogarty 1993; Henderson, Jaffe, and Trajtenberg 1995.) However, as with the BA+ variable, our expectations were not borne out. The university R&D variable has a small, negative, statistically insignificant coefficient. While universities may have an important impact on generating new technologies, our results suggest that they have little to do with the diffusion of fairly mature technologies such as those measured by the SMT.

The last three geographic variables included in the specification are a set of dummy variables indicating whether the plant is located in a county assigned Beale codes 1 or 2 (non-core but large metro counties), 3 through 5 (small metro or large urban counties), or 6 through 9 (small urban and rural counties); the omitted category is Beale code 0 (central city counties of large metro areas). The Beale code dummy coefficients are all quite small and, with one exception, negative. This result reinforces the impression made by the simple tabulations shown in

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[36] For instance, exceptions to the significant positive link between HIGH SCHOOL+ and adoption of specific technologies, discussed below, occur in the case of: 1) the relatively large-scale and little-used flexible manufacturing systems suitable for long production runs; 2) lasers, robots, and automated materials handling systems, also generally found in large-scale facilities in specific industries; and 3) the older programmable controllers now being replaced by more flexible CAD/CAM and LAN systems.

[37] Crude preliminary attempts at addressing this issue by adding measures of housing costs and average manufacturing earnings to the specification did not change the flavor of the results. An exploratory effort to control for variations in economic conditions across QMSAs, as measured by the change in manufacturing employment in the QMSA between 1987 and 1992, also had little perceptible impact on the results.

[38] The RD_{1990} variable is based on research and development expenditures of the top 280 research universities (ranked by R&D spending).

Table 4: Although the central urban counties may have lagged in technology adoption at one point, that effect is not apparent in the more recent data.

In addition to the regressions for change in number of technologies used, Table 5 also shows the results of estimating negative binomial regressions where the dependent variable is the number of advanced technologies used in 1993 (with identical conditioning variables, excluding the number of technologies used in 1988). The results are very similar to those discussed earlier, an outcome suggesting that technology adoption occurred via a similar process both before 1988 and between 1988 and 1993.[39]

While a count of the number of technologies used is a useful scalar measure of technology intensity, we were also interested in examining the diffusion of specific technologies. For this purpose, we grouped the 17 technologies covered by the SMT into 10 relatively homogeneous categories. For each category, we formed an ordinal variable measuring the speed of technology adoption. This variable takes on the highest value if the plant adopted the technology more than five years ago, and the lowest value if the establishment had not yet adopted the technology (as of 1993).[40]

For each of the 10 technology groups, we estimated an ordered probit regression relating the ordinal speed of technology adoption to the same set of variables used in the technology count analysis already discussed. But proximity is now measured as the fraction of SMT employment within the QMSA using the technology in question in 1988.[41] As before, we first condition on proximity alone, then add establishment characteristics, and finally include QMSA variables. Estimation results are shown in Table 6; to conserve space, the establishment characteristic coefficients are not shown in the text (but are presented in Appendix 6).

When we control only for proximity, once again the proximity effect is sizable and nearly always statistically significant. In these regressions the dependent variables are latent measures of the speed of technology adoption, normalized to have unit variance. Thus, the proximity coefficient of 0.46 for the first technology group (computer-aided design or engineering), for example, can be interpreted as indicating that if CAD

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[39] In a future revision of this paper, we will address this hypothesis more directly by estimating regressions with the number of technologies used in 1988 specified as the dependent variable.

[40] The two intermediate categories are: adopted two to five years ago, and adopted within the past two years—again relative to 1993. For each technology group, the technology was considered "adopted" at the earliest time any component technology was used.

[41] The proximity measure was calculated using steps similar to those described for the proximity variable used in the negative binomial regressions, as described above in the text and in footnote 28. Again, they are subject to the same limitation, being based only on plants observed in the 1988 SMT.

Table 6
Technology Adoption Estimation Results
Ordered Probit Specification

	Technology Groups									
Variable	1	2	3	4	5	6	7	8	9	10
	Controlling Only for Proximity									
PROXIMITY	.460	.478	.537	.247	.430	.417	.390	.500	.705	.403
	(.129)	(.105)	(.128)	(.140)	(.124)	(.125)	(.109)	(.111)	(.126)	(.131)
	Controlling for Proximity and Establishment Characteristics[a]									
PROXIMITY	.396	.408	.297	.183	.361	.229	.339	.428	.377	.373
	(.134)	(.111)	(.138)	(.150)	(.141)	(.137)	(.114)	(.116)	(.134)	(.137)
	Controlling for Proximity, QMSA Characteristics, and Establishment Characteristics[a]									
PROXIMITY	−.097	.093	.140	.196	.358	.150	.080	.247	.287	.250
	(.167)	(.129)	(.146)	(.155)	(.149)	(.147)	(.130)	(.123)	(.140)	(.143)
HIGH SCHOOL+	1.821	1.604	1.122	.616	.688	1.583	2.696	2.366	.314	1.272
	(.403)	(.432)	(.409)	(.519)	(.536)	(.507)	(.430)	(.427)	(.430)	(.433)
BA+	−.111	1.499	1.702	−.016	−.361	.135	1.289	−.265	−.973	1.353
	(.513)	(.511)	(.481)	(.630)	(.640)	(.608)	(.535)	(.490)	(.504)	(.512)
RD_{1990}	.148	.029	−.006	−.014	−.183	.161	.255	.127	.215	.011
	(.089)	(.100)	(.099)	(.124)	(.150)	(.113)	(.092)	(.094)	(.097)	(.098)
$BEALE_{12}$	.007	−.037	−.042	.044	−.082	−.060	−.017	−.018	−.006	−.011
	(.039)	(.043)	(.042)	(.055)	(.056)	(.052)	(.044)	(.043)	(.045)	(.045)
$BEALE_{35}$	.068	−.040	.028	.192	−.008	−.002	.043	−.135	−.030	.065
	(.058)	(.065)	(.064)	(.080)	(.082)	(.078)	(.065)	(.064)	(.066)	(.067)
$BEALE_{69}$	.024	−.110	−.046	.066	−.002	−.034	−.063	−.038	.030	.141
	(.061)	(.068)	(.067)	(.086)	(.085)	(.082)	(.070)	(.067)	(.070)	(.070)
CUTOFF POINT 1	3.778	3.667	4.610	2.951	3.768	2.859	4.392	3.873	2.448	3.773
	(.355)	(.398)	(.393)	(.481)	(.504)	(.465)	(.404)	(.389)	(.403)	(.405)
CUTOFF POINT 2	4.176	3.942	4.769	3.183	3.989	3.067	4.795	4.317	2.636	4.049
	(.356)	(.399)	(.394)	(.482)	(.504)	(.465)	(.404)	(.389)	(.403)	(.405)
CUTOFF POINT 3	5.099	4.578	5.175	3.637	4.380	3.470	5.515	4.956	3.100	4.584
	(.357)	(.399)	(.394)	(.482)	(.504)	(.465)	(.405)	(.390)	(.404)	(.406)
Observations	6165	6177	6141	6182	6165	6171	6121	6119	6095	6115

Technology Groups

1 CAD or CAE alone
2 CAD used to control machines or in procurement
3 NC/CNC
4 Flexible manufacturing cells or systems
5 Materials working lasers, robots, and automated materials handling equipment
6 Sensor-based inspection/testing
7 LAN for technical data
8 LAN for factory use and intercompany computer networks
9 Programmable controllers
10 Computers used to control the factory floor

See Appendix 5 for criteria used for dropping observations.

[a]Coefficients for establishment characteristics are shown in Appendix 6.

Source: Authors' calculations, using 1993 Survey of Manufacturing Technology.

or CAE technology had been used by an extra 10 percent of a QMSA's work force, the latent technology index would have been roughly 0.05 standard deviations higher.[42] The proximity effects generally seem closer in magnitude to each other than one would expect a priori; eight out of the 10 coefficients have values between 0.35 and 0.55.

When plant and firm characteristics are added to the specification, the proximity coefficients tend to drop by a somewhat greater percentage than in the count regressions. This result probably reflects the fact that industry specificity is greater for use of particular technologies than for the number of technologies used. Overall, however, proximity to other users of the same technology remains important even when plant characteristics are taken into account.

The addition of geographic characteristics changes the picture considerably. The value of several of the proximity coefficients drops a good deal, and most (taken individually) are now statistically insignificant. The educational attainment coefficients also vary a good deal in magnitude, although the share of the adult population who had graduated from high school generally emerges as an important determinant of the speed of technology adoption. The R&D and Beale code coefficients are erratic, varying in both magnitude and sign over the technology groups.

Why are the results so much weaker when we examine the effects of proximity and other geographic characteristics on the adoption of individual technologies, rather than on the total number of technologies used? One possibility is that, beyond the impact of proximity to users of a specific technology, proximity to technologically advanced plants in general has an independent effect on technology adoption. This omitted variable may be biasing the coefficients of the other local area variables in ways that vary over the technology groups. Another possibility is that each ordinal variable is too crude an indicator of the speed of technology adoption to permit us to decipher the separate influences of the geographic variables. Finally, it may be the case that, in truth, the proximity and other geographic characteristics affect technology adoption in ways

[42] A somewhat more down to earth interpretation can be made by examining the estimated cutoff points shown in the Appendix. The cutoff points show how the ordinal variable categories are mapped into ranges of the latent (unit variance) speed of adoption variable. The first cutoff point divides the "have not adopted" and "adopted within the past two years" categories; the second cutoff point divides the "adopted within the past two years" and "adopted two to five years ago" categories; the third cutoff point divides the "adopted two to five years ago" and "adopted more than five years ago" categories.

that vary widely over technology groups. Further research is needed to explore these possibilities.[43]

CONCLUSIONS

Geography does make a difference to the speed of adoption of advanced technologies. Proximity to other users of technology is associated with higher rates of adoption, and this effect remains apparent even when industry and other plant characteristics are taken into account. In many ways, this outcome is surprising. Given the well-developed communications and transportation networks, and national markets for capital goods and skilled workers, one might expect the United States to approach the limiting case of immediate, costless diffusion of technology.

Human capital appears to be an important component of the proximity effect. Access to a work force with at least a high school

[43] In his thoughtful comments on this paper at the June conference, John Haltiwanger emphasized the drawbacks of using retrospective data to measure the change in the number of technologies used between 1988 and 1993 (in the negative binomial regressions) and the timing of technology adoption (in the ordered probits). As Haltiwanger pointed out, comparing responses given in 1988 and 1993 for establishments in both the 1988 and 1993 SMT reveals a large number of inconsistencies.

In response to these comments, we reran all of our regressions using data from the 1988 and 1993 SMTs for 2,228 establishments appearing in both surveys. Using current 1988 and 1993 responses rather than retrospective information for this relatively small sample does not change the overall flavor of the results. If anything—to our surprise—this change strengthens the conclusion that proximity to early users encourages technology adoption. Results for the regressions estimating the change in the number of technologies used for the matched subsample reveal that the size of the proximity coefficient is nearly twice as large when the 1988 SMT information is used as when only the retrospective information from the 1993 SMT is used. However, in the case of the ordered probits, the differences between the results based on the 1988 SMT information and the results based solely on the 1993 retrospective data are less clear.

We note one interesting difference between the full sample results shown in Table 5 and the results for the same specifications estimated using the subsample of plants found in both the 1988 and 1993 SMTs. In the subsample, the size of the proximity coefficient is much larger when establishment characteristics are held constant than when proximity is the only explanatory variable. This difference holds whether the dependent variable is based only on retrospective information or on information from the matched 1988 and 1993 SMT observations. The proximity coefficient drops somewhat when the geographic characteristics are added to the set of explanatory variables, but the drop is much smaller than occurs with the full sample. A likely reason for the differences between the results for the full and subsamples is that the matched 1988-93 subsample contains relatively large firms. Since the distribution of plant characteristics differs markedly between the full sample and the subsample, it is not surprising that adding plant characteristics to the specification has quite different effects on the magnitude of the proximity coefficients estimated from the two samples.

The authors would be glad to supply regression results for the matched 1988–93 subsample upon request.

education is associated with a faster rate of technology adoption, and some, perhaps much, of the remaining proximity effect likely reflects technical knowledge spread through social interactions within geographic areas. In other words, human capital seemingly influences not just the productivity with which a given stock of physical capital is used, but also the technology incorporated in that capital stock.

To summarize more specific results, the regression analysis generally confirms previous research linking technology adoption to establishment size; however, it finds little association between multi-establishment firm size or multi-establishment status and technology use. The limited impact of firm size suggests that the positive link between size and technology use reflects plant scale rather than favored access to capital or firm-level technological sophistication. The research also reconfirms that facilities that engage in fabrication use relatively large numbers of technologies.[44] By contrast, unlike previous studies, this paper also finds some evidence of a significant negative relationship between plant age and technology adoption. As expected, moreover, manufacturing to military specification has a sizable and consistently positive impact on technology adoption, a finding that demonstrates yet again how defense spending serves as this country's industrial policy. Foreign ownership also has a positive association with technological sophistication. Finally, this research finds almost no evidence that, in 1993, center-city counties of large metro areas were at a significant disadvantage in terms of technology use compared with smaller or less urban areas. Indeed, if anything, the data suggest a positive association between a core urban location and the increase in the number of technologies used between 1988 and 1993.[45] Possibly, in other words, the new CAM and LAN technologies are especially suited to urban manufacturing needs.

As for the geographic characteristics, although we were not able to disentangle proximity/spillover effects from the impact of educational attainment/university R&D in a satisfactory manner, we generally find a significant link between technology adoption and the availability of a relatively well-educated work force, particularly in the case of the newer CAD and LAN technologies. However, the relatively great importance of high school graduates as compared with individuals with college degrees remains puzzling. Nevertheless, we believe we see enough evidence of uneven technology diffusion, particularly of the newer technologies, to warrant further research on this topic. Exploring the impact of other locational variables that may be more directly linked to technology adoption—the availability of engineers and technicians or

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[44] The association is less pronounced in the case of the CAD and LAN technologies.
[45] Including, in particular, LAN for factory use and intercompany networks.

software designers, for example, or proximity to leading vendors of high-tech equipment—might be a promising approach. In addition, we need to develop a more complex model of the endogenous relationships between proximity and location and between investment and technology adoption.

In sum, the results of this first effort to explore the geographic dimensions of the SMT suggest that locational characteristics do play a role in technology diffusion. Because the repetitive process of technology adoption is extremely expensive for individual firms and the nation, gaining a better understanding of this process remains an important goal.

Appendix 1—Description of Manufacturing Technologies, Taken from "Manufacturing Technology: Prevalence and Plans for Use 1993"

1. Design and Engineering

a. **Computer Aided Design (CAD) and/or Computer Aided Engineering (CAE)**—Use of computers for drawing and designing parts or products and for analysis and testing of designated parts or products.

b. **Computer Aided Design (CAD)/Computer Aided Manufacturing (CAM)**—Use of CAD output for controlling machines used to manufacture the part or product.

c. **Digital Data Representation**—Use of digital representation of CAD output for controlling machines used in procurement activities.

