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Globalization of technology-based growth: the policy imperative

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Abstract The United States became the dominant technology-based economy after World War II and held that position for decades by accumulating a huge base of superior technical, physical, organizational, and marketing assets. However, the world is witnessing the rapid globalization of technology-based competition, which is the result of major commitments by many nations to investment in technology and its effective utilization. The changing dynamics of such competition requires revisions to the centuries' old law of comparative advantage and the Schumpeterian process of creative destruction. However, U.S. technology-based growth policies have at best stood still for most of this period. The R&D intensity of the U.S. economy is below its peak in the 1960s and its vaunted "high-tech sector" is too small and increasingly challenged to carry the remaining sectors, as was the case before globalization began in earnest. A major reason for inadequate adaptation is the "installed base effect," which results from the accumulation of the above types of economic assets and in turn creates both complacency and resistance to the need for adaptation. Weak recoveries from the most recent recessions and the sluggish growth in real incomes are major indicators of structural problems that are not being addressed. Catch-up will require adoption of more comprehensive growth policies, implemented with considerably more resources and based on substantive policy analysis capabilities.

Keywords Economic growth policy · Globalization, Innovation · Technologial change · S&T policy

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Based on the author's recent book, *The Technology Imperative* (Edward Elgar 2007).

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Industrialized and emerging economies alike are becoming steadily more R&D intensive. The reason is the fact that the output of this investment, technology, drives long-term productivity growth and thereby real incomes (Tassey 2007a). The growing pace of investment in technological change means that the competitive economy of the future must be more fluid, adaptive, and efficient than any before it. Doing so will require modifying the market-dominated growth models of the past half century with a new paradigm based on a "public-private asset" investment strategy. The core of this strategy is the premise that the public and private sectors have essential and complementary roles. This proposed shift to a neo-Schumpeterian (two-sector) growth model does not replace Schumpeter's "creative destruction" process. Nor does it ignore the fact that government has had a significant role in the post-World War II emergence of the United States as the dominant technology-based economy. Rather, the critical difference is the need for a larger, more diversified, better managed, and more closely coordinated government role than in the past. Unfortunately, the philosophical basis for such a shift is as much an institutional barrier for the U.S. economy as its market dynamism is an asset.

If this barrier is to be overcome, several critical themes must be accepted and allowed to drive a new national economic growth strategy. First, globalization has changed the dynamics of technology-based competition with one result being more rapid shifts of market shares among national economies. Second, corporations are becoming truly global in their R&D, manufacturing, and marketing strategies. They partner as much with foreign-based companies as with domestic ones and, with increasing frequency, collaborate with foreign governments. As a result, competition among uniquely domestic industries in different countries is rapidly becoming an anachronism. Third, these two points together mean that competition among governments is becoming an increasingly important factor in determining cross-border investment flows and ultimately domestic shares of global markets. Thus, the quality and timing of a government's technology-based investment strategies become primary determinants of national economic success.

1 Indicators point to a long-term decline in the competitiveness of the U.S. economy

Most Americans think of their economy as the dominant technology leader, but trends clearly show that U.S. investments in R&D and more broadly in "innovation infrastructure" are increasingly inadequate to maintain that position. Those in denial argue that the United States still leads the world in total R&D spending. While true, the U.S. global share of R&D is steadily shrinking, and, with only 4.5% of the world's population, this country's once-dominant share is destined to sink further. Moreover, the U.S. economy's R&D intensity (R&D as a percent of GDP), which is a more revealing macroeconomic indicator than simply the level of spending, is actually below the peak reached 44 years ago in 1964 of 2.9% (Fig. 1).[1] This peak occurred in response to President Kennedy's warning that emerging challenges to U.S. leadership in science and technology required increased investment in science, even though at that time the country was the world's most R&D-intensive economy. However, today the United States ranks seventh with the potential to fall further, especially as it is one of the few nations that does not have increasing its R&D intensity as a national goal.

[1] The importance of this ratio stems from the fact that it indicates the portion of an economy's output of goods and services that is being invested in technology as the basis for competing in the future.

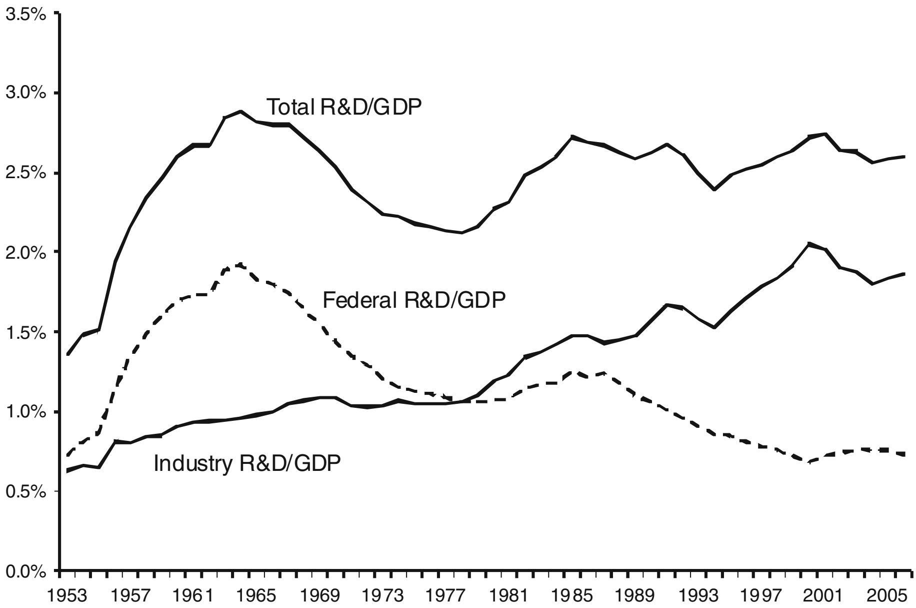

Fig. 1 R&D intensity: funding as a share of GDP, 1953–2006. *Source*: National Science Foundation

The core of an economy's technological prowess is its "high-tech sector." In the United States, this sector, as commonly defined, accounts for only about 7% of U.S. GDP.[2] The remainder of the private-sector's share of economic output (81% of GDP) does small to modest amounts of R&D, but these industries are largely dependent on technology imported from domestic and foreign high-tech sectors. This situation leaves a large portion of the U.S. economy vulnerable to shifts in market shares to other countries, which are increasingly capable of combining some R&D and technology assimilation with advantages in other factors such as lower labor costs and government incentives. Moreover, U.S R&D is concentrated geographically, with 10 states accounting for two-thirds of national R&D performance. These states account for less than one-half of the population, indicating that most of the other 40 states' economies are moderate-to-low R&D intensive and hence are vulnerable to offshoring.

