SUSTAINING MOORE'S LAW AND THE US ECONOMY

Faster and cheaper information technologies have ushered in fundamental transformations in the US economy. The continuing potential of the semiconductor industry to power this IT revolution rests on its ability to remain on the trajectory foreseen by Gordon Moore.

Semiconductors are indispensable to the modern economy. The semiconductor—through its synchronous increase in power and decline in price—has contributed significantly to the United States' economic growth over the past decade.[1,2] The technological advances spurred by this regular and predictable rate of growth in power (as described by Moore's law) have enhanced the level of productivity in the US economy, not only in "New Economy" sectors such as computers, telecommunications, and software, but in traditional industries such as banking and trucking as well. The cumulative effect of this pervasive technology, and the organizational changes undertaken to capture its benefits, continue to transform important elements of the US economy.

The advantages of semiconductors are not confined to their applications. The production of semiconductors brings significant advantages, not just in the context of high value-added semiconductor production, but also in terms of dynamic effects—often through the growth of clusters—that the industry's presence brings to a region or a national economy.

There is, in recognition of such benefits, a fierce locational competition for the semiconductor industry. Although this competition is global, its economic consequences are local. Overlaying this competition is the shared challenge of sustaining the performance predicted in Moore's law, which highlights the need for cooperative efforts to overcome current technical challenges facing the industry.

CHARLES WESSNER
The National Academies

A Driver of Change in the US Economy

As Figure 1 illustrates, the secular trend in US productivity growth of about 1.5 percent per annum from the mid 1970s through to the middle 1990s is significantly below the roughly 2.5 percent growth characterizing the preceding period from the early 1950s through the early 1970s. In the mid 1990s, the slower growth trend that began in the 1970s shifted dramatically. Productivity growth now seems to have returned to a pace closer to that experienced in the 1950s and 1960s. This growth has thus far continued into the early part of the 2000s, the recent recession notwithstanding. Several leading economists believe that the source of this growth lies in the falling costs and surging performance of semiconductors and related equipment in the latter part of the 1990s.

Productivity in the 1990s grew in part from the greater efficiencies in computer production in addition to the expanded use of information technologies.[3] Figure 2 shows that the rapid advance and application of these semiconductor-intensive information technologies enabled the proliferation of complex knowledge networks.[1] These, in turn, created new economic opportunities. Phenomena such as business-to-business e-commerce and Internet retailing continue to alter how firms and individuals interact, enabling greater efficiency in purchases, production processes, and inventory management.[4]

Although the dot-com boom has subsided, the cumulative effect of these innovations is changing the way people work, commute, and consume. Such structural changes will continue to take place as information technology further evolves.

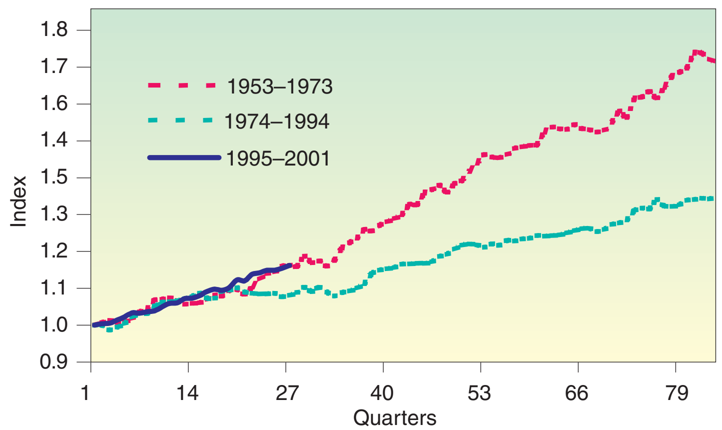

Figure 1. Productivity growth for three periods in recent US history. Productivity between the early 1970s and the early 1990s fell compared to the periods before and after it. (Figure source material courtesy of the US Bureau of Labor Statistics.)

The Semiconductor: Industry's Place in the Economy

The semiconductor industry directly influences the US economy. It is, most notably, a major generator of high-wage jobs, employing 283,875 people in 2000. Moreover, the industry's sales reached US$102 billion in a global market estimated at $204 billion in 2000, and US semiconductor sales averaged 50 percent of total worldwide sales for the past six years (see www.semichips.org/ind_facts.cfm). In 1999, the semiconductor industry was the largest value-added industry in manufacturing in the US—almost five times the size of the iron and steel sector that year. In fact, it is larger in terms of valued added than the iron and steel and motor-vehicle industries combined.

Furthermore, although the manufacturing sector's contribution to US gross domestic product has shrunk (accounting for just under 16 percent of GDP in 2000), semiconductor sales as a percent of output in the manufacturing sector have increased steadily over the past 15 years, climbing from 1.5 percent of manufacturing GDP in 1987 to 6.5 percent in 2000 (see Figure 3).