2. Fabrication/Machining and Assembly

a. **Flexible Manufacturing Cells (FMC)**—Two or more machines with automated material handling capabilities controlled by computers or programmable controllers, capable of single-path acceptance of raw material and single-path delivery of finished product.

Flexible Manufacturing Systems (FMS)—Two or more machines with automated material handling capabilities controlled by computers or programmable controllers, capable of multiple-path delivery of finished product. An FMS also may be comprised of two or more FMCs linked in series or parallel.

b. **NC/CMC Machines**—A single machine either numerically controlled (NC) or computer numerically controlled (CNC) with or without automated material handling capabilities. NC machines are controlled by numerical commands punched on paper or plastic mylar tape. CNC machines are controlled electronically through a computer residing in the machine.

c. **Materials Working Laser(s)**—Laser technology used for welding, cutting, treating, scribing, and marking.

d. **Pick and Place Robot(s)**—A simple robot, with one, two, or three degrees of freedom, which transfers items from place to place by means of point-to-point moves. Little or no trajectory control is available.

e. **Robot(s)**—A reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized device through variable programmed motions for the performance of a variety of tasks.

3. Automated Material Handling

a. **Automatic Storage and Retrieval System (AS/RS)**—Computer-controlled equipment providing for the automatic handling and storage of materials, parts, subassemblies, or finished products.

b. **Automatic Guided Vehicle Systems (AGVS)**—Vehicles equipped with automatic guidance devices programmed to follow a path that interfaces with work stations for automated or manual loading and unloading of materials, tools, parts, or products.

4. Automated Sensor Based Inspection and/or Testing Equipment

Automated Sensor Based Inspection and/or Testing Equipment—Includes automated technical data within design and engineering departments.

5. Communications and Control

a. **Technical Data Network**—Use of local area network (LAN) technology to exchange technical data within design and engineering departments.

b. **Factory Network**—Use of local area network (LAN) technology to link subcontractors, suppliers, and/or customers with the plant.

c. **Intercompany Computer Network**—Use of network technology to link subcontractors, suppliers, and/or customers with the plant.

d. **Programmable Controller(s)**—A solid state industrial control device that has programmable memory for storage of instructions, which performs functions equivalent to relay panel or wired solid state logic control system.

e. **Computer(s) Used for Control on the Factory Floor**—Excludes computers imbedded within machines, or computers used solely for data acquisitions or monitoring. Includes computers that may be dedicated to control but are capable of being programmed for other functions.

Appendix 2— Use of SMT Sample Weights in Constructing Geographic Estimates

To understand the importance of using weighted data for geographic analysis, suppose that a region has a disproportionately large share of big firms, which have a relatively high probability of both sample inclusion and advanced technology use. While unweighted data would tend to exaggerate the extent of technology adoption in that area, weighted data (normalized by region-specific factors) will not be subject to that bias since the weights correct for differences in probability of sample inclusion across strata.

Regionally normalized sample weights are appropriate for our purposes because they result in unbiased estimates of means and proportions within regions. Suppose, for example, that N and n are the overall population and sample sizes, that N_h and n_h are the population and sample sizes in stratum h, and that N_g and n_g are the population and sample sizes in geographic area g. Thus, N_{gh} and n_{gh} are the population and sample sizes of establishments in both stratum g and area h. The sample weight for establishments in the SMT is N_h / n_h, the inverse of the sampling probability. A standard result in sampling theory is that sample means and proportions computed using these weights, multiplied by n/N to normalize to one, will be unbiased estimators of their population counterparts (Cochran 1963, chapter 5). In other words, the arithmetic mean of $(n/N)(N_h/n_h)y_i$ will be an unbiased estimator of the population mean of y.

Within geographic area g, the appropriate sample weight to use in estimating population means and proportions is N_{gh}/n_{gh} normalized to average one within region g. However, simple random sampling within strata leads to the result that $N_{gh}/n_{gh} = N_h/n_h$. In other words, since the probability of sample inclusion within a given stratum does not vary over regions, the sample weight for an establishment in stratum i relative to the sample weight of an establishment in stratum j should also not vary over regions.

The normalization factor for region g is n_g/N_g. This factor, the probability of sample selection in region g (not conditioning on stratum membership) will vary over regions because of interregional differences in industry mix and the distribution of employment size. Thus, region-specific normalization factors must be applied in computing estimates by region. The normalization factors can be simply calculated as the multiplicative scalar factors which result in the weights having mean values equal to one within each region. They do not need to be estimated using an external data source.

APPENDIX 3—DISTRIBUTION OF OBSERVATIONS BY CMSA, 1993

Number of Observations	Number of QMSAs	Cumulative Observations	Total Share of Observations
6–7	12	76	1.07
8–10	15	214	3.01
11–15	29	596	8.38
16–20	14	843	11.85
21–25	12	1112	15.63
26–30	7	1310	18.41
31–35	2	1376	19.34
36–40	10	1754	24.65
41–45	6	2016	28.33
46–50	5	2256	31.71
51–55	7	2629	36.95
56–60	6	2978	41.86
61–65	1	3043	42.77
66–70	3	3251	45.69
70–75	6	3689	51.85
76–100	5	4117	57.86
101–125	4	4578	64.34
126–150	2	4844	68.08
151–200	2	5166	72.61
201–250	3	5857	82.32
251–400	2	6558	92.17
Over 400	1	7115	100.00

Source: U.S. Bureau of the Census, Survey of Manufacturing Technology, 1993.

Appendix 4—Variable Definitions and Data Sources

Variable	Description	Source and Comments
Dependent:		
TECH NUM_{93}	Number of technologies used by establishment in 1993, used in negative binomial regressions	Survey of Manufacturing Technology (SMT) 1993, extract provided by the U.S. Bureau of the Census, Center for Economic Studies (CES)
Δ TECH $NUM_{88\text{-}93}$	Change in number of technologies used by establishment 1988–93, used in negative binomial regressions	SMT 1993, extract provided by the CES. (SMT 1988 used in regressions described in footnote 43.)
PROB($TECH_t$)	Probability of establishment adopting $technology_t$: not yet, less than 2 years ago, 2 to 5 years ago, or more than 5 years ago, for technology groups 1–10, used in ordered probit regressions	SMT 1993, extract provided by the CES. (SMT 1988 used in regressions described in footnote 43.)
Independent:	Establishment Characteristics:	
LN (TECH USE_{88})	Natural log of number of technologies used by establishment in 1988, used in regression for Δ tech $num_{88\text{-}93}$	SMT 1993, extract provided by the CES. (SMT 1988 used in regressions described in footnote 43.)
LN (EST SIZE) [LN (EST SIZE)]^2	Establishment size: natural log and natural log squared of total employment at establishment in 1992	Census of Manufactures (CM) 1992, extract from the Longitudinal Research Database (LRD) provided by the CES
LN (FIRM SIZE) [LN (FIRM SIZE)]^2	Firm size: natural log and natural log squared of total 1992 employment at firm to which establishment belongs, for multi-establishment firms	CM 1992, extract from the LRD provided by the CES
AGE 16–30 AGE >30	Dummies for age of establishment: ages 16 to 30 and above 30 versus ages 6 to 15	CM 1992, extract from the LRD provided by the CES
$IND_2 \ldots IND_{25}$	Dummies for 3-digit SIC cluster; see list below	SMT 1993, extract provided by the CES
MULTI-EST	Dummy for multi-establishment firm in 1992	CM 1992, extract from the LRD provided by the CES
MILITARY SPEC	Dummy: establishment produces some goods to military specification: yes versus no or don't know	SMT 1993, extract provided by the CES
FABRICATION NO FABRIC/ NO ASSM	Dummy for type of operation: fabrication or fabrication and assembly versus assembly only and neither versus assembly only	SMT 1993, extract provided by the CES

Appendix 4—continued

Variable	Description	Source and Comments
FOREIGN OWN	Dummy for foreign owned: yes versus no or don't know	SMT 1993, extract provided by the CES
	Location Characteristics:	
PROXIMITY	Proximity to other users of SMT technologies: natural log of mean number of technologies used in QMSA by unrelated establishments in 1988, weighted by plant employment, in the negative binomial regressions; share of SMT employment in QMSA at unrelated establishments using the same $technology_t$ in 1988, in the ordered probits	SMT 1988 and 1993, extract provided by CES
HIGH SCHOOL+	Share of the population 25 years of age and over with a high school diploma but less than a B.A., 1990, in QMSA	U.S. Bureau of the Census, *County and City Data Book*, 1994
BA+	Share of the population 25 years of age and over with a bachelor's degree and above, 1990, in QMSA	U.S. Bureau of the Census, *County and City Data Book, 1994*
RD_{90}	Academic science and engineering R&D expenditures by top 280 research universities, per worker, in QMSA, in FY 1993	National Science Foundation/SRS, Survey of Scientific and Engineering Expenditures at Universities and Colleges
$BEALE_{12}$ . . . $BEALE_{69}$	Dummies for Beale codes, 1993: 1 and 2; 3, 4, 5; and 6, 7, 8, 9 versus 0	Butler and Beale, U.S. Department of Agriculture, Economic Research Service, 1993

SIC Groups

34 Fabricated Metal Products

341 + 343	Metal cans and shipping containers + plumbing and heating except electric
342	Cutlery, handtools, and hardware
344	Fabricated structural metal products
345 + 346	Screw machine products, bolts, etc. + metal forgings and stampings
347 + 349	Metal services, nec + miscellaneous fabricated metal products
348	Ordnance and accessories

35 Industrial Machinery and Equipment

351	Engines and turbines
352 + 353	Farm and garden machinery + construction and related
354	Metalworking machinery
355 + 358	Special industry machinery + refrigeration and service machinery
356 + 359	General industry machinery + industrial machinery, nec
357	Computers and office equipment

Appendix 4—continued

36 Electronic and Other Electric Equipment

361 + 362	Electric distribution equipment + electrical industrial apparatus
363 + 364 + 365 + 369	Household appliances + electric lighting and wiring + household audio and video equipment + miscellaneous
366	Communications equipment
367	Electronic components and accessories

37 Transportation Equipment

371	Motor vehicles and equipment
372	Aircraft and parts
373	Shipbuilding, boats and repair
376	Guided missiles
374 + 375 + 379	Railroad equipment + motorcycles, bicycles, and parts + miscellaneous

38 Instruments and Related Products

381	Search and navigation
382	Measuring and controlling devices
384	Medical instruments and supplies
385 + 386 + 387	Ophthalmic goods + photographic equipment and supplies + watches and clocks

Technology Groups

1 CAD or CAE alone
2 CAD used to control machines or in procurement
3 NC/CNC
4 Flexible manufacturing cells or systems
5 Materials working lasers, robots, and automated materials handling equipment
6 Sensor-based inspection/testing
7 LAN for technical data
8 LAN for factory use and intercompany computer networks
9 Programmable controllers
10 Computers used to control the factory floor

Rural–Urban Continuum Codes for Metro and Nonmetro Counties (Beale Codes)

Metro Counties

0 Central counties of metro areas of 1 million population or more
1 Fringe counties of metro areas of population of 1 million or more
2 Counties in metro areas of 250,000 to 1 million population
3 Counties in metro areas of fewer than 250,000 population

Nonmetro Counties

4 Urban population of 20,000 or more, adjacent to a metro area
5 Urban population of 20,000 or more, not adjacent to a metro area
6 Urban population of 2,500 to 19,999, adjacent to a metro area
7 Urban population of 2,500 to 19,999, not adjacent to a metro area
8 Completely rural or less than 2,500 urban population, adjacent to a metro area
9 Completely rural or less than 2,500 urban population, not adjacent to a metro area

Appendix 4—continued

Descriptive Statistics for Variables

Variable	Mean	Standard Deviation
TECH NUM_{93}	3.686	3.116
Δ TECH NUM_{93}	2.267	2.245
LN (TECH USE_{88})	1.420	1.976
LN (EST SIZE)	4.282	1.070
[LN (EST SIZE)]^2	19.485	10.494
LN (FIRM SIZE)[a]	7.352	2.036
[LN (FIRM SIZE)]^{2}[a]	58.199	31.475
AGE 16–30	.330	
AGE >30	.275	
MULTI-EST	.397	
MILITARY SPEC	.382	
FABRICATION	.796	
NO FABRIC/NO ASSM	.061	
FOREIGN OWN	.079	
PROXIMITY	6.794	1.724
PROX1	.727	.108
PROX2	.442	.147
PROX3	.661	.118
PROX4	.320	.138
PROX5	.514	.150
PROX6	.428	.149
PROX7	.483	.146
PROX8	.556	.140
PROX9	.667	.128
PROX10	.603	.125
HIGH SCHOOL+	.554	.044
BA+	.203	.054
RD_{1990}	.131	.185
$BEALE_{12}$	.251	
$BEALE_{35}$	.126	
$BEALE_{69}$	.116	
Observations	6214	

[a]These variables are reported only for establishments that are part of a multi-establishment firm; therefore, the number of observations for these variables is 3482.

Source: Survey of Manufacturing Technology, 1988 and 1993.