As with all economies that have reached a leadership position and then begin to decline, "apostles of denial" have appeared. They assert that the current investment strategies—both public and private—are still adequate to maintain leadership positions in the global economy and even cite such negative factors as a declining currency to rationalize predictions of future competitiveness. They rationalize the offshoring of jobs and private capital as the traditional manifestation of free trade, which will grow global economic

[2] Author's estimate. No consensus definition of the "high-tech sector" exists. It is defined here as including four-digit NAICS industries that have an R&D intensity (R&D divided by net sales) greater than 5%. However, the Bureau of Economic Analysis does not calculate value added at the four-digit industry level (they do so only for three-digit industry groups and above). Thus, only a rough estimate can be made. Note that even if the value added by the three-digit groups in which these R&D-intensive industries are classified were used (a significant over estimate because these groups contain low and moderate R&D-intensive industries), the total contribution to GDP would still only be 12.5%.

welfare. The presumption is that the tide of global resource reallocation will lift all economic boats, including the U.S. domestic economy. They point to past adjustments by the United States to shifts in relative competitive position, which were ultimately followed by higher national incomes.

Certainly, world economic welfare will be increased through trade, as maintained by the centuries-old law of comparative advantage.[3] However, the belief that adaptation by the domestic economy will continue to occur automatically through private market forces and leave the country's domestic industry and consumers better off is out of touch with the rapidly changing dynamics of global competition. The problem with the law of comparative advantage for today's global marketplace is that it assumes relatively slow changes in endowments of resources across economies, which historically has allowed market forces to effect appropriate adjustments. As the dominant innovator, the United States has always been able to move to new and more productive technologies, no matter how inefficient the process and how long it took. The end result was to create new, higher paying jobs.

Unfortunately, many countries are now capable of changing relative factor endowments and doing so relatively rapidly through investments in the development and assimilation of technology.[4] Thus, the high-income economy can only gain from trade relative to its competitors if it invests in technologies and skilled labor to the extent that its relative productivity growth is above average. Otherwise, while it will be bettor off from free (and fair) trade than without it, that economy's standard of living will fall *relative* to other nations. The U.S. domestic economy is losing absolute advantage to varying degrees in portions of most high-tech industries, which reduces the number of adjustment options for maintaining a higher standard of living compared to its competitors. In fact, the growing competitive capabilities across the global economy mean that attempted transitions are increasingly chasing moving targets created by the development and use of technology elsewhere in the world.

The policy implications are (1) the response to rapid and widespread global technological change requires faster and more efficient reallocation of resources to new domestic industries that are capable of sustaining prosperity, and (2) the domestic economy can no longer be counted on to effect these adjustments solely through traditional market mechanisms. That is, the assertion that the U.S. economy will continue to be able to shift away from offshored low-tech industries to new high-tech manufacturing and service industries, as has been the case for most of the post-World War II period, is increasingly less valid. In fact, a one-sector Schumpeterian growth model in which new technologies

[3] The traditional law of comparative advantage, as conceived by English economists in the late 1700s, states that if two countries, A and B, produce two goods, x and y, aggregate economic welfare is increased through trade even if one country has an absolute advantage in both goods. This is because if country A has an absolute advantage in both x and y, both it and country B are better of if A specializes in the good in which is has the relatively greater (i.e., comparative) advantage (say, good x), leaving production of the other good (y, in this case) to country B.

[4] In the previous footnote, country A is assumed to be the high-income economy because of its superior technology in both goods. It raises its national income even more through trade by specializing in the higher technology good x. But, suppose country B increases the technological content of good y to the point that it now has an absolute advantage in that good. The structure of trade can remain the same if comparative advantage does not reverse (country A produces good x and country B produces good y). However, it is now less clear who is the high-income economy. At a minimum, the income gap has narrowed. Now suppose country B also advances the technology underlying good x, so that it has an absolute advantage in both goods. If the comparative advantages remain the same as before technological change occurred, both countries will continue to produce the same good. However, because technological advantage and income are correlated, country B is now likely the high-income economy.

are counted on to magically appear when needed and thereby provide new, higher paying industries to which domestic labor can migrate is increasingly out of date.

Figure 2 shows the negative effects of globalization on domestic employment growth when resources shift offshore without adequate response mechanisms. The top line is the average growth of employment from the levels at the troughs of the first seven recessions after World War II. On average, only four months were required to reach a higher level of employment compared to the trough. This fast response time was largely due to the closed nature of the U.S. economy over much of the post-war period. With relatively little foreign competition, growing demand in business recoveries was largely met with domestic output and therefore domestic employment.

However, the 1990–1991 recovery was much slower (19 months to a higher employment level). This sluggish response was due to growing foreign competition and hence offshoring and also to U.S. companies' efforts to respond through increased domestic investment in labor-saving information technology and automation of production. The recovery from the 2001 recession required a staggering 30 months to reach a higher level of employment compared to the trough. This unprecedented delay in employment recovery was caused by major offshoring of jobs in low and moderate technology-based industries. An analysis by Morgan Stanley economists shows a similar lag in real income growth during this most recent recovery (Roach 2008). These trends have occurred in spite of the fact that these two recessions were relatively mild in terms of length and decline in GDP growth. The implication is that structural problems in the U.S. economy exposed by growing foreign competition are causing a decline in domestic employment growth and in workers' share of GDP.