Appendix 5—Criteria for Dropping Observations from Analysis

Criteria for dropping observations include:

1. Establishment shipments valued at less than $1,000
2. Establishment employment of less than 10 for production workers or total employees
3. Observations coded AR (administrative record) in 1988, for which data were fully imputed
4. Establishments lacking unique permanent plant numbers (an issue in 1993 only)
5. Establishments with inconsistent geographic codes
6. Multi-establishment plants without an identifiable parent firm in 1992
7. Establishments with illogical or out-of-range survey responses
8. Establishments less than six years old (for the regression analysis)
9. Establishments in Alaska and Hawaii

APPENDIX 6—TECHNOLOGY ADOPTION ESTIMATION RESULTS

Technology Adoption Estimation Results: Ordered Probit Specification

	Technology Group 1			Technology Group 2		
Independent Variable	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)
PROXIMITY	.460 (.129)	.396 (.134)	−.097 (.167)	.478 (.105)	.408 (.111)	.093 (.129)
MULTI-EST		.454 (.295)	.443 (.296)		.194 (.325)	.095 (.327)
LN (EST SIZE)		.563 (.101)	.567 (.101)		.183 (.103)	.206 (.104)
$[\text{LN (EST SIZE)}]^2$		−.014 (.011)	−.015 (.011)		.011 (.011)	.009 (.011)
LN (FIRM SIZE)		−.099 (.081)	−.098 (.081)		−.066 (.088)	−.041 (.089)
$[\text{LN (FIRM SIZE)}]^2$		.007 (.005)	.007 (.005)		.004 (.006)	.003 (.006)
MILITARY SPEC		.140 (.031)	.131 (.032)		.241 (.034)	.227 (.035)
FABRICATION		.104 (.047)	.107 (.047)		.460 (.056)	.465 (.056)
NO FABRIC/ NO ASSM		−.645 (.083)	−.642 (.083)		−.166 (.103)	−.167 (.103)
FOREIGN OWN		.052 (.055)	.056 (.055)		.019 (.060)	.022 (.061)
AGE 16–30		.012 (.034)	.013 (.035)		.003 (.038)	.004 (.039)
AGE >30		−.111 (.038)	−.118 (.038)		−.040 (.042)	−.053 (.042)
HIGH SCHOOL+			1.821 (.403)			1.604 (.432)
BA+			1.707 (.466)			1.499 (.511)
RD_{1990}			.148 (.089)			.029 (.100)
$BEALE_{12}$			.001 (.039)			−.037 (.043)
$BEALE_{35}$			.068 (.058)			−.040 (.065)
$BEALE_{69}$			.024 (.061)			−.110 (.068)
CUTOFF POINT 1	−.042 (.095)	2.751 (.284)	3.778 (.355)	.605 (.050)	2.586 (.298)	3.667 (.398)
CUTOFF POINT 2	.290 (.095)	3.147 (.285)	4.176 (.356)	.849 (.050)	2.860 (.298)	3.942 (.399)
CUTOFF POINT 3	1.082 (.096)	4.067 (.286)	5.099 (.357)	1.421 (.052)	3.494 (.298)	4.578 (.399)
Observations	6165	6165	6165	6177	6177	6177
Log Likelihood	−8177	−7371	−7354	−6280	−5821	−5807

Source: Authors' calculations, using 1993 Survey of Manufacturing Technology.

Appendix 6 (cont'd)
Technology Adoption Estimation Results: Ordered Probit Specification

	Technology Group 3			Technology Group 4		
Independent Variable	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)
PROXIMITY	.537 (.128)	.297 (.138)	.140 (.146)	.247 (.140)	.183 (.150)	.196 (.155)
MULTI-EST		.427 (.320)	.367 (.322)		−.469 (.421)	−.442 (.422)
LN (EST SIZE)		.441 (.107)	.469 (.107)		.289 (.124)	.261 (.125)
$[LN (EST SIZE)]^2$		−.013 (.011)	−.016 (.011)		.004 (.012)	.006 (.012)
LN (FIRM SIZE)		−.131 (.088)	−.118 (.089)		.102 (.110)	.093 (.110)
$[LN (FIRM SIZE)]^2$		.009 (.006)	.008 (.006)		−.003 (.007)	−.002 (.007)
MILITARY SPEC		.270 (.034)	.256 (.035)		.173 (.044)	.182 (.044)
FABRICATION		1.221 (.059)	1.228 (.060)		.154 (.067)	.149 (.067)
NO FABRIC/ NO ASSM		.150 (.099)	.143 (.099)		−.347 (.132)	−.349 (.133)
FOREIGN OWN		.067 (.061)	.069 (.061)		.073 (.070)	.077 (.070)
AGE 16–30		−.033 (.038)	−.028 (.038)		−.107 (.050)	−.116 (.050)
AGE >30		−.003 (.041)	−.006 (.041)		−.142 (.054)	−.152 (.054)
HIGH SCHOOL+			1.122 (.409)			.616 (.519)
BA+			1.702 (.481)			−.016 (.630)
RD_{1990}			−.006 (.099)			−.014 (.124)
$BEALE_{12}$			−.042 (.042)			.044 (.055)
$BEALE_{35}$			.028 (.064)			.192 (.080)
$BEALE_{69}$			−.046 (.067)			.066 (.086)
CUTOFF POINT 1	.262 (.086)	3.666 (.306)	4.610 (.393)	1.157 (.049)	2.642 (.351)	2.951 (.481)
CUTOFF POINT 2	.384 (.086)	3.824 (.306)	4.769 (.394)	1.359 (.050)	2.873 (.351)	3.183 (.482)
CUTOFF POINT 3	.711 (.086)	4.228 (.307)	5.175 (.394)	1.761 (.053)	3.326 (.352)	3.637 (.482)
Observations	6141	6141	6141	6182	6182	6182
Log Likelihood	−6954	−5997	−5982	−3457	−3128	−3121

Source: Authors' calculations, using 1993 Survey of Manufacturing Technology.

Appendix 6 (cont'd)
Technology Adoption Estimation Results: Ordered Probit Specification

	Technology Group 5			Technology Group 6		
Independent Variable	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)
PROXIMITY	.430 (.124)	.361 (.141)	.358 (.149)	.417 (.125)	.229 (.137)	.150 (.147)
MULTI-EST		.630 (.431)	.655 (.431)		.143 (.391)	.124 (.392)
LN (EST SIZE)		.355 (.137)	.335 (.137)		.068 (.121)	.057 (.122)
[LN (EST SIZE)]^2		.019 (.013)	.021 (.013)		.028 (.012)	.028 (.012)
LN (FIRM SIZE)		−.228 (.113)	−.235 (.114)		−.054 (.103)	−.051 (.104)
[LN (FIRM SIZE)]^2		.020 (.007)	.020 (.007)		.006 (.007)	.006 (.007)
MILITARY SPEC		.190 (.044)	.191 (.044)		.201 (.042)	.200 (.042)
FABRICATION		.279 (.066)	.282 (.066)		.126 (.062)	.125 (.062)
NO FABRIC/ NO ASSM		−.144 (.128)	−.139 (.128)		.066 (.106)	.074 (.106)
FOREIGN OWN		.190 (.067)	.194 (.067)		.212 (.066)	.221 (.066)
AGE 16–30		−.000 (.049)	−.006 (.049)		−.063 (.047)	−.064 (.047)
AGE >30		−.135 (.055)	−.144 (.055)		−.096 (.052)	−.109 (.052)
HIGH SCHOOL+			.688 (.536)			1.583 (.507)
BA+			−.361 (.640)			.135 (.608)
RD_{1990}			−.183 (.150)			.161 (.113)
$BEALE_{12}$			−.082 (.056)			−.060 (.052)
$BEALE_{35}$			−.008 (.082)			−.002 (.078)
$BEALE_{69}$			−.002 (.085)			−.034 (.082)
CUTOFF POINT 1	1.163 (.067)	3.567 (.382)	3.768 (.504)	1.120 (.058)	2.024 (.339)	2.859 (.465)
CUTOFF POINT 2	1.326 (.068)	3.788 (.383)	3.989 (.504)	1.296 (.058)	2.232 (.339)	3.067 (.465)
CUTOFF POINT 3	1.613 (.069)	4.178 (.383)	4.380 (.504)	1.640 (.060)	2.634 (.339)	3.470 (.465)
Observations	6165	6165	6165	6171	6171	6171
Log Likelihood	−3961	−3215	−3210	−3994	−3554	−3547

Source: Authors' calculations, using 1993 Survey of Manufacturing Technology.

Appendix 6 (cont'd)
Technology Adoption Estimation Results: Ordered Probit Specification

	Technology Group 7			Technology Group 8		
Independent Variable	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)
PROXIMITY	.390 (.109)	.339 (.114)	.080 (.130)	.500 (.111)	.428 (.116)	.247 (.123)
MULTI-EST		−.006 (.330)	−.089 (.332)		.714 (.318)	.658 (.320)
LN (EST SIZE)		.333 (.105)	.324 (.106)		.455 (.103)	.436 (.103)
$[LN (EST SIZE)]^2$		.005 (.011)	.006 (.011)		−.012 (.010)	−.010 (.010)
LN (FIRM SIZE)		−.014 (.089)	.003 (.089)		−.179 (.086)	−.165 (.087)
$[LN (FIRM SIZE)]^2$		.004 (.006)	.003 (.006)		.015 (.006)	.015 (.006)
MILITARY SPEC		.100 (.036)	.098 (.036)		.128 (.035)	.128 (.035)
FABRICATION		.085 (.053)	.086 (.053)		.072 (.052)	.075 (.052)
NO FABRIC/ NO ASSM		−.129 (.094)	−.121 (.094)		−.230 (.091)	−.222 (.091)
FOREIGN OWN		.133 (.058)	.147 (.058)		.122 (.057)	.138 (.057)
AGE 16–30		−.146 (.040)	−.143 (.040)		−.074 (.038)	−.074 (.039)
AGE >30		−.242 (.044)	−.261 (.044)		−.189 (.042)	−.207 (.043)
HIGH SCHOOL+			2.696 (.430)			2.366 (.427)
BA+			1.289 (.535)			−.265 (.490)
RD_{1990}			.255 (.092)			.127 (.094)
$BEALE_{12}$			−.017 (.044)			−.018 (.043)
$BEALE_{35}$			.043 (.065)			−.135 (.064)
$BEALE_{69}$			−.063 (.070)			−.038 (.067)
CUTOFF POINT 1	.673 (.055)	2.766 (.304)	4.392 (.404)	.665 (.064)	2.786 (.291)	3.873 (.389)
CUTOFF POINT 2	1.019 (.056)	3.165 (.305)	4.795 (.404)	1.047 (.065)	3.227 (.292)	4.317 (.389)
CUTOFF POINT 3	1.654 (.058)	3.881 (.305)	5.515 (.405)	1.610 (.066)	3.864 (.292)	4.956 (.390)
Observations	6121	6121	6121	6119	6119	6119
Log Likelihood	−5860	−5337	−5309	−6276	−5735	−5717

Source: Authors' calculations, using 1993 Survey of Manufacturing Technology.

Appendix 6 (cont'd)
Technology Adoption Estimation Results: Ordered Probit Specification

	Technology Group 9			Technology Group 10		
Independent Variable	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)	Coefficient (Std. Error)
PROXIMITY	.705 (.126)	.377 (.134)	.287 (.140)	.403 (.131)	.373 (.137)	.250 (.143)
MULTI-EST		.457 (.335)	.478 (.336)		.127 (.337)	.121 (.338)
LN (EST SIZE)		.355 (.111)	.332 (.112)		.402 (.107)	.396 (.107)
[LN (EST SIZE)]^2		.006 (.011)	.008 (.011)		−.006 (.011)	−.006 (.011)
LN (FIRM SIZE)		−.094 (.091)	−.102 (.091)		−.040 (.090)	−.040 (.091)
[LN (FIRM SIZE)]^2		.010 (.006)	.010 (.006)		.006 (.006)	.006 (.006)
MILITARY SPEC		.068 (.036)	.075 (.036)		.213 (.036)	.208 (.036)
FABRICATION		.413 (.057)	.412 (.057)		.206 (.056)	.208 (.056)
NO FABRIC/ NO ASSM		.449 (.089)	.460 (.089)		.108 (.093)	.116 (.093)
FOREIGN OWN		.075 (.060)	.080 (.060)		.186 (.059)	.188 (.059)
AGE 16–30		−.088 (.040)	−.088 (.040)		−.050 (.041)	−.052 (.041)
AGE >30		−.054 (.043)	−.055 (.043)		−.116 (.044)	−.124 (.045)
HIGH SCHOOL+			.314 (.430)			1.272 (.433)
BA+			−.973 (.504)			1.353 (.512)
RD_{1990}			.215 (.097)			.011 (.098)
$BEALE_{12}$			−.006 (.045)			−.011 (.045)
$BEALE_{35}$			−.030 (.066)			.065 (.067)
$BEALE_{69}$			.030 (.070)			.141 (.070)
CUTOFF POINT 1	.888 (.086)	2.568 (.309)	2.448 (.403)	.793 (.081)	2.858 (.306)	3.773 (.405)
CUTOFF POINT 2	1.044 (.086)	2.755 (.309)	2.636 (.403)	1.032 (.081)	3.133 (.306)	4.049 (.405)
CUTOFF POINT 3	1.437 (.087)	3.219 (.309)	3.100 (.404)	1.505 (.082)	3.667 (.307)	4.584 (.406)
Observations	6095	6095	6095	6115	6115	6115
Log Likelihood	−5969	−5328	−5322	−5621	−5143	−5135

Source: Authors' calculations, using 1993 Survey of Manufacturing Technology.

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Discussion

John C. Haltiwanger*

The paper by Jane Sneddon Little and Robert K. Triest reflects careful empirical work with a rich and relatively new source of establishment-level data on the use of advanced manufacturing technologies. Using data from the 1988 and 1993 Surveys of Manufacturing Technology (SMT) combined with other establishment-level data from the Census and Annual Survey of Manufactures, Little and Triest explore important issues regarding the process of technological diffusion. Their basic question is: Do your technological neighbors matter? That is, are individual producers more likely to adopt advanced technology if other producers in their local geographic area have also adopted advanced technologies? The investigation into this question provides a fascinating glimpse into the complex process of adoption and diffusion of advanced technologies in the U.S. economy. Understanding this process is of fundamental importance for understanding the determinants of economywide and regional growth.

The results from the specific empirical exercises undertaken in this paper are a bit mixed. Using a broad measure of the number of advanced technologies an individual producer has adopted, they find that, even controlling for other factors, technological neighbors exhibit a positive and significant influence on adoption of advanced technologies. When the authors try to push the data a bit harder to investigate the connection between specific technologies and the detailed timing of adoption, the results are weaker. It is apparently more difficult to find a robust technological neighborhood effect in this more detailed level of analysis.

Since the analysis is carefully done, most of my comments reflect

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concerns about data and measurement issues as well as broader concerns about the interpretation of the results. To begin, I raise some data and measurement issues that should be considered in evaluating the current results.

Data and Measurement Issues

A key aspect of this study is the use of responses from the 1993 SMT that asked retrospectively about the timing of adoption of specific technologies. The survey asks respondents whether they have adopted a specific technology in the past two years, within the past two to five years, and more than five years ago. The timing is important in this context since the core empirical specification involves investigating the probability of adopting a technology between 1988 and 1993 as a function of initial conditions in 1988, where the latter includes information on the extent of technology adoption in the local geographic area.

Unfortunately, recent research with these data by Dunne and Troske (1995) indicates that the responses to the retrospective questions on the 1993 SMT are suspect, with substantial evidence of systematic recall bias. Respondents appear to systematically date adoption more recently than actually occurred. Consider, for example, the adoption of computer-aided design (CAD). Using the 1993 SMT, about 60 percent of respondents had this technology in use in 1993 and, based upon retrospective responses, only about 20 percent had this technology in use in 1988. This pattern suggests a tremendous increase in the use of CAD over this five-year period. However, the 1988 SMT indicated that about 40 percent of plants had this technology in use in 1988.

One possible explanation for this wide difference is that the 1988 and the 1993 SMTs represent different samples. Dunne and Troske investigate this by examining a matched sample of plants that responded to both the 1988 and the 1993 SMTs. Based upon a matched sample of approximately 2,300 plants, they examine the set of plants that had adopted CAD by 1988, based upon the 1988 SMT, and still were using CAD in 1993 based upon the 1993 SMT. One would hope that the responses to the retrospective questions in the 1993 SMT would be such that virtually all such plants would indicate that they had this technology in place in 1988. However, Dunne and Troske found that only 60 percent of such plants indicated in the retrospective responses that they had adopted CAD by 1988.

These measurement issues raise a variety of questions about the interpretation of the results in Little and Triest. Their strongest results are based upon the relationship between the number of technologies purportedly adopted between 1988 and 1993 and initial conditions. However, it may be that their dependent variable is a better measure of the number of technologies in place in 1993 rather than the number of technologies adopted between 1988 and 1993.[1] Thus, while their results indicate some degree of clustering of advanced technologies, the potential timing problems raise related questions about causality and in turn about the underlying source of this clustering. While many other geographic controls are considered in the analysis, omitted variable problems are always a concern. The potential problems from omitted variables are exacerbated if these results primarily reflect generic clustering as opposed to specific results on the timing of adoption. Further, the weaker results that emerge when the authors try to exploit the detailed data on specific technology adoption and timing may reflect these measurement problems.

Another measurement issue that may be important in this context is also raised by the work of Dunne and Troske (1995). Dunne and Troske find that "de-adoption" of specific technologies apparently is significant. That is, on the basis of the matched 1988–93 sample, a large fraction of establishments had a number of specific technologies in use in 1988 but no longer used them in 1993. For example, the de-adoption rate for LANs (local area networks) is 39 percent, while the de-adoption rate for pick and place robots is 37 percent. These large de-adoption rates suggest either additional measurement error problems or an interesting economic phenomenon. Under this latter interpretation, it looks as if many plants experiment with advanced technologies but may ultimately not use them. If this de-adoption phenomenon is real, then the process of adoption and diffusion should be modeled (theoretically and empirically) as one that involves gross positive and negative changes. In an environment with substantial gross positive and negative changes, an increase in the net adoption rate may reflect either an increase in the number of plants that have adopted the technology or a decrease in the number of plants abandoning the technology. The idea that a region or sector might be deemed more technologically advanced because the pace of de-adoption is slower there suggests that we should be thinking about the process of technical change in richer ways.

Interpretation of the Results

Beyond these measurement issues lie more basic questions about the interpretation and implications of the results. A key question in interpreting these results is whether the adoption of advanced technologies matters for outcomes that we really care about. Adoption of advanced technologies per se is not an objective of households, firms, or policymakers. They are concerned about the maximization of outcomes such as

[1] Indeed, the results of their Table 5 (rightmost columns) appear to confirm this hypothesis, since they obtain very similar results when using the number of technologies used as the dependent variable rather than the change in the number of technologies used.

the growth of income, employment, productivity, and profits (ultimately, of course, of economic welfare). One might presume that a tight link exists between indicators of the success of an individual company (and ultimately a particular region or the entire economy) and the adoption of the latest advanced technology. However, a number of recent studies of establishment-level behavior of employment and productivity growth raise a variety of questions about the link between observable establishment characteristics and measures of productivity and employment growth.[2]

While the literature on plant-level productivity and employment dynamics is still in its early stages, a number of patterns relevant for the current analysis are beginning to emerge. Even after controlling for differences in detailed industry, establishment size, establishment age, region, and factor intensities (such as energy or capital intensities), large residual differences across plants are found in the growth rates of employment and in productivity growth (either labor or total factor productivity). Indeed, within-group differences dwarf between-group differences, so that idiosyncratic factors dominate the determination of the fortunes of individual plants.

For those of us who have been involved in generating such results, considerable speculation has followed about what these idiosyncratic factors represent. Possible suggestions include differences in technology (broadly defined to include both "hardware" differences such as those investigated in this paper and differences in organizational capital), managerial ability, human resource practices, and just plain luck. The SMT data provide a means for evaluating the contribution of the adoption of specific advanced technologies to explain differences in outcomes across seemingly similar plants. Results in Doms, Dunne, and Troske (1995) suggest that differences in technology adoption rates are *not* particularly helpful in this regard. The latter paper finds that, after controlling for detailed industry, region, size, age, and capital intensity, there remains a positive and significant effect of adoption of advanced technologies on plant-level labor productivity.

However, even in this cross-sectional result, it is important to distinguish between statistical significance and overall economic significance. It turns out that differences in adoption rates account for only a very small fraction of the overall variation in labor productivity. All observable factors taken together account for about 28 percent of the cross-sectional variation in labor productivity, but the marginal contribution of the adoption rates is only about 1 percent. Even more striking are the results on labor productivity growth rates. For the same set of observables (in first differences now, as appropriate), Doms, Dunne, and

[2] Relevant studies include Baily, Campbell, and Hulten (1992); Davis, Haltiwanger, and Schuh (1996); and Baily, Bartelsman, and Haltiwanger (1996).

Troske (1995) find that over a 15-year horizon, observables account for only about 10 percent of the variation across plants in labor productivity growth rates. Further, they find no statistically significant relationship between adoption of advanced technologies and labor productivity growth at the plant level. Putting these results together suggests that knowing whether individual plants have adopted an advanced technology is not particularly helpful in determining the variation in outcomes across plants.

Understanding the sources and dynamics of the differences across plants is important, not only for the micro dynamics of job and productivity growth but also for aggregate dynamics. It turns out that the high rates of job reallocation evidenced by the large differences in employment growth rates, and the large differences in productivity and productivity growth rates, are intimately linked. That is, the ongoing reallocation process of capital and labor tends to shake things up in the right direction. For example, Baily, Campbell, and Hulten (1992) and Baily, Bartelsman, and Haltiwanger (1996) show that an important component of aggregate productivity growth is the reallocation of resources away from less productive plants toward more productive plants (both between and within industries). In many ways, these are precisely the results one would expect from a market-oriented economy in which resources are allocated to their highest-valued uses. The striking nature of these findings from recent studies is the magnitude of the within-group variation and in turn its contribution to aggregate growth.

These results on the dominance of idiosyncratic factors and the importance of the reallocation processes in moving resources between seemingly similar plants do not imply that the processes of adoption and diffusion are unimportant for aggregate dynamics. Instead, these findings serve as a caution for both the micro and macro implications of the results on adoption and diffusion. The process of growth at the micro and ultimately the macro level involves a very noisy and complex process of change at the micro level. Apparently, considerable experimentation occurs on a variety of dimensions, including products, processes, locations, organizational structures, and human resource practices. Further, some plants that innovate and adopt new technologies do it well, while others do it poorly. Resources ultimately flow to the more successful, but the continuous underlying process of reallocation is both time- and resource-consuming, with some individuals undoubtedly hurt in the process. It is this large-scale, ongoing process of reallocation that lies at the heart of popular concerns about job insecurity and the link between technological change and job insecurity. Understanding the factors that generate this noisy process of growth and change and the factors that facilitate the necessary but sometimes painful ongoing process of reallocation should be a first-order priority.

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Discussion

George N. Hatsopoulos*

I found the paper by Jane Sneddon Little and Robert Triest very interesting and also very gratifying: interesting because I believe that technology diffusion is at least as important as technology creation, and gratifying because it confirms some of my own empirical, subjective discoveries over my 40 years in high-technology manufacturing. I also appreciate the comments of Professor Haltiwanger because he, too, touches on things that I believe are important.

Over my years in general management, I have discovered that peer pressures, or peer effects, are more significant to the performance of the labor force than are influences by superiors. This is a very important lesson for businessmen to understand. It is really an expansion of the syndrome of "keeping up with the Joneses." If your peers do certain things, you are much more desirous of adopting tools or practices or even technologies than if you are told by your bosses, by the head of the corporation, to do certain things in a certain way. In fact, I have even found that subordinates can have, in many cases, just as much influence on local managers as their superiors. But certainly their peers have the most influence. Let me select as examples some of the findings of the paper that we are discussing right now.

Little and Triest have found that proximity has a strong effect on the adoption of technology, but they found that strength to be independent of establishment and firm characteristics. That is something that I would expect intuitively as a manager. I believe that technology adoption is influenced very much by interactions between employees of a certain level—middle management, foremen, from the plant and from neighbor-

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ing plants—and much less by the directives of some corporate headquarters, probably far away from the plant.

I would like to give you a specific example. A number of years ago we acquired a plant in the United Kingdom, up north in Manchester. That plant was making exactly the same products we were making in Auburn, Massachusetts. But we found its productivity was substantially lower, by a factor of two. In other words, the added value per hour of work was only half that of our Auburn plant. So, we started to study what was going on. Many factors were involved, including organization and technology adoption. I went up to Manchester and personally talked to the people running the plant and to their direct reports, the foremen, and I asked why they were not using certain technologies and organizational techniques. Basically, the conclusion I reached was that they were not doing it because their neighboring plants were doing something different. They were catering more to the neighboring plants. The product we were making is used by the paper industry, and Manchester has tremendous concentration of manufacturers for the paper industry. Their influence was so overwhelming that we had a hell of a time trying to change our plant's behavior. We did, eventually; we had to import some American managers and it was like pulling teeth, but we finally got them close. They are still less productive today than their American counterparts, but at least they are much closer.

Authors Little and Triest found another puzzle in the dependence of technology adoption on employment size. This finding might also be expected, for the usual reasons of economies of scale and access to capital. But they also found, and were puzzled to find, that the employment size of the plant per se matters, but the employment size of the firm to which the plant belongs is irrelevant. That, of course, can very well be explained, and it would be a conclusion I would reach, too. We have divisions all over the world, and we have plants all over the world. And I have found that it is very hard to change local culture. Access to capital is of course a central characteristic of the firm. Some firms have access to a lot of capital and have different capital costs than other firms, but I would not expect that factor to be anywhere near as dominant as the local culture. And, of course, plant size does affect technology adoption, because of the obvious economies of scale at the plant level.

Now, let me turn to the third puzzle, where Little and Triest found that the availability of employees with a high school diploma was a factor very strongly correlated with the adoption of technology, but they also found that technology adoption was negatively correlated with the presence of employees with college degrees. Now I do not quite believe the negative part of it, but I do believe in a zero effect. These effects are primarily due to the influence of middle management, usually foremen; and it is very important to these people to be in a location where a lot of employees with high school degrees are available.

In conclusion, let me say that I have found this discussion and this inquiry to be very important, not only to economists but also to managers. Plant culture can have much more influence, not only on productivity but also on innovation and on the economic growth of the plant, than any directives that come from a boss.

Panel Discussion
Trends in Productivity Growth

Martin Neil Baily*

According to Administration estimates, potential GDP growth is 2.3 percent per year. That growth rate is based on three elements: the growth of labor input, the productivity growth trend, and capital growth. Labor input now is growing at a rate of about 1.1 percent, more slowly than in recent years because of the slowing increase in female participation in the work force and the continued decline in male participation. In addition, the baby boom generation has moved into the work force and now begins to approach retirement. The second element in potential growth is productivity. The historical trend of productivity growth in nonfarm business has been about 1.1 percent per year since 1973 (Figure 1). Prior to 1973 the growth rate was substantially higher. In the first quarter of 1996, productivity indicators looked fairly good, but after benchmark revisions to labor input, the trend still appears to be about 1.1 percent growth per year. In the forecast, however, we anticipate a 0.1 percent gain in productivity growth resulting from the increase in capital accumulation associated with balancing the federal budget.

The part of productivity growth we can explain has been remarkably constant since about 1960 at about 1.1 percent. We also got a growth bonus, or extra residual, prior to 1973 (Figure 2) but we did not know where it came from then, and now we do not know where it has gone. Another puzzle is that the most recent time period has been associated with a sharp bias in the effect of technological change on workers' returns to skill and education. The return to education has risen considerably, as shown by the rising difference between earnings of college- and high-school-educated workers (Figure 3). One of the most important explana-

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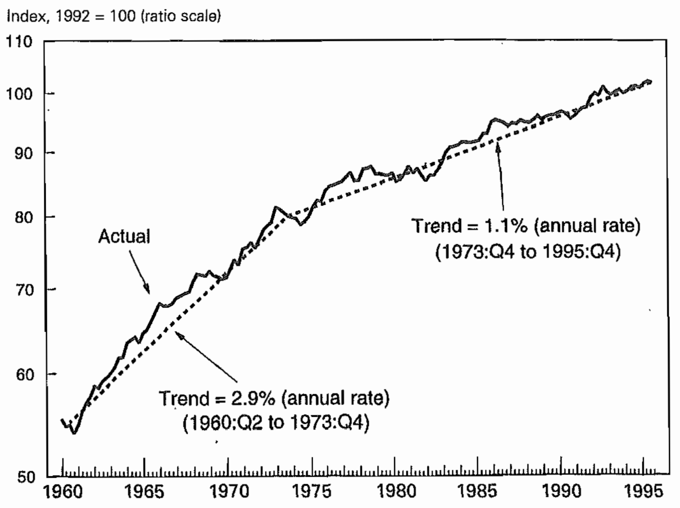
Figure 1
Actual and Trend Labor Productivity



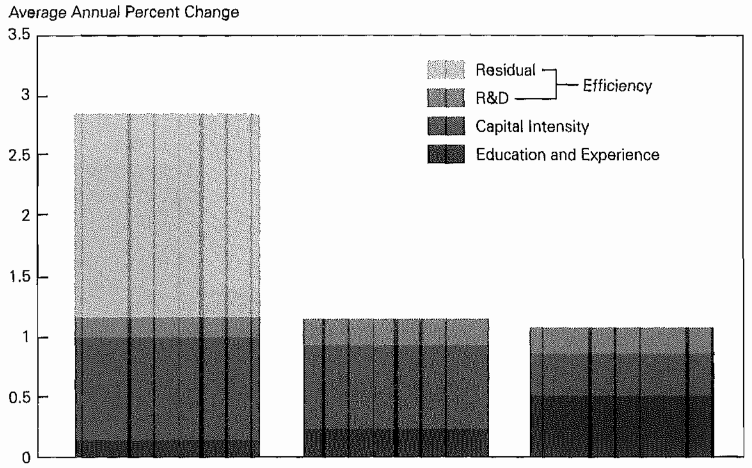
Source: Council of Economic Advisers.

tions for the rise in wage inequality points to the effect of technology. As writers like Robert Lawrence of Harvard and Dan Sichel of the Federal Reserve have noted, the recent period is unusual because it couples so much bias in the returns to education with so little apparent technological change as indicated by the productivity growth trend. No consensus has developed in the profession as to what could explain either this biased impact of technological change or the apparent absence of technological gains in measured productivity growth.

What, therefore, are the policy implications? Few, for monetary policy. Although I would not necessarily make this statement about other countries, monetary policy in the United States is not seen as a significant restraint on faster growth over the next few years. Macroeconomic disturbances may change things, of course, but our estimated growth rate of 2.3 percent is essentially based on the supply side of the economy, with no expectation that an absence of aggregate demand will act as a constraint on growth. Policy must therefore address ways to improve the supply side of the economy.