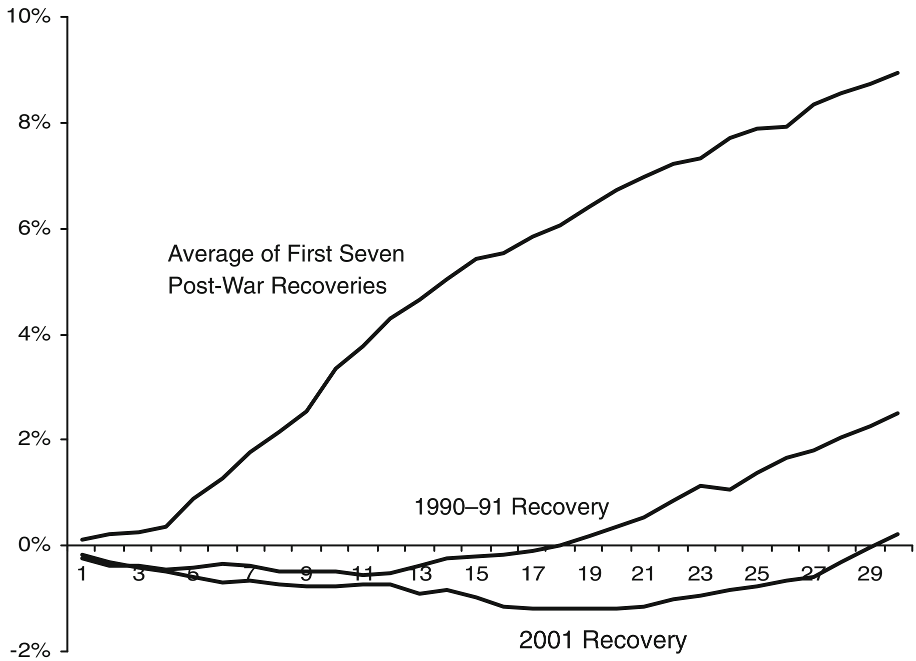

Fig. 2 Post World-War II employment growth: percent change from recession trough by month. *Sources*: BLS for employment data; NBER for recession trough dates. See Tassey (2007a)

To the extent these structural problems are recognized, a frequent proposal is to conduct more R&D. Because R&D leads to new products and processes, a domestic manufacturing sector can add additional value by developing and absorbing new technology. If adequate amounts and types of R&D investment are not forthcoming, the resulting lower technological content of manufactured goods makes them susceptible to offshoring.

However, even modest amounts of R&D are no longer sufficient to prevent offshoring. Typically, when manufacturing is offshored to other economies, at least some R&D follows. This phenomenon frequently occurs in the middle and latter phases of a technology's life cycle. The insidious aspect of this process of offshoring is that the emergence of foreign competitors in the current life cycle also conveys innovation capabilities to these newcomers in the next life cycle. The R&D capability established to manage the offshored manufacturing serves as the genesis of a growing innovation infrastructure, which gives the host country the opportunity to be the "first mover" for emerging technologies that drive the next life cycle. Semiconductors is a stark example. The offshoring of a majority of state-of-the-art U.S. manufacturing capacity has afforded other economies not only production technology experience but created domestic demand for scientists and engineers, some of whom are now participating in their economies' R&D efforts to become first movers in the next semiconductor technology life cycle (post-CMOS).

When technological advances take place in the foreign industry, manufacturing is frequently located in that country to be near the source of the R&D. The issue of co-location of R&D and manufacturing is especially important because it means the value added from both R&D and manufacturing will accrue to the innovating economy, at least when the technology is in its formative stages. This phenomenon occurs because much of the knowledge produced in the early phases of a technology's life cycle is tacit in nature and such knowledge transfers most efficiently through personal contact. Intel's major R&D program in Israel is an example. This collaborative research developed a new architecture for the company's 64-bit microprocessor, which was followed by investment in a $4 billion manufacturing plant near the R&D facility. Thus, an economy that initially controls both R&D and manufacturing can lose the value added first from manufacturing and then R&D in the current life cycle followed by first R&D and then manufacturing in the subsequent life cycle. This is the economics of decline.

2 Globalization is increasing but not everyone is adapting

The United States has been the first mover in every major technology to appear in the world economy since World War II (semiconductors, digital computers, software, advanced materials, network communications, and biotechnology). The development of these technologies has benefited from not years but decades of government support of both scientific research and early-phase generic technology development. However, shrinking technology life cycles mean that the economic benefits from these technologies diffuse much more rapidly from the innovating economy. Certainly, IT-based technologies have experienced rapid global distribution. Currently emerging technologies, such as biotechnology, are in the early phases of similarly rapid diffusion patterns. Looking forward, nanotechnology will be the first emerging technology for which the United States will not automatically be the first mover. In fact, multiple economies are competing on equal footing to be innovators for this eventually broad and high-impact technology.

In response to the new technology-based dynamic of globalization, corporate strategies are evolving even beyond a multinational mode (worldwide production and marketing but with a dominant home base, especially for R&D). Today, the truly global corporation allocates all categories of resources (R&D, production, marketing) rapidly and without regard to national boundaries to locations where investment incentives are superior. Large companies such as IBM, Microsoft and Intel have R&D facilities all over the world, and even medium companies are now diversifying their R&D assets globally. A major implication for domestic growth policy is the fact that such global strategies dilute a corporation's stake in any one economy. With multiple options for locating R&D and manufacturing, industry is becoming progressively less concerned with the state of innovation infrastructure in any one economy. Officials of a number of U.S.-headquartered companies have said basically the same thing: as Americans, they would like their companies to invest in the U.S. economy; but, as corporate managers, they must allocate resources wherever the interests of their stockholders are best served. Hence, these managers now spend more time assessing the relative attractiveness of alternative national investment environments than lobbying for better incentives from the "home" country.

Yet, in spite of such signals of increased competition among countries for R&D assets, denial remains strong. One can always point to data from the past or even the present to argue that a situation is better than is actually the case. For example, NSF provides data from the Bureau of Economic Analysis, which shows that, as of 2000, the R&D intensity of foreign affiliates operating in the U.S. economy was greater than the R&D intensity of U.S. affiliates in other economies. The implication is that the U.S. research environment is relatively more attractive than other locations, in spite of the recently increased investment in research infrastructure by other countries. In fact, most international R&D investment flows are between industrialized nations where the majority of R&D capacity still resides.

Such indicators can be used to deny the warning signs from emerging R&D investment patterns among industrialized nations and developing economies. However, current distributions of foreign-owned R&D assets are a legacy of past investment decisions in response to differences in innovative capacity and other incentives across economies. Global investment trends are decidedly in the direction of ever-wider diffusion of such capacity. For example, between 1994 and 2002, NSF data also show that R&D spending by majority-owned foreign affiliates of U.S. multinational companies (MNCs) grew more than 50% faster (9.8% average annual rate) than such spending by their parents (6.3%). Thus, the growing R&D spending by U.S. MNCs in developing nations such as India and China, while hyped by the media, is currently not large relative to total offshoring of R&D. However, the trend clearly indicates greater future impact by these large-population and determined competitors.

Globalization of corporate strategies is an attempt to manage the technology life cycle. The companies that excel over an entire life cycle and thereby preserve the option of transitioning to the next life cycle innovate by drawing upon the generic technology platforms that are the basis for their industries' existence. As their markets grow, these companies not only innovate at the product level but also optimize process technologies to produce their products and services more efficiently. To take advantage of these intangible technology assets, they accumulate substantial other assets—physical, organizational, and marketing—that deliver the industry's output to its customers. As an industry's technology evolves, an enormous amount of learning takes place through the accumulation and use of these assets. Even as the generic technology underlying a life cycle matures and affords increasingly limited innovation potential, the industry's products or services can maintain cash-cow status through cost reductions and marketing expertise. Eventually, however, the process of creative destruction forces them to transition to the next life cycle or likely go out of business.[5]

The problem is that transitions between life cycles are typically daunting for a majority of companies and governments that support industries based on the existing technology. Most fail at the task. The reason is not the fundamental fact that technologies mature and then become progressively obsolete. Rather, it is ironically the accumulated investments in the set of technical and other assets over the current technology's life cycle that present a significant barrier to adaptation to the requirements of the next life cycle. The sunk costs, both tangible and intangible, constitute a huge asset base whose optimization and consequent relatively secure cash flow create a vested interest in the status quo. Even in the face of clear signals that the time for transition to a new technology has arrived, this "installed-base effect" leads to hesitation and even outright resistance to change. Further, the prospect of the considerable trauma associated with transitioning to new technology, production, marketing, and organizational strategies creates fear of the unknown. The combination of the installed-base effect and the fear of change results in the self-imposed delusion that the current economic growth model will work indefinitely. The bottom line is stubborn denial, especially by the leading economy even as its once dominant competitive position is progressively hollowed out by more aggressive and resourceful foreign industries supported by their governments.

Because the United States has been the dominant technology-based economy, both the old and new industries have been domestic (U.S. semiconductor firms replaced U.S. vacuum tube firms; U.S. biopharmaceutical firms have taken market shares from the dominant U.S. pharmaceutical firms). In a flat world, domestic transfers of market leadership are increasingly less likely to be the case. More global players mean more potential first movers and imitators who will come from an increasingly large pool of technology-based economies. Shifts in the locus of global competitive advantage across technology life cycles will occur with increasing frequency.

Therefore, the victim of creative destruction is increasingly domestic economic growth. In addition to sluggish employment growth coming out of recessions, recent business cycles have also been characterized by a shift in the shares of GDP with labor's declining and industry's increasing. This latter phenomenon is the direct result of the offshoring of economic assets to more attractive investment environments and the subsequent importation of identical but cheaper products. Thus, while this aspect of globalization makes measured labor productivity go up, at least for a while, both companies and workers know the truth, which is reflected in wage growth considerably lower than the rate of increase in productivity.

3 The law of comparative advantage is outdated

The policy message is that the flat world can be tipped by conscious and more efficient creation of new technologies. Wealth often drains away from the leading economy to competitors who both perceive the opportunity offered by an emerging technology and

[5] Described over 60 years ago by the famous Austrian economist, Joseph Schumpeter, this process refers to the periodic appearance of radically new technologies that replace existing ones and often do so in rather traumatic fashion in which an entire industry based on the existing technology is replaced by a new industry driven by the emerging technology.

make the required investments in R&D and supporting infrastructures. The new economic growth model is a much more manipulated and dynamic process of changing comparative advantage than the historical shifting of production among nations in response to differences in natural endowments and slowly changing infrastructure, such as transportation networks, as has been the case for several centuries.

Today, the conscious timing and efficiency of technology-based growth policies are essential characteristics of successful attainment of comparative advantage. However, the conventional wisdom in the United States still assumes long technology life cycles, so the associated investment and learning requirements continue to be managed in the same unstructured manner as in the past. This conventional wisdom applies not only to the act of innovation (the first-mover phenomenon) but also to the holding of dominant market shares over a technology's life cycle.

Such denial is increasingly destructive. The global convergence now in process is truncating the middle portion of the life cycle in which innovators have in the past typically appropriated the majority of the economic rewards from investment in the technology. Equally serious, this erosion of domestic competitive position constrains the ability to generate innovations in the next life cycle as technical, production, and marketing knowledge accumulate faster in competing economies.

As a consequence of the globalization of corporate strategies and the subsequent rapid allocations and reallocations of private-sector resources across national boundaries, governments are increasingly becoming competitors in that they are now important determining factors in corporate investment location decisions. This rise of governments as competitors is forcing a restatement of the traditional law of comparative advantage. However, the precise governmental roles and the mechanisms that implement these roles are complex and require considerable analytical capability to manage effectively.

Another dimension of denial is free-trade advocates' reliance on the traditional version of this law as the main rationale for their position that markets will continue to reallocate resources to everyone's advantage. Meanwhile, free-trade economists are attacked by populists and others who argue that trade with many, especially emerging, economies is not "fair" in that these countries exploit their domestic labor, employ multiple barriers to trade, and ignore environmental standards. While valid, the singular focus on fair trade misses and, in fact, enables denial of the long-term structural problems that adjust the intrinsic terms of trade. Even if all U.S. trading partners agree to adhere to internationally recognized norms, the domestic economy will still experience declining competitive position because it is not addressing underlying fundamental problems of depreciating competitive assets.

In summary, structural problems such as underinvestment in R&D, innovation infrastructure and education take a long time to manifest themselves. Moreover, obvious negative trends seldom appear in an entire supply chain at once. Rather, the process is one of progressive hollowing out of the supply chain's aggregate domestic value added. As such, these problems are rather easily ignored, as has been the case for decades. Even today, in the face of the many indicators of declining competitiveness, the threat of change leads to widespread resistance. Thus, the lengthy period of revitalization has hardly begun. Unfortunately, once a nation is sufficiently burdened by the accumulated effect of underinvestment to finally admit to the need for change, a long time is required to remove these barriers to sustained economic growth.