As illustrated in both Figure 2 and Figure 4, one of the declining contributors to productivity growth has been capital investment, or the increase in the capital stock per worker hour. The declining contribution

Figure 2
Growth of Output per Hour

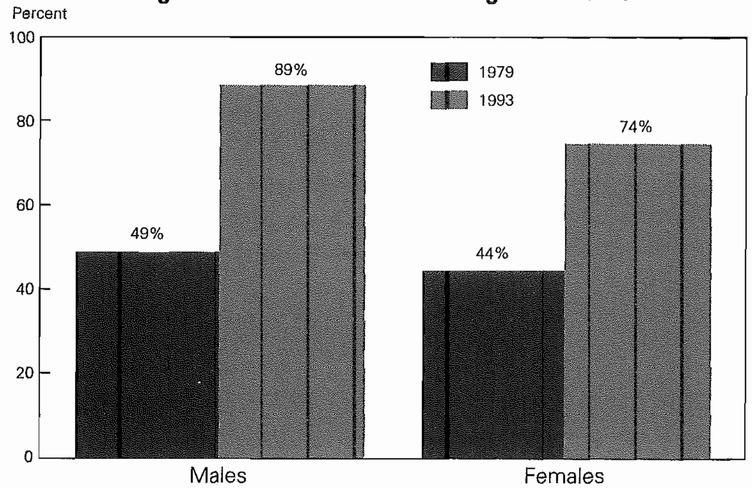


Source: Council of Economic Advisers.

of capital as shown in Figure 4 is somewhat misleading, however. When the growth rate of output slows, even if the same share of output is saved and invested, the capital stock will not grow as rapidly as before. To some extent, therefore, the decline in the contribution of capital investment is itself a consequence of the decline in the growth bonus, or the growth residual. Over and above that effect, the contribution from capital has fallen because of the decline in the share of output devoted to saving and investment. An important way to improve growth, therefore, is to reduce the federal budget deficit, which was one of the main causes of the low national savings rate in the 1980s. I know Richard Cooper is concerned about this point, so let me hasten to add that as we reduce the budget deficit, we will reduce the current account deficit as well as increasing domestic investment. The best rule of thumb may be 50 percent of any increase in saving goes to reduce the current account deficit and 50 percent goes into investment. Not all of the increase in domestic investment will be in business equipment. Quite a bit will be in structures and in housing. Nevertheless, one benefit of reducing the federal budget deficit will be some increased business capital formation, an important growth-enhancing result.

The second important element in the Administration's program to

Figure 3
Differences in Mean Annual Earnings: High School Graduates vs. College Graduates

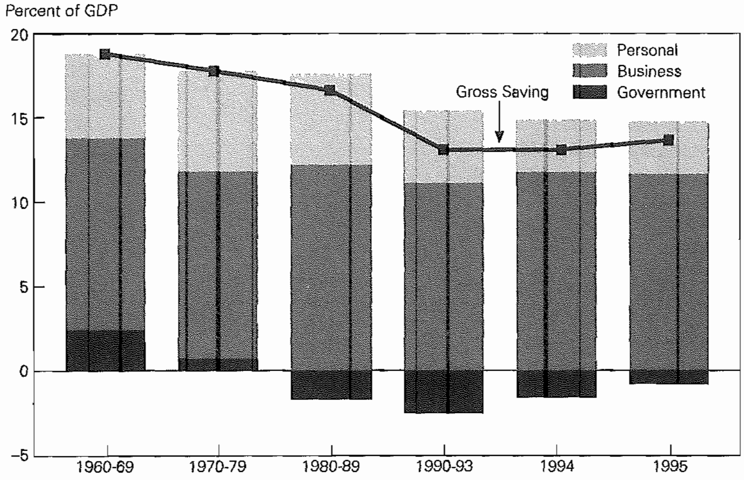


Note: Data are for year-round, full-time workers, age 25 and over.
Source: U.S. Department of Labor.

increase growth involves the various education initiatives the President has emphasized. Figure 2 groups together education and experience into one category. This is somewhat misleading, because the increased contribution to output growth from that combination results from the aging of the baby boom generation. More experience, rather than more education, caused the rise in the contribution from experience and education shown in Figure 2.

One thing we do know from recent years is that the returns to skill and education have increased. The bad news from that is that the wage distribution is widening as a result. The good news is that an opportunity for investment emerges; if we can increase the amount of education and training in the work force, that gain should translate into improved productivity. In particular, the return to computer literacy appears to be strong. As Alan Krueger's work has shown, the ability to use computers is an important contributor to wages and, therefore, should be a contributor to productivity. Accordingly, one of the President's education initiatives focuses on improving the technological literacy of our work force. The federal government can have only a limited direct impact on education because most expenditures are state or local. But the President believes that federal leadership in this area and seed money for experi-

Figure 4
Components of Gross Saving



Source: Council of Economic Advisers.

mentation could help state and local authorities to improve their own programs.

Tables 1 and 2 and Figures 5 to 7 draw on different strands in the literature to show the very substantial return to the economy from both public and private R&D. The studies of Edwin Mansfield and other econometric studies have shown a substantial social return as well as a private return to private R&D. Programs that encourage private R&D,

Table 1
Sources of Funds for R&D in 1995
Percent

	All R&D		Basic Research	Applied Research	Development
	$ Billions	Percent			
Federal Government	60.7	35	58	36	29
Industry	101.7	59	25	57	70
Universities and Colleges	5.5	3	12	4	[a]
Nonprofits	3.2	2	5	3	[a]
Total	171.0	100	100	100	100

[a] less than 1 percent.

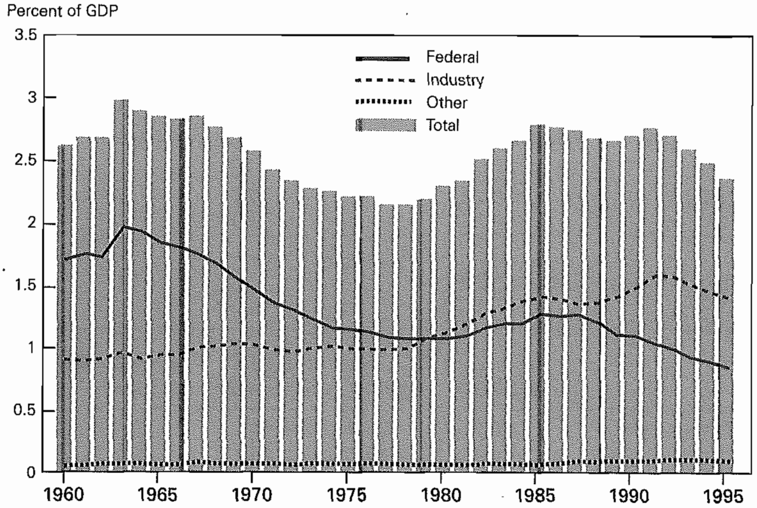
Table 2
Private and Social Rates of Return to Private R&D
Percent

	Estimated Rates of Return	
Author (year)	Private	Social
Nadiri (1993)	20–30	50
Mansfield (1977)	25	56
Terleckyj (1974)	29	48–78
Sveikauskas (1981)	7–25	50
Goto-Suzuki (1989)	26	80
Bernstein-Nadiri (1988)	10–27	11–111
Scherer (1984)	29–43	64–147
Bernstein-Nadiri (1991)	15–28	20–110

Note: Table adapted from Zvi Griliches, "The Search for R&D Spillovers," *Scandinavian Journal of Economics*, 1992 Suppl., pp. 29–47, and Nadiri (1993).

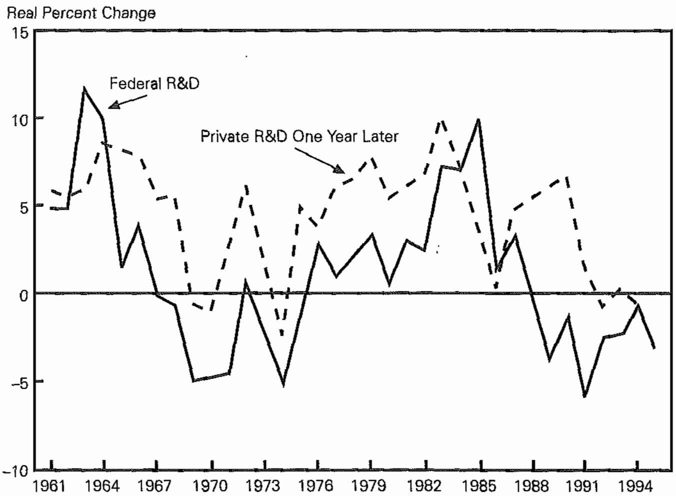
therefore, will add to productivity growth and, thus, to the growth residual. We can foster private R&D by giving tax incentives and also by supporting public R&D. Figure 6 shows that private R&D appears to be correlated with prior federal R&D and suggests some spillover effects from federal government spending to private sector spending. Since

Figure 5
Expenditures for Research and Development



Source: Council of Economic Advisers.

Figure 6
Change in Federal R&D Expenditures and Change in Private R&D Expenditures One Year Later



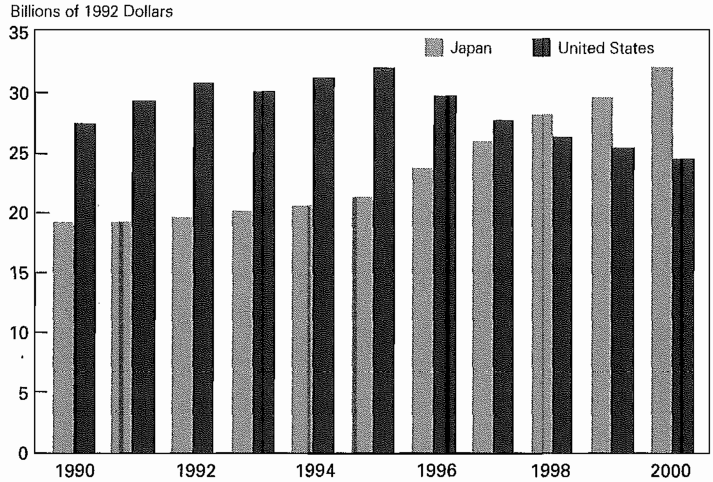
Source: Council of Economic Advisers.

public R&D does give productivity benefits, efforts to sustain or increase it should be a focus for policy. Figure 7 illustrates that under current congressional proposals, the rate of public nondefense R&D spending would decline over time. I do not believe this is good policy for growth. If anything, we should be trying to increase the public contribution to R&D.

I will turn now to the question of how the economy might get back some of its growth bonus. But before doing this I should warn that we may have to live with the fact that we cannot get back all of it. Some of the residual growth that occurred in the early part of this century may have resulted from a burst of innovation and industrialization, from automation, and from a shift from craft production to mass production, and that period now is over. We have exhausted many of the simpler ways of moving to mass production, shifting from corner grocery stores to large supermarkets, from telephone operators to electronic switches, and so on. From a policy perspective, therefore, we must learn to live in an economy where it is harder to find ways to increase productivity. Such an economy generates an environment with winners and losers, and requires attention to policy dimensions such as the provision of safety nets.

On the more positive side, however, we may actually be getting more

Figure 7
Estimated Japanese Governmental Expenditures on Non-Defense R&D Compared with Projected Congressional Allocations

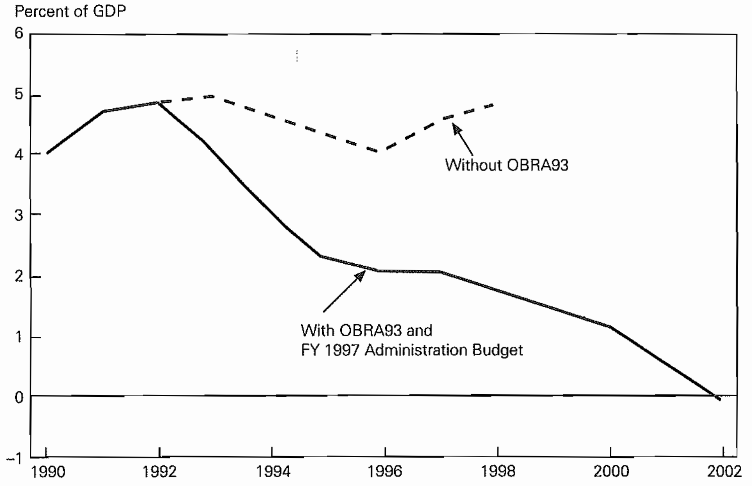


Source: Council of Economic Advisers.

of a growth bonus now than is apparent from the figures I have shown here because of measurement problems, an issue brought up earlier in the conference. There are substantial problems in the way we measure productivity growth. In many areas of the economy— from accounting for the convenience factor in services to measuring nonphysical capital such as software—we do not pick up output and, consequently, we do not pick up productivity growth. That may not explain the apparent slowdown, as presumably there were problems before 1973 as well. However, it would be nice to know if productivity growth were faster than the current measurements indicate. It would change our thinking about policy and the economy. One recommendation I would make, therefore, is to improve the quality of our statistics to get a better handle on productivity growth. At the moment, we are starving our statistical agencies. We should instead be investing more in them, as a cheap way of getting better information and, as a result, better policy.

There may be a growth bonus from increased investment in education. Much of the literature notes that education contributes a social as well as a private return. This externality is difficult to judge. The statement that one person will be more productive working with other educated and productive people certainly is true, but it does not in itself

Figure 8
Federal Budget Deficit



Note: The GDP measure used is pre-January 1996 benchmark revision.
Source: Office of Management and Budget and Congressional Budget Office.

prove an externality. But despite this reservation about the economics literature in this area, I have some hope that there is a positive externality from education that would boost growth if we succeed in raising the growth rate of human capital.

Another way to get a growth bonus is through increased competition. To a certain extent we already are doing that by deregulating our markets, opening them to foreign competition, and increasing our access to foreign markets. In a number of industries, such as railroads, deregulation has led to substantial productivity growth. Before I joined the Council, my research comparing productivity rates across countries suggested that competition provides an important impetus towards the adoption of more productive technologies. Maintaining an open economy, therefore, is an important part of improving productivity growth and getting a growth bonus.

I am a productivity and technology optimist. We have overcome those afflictions of the 1970s and 1980s—high unemployment and high inflation and very large budget deficits. We now have a full employment economy without much inflation, and a budget deficit that is lower and heading towards zero (Figure 8). If we can recreate the economic climate of the 1950s and 1960s, we may get back some of the mysterious growth bonus.

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Panel Discussion
Inherent Conflict in International Trade

Ralph E. Gomory*

I should like to address the impact of economic development in technically backward countries on economic welfare in the industrialized nations, a topic of great concern to many policy makers. As countries that have been underdeveloped improve their industrial capabilities, they can become significant contributors to the total world economy. From a purely national perspective, however, their industries also are new competitors to existing national industries. What is the net effect of this change on the already industrialized countries?

It seems natural to take the classical Ricardo model of international trade and see if it has something to say about this question. William Baumol and I have done this in two recent papers (Gomory and Baumol 1995a, 1995b), summarized briefly here. We find that the model points clearly to the possibility of conflict in the interests of the trading partners. Outcomes that are very good for one country may not be good for its trading partner, and the strengthening of one country often will come at the expense of the welfare of the other.

Model and Method

We work with the classical linear Ricardian model of international trade. We assume single-input linear production functions $e_{ij} l_{ij}$ for good i in Country j and Cobb-Douglas utility U_j for Country j. We will fix the sizes L_j of each country's labor force and the demand parameters d_{ij} of the two countries as well as n, the number of industries. A model is then specified by the vector of average labor productivities $\varepsilon = \{e_{ij}\}$. *However,*

*President, Alfred P. Sloan Foundation.

instead of dealing with one model, we will discuss the equilibrium outcomes of a family of models. Specifically we will consider all possible productivity values ε restricted only by a maximum productivity condition[1] in each industry in each country $e_{ij} \leq e_{ij}^{max}$. Different productivities ε lead to different equilibria and therefore to different utility outcomes. This approach will enable us to analyze the effect of different productivities ε on the welfare of the two countries.

For any particular choice of ε with $e_{ij} \leq e_{ij}^{max}$, there is at equilibrium a resulting national income Y_j and a utility U_j for each country. From the Y_j we compute the relative national income $Z_j = Y_j/(Y_1 + Y_2)$, which we also refer to as *share.* We can then plot the equilibrium associated with that choice of ε as a point in a share versus utility (Z_1, U_1) diagram for Country 1. This is done in Figure 1, which shows a few randomly chosen equilibria. We can do the same for Country 2. Figure 2 shows the same equilibria as points in a (Z_1, U_2) diagram. Note that in both diagrams Z_1, which is Country 1's share, is measured from the left vertical axis and Z_2, which is Country 2's share and is therefore $1 - Z_1$, is the distance from the right vertical axis.

Alternatively, we could plot each point in a (Z_1, Y_1) diagram instead of a (Z_1, U_1) diagram. This would be a plot of share versus national income. The graphs in both cases look much the same and have the same economic consequences. Our theory has been developed with utility rather than national income, and most of the calculations have in fact used utility as the vertical axis rather than national income. However, the use of national income sometimes makes the results more intuitive, as we will see below.

In either plot, each possible ε gives us a single equilibrium point in the Country 1 diagram and another point in the Country 2 diagram. The ensemble of all such equilibrium points gives us a *region* of equilibria in each diagram. Figure 3 shows the region of equilibria for Country 1. The dark line is the approximate upper boundary[2] of the region and every point below it is an equilibrium for some choice of ε. This region of equilibria has a definite shape whose main characteristics are the same for all choices of maximal productivities e_{ij}^{max}. This shape can be shown to emerge from the model by a careful mathematical analysis as is done in Gomory and Baumol (1995b), but it also has a very intuitive basis, which we will describe below. Figure 4 shows the region for Country 2.

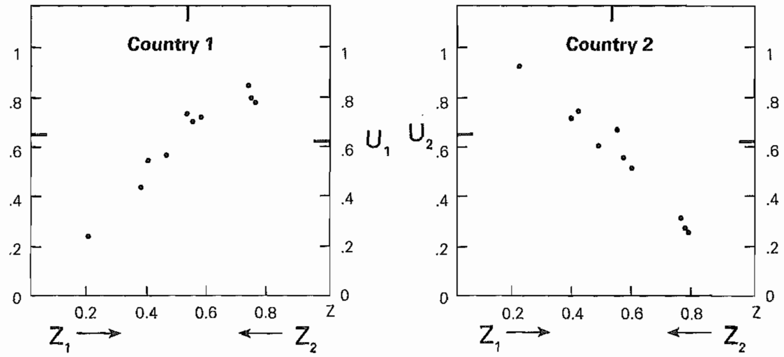
Since $Z_2 = 1 - Z_1$, we can combine the two diagrams as in Figure 5. U_1 is read from the right vertical axis and U_2 from the left vertical axis. The two points representing the same equilibrium are now vertically above

[1] It is easy to amend this restriction to allow for the increase of the maximum productivity over time.

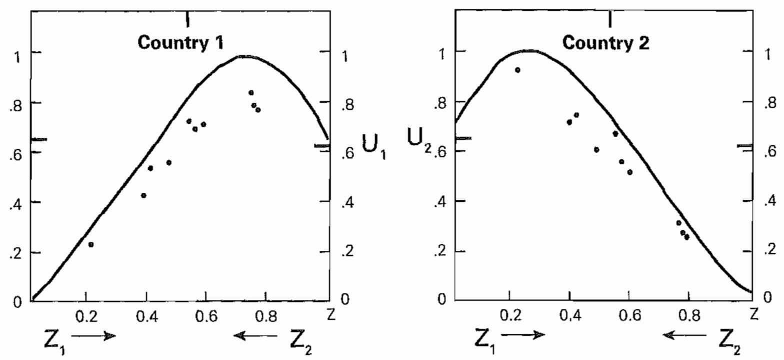
[2] The boundary has some fine structure. It is not a smooth curve but instead rather jagged. As *n*, the number of industries, increases, however, the jaggedness decreases in scale and the curve rapidly becomes indistinguishable from the one in the figure.

Figures 1 to 4

Equilibria Associated with Randomly Chosen Productivity Values on a Share versus Utility Diagram for:



Region of Equilibria for:



each other but they have different heights, representing the different utility outcomes for the two countries. The highest point in Country 1's equilibrium region always lies to the right of that for Country 2. We can see from Figure 5 that the best outcome for Country 1 is always a poor outcome for Country 2 and vice versa. Thus, the regional shape suggests the following:[3]

[3] These results tend to resemble those of the new trade theory, based on economies of scale, to which recent writings have contributed so much (Helpman and Krugman 1985; Krugman 1979 and 1990). There is in fact a close inherent connection between the regions

1. There is inherent conflict in the interests of two trading partners in the sense that the best outcomes for one country usually are poor outcomes for the other.
2. While in parts of the region improvements in productivity in Country 2 (which easily are shown to increase its share) will produce improvement in welfare in both Country 2 and Country 1, in other parts of the region improvements in productivity (and hence share) in Country 2 will strictly decrease the utility of Country 1.[4]

INTUITIVE EXPLANATION OF THE REGIONAL SHAPE

The shape of the region can be derived in a purely mathematical way. The boundaries in many industry problems can even be very closely approximated by a very simple linear programming calculation. However, there is also a direct intuitive explanation.

For this intuitive explanation we will use the plot of national income versus share. Let us imagine two countries that are roughly equivalent.[5] Their maximal productivities e_{ij}^{max} are near to each other, their labor forces are roughly the same size, and their demand structures are similar. Let us ask what a plot of *world* output, the sum of both countries' output, looks like under these circumstances. Intuitively, we would expect it to peak in the middle of the diagram as it does in Figure 6. Certainly, toward the right-hand end of the diagram Country 1 has a share of almost 100 percent, so it does almost all the producing. At these equilibrium points the productivities of Country 2 are very small in almost all industries. At these points total world output is only slightly in excess of what Country 1 can produce in autarky. As we move toward the middle and Country 2's share increases, world output increases because at these equilibria the productivity in Country 2 is much greater; it is the producer in more and more industries. This argument can be replicated starting from the extreme left of the diagram where Country 2 is the producer in almost every industry. So by intuitive means we come to the conclusion that the peak in total world output should be roughly in the middle.

If we now consider that Country 1, at each equilibrium, gets its share

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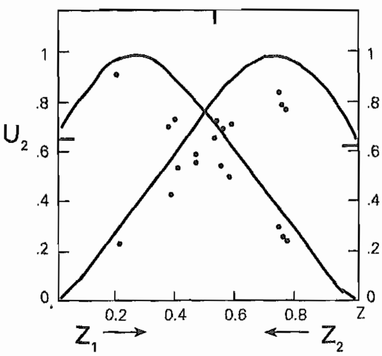
of equilibria that are obtained in the linear models and the regions of equilibria introduced in Gomory (1994) for economies of scale models. The shape of these regions has been elucidated in Gomory and Baumol (1994). This connection between the linear family and the economies of scale models is explained in Gomory and Baumol (1995b).

[4] The important possibility that an increase in the productivity in one country can be harmful to another in linear Ricardo models first was pointed out in Hymans and Stafford (1995) and Johnson and Stafford (1993).

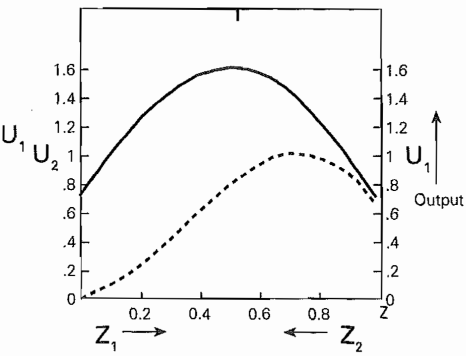
[5] These assumptions are made only to simplify the intuitive explanation. Equivalent reasoning can be carried through for countries that are completely different, but the explanation becomes more elaborate and less intuitive.

Figures 5 to 8

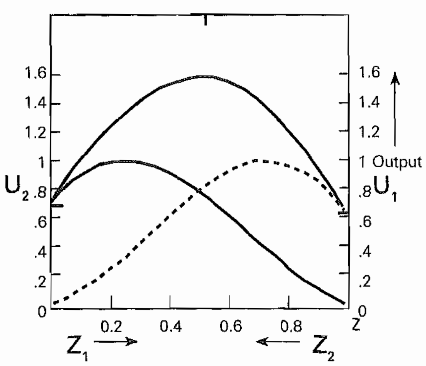
Combined Equilibria Regions for Countries 1 and 2



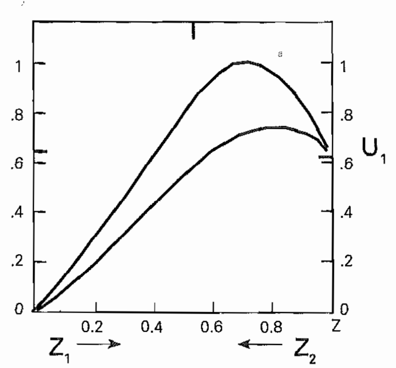
Combined World Output (Countries 1 and 2) and Upper Boundary of Output for Country 1



Combined World Output and Upper Boundaries of Output for Countries 1 and 2

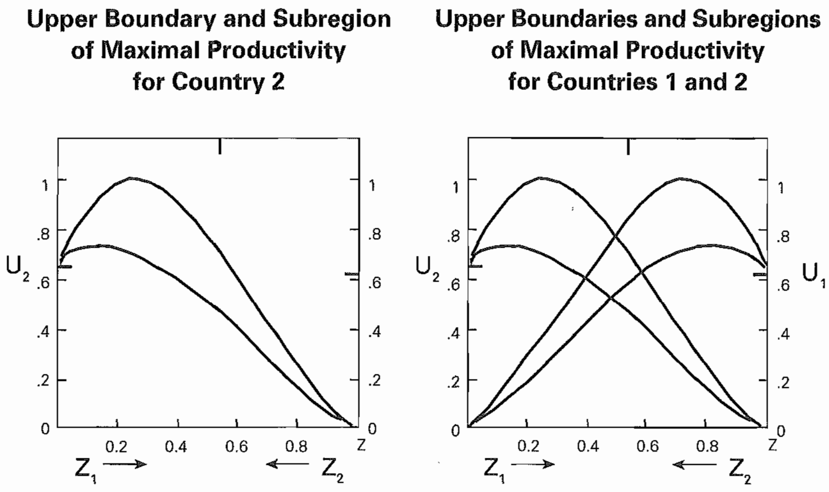


Upper Boundary and Subregion of Maximal Productivity for Country 1



of total world output, then the Country 1 income at the 50 percent share point is one-half the total world income, at the 75 percent share mark is three-fourths of the world income, and so on. If we plot in all these points, we will get the upper boundary for Country 1 as it is shown in Figure 6. Thus, the upper boundary curve for Country 1 is easily derived from the world curve.

Figures 9 and 10



Exactly the same reasoning applies to Country 2. If we derive Country 2's upper boundary from the world curve, we obtain Figure 7, which shows the regions for both countries. Thus we arrive in an intuitive way at the shapes of both countries' regions and at the relation of the two regions to each other. We can see that Country 1's peak is to the right because although world output is decreasing, Country 1's share of it is increasing. Similarly, Country 2's peak is to the left, because as we move to the left from the middle, world output decreases but Country 2's share increases. It is the role of *share* that introduces the element of conflict between the two trading partners.

THE REGION OF MAXIMAL PRODUCTIVITY

If at an equilibrium the producing country in each industry is using its maximal productivity, we will call this a maximal productivity equilibrium. All maximal productivity equilibria lie in the subregion of maximal productivity, whose shape is illustrated for Country 1 in Figure 8, for Country 2 in Figure 9, and for the two together in Figure 10. The approximate boundary of this subregion also can be calculated by linear programming methods. When the producing countries are practicing something near the best possible technology (for that time), the resulting equilibria always will lie in the region of maximal productivity.

The Ideal Trading Partner

If Country 1 has productivities ε_1, which of Country 2's many possible parameter values make Country 2 the ideal trading partner for Country 1 in the sense of maximizing its utility? Based on the regional shape, a rough answer can be summarized as follows: For countries of roughly the same size, the ideal trading partner for Country 1 is one whose productivities allow Country 1 to make most of the world's goods while Country 2 produces at maximal productivity in the smaller set of goods it does make. A high-technology country making most things for itself but trading for a few goods with an agricultural country is an illustrative example. This outcome, while the most desirable one for Country 1, is not a good outcome for Country 2. Note that if Country 2 is the ideal trading partner for Country 1, then *any* change in Country 2's production parameters, whether an increase or a decrease, will be detrimental to Country 1.

Summary and Conclusions

We have described the existence of a well-defined region of possible equilibria that has a robust characteristic shape. One consequence of the shape is that the best equilibria for one country are generally poor ones for its trading partner, so that a successful national policy aimed at attaining or retaining such a position involves inherent conflict in the interests of the two countries.

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Panel Discussion
Implications of Growth Theory for Macro-Policy: What Have We Learned?

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We are witnessing, in the second half of this century, an unprecedented wave of growth across the world. The experience of the East Asian and OECD economies has proved that real convergence can be achieved within a few decades. However, the welfare and technological gap between the developed and the least developed countries continues to widen, even as large sections of the world economy have recently joined the international trading system.