The major economic principles that need to be internalized by policy makers are two. First, the shifting of comparative advantage, even though it increases aggregate global welfare, nevertheless conveys relatively more benefits on the economies that create and utilize productivity-enhancing technologies. That is, the economies that invest more in technology and do so efficiently will attain comparative advantages in the higher-income industries. Thus, if semiconductor technology assets accumulate in other economies to a greater extent than in the United States, the relative shrinkage in the domestic industry increases the probability that U.S. workers will not be able to transition to the next semiconductor life cycle (post-CMOS). The bottom line is that unless a nation becomes the first mover in some other advanced technology and maintains that position long enough to retrain and absorb the structurally unemployed workers resulting from offshoring semiconductor technology, the only employment options are lower-paid jobs in other existing industries.

Second, these realignments of comparative advantage due to trade require a different view of the process of creative destruction. The trauma associated with this process traditionally occurs because the new technology is seldom provided by the same industry that delivered the old one. For the U.S. economy as a whole, this was not a problem when it dominated technology-based markets. The U.S. companies that created the industry built on the old technology were replaced by U.S. companies that ascended by developing and producing the new technology. Hence, for the economy as a whole, the gains in economic welfare were internalized.

This closed-economy phenomenon was so dominant for most of the past half century that American economists attempting to explain the economy's growth path were not concerned with the process that produced technology or the efficiency of technology's assimilation by industry. As such, they did not include this economic asset or its absorption patterns explicitly in their models. They simply assumed that technology occasionally appeared and created new growth trajectories. Their models then explained the economy's growth path based only on allocations to capital and labor where a fixed amount of technology was assumed to be embodied in the economy's capital stock.

Another major difference is that the process of creative destruction is becoming more of a national economic growth issue than simply one of the birth and death of companies. Unlike past transitions to radically new technologies in which the dominant companies fade away with the emergence of a new set of upstart firms, many modern corporations are finding ways to survive such shifts. They are learning how to adapt within and across technology life cycles and thereby avoid becoming victims of the creative destruction process. In doing so, they respond to differences in incentives among national economies by shifting assets to where they can be most productively used, including partnerships with foreign companies and governments. Thus, the "new" industry rising to the forefront in another economy is increasingly likely to contain firms that were leaders in the previous life cycle and headquartered somewhere else in the world. IBM, Intel and Microsoft are not going away but larger portions of their R&D investment, including breakthrough research, are occurring outside the U.S. economy. Therefore, in a neo-Schumpeterian world, such shifts in assets by global companies mean that domestic economies will trade places in response to shifting technological advantage almost as frequently as existing companies are replaced by new ones.

The bottom line is that more and more technology-based competitive advantage is being created outside the U.S. economy by an increasing number of competitors. The result is shorter technology life cycles and a greater imperative to better manage the creation and use of technology. Thus, an explicit knowledge production function is now required for the growth models that drive policy analysis.

4 The public-good elements of industrial technology

A major requirement of new growth models is that they address the compression of life cycles and the global reach of corporate investment strategies by acknowledging the importance of public-technology assets. Public technology assets have unique and complementary roles with private technology assets. Thus, the nature of technological change and its use in economic growth demand that the process of creative destruction be viewed by a two-sector model in order to manage technology life cycles more efficiently. As a result, economists are being forced to not only represent technology explicitly in their growth models, but this technology variable must be disaggregated into its public and private elements (Tassey 2005b, 2008).

One of the critical categories of public technology assets is a complex and inadequately understood "technical infrastructure." This infrastructure consists of a ubiquitous set of infratechnologies (measurement and test methods, process-control techniques, science and engineering data, data formats, and interface protocols), which often become industry standards. Every technology currently driving the global economy is supported by a variety of infratechnologies and associated standards. Economic studies have shown substantial net economic benefits in the form of productivity gains and lower entry barriers. For example, a recent NIST study estimates that the U.S. semiconductor industry spent more than a billion dollars per year over the past decade to improve its measurement capabilities (Gallaher et al. 2007b). Such improvements have yielded approximately $39 billion in net economic benefits (constant dollars).

Yet, the public-good characteristics of technical infrastructure lead to substantial underinvestment by industry. The result is that the economic benefits could be substantially increased with additional investment, as demonstrated by a NIST study of the biopharmaceutical industry. This study estimated that the average cost of developing a new drug through FDA approval could be reduced from 25% to 48% and the average length of the R&D cycle could be reduced by 20% through improved technical infrastructure (Gallaher et al. 2007a).

These substantial projected cost and time reductions indicate the critical importance of assuring adequate investment to support emerging industries and to achieve national goals (in this case, reduced cost and improved quality of medical care). However, governments often pick up only part of the investment shortfall because of inadequate understanding of the economic roles of this infrastructure and the fact that its quasi-public-good character makes defining the government's role difficult. As a result, competitive differences exist among national economies with respect to breadth, depth and quality of technical infrastructure, just as is the case for generic technology platforms and domestic rates of innovation.

Moreover, the complex multidisciplinary basis for new technologies demands the availability of well-developed generic technologies before efficient applied R&D that leads to innovation can occur. Thus, the R&D cycle is more linear than in the past and the R&D must be performed by teams possessing the multiple skills to produce the systems that characterize modern technologies. Even large companies are increasingly networking their R&D to access complementary research assets. At the national level, the required R&D must be managed as a portfolio of projects and government must increasingly assume the role of partner with industry in developing the generic technology platforms, which allow innovative activity to proceed and to do so efficiently.

Largely ignored is the fact that this complex R&D infrastructure will not work without a complement of infratechnologies and standards. The Internet, with its huge economic and social impact, could not function without a set of highly complex standards. The Internet Protocol (IP) illustrates this point.[6] The IP is an excellent case study in the many requirements for modern technical infrastructure to complement private investment over all phases of the technology life cycle. The importance of the IP stems from the enormous global reach of the Internet. The worldwide IT market is forecast to reach $1.3 trillion by 2009. By that time, virtually all IT equipment and software will be networked, making the Internet the most important single information infrastructure of all time. Thus, the IP is arguably one of the most important industry standards.

However, the complexity of the IP and other Internet standards present extreme challenges for IT policy. The Internet is thought of by most as simply a set of connected communications networks. In fact, it is a highly structured combination of hardware and software, linked by a controlled and tightly specified set of standards that have considerable technical content. The complexity of this infrastructure becomes apparent when a major existing standard needs to be replaced by a new generation. Suddenly, the entire supply chain involved in developing and delivering market applications (innovations) becomes active and various positions on transition strategies appear. For more than 10 years, an international task force has been developing the many components of the next-generation IP and still the work is not finished. Transition to the new version of the IP will be time consuming and expensive for industry.

The motivation to incur such costs is complex. Industry may foresee opportunities to innovate once the new generation of the IP is in place, but the uncertainties that accompany first-mover strategies present barriers to substantial investments in the transition. Governments around the world understand these investment barriers but are reluctant to commit public funds to support the transition without assurances that innovations will rapidly be forthcoming. In other words, the quasi-public-good nature of the underlying infratechnologies and the considerable assimilation costs during the transition present a formidable "chicken-or-egg" problem for technology-based growth policy. On the one hand, improvements in technical infrastructure facilitate innovation and therefore potential innovators take its availability into account. On the other hand, investment in this complex and expensive infrastructure may not happen without the pulling effect of demand from emerging innovations that require it.

Taken together, these characteristics of the modern technology development and assimilation process require comprehensive policy management driven by accurate economic models and data. However, U.S. economic growth policy has never been well organized or conceptually strong. In fact, less institutionalized S&T policy analysis capability exists today than in the 1970s and 1980s, when both the legislative and executive branches had at least modest levels of effort. The current dearth of such capability is an important reason for the domestic economy's decline in relative competitiveness. Existing technology-based policies continue to be driven by the "black-box" model in which science is viewed as a pure public good and technology as a pure private good (the black-box). Such a framework grossly oversimplifies the reality of technological change and subsequent innovation, and it leads to negative views of government support for technology development and utilization.

[6] The IP, which is really many standards integrated into a single system of standards, controls information flows over the Internet and enables applications (software that provides various services to users of the Internet) to be implemented efficiently. It does this by providing a standardized "envelope" or "header" that carries addressing, routing and message-handling information. The information in this header enables a message to be transmitted from its source to its final destination over the various interconnected networks that comprise the Internet (Tassey 2007a).

5 "Tipping a flat world" requires a more efficient government role

Management of the creative destruction process in a global technology-based economy requires R&D efficiency. Such a metric was hardly even considered for most of the post-war period. Now, however, with over $1 trillion invested in global R&D last year, the growing competition demands attention be given to how much, what type, and by whom R&D is conducted over an entire R&D cycle.

Managing the R&D efficiency imperative requires a public-private technology asset model of knowledge production. The main targets of this model are (1) the transition from a pre-existing science base to proofs of technology concept, (2) provision of an array of infratechnologies and standards, and (3) rapid diffusion of this generic technical knowledge throughout the domestic supply chain to enable high rates of innovation.

An important implication of science-driven technological change is that the so-called "Pasteur's quadrant" is shrinking. This quadrant refers to the portion of innovation space in which important technologies have appeared through spontaneous (often trial-and-error) inventions and have been commercialized before the underlying science was understood.[7] However, most elements of all major technologies appearing over the past 50 years have advanced largely in a linear fashion. The reason is that technology is becoming more and more science based (semiconductors, network communications, biotechnology, and nanotechnology). Consequently, fewer and fewer inventions can appear ahead of significant advances in the underlying science.

In fact, innovation efforts will be inefficient even with the availability of a substantial science base if the transition phase of the R&D cycle between scientific research and applied R&D aimed at innovation is not adequately developed. This transition phase is the development of generic technologies that provide the technology platforms (proofs of concept) that enable high rates of innovation. Unfortunately, continued adherence to the black-box model introduces substantial inefficiencies in the process of developing market applications of new technologies. For example, NIH has created the biotechnology industry but largely through a brute-force approach to achieving innovation, i.e., applying large amounts of funds to make the black-box model work. The lack of an explicit disaggregated (public-private-asset) R&D model with appropriate real-options or stage-gate progress assessment methods to both guide funding and make missing elements of generic technologies more visible have led to incomplete development of proofs of concept before substantial private-sector attempts at innovation occurred. The result has been wasted effort by biotechnology firms in new drug development and billions in venture capital unproductively spent. Monoclonal antibody and antisense technologies are examples. In both cases, first-generation drugs did not work. A decade or more elapsed before second-generation drugs, based on more complete proofs of concept, were developed and commercialized. Application of the correct technology development model could have greatly reduced the time and money spent (Tassey 2007a).

Corporate managers understand that the correct technology-based growth model embodies the concept of a multi-element technology, where the major elements respond to distinctly different investment incentives. Unfortunately, too many policy makers still adhere to the black-box model. The result has been poor policy. For example, the R&E tax credit has been "temporary" for 25 years and is largely ineffective for its stated purpose. Yet, both industry and government supporters have argued relentlessly to make the credit

[7] Pasteur discovered the vaccine before the underlying principles of microbiology were understood. See Stokes (1997).

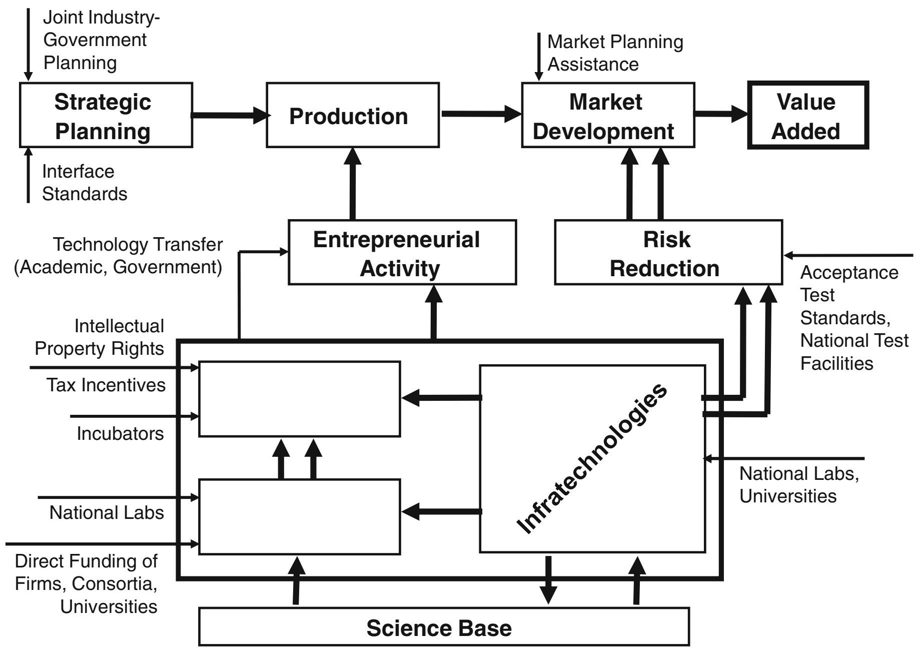

Fig. 3 STID policy roles

permanent, even though its current incremental structure and formula for calculating the base R&D spending level on which the credit is based have been barely discussed, let alone systematically analyzed.[8] Similarly, federal funding of generic technology (proof-of-concept) research has been acceptable only for technology research that supports a social objective other than economic growth (defense, health, space exploration, etc.). When increasing economic welfare is the objective, publically funded technology research receives the "corporate welfare" label.