Confronted with the extraordinary amount of quantitative and institutional data amassed by statistical and case studies, we need theories to interpret these phenomena. Economists of the "old" and "new" growth theories have gone a long way in explaining why some countries grow faster than others, but I believe that any model that could explain such a variety of experiences would have to be quite complex. Otherwise, we would already have discovered the "recipe for making miracles," as Lucas (1993) has wisely reminded us, and countries around the world could already have applied such a simple model. I will attempt here not to review models of growth theory, but to underline some of the most important traits of the theory that are relevant for macro-policy. Let me begin by reviewing some assumptions about growth and technology that seem to come out of the recent flurry of empirical work.

First, technological progress is of overriding importance in explaining growth in developed economies, while most of the growth in developing countries takes place through human and physical capital accumulation that incorporates ideas, products, or processes transferred from the more

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advanced countries.[1] A recent World Bank study by Nerhu and Dhareshwar (1994) estimates the factors contributing to growth for about one hundred countries in the post-World War II era. The average growth rate of total factor productivity for developing economies is a mere 0.07 percent per annum, while for developed economies it is 1.7 percent.[2]

Second, one of the most important relationships is that between GDP growth and the accumulation of human and physical capital. I believe that the failure of some studies to detect any important channel of causation from exports (or outward orientation) to growth reflects the fact that external trade acts not directly on the "growth residual" or growth in total factor productivity but through the embodiment of new technologies and new products in the economy, and is thus complementary to the accumulation process.

Third, technological leadership persists secularly. The United States overtook Great Britain in the late 1800s and it has maintained its leadership since then. As of 1990, the technologically closest competitors (Germany and France) could produce only 80 percent of U.S. output using the same measured inputs (Lau 1996). However, the OECD countries have narrowed the technological gap significantly since World War II.

And fourth, technical progress augments both physical and human capital. All three assets complement each other.

Two types of models are relevant to our discussion: first, a model of the growth process of a small open economy. Such models explain growth in terms of human and physical capital accumulation and in terms of shifts in the production efficiency frontier as a "quality ladder" or "expansion of varieties," generated by inventions, by the external effects of human capital, and by "learning by doing." In all such models,

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[1] This has led some authors to describe East Asian growth as less than miraculous. In fact, recent empirical studies carried out by Young (1993) and Lau (1996) have confirmed that total factor productivity growth for these economies is not higher than the world average (and even null, for certain cases). But this should not distract from the basic fact that the Asian Tigers have converged at an unprecedented pace in the past three decades. Indeed, most of their growth is due to human and physical capital accumulation combined with the right policies: outward orientation and macroeconomic stability. Recent evolution has proved wrong the prediction of a slowdown in the Asian Tigers because of the law of diminishing returns. Singapore and Hong Kong have been developed countries for some time, and their growth rates continue to be among the highest in the world. The others, although entering the league of developed economies, also have not experienced a decrease in growth rates. The reason is that these economies, all small, have already established themselves as technological leaders in some niches and thus have started to generate technological progress themselves (Mateus 1995 and references therein).

[2] The same conclusion is reached in several studies by Lau (1996) and associates. Using a translog, they have found that physical capital is the most important factor of growth in developing countries and, jointly with human capital, much more important in developing than in developed economies. While local scale economies are important for developing countries, technological progress explains about one-half of the growth in developed countries.

the interaction between exports and technological diffusion is fundamental to a productivity increase in the domestic economy. This will be dealt with in the first section of this paper.

The second type of model is concerned with the international diffusion of technology and the convergence process. These models stress the importance of innovation and growth in the developed economies and the diffusion of inventions and new techniques to the follower economies. With the tendency for transfer costs to increase, the rate of convergence would decelerate as economies become more developed. This will be dealt with in the second section.

The third section will consider some aspects of globalization and the transfer of technology. Then I will refer to some other macro-policies that underlie the productivity of technology, and in the final section I will offer some conclusions.

Growth of a Small Open Economy and Macro-Policies

Most recent studies show that growth takes place through externalities generated by human capital accumulation, by the resources dedicated to R&D activities, and by the "learning by doing" effects that occur in the production process. Growth can occur with the expansion of existing production, the introduction of new goods, improvements in quality, or an increase in varieties.

Here we rely heavily on the contributions of Grossman and Helpman (1991a and b), Stokey (1991), and Young (1991). A fast-growing economy, with a technology consistent with a "growth miracle," is one that accumulates human capital—knowledge—at a fast pace, and uses that knowledge to build and operate private physical capital and infrastructure.[3] Such an economy succeeds in concentrating its work force on the production of goods that are near its own quality frontier and, thus, in accumulating human capital rapidly, through the high learning rates associated with new activities and through the spillover of this experience to the production of still newer goods.

Because human capital accumulation takes place primarily in schools, the quality of and time allocated to the formal schooling of the labor force are the essential elements. Several studies have demonstrated that all the other activities that augment human capital (learning by doing, health, nutrition, research activity, "openness of mind to innovation") are related to the general literacy and numeracy of the population.

[3] Singapore is an interesting case in this regard. Several economists have considered that despite its high growth rate, the lack of total factor productivity growth observed in the last three decades results from "excessive technological change" caused by state policies.

Obviously the learning process will occur at a faster pace if a society can benefit from world knowledge and "best practice technologies" so that workers and managers move up what Grossman and Helpman call the "quality ladder," continuously taking on new tasks and new processes. To import advanced capital goods and technologies and interact with more demanding markets requires that the economy be a relatively large-scale exporter. In other words, in order to start a "growth miracle," the economy must experience a large disparity between the mix of relatively sophisticated goods produced and the mix consumed by the local population, a difference that could even widen over time. A large volume of external trade is, thus, essential to a learning-based growth episode.[4]

Despite these deterministic theories, an important element of randomness crops up in technological development. Not only are inventions random, but so too are the outcomes of firm strategies to target a specific product or process, which eventually reveals itself to be either a "leading sector" or a "dead end." The United States and Japan have specialized in industries that are dynamic in both technological development and market impact, while Europe in the 1980s and 1990s has been unable to develop such sectors, a failure that explains in part why Europe is lagging in technological progress.[5]

Lucas (1988) and Krugman (1981) have shown that when an economy is too far apart in technological terms from others, it may never converge. Worse, it could even lose welfare by external trade. The logical consequence of Schumpeterian creative destruction has been witnessed in full force (at present, with more destruction than creation) in the case of the Eastern European economies.[6] What would be the most sensible macroeconomic policy for these transition economies? Revert to autarky? Give production subsidies or impose tariffs on imports in the context of an "infant industry" argument? As the next section will make clear, and the experience of East Asian economies shows, there is no shortcut to the process of institutional change and industrial restructuring required

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[4] Forms of technology transfer do not take necessarily the form of patents. A survey carried out among entrepreneurs in East Asia has revealed that contact with final markets (and marketing firms), imports of machinery and related technical assistance, reverse engineering, and technical assistance among suppliers and subcontracting are all important (Rhee, Ross-Larson, and Pursell 1984).

[5] Microeconomic studies have revealed that open competition and large market access and integration are important factors in this regard.

[6] This most interesting historical experiment should be studied by the new development economists. Not only do the factories in these countries demonstrate an abysmal technological gap, but also these countries lack the institutions and economic fundamentals (macroeconomic stabilization) that are essential to put those economies on a path of sustainable growth. Within our model, this would require the integration of those economies into the international trading system, where the process of technology transfer could operate.

when integrating an economy into the international trade system. Indeed, the new theories have shown that the process may be long and painful.

However, I do think that this result—the possibility of welfare reducing trade—applies mainly to the manufacturing sector. It may apply in the case of the Czech Republic and Poland or Hungary, but not to Moldavia, Armenia, or Mozambique. In these latter cases the old Heckscher-Ohlin theory of intersectoral resource-based trade would apply, and the traditional pattern of specialization and welfare-enhancing free-trade policies would be relevant.

The policy implications of all these theories put high priority on human capital accumulation through formal schooling (universality of primary schooling and large-scale secondary schooling), along with the university and R&D activities required for invention and innovation. Because of the non-rival character of knowledge, government action (for example, subsidies or public organizations) to promote investments in those areas can generally lead to outcomes that are superior to pure decentralized market solutions. Patenting systems and property rights protection are also essential to increased R&D.

Another important implication is the need for an open and highly competitive market system to promote efficiency. In this regard, and to facilitate technology transfer from abroad, external trade policies that foster export growth and openness are essential.

International Diffusion of Growth and Macro-Policies

Sometimes overlooked is the fact that technological growth, the "residual factor," is much more important in developed than in developing economies and, therefore, that the transition from a developing to a developed economy requires the buildup of capacity for "leadership, invention, and innovation" specific to that country, within the context of comparative advantage. The developed economy has already built most of its human and physical infrastructure, and most of its growth has to come from technological progress. In industrializing countries, the accumulation of human and physical capital is dominant, and the country grows faster if it adopts the "best practice" available in the world stock of knowledge. This theory has an important policy consequence: A developing country cannot become developed unless it builds the capacity to invent and innovate on a scale that makes it a technological leader in some sectors or subsectors.

In this context, long-term growth in developed nations must have as its engine technological progress. Most such progress stems from the private research that underlies commercial discovery, motivated along Schumpeterian lines by the flow of profits that accrues to an innovator. As we know, the profit flow depends on some form of monopoly power, secured by patents and property rights, to appropriate the benefits of the research investment. Another, more limited form of progress takes the form of "learning by doing," which improves techniques and processes economywide, for example, by the spread of computers and automation.

Here we will follow mainly the work of Barro, Mankiw, and Sala-i-Martin (1995) and Barro and Sala-i-Martin (1995a and b). For cross-country comparisons, the key element is that imitation typically is cheaper than invention. Most countries therefore prefer to copy rather than invent. Moreover, the relatively low cost of imitation means that the typical follower grows relatively fast—assuming an outward-looking society, alert to the new inventions and processes occurring randomly in different places all the time[7]—and tends to catch up to the leaders, given favorable government policies and favorable returns to the introduction of new technologies. As the pool of copyable material decreases, however, the costs of imitation tend to rise and the follower's growth rate tends to fall, unless the follower economy has already built in the necessary capacity for invention and innovation.[8] Hence, in this model, a pattern of conditional convergence emerges that seems consistent with actual observations. A country that is a follower can avoid a deceleration in its growth rate (as the case of Singapore illustrates) if it develops enough technological capability to innovate and generate technological progress.

An important distortion occurs in these models when agents in the leader country have insufficient incentive to innovate because they do not take into account the benefits to follower countries from an increase in the pool of copyable ideas. This effect would be internalized if each innovator in the leader country retained international property rights over the use of her idea. This conclusion has been challenged by Helpman (1993). He concludes that a stricter enforcement of international property rights leads to loss of welfare to the follower countries and sometimes even to the leaders. However, his results are derived from a model that puts too much emphasis on a duopoly context and not enough on the impact of expanding the frontier of world knowledge.

Once again, one of the most important policy conclusions is that technological diffusion requires a fairly open world system, and an economy will most readily reap the benefits of technological progress if it maintains an outward orientation. Also note that the rate of technological transfer usually depends on at least a minimum of human capital, and the most advanced followers will copy the most advanced products. There is

[7] In this regard, the experience of the East Asian economies is important.

[8] This is the reason why the growth rate of countries such as Japan and Singapore did not decrease substantially, even after they had achieved catch-up. But in Japan a deceleration in the growth rate did occur from the '80s to the '90s, even if we abstract from the impact of the business cycle.

a continuum of imitators, by order of sophistication. So, developing countries should start early to build their own capabilities for invention and innovation.

The next section will develop further the importance of the phenomenon of globalization. We will discuss briefly the case for international portfolio diversification and criticize some of the current policy stands arguing for "fair trade."

GLOBALIZATION AND THE SPREAD OF TECHNOLOGY

An open system of free, market-oriented trade and a free flow of ideas and technologies are essential to fostering world growth and real convergence among nations. However, this conclusion has been hotly questioned recently because of the impact of increasing globalization on unemployment and the wage rates of low-skilled labor in developed economies. What does economic theory have to add to the debate?

What would be the impact on the rate of innovation in the leader countries of an expansion in the follower economies? This question is of paramount importance in view of the ongoing access of large entrants such as Russia and China into the world trading system. In a Grossman-Helpman type of model, the impact most likely is positive.[9] Greater intensity of imitation will lead to a decline in the average length of time that a firm in a developed country can expect to earn positive profits. However, the profit rate enjoyed by industry leaders may be higher when the developing area is larger.

Present levels of globalization are not high, from a historical perspective. In fact, trade, capital flows, and human migration are not much higher, in relative terms, than the levels achieved before World War I. What is new is the large drop in transportation costs, and the much more efficient networks of telecommunications and computer technology. Krugman (1996) has assessed the impact of the dramatic reduction in transportation costs on globalization. He finds a convergence of real incomes, in which peripheral regions gain relative to the core regions. This result is consistent with some of the hypotheses just discussed.[10]

But even among developed countries, increased integration has made several industries more "footloose" than ever; they all face fierce competition with a much-reduced buffer for their competitive edge vis-à-vis their rivals. Today's technology can be accessed simply by having skilled technicians with the necessary scientific training—hence the frantic search for patent rights in order to secure royalties. Compar-

[9] See, particularly, Grossman and Helpman (1991a).

[10] This situation may apply to cases like the OECD versus the East Asian region, or Northern Europe versus Southern Europe.

ative advantage in these industries is *kaleidoscopic* (Bhagwati's terminology), because it will move across developed countries almost randomly.

Notwithstanding, several authors (for example, Obstfeld 1994) have shown that financial globalization, which generates international risk-sharing, can yield substantial welfare gains at the world level through its effect on expected growth in consumption. We know that growth depends on the availability of an ever-increasing array of specialized, hence inherently risky, production inputs. Global diversification will allow shifting the world portfolio from safe low-yield capital to riskier high-yield capital. Using some simple and purely illustrative exercises, Obstfeld estimates that the welfare gains accruing with international technology transfer can reach 22 percent in Southern Europe and 43 percent in North America, 107 percent in South America, and about 270 percent in developing Asia and Africa. Purely financial integration can add about 60 percent to North Europe, 100 percent in the Americas and about 200 percent to the developing countries.

Long-Run Fundamentals: Selected Lessons on Fiscal Policy

Empirical studies have proved that economies do converge on a conditional basis. In the Solow model, "steady states" are defined by saving rates, population increase, and rates of technological progress. In the new theories, "steady states" depend on government policies, intertemporal discount rates, intertemporal marginal rates of substitution of consumption, and other variables like the time required for human capital accumulation, or various parameters related to external effects. Among these variables we are going to select the ones more directly related to macro-policies and thus controllable by the government.