Only with a multi-element model can different types of underinvestment be correctly identified and each type matched with and most efficient policy response (Tassey 2005a, 2007a). As indicated in Fig. 3, a variety of policy instruments are available. The larger arrows (from each technology element or stage of economic activity) indicate direction of economic impact and hence the potential path of impact of specific policies targeted at that point (smaller arrows). However, knowledge of each policy mechanism's suitability for addressing specific underinvestment phenomena is largely absent from policy deliberations. The reality of the typical technology-based industry is complexity, which the black-box model does not recognize.

For most of the post-World War II period, the barrier posed by the black-box model has been overcome to a significant extent through substantial funding of technology research by mission-oriented agencies. For these agencies, economic growth is not the driving motivation—even though all public-good objectives require viable industries to deliver components of the desired system technologies through the market place. For example, support by DoD's DARPA has been responsible for the emergence of a number of major

[8] In 2008, legislation was drafted by Congressional staff that would convert the credit to a "level" from an "incremental" structure. See Tassey (2007b) for a discussion of the rationale for a level credit.

new technologies (computing, network communications, VLSI, artificial intelligence, advanced materials). However, in recent years, a refocusing of DoD's budget on more applied, military-specific objectives is resulting in slower growth and even cuts in the S&T research portion. The implication is a reduction in DoD's future role in stimulating new technology platforms and subsequent innovation and economic growth.

Even without such cuts in DoD S&T budgets, the rapidly growing dependency of the U.S. economy on technology demands larger and broader support than DoD can supply. However, only the health-care portion of the non-defense federal R&D budget has experienced growth in constant-dollar terms over the past 30 years. A static non-defense, non-health-care R&D budget is clearly a serious concern with respect to providing technology platforms for a range of breakthrough technologies in critical areas such as electronics, optoelectronics, software, communications, and advanced materials that can launch new industries and provide an essential diversified technology base for the domestic economy. Equally important, the historical approach of funding long-term technology research through mission-oriented agencies, which counts on spinoffs into commercial applications, is increasingly inefficient in a global economy where other countries are attempting to employ R&D strategies aimed directly at economic growth. Finally, in spite of large budgets for mission-oriented R&D, these agencies are increasingly dependent on foreign sources of needed technologies as the relative technology intensiveness of the U.S. economy declines. As Fig. 1 shows, the main culprit in the relative decline is government funding for R&D. The shrinking non-defense, non-health-care portion therefore implies a smaller domestic technology-based sector to supply the future needs of these mission agencies, as well as the needs of the economy as a whole.

To reverse current trends and maintain the status of a leading technology-based and high-income economy, the United States must raise its R&D intensity to the 4–5% range. This would constitute a large increase from the current national rate of investment (2.6%).[9] While such a jump is an imposing challenge and will require reallocation of resources from other types of investment, consider that six countries with more R&D-intensive economies than the United States have R&D/GDP ratios ranging from 2.8% to 4.5%. As the U.S. slide down the global rankings has been due largely to the federal government's declining share of GDP, its funding must be a target for substantial increases. Increasing government funding also allows rebalancing of the composition of R&D, as government can rationalize more funding of the long-term, pre-competitive technology research that results in new technology platforms and thus new technology life cycles and even new industries.

The payoff from a more R&D-intensive and a more R&D-efficient economy would be huge. The productivity advantage of the United States over OECD countries as a group has accounted for three-quarters of its per capita income advantage (Conference Board 2002). However, if the U.S. economy is to continue to regenerate itself through the periodic rebirth of established companies and especially the creation of new firms to populate emerging industries and deliver new jobs and high wages through diversified innovations, a much more efficient R&D infrastructure (sum of all incentives and support mechanisms) is needed.

To this end, more enlightened policies are required to respond to the growing complexity, R&D investment risk, and systems structure that characterize emerging technologies. For example, new R&D mechanisms such as regional technology clusters

[9] The current U.S. R&D intensity is actually somewhat of an overstatement with respect to support for economic growth because the United States allocates proportionately more of government R&D spending to military objectives, which have less relevance for commercial markets.

and portfolio management at the technology systems level need to be emphasized to promote greater R&D efficiency. R&D funding strategies must be coupled with truly nationwide technology-diffusion channels, as well as with local entrepreneurial support programs, thereby producing more technology more quickly and promoting wider use. Moreover, this innovation infrastructure must recognize the life-cycle character of modern technologies and adapt by shifting emphasis among policy instruments as technologies are created, penetrate markets, and finally become obsolete. Some state governments are experimenting with new R&D and technology-based growth (cluster) models, but the federal government has provided very little support.

The need for R&D efficiency cannot be emphasized enough. Not only are technology life cycles being progressively compressed by global competition, but industry faces severe transition barriers when attempting to move from one life cycle to the next. Figure 4 indicates that the performance of an emerging technology relative to its cost (point B) is initially below that of the mature technology (point A). This is because immature technologies, even though they have greater economic potential, typically have significant imperfections in at least some of their performance attributes, which lower overall performance. At the same time, costs are higher due to initially small markets that inhibit economies of scale and the fact that process technologies are not optimized for cost minimization and quality assurance.

The concept of the transition between technology life cycles is just one of many elements of the needed technology-based growth model, as summarized in Fig. 3. Such a model is needed to determine which policy mechanisms should be used for each category of underinvestment. The major elements of U.S economic growth policy—science, technology, innovation, and diffusion (STID)—are under-researched and hence underdeveloped. The U.S. economy achieved the greatest systems design and deployment of

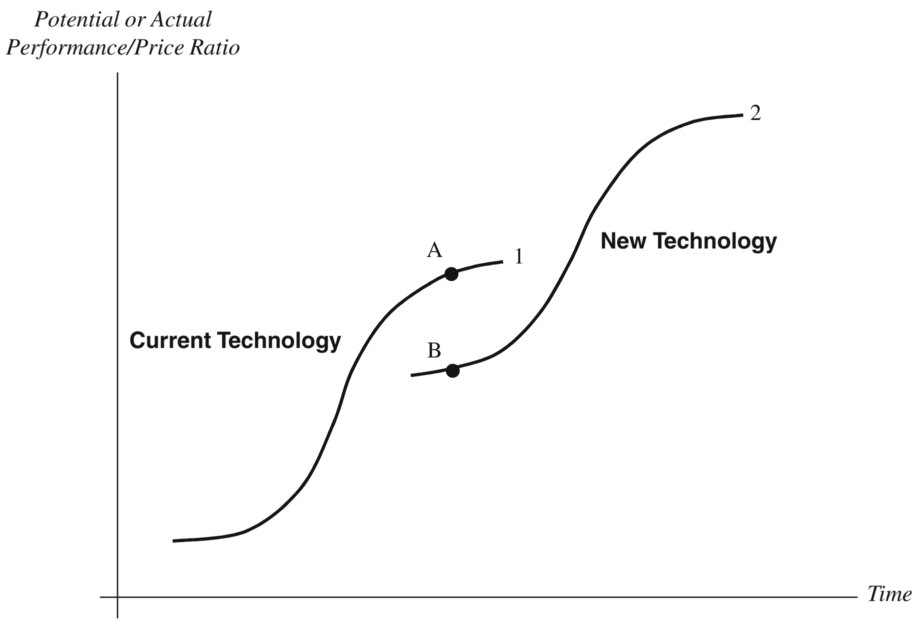

Fig. 4 Transition between two technology life cycles

technology in history when it placed the first human on the moon. Yet, when it comes to managing its economic system, the historical bias against the public-private technology model in support of economic growth is handicapping the needed responses to increasing technological complexity and growing global competition. As a result, R&D, innovation, technology transfer, intellectual property rights, workforce, and venture capital issues are not being adequately addressed.

In essence, one wants government policy to induce curve 2 in Fig. 4 to shift higher and to the left and to become steeper. Unfortunately, the government innovation-related policies needed to make this happen are not being developed. Current policies remain at best educated guesses. To respond to the rapid growth in the ability among other nations to both create and use technology, a much more analytical and data-informed infrastructure for STID policies is needed.

6 The bottom line

A critical driver of economic growth policy should be the fact that some economic assets are less mobile than others. Investment in immobile assets should be emphasized because they confer more sustained advantages on the domestic economy and increase the ability to manage the more mobile assets over a technology's life cycle. Specifically, while applied R&D capabilities can diffuse across economic borders relatively easily, the skilled labor and research infrastructure associated with more radical technology research and the synergies created by a complete and integrated innovation infrastructure are much harder to imitate and hence are less mobile in an economic sense. That is, it is easier for economies to acquire competitive assets that function in the middle and latter phases of the technology life cycle than it is to successfully implement first-mover strategies. However, while the need for expansion and upgrading of the S&E labor pool is a relatively understandable issue, the concepts of innovation infrastructure and its management are complex. Hence, they present a particularly difficult challenge for STID policy management.

This complexity explains why discussions of competitiveness strategies often focus on relatively easy-to-understand policy options such as corporate tax rates. However, research has shown that other factors rank high when global companies are evaluating locations for R&D investment. The most important factors are market-growth opportunities, quality of R&D talent, collaboration with universities, and intellectual property protection. Of these, collaboration with universities is a particularly relevant factor for expanding into emerging economies, even though these countries provide lesser degrees of IP protection (Thursby and Thursby 2006). In these studies, cost was not identified as a major decision factor. The bottom line is that innovation infrastructure is the main driver of corporate investment location decisions, especially in the early phases of the R&D cycle.

Complaints in the United States with respect to offshoring of high-tech manufacturing jobs are similarly misplaced. For example, explanations of the rapid expansion of semiconductor manufacturing in Asia often focus on lower labor costs. However, in advanced manufacturing industries, automation has significantly reduced labor cost as a percentage of total cost. The Semiconductor Industry Association (SIA) estimates that Chinese government policies, not lower labor costs, are the major contributor to a cost differential of $1 billion over 10 years for building and operating a semiconductor plant in China compared to the United States. About 70% of the cost difference is due to tax benefits, 20% is due to direct funding subsidies, and only 10% is attributable to lower labor costs (Scalise 2005). Such a relatively small advantage in labor costs may seem surprising, given the widely publicized huge wage differentials between average Chinese workers and those in the United States. However, the larger wage differentials are found among lower-skilled workers. Moreover, SIA points out that semiconductor fabs are so capital and technology intensive that even an 80% differential in labor rates results in barely a 10% difference in total costs.

The most important point from an economic growth policy perspective is that, even though the labor intensity of high-tech manufacturing is relatively low, jobs in this sector are highly skilled and hence highly paid. In this regard, the concern over offshoring of manufacturing jobs in general is miscast not only because most of these jobs are low-skilled and hence low-paid, but also because many of them will be replaced by automation in the next decade on so.

Overall, the seriousness of the U.S. economic growth problem is evidenced by the fact that even the more straightforward and hence easily understood problems are not being addressed. It is abundantly clear from international test scores that U.S. students are not receiving the education and training to compete in the global market place. It should also be clear, although this point is seldom mentioned, that even if the quality of K-12 education in this country were improved, the fact that the school year is so short compared with competing economies means that by the time a U.S. student graduates from high school, he or she has received about one full year less of school time.

In the final analysis, the high-income economy must be the high-tech economy. Unfortunately, denial of the structural problems and the long-term relative economic decline that these problems are producing is pervasive. In response, national discussions are held and high-level reports are written. While useful in that they convey a significant level of concern, ad hoc studies can never substitute for institutionalized policy analysis. The installed-base and conventional-wisdom effects are preventing investment in such capability. As a result, the issues discussed here are barely on the radar screen of the broader economic growth policy establishment. The long run is not a problem until one gets there, but then it becomes a crisis, which is not easily or quickly solved.

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