It is often forgotten that innovation and diffusion take place in a macro environment, and the profitability of these processes depends on several important parameters that are controlled by macro-policy.[11] The rate of return of an R&D project, a new discovery in the productive process, or a new plant using an imported technology, depends on parameters like the marginal tax rate, the cost of private and public capital, and direct and indirect labor costs. In their extensive work, Barro and Sala-i-Martin (1995b, ch. 12) find that after the accumulation of human capital, the most important variables are the ratio of government consumption to GDP, the black-market premium on foreign exchange, and political instability. The first two relate mainly to fiscal policy and trade policy. Thus, we encounter once again the same policies emphasized by international organizations and in several large-scale studies by

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[11] For a simple model that touches on most of these policies, see Easterly et al. (1993).

the OECD, the World Bank, and the NBER: macroeconomic stability and trade liberalization.

This section will raise some medium-term issues related to those policy parameters, in light of recent growth theories. Governments often have been accused of following relatively myopic rules because they are interested only in being reelected. But if we take dynamic consistency seriously, a credible government (one that may be rewarded by being reelected) is the one that can pursue growth-enhancing policies. Ideally, an optimal policy should not only produce effects over the short term, but shift the growth path towards a higher intertemporal welfare.

What are the implications of growth theory for the intertemporal budget constraint? This problem is related to the calls for a balanced budget over the cycle, as in the recent German proposal for the European Monetary Union. Can we derive any guidelines for the structure of the government budget? For example, what lessons have we learned in Europe, with our high social expenditures and wage replacement ratios? A major problem afflicting both Europe and North America is the question of the solvency of the social security system. Have we taken the challenge seriously? Is not our inability to learn some of the teachings of modern growth theory hampering the ability of our economies to reach a higher level of intertemporal welfare?

Blanchard-type models of overlapping generations suggest that public debt crowds out the private stock of capital. In the case of overlapping generations with an infinite horizon, Ricardian equivalence will not hold, for a number of reasons. Thus, for all these reasons, over the long term, a high and rising debt ratio would lower the long-term growth rate. A large empirical study carried out at the World Bank confirms this result. A 1 percentage point increase in the government surplus as a share of GDP is associated with a 0.37 percentage point increase in per capita GDP growth and a 0.24 percentage point increase in the investment ratio. An interesting negative and significant correlation exists between per capita growth and the variance of fiscal balances.[12] Studies carried out at the European Monetary Institute have also shown that increases in long-term risk premia are positively related to both debt ratios and budget deficits. The increase in gross public debt as a share of GDP from 38 percent in the early 1970s to 70 percent in the mid 1990s in the European Union has had a substantial impact on the slowdown of the economy.

These results underline the importance of the European Union initiative proposing a "stability pact" within the future Monetary Union.[13] That proposal would require all countries to have balanced budgets over the

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[12] See Easterly, Rodriguez, and Schmidt-Hebbel (1994), p. 24.

[13] The other purpose is to avoid "free-rider" and "bail-out" problems among Monetary Union members.

business cycle but would allow the use of automatic stabilizers for stabilization purposes. Similar proposals have also been voiced in the case of the United States.

Budget Structure: Taxes and Expenditures

Using the neoclassical theory of public finance in a growth model enables us to illustrate some results concerning the optimal level of the public sector and the structure of taxes and expenditures. State activities are essential for welfare, but when overproduced they can lead to a substantial deceleration of growth, as various empirical studies have shown. The level and structure of state activities depend on several trade-offs: First, the provision of public goods can either increase societal welfare (basic education, sanitation and public health, defense) or increase the productivity of private activities (physical and human infrastructure). Second, the activities that reinforce property rights increase the expected rate of return and thus the probability of capital investment. However, in order to finance production of public goods, the state has to raise taxes, thereby distorting relative prices, decreasing the marginal productivity of capital, and reducing labor income and savings, thus decreasing the efficiency of the economy. Furthermore, some public goods are subject to congestion, which lowers individual utility. We could also consider the state's redistribution activities that prevent absolute poverty and partially correct skewed wealth and income distributions. These trade-offs have been recently modeled in abstract terms. The theory of project evaluation developed in the late 1970s and early 1980s has also recognized those effects, but apart from some interesting applications by international organizations, the theory has been largely neglected.

A wider use of consumption-based tax systems and a significant reduction in the scale of the public sector, with more taxation of benefits and better project and activity appraisals, together with better governance and more control over the number and behavior of beneficiaries, would go a long way towards correcting most of the major fiscal distortions prevailing in our societies. Removing current distortions would certainly enhance long-term growth substantially.

The Social Security Problem and the Costs of the Welfare State

One system that is clearly unsustainable on present parameters is the social security system, not only in developed countries but in transition economies and developing countries as well. The unfunded liabilities of social security systems in most of the OECD countries are above 100 percent of GDP. These liabilities put an enormous burden on future generations and could lead to unbearable indirect labor costs. (The World

Bank has estimated that in some Eastern European countries, with the present system, social insurance contributions could exceed 60 percent of payroll in the near future.) Coupled with unemployment schemes that create disincentives to work and other rigidities in labor markets, these distortions have created very high levels of unemployment in Europe for more than a decade. Increasing growth urgently requires reforms to lower marginal tax rates on saving and investment and to increase the incentive to work.

Conclusions

We can learn a great deal from theoretical models of growth as well as from the economic experiments with macro-policies of recent decades. From the interaction of these two fields, I would emphasize the following conclusions. First, the policy advice of international organizations that has centered on macroeconomic stability, trade liberalization, and market-oriented policies and has emphasized the building of human capital, seems to be vindicated by the new growth theory and by the current spurt of growth in at least a part of the developing world. Second, the potential for improving welfare through technological diffusion and portfolio diversification on a worldwide scale is still enormous. Some illustrative simulations show an increase in welfare of two to four times in the developing regions of the world. Besides getting the fundamentals right, however, realizing such benefits requires a continuous process of building human capital, transfer of technology, and financial integration.

I believe that most of the problems witnessed in developed countries can be resolved by domestic policies, and that blaming globalization and "social dumping" is misplaced. Reducing unemployment in Europe will require a more flexible labor market and cuts in the marginal rates of taxation and other "welfare state" costs.[14] Stagnant wages for unskilled workers in North America could be addressed by more adequate redistribution policies.[15] Similarly, slow growth in Japan requires external and domestic trade liberalization, side by side with cleaning up the aftermath of the inflationary bubble of the early 1990s.

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[14] Tax wedges in 1991 were 39 percent for blue-collar workers in the United States, but reached 60 percent in Italy, the Netherlands, and Belgium. For white-collar workers, tax wedges reach up to 90 percent and more in some European countries (data from the OECD, *Economic Perspectives*, January 1993).

[15] Minford, Riley, and Nowell (1995) have proved, within the context of a model with constant returns to scale and non-traded goods where comparative advantage depends on endowments of immobile skilled labor, raw labor, and land, that technology transfer enhances world welfare—improving the terms of trade of the OECD or North while raising productivity in the "emerging economies" of the South. But they calculate, with reasonable parameters, that the impact of that integration translates into skilled wages increasing in the North by 1.6 percent per annum and unskilled wages falling by 2 percent per annum, which is a pretty dramatic redistribution of income.

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Panel Discussion
The Role of Macroeconomic Policy

Robert M. Solow*

I interpreted this session as asking for answers to a definite question: What can macroeconomic policy specifically contribute toward stimulating innovation and promoting long-term growth? By the way, I am glad that we are talking about macro policy, as if there really were such a thing, and not just about monetary policy. Poor old Jan Tinbergen must be rotating in his grave at the way it is often supposed that the single instrument of monetary policy can be assigned any number of targets. When I was a boy, Tinbergen explained to us that a government with 12 policy objectives generally will need 12 instruments to achieve them. I do not fault our monetary policymakers for becoming neurotic about the fact that they are expected with their one policy instrument to accomplish every conceivable objective. Tax and expenditure decisions have macro effects too, and of course they can be shaped to have allocational implications as well. Nor is monetary policy neutral as between classes of expenditure. If it were otherwise, there would be no point in talking about the use of macroeconomic policy in the interests of long-term growth.

The first item on my wish list is easy: Protagonists should stop making grossly inflated, hyped-up statements about what their favorite policy option can accomplish. One way to promote rational policy on economic issues is to stop promising too much. Among the wisest words on macroeconomics I have heard over the past 20 years were Charlie Schultz's pronouncements on supply-side economics—he said there is nothing wrong with supply-side economics that dividing by 10 could not cure. A flat tax may be a bad idea or a good idea—and its effects on

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innovation and growth are not the only relevant considerations—but the most it could legitimately be said to do on the growth side is to add a tenth of a percent or two to the long-term growth rate, and even that effect is likely to be uncertain and delayed. It would have been nice if some academic proponents of the flat tax had insisted at the time that Mr. Forbes was overpromising wildly and in such a way as to discredit the proposal among any rational observers.

Exactly the same could be said about proposed reductions in the tax rate on capital gains. The effects on long-term growth might be anything from negligible to small, but you would never know that from listening to protagonists. Just to show that this is not an ideological point, I will add that proposals for increases in training programs or improved access to health care for displaced workers or for those just entering the labor force may eventually work against the trend toward widening inequality, and may or may not prove to be an effective anti-poverty program, but they will provide only small increments to the rate of long-term economic growth, and they should not be advocated on those grounds. I put this item first, not just because it is annoying but because the hype runs a great risk of turning intelligent people against policies that would, on their own modest grounds, be reasonable things to do.

This injunction is directed against theorists as well as advocates. It has become fashionable to manufacture powerful policy options for faster long-term growth by a mere flick of the theorist's wrist. Anyone familiar with logarithms can invent a model in which making one small policy change will alter the whole steady-state growth rate of the economy. We all know you can change levels, and the level of human capital affects the level of output, as anyone will agree. Merely assume, say, that a high *level* of schooling will increase the *rate of growth* of human capital, or merely assume that a high *level* of research activity will increase the *rate of growth* of the stock of productive knowledge, and the result is two easy ways in which tax policy can affect the permanent rate of growth of output, because no one doubts that feasible incentives could raise the level of schooling or R&D. But how do we know that more time spent in school per year will speed up the proportional growth rate of human capital, or that a step-increment in x will cause y to grow faster, and not just generate a one-time shift? That is a spoilsport's question.

It follows from the first item on my list that the second item will be very hard to come by. However, certain commonplaces bear repeating. For instance, investment is good for growth, whether it comes in the form of plant and equipment, or research and development, or the formation of human capital. So, whenever there is a choice, growth-oriented macro policy should opt to favor investment over consumption. (I do not mean that growth is always worth buying at the expense of current living standards, only that anyone who wants more growth should want more investment.)

It may be a little late in the day to say this, but I wish we could agree to define as a contribution to growth anything that increases potential output in a permanent way. Then it would be possible to say, in good conscience, that any policy that induces an increase in the fraction of GDP invested is a policy that promotes growth. It may not make any permanent change in the growth rate; the point is that asking for that is asking too much, and unnecessarily. It is no mean achievement to shift the steady-state growth path upward, parallel to itself. The advantage of this semantic change is not only that it removes a temptation to make silly claims but also that it allows one to see clearly what the long-run scope for macro policy might be. Then the various proposals that I began by dismissing as serious factors in the steady-state rate of growth could be reassessed, modestly and realistically.

Just to confess how old-fashioned I am, I do not count a pro-saving macro policy as *ipso facto* a pro-investment policy. My preference would be for more complex policy moves that improve both the incentive to save and the incentive to invest. A tax or budgetary change that improves the incentive to save would have a much better chance of contributing to growth if it were accompanied by fiscal or monetary policy choices that operate more directly on aggregate demand for goods and services, and especially demand for investment goods. Even a temporary surge of net investment will add to the stock of capital—physical, human, or intellectual—and therefore to potential output. There is no reason in theory or practice why such temporary bursts of investment have to be reversed.

Let us agree to count as growth-promoting any act that permanently enlarges the stock of tangible capital, or human capital, or knowledge capital, in the sense that it causes the stock of capital to be forever larger than it would have been if that act had not occurred. Then, of course, there is a reasonable growth-promoting role for macro policy in general and monetary policy in particular, as part of macro policy. One route for doing this has already been mentioned: At any level of aggregate output, anything that shifts the composition of demand in favor of investment—in the broadest sense—is growth-promoting. The most obvious vehicle for this route is the tax-and-subsidy system, and the same goes for the expenditure side of the budget. Any overall fiscal stance can be weighted to stimulate investment in plant and equipment, education and training, and research and development.

A second vehicle is an old model, but I do not see why it is not capable of many more miles, if properly maintained. I have in mind the old proposition that any overall macro posture can be achieved through many different combinations of fiscal ease or tightness and monetary ease or tightness. Growth is served by combinations that feature relatively tight fiscal policy and relatively easy monetary policy, because the fiscal side favors national saving and the monetary side favors domestic investment. Growth-promoting macro policy would like the expected return on investment to be high and the expected cost of capital to be low. That again suggests that tight fiscal policy and relatively easy monetary policy mixes are favorable to investment, but only if the overall package is compatible with economic stability at high levels of employment and output.

I hope the next thing I want to say is a platitude; it used to be, but I am no longer sure. Capitalist economies do not behave like well-oiled equilibrium machines. For all sorts of reasons they can stray above or below potential output for meaningful periods of time, though apparently they are slightly more likely to stray below than above. Even apart from considerations of growth, macro policy should lean in the general direction that will nudge aggregate demand toward potential, whenever a noticeable gap appears. The relevant point is that this strategy is also growth-promoting. Whatever the level of real interest rates, excessively weak aggregate demand—and the prospect of weak and fluctuating aggregate demand—works against investment. Few things are as bad for the expected return on investment as weak and uncertain future sales. The case of slight overheating is less clear; but most of us believe that the direction of investment, and probably the volume too, will be better adapted to underlying circumstances if measured inflation is kept low and under control. Successful stabilization contributes to growth, too. So all we need to do is put together a fiscal and monetary package that favors investment and avoids inflation, although not, certainly not, at the cost of weak output. We want to make investment profitable, not merely cheap. It's a piece of cake, really!

Here I will just mention an old question that I do not feel knowledgeable enough to answer. Perhaps others in this group already know. It is generally accepted that long rates of interest are the relevant ones for decisions about investments that will not pay off for many years. Open-market operations affect short rates directly; any influence on long rates is passed along the yield curve indirectly, by normal market processes. Would there be any point in conducting open market operations at maturities all along the yield curve, so that monetary policy could operate directly on long rates, in either direction, if that were desirable for economic growth, or for any other purpose? My impression is that "Operation Twist" in the 1960s is not thought to have been a great success; but perhaps the attempt was not pursued seriously and skillfully. It may be that the market influences on the yield curve are so various and so strong that monetary policy ought to lay off. Presumably that argument would not extend to the debt management operations of the Treasury, however. But this is no place for me to get in over my head.

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