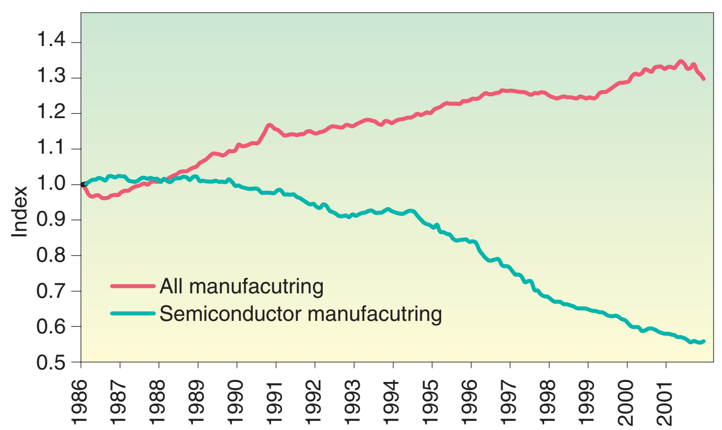

Figure 2. Price comparison between semiconductor manufacturing and all other types of manufacturing. (Figure source material courtesy of the US Bureau of Labor Statistics and the Producer Price Index.)

However, the US semiconductor industry's present robustness shouldn't mask potential challenges to its global position. Significant technical hurdles, rising concerns about the availability of skilled workers, and the entry and growth of increasingly more competitive overseas producers pose new challenges to the US industry's present position.

Technical Challenges

The semiconductor industry's progression is rooted in its underlying technical structure. In 1965, just seven years after the invention of the integrated circuit, Gordon Moore predicted that the number of transistors that would fit on an integrated circuit (or chip) would double every year and tentatively extended his forecast of this growth for "at least 10 years."[5] At that time, the world's most complex chip had 64 transistors.

Moore's extrapolation proved highly accurate in describing the evolution of a chip's transistor density: by 1975, some 65,000 transistors fit on a single chip. More remarkably, Moore's general prediction has held true to the present day, a time in which microcircuits hold hundreds of

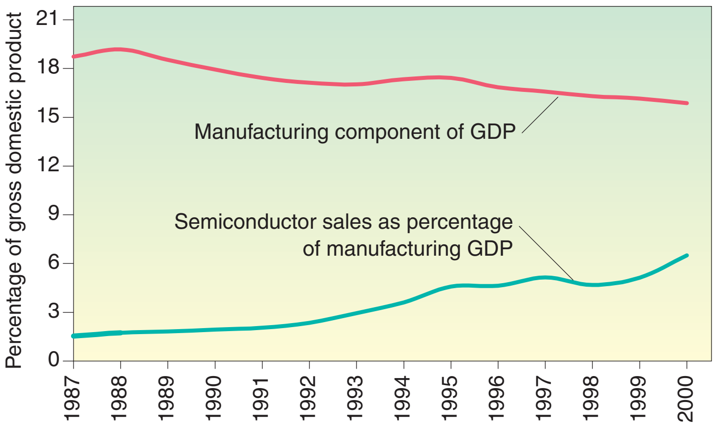

Figure 3. Semiconductor sales as a percent of US manufacturing's gross domestic product. (Figure source material courtesy of National Research Council. Calculations derived from sales data from the Semiconductor Industry Association and GDP data from the US Bureau of Economic Analysis.)

millions of transistors per chip, connected by astonishingly complex patterns.[5]

Beyond its technical accuracy, Moore's law has had other far-reaching implications. Because a commensurate increase in cost did not accompany the doubling in chip density, each transistor's expense halved with each doubling, giving users increased computer processing power at a lower price.[1]

The reduction in semiconductor size, however, could now be approaching critical limits. The consensus in the engineering community is that improvements, both large and small, will continue to uphold Moore's law for another decade or so, even as scaling brings the industry close to the theoretical minimum size of silicon-based circuits.[6]

The industry also faces the challenge of soaring chip-manufacturing costs. When Moore and Robert Noyce founded Intel in 1968, the equipment required to produce semiconductor chips cost roughly US$12,000. Today, a chip-fabricating plant costs billions of dollars, and the expense will continue to rise as chips grow more complex. This trend is disturbing, because as Moore said in a recent interview, "capital costs are rising far faster than revenue."[7] In 2000, for example, average total expenditures for a six-inch equivalent wafer were $3,110—an increase of 117 percent over the average total costs for a six-inch wafer in 1989, a 390 percent increase since 1978.[8] (A wafer is a thinly sliced—less than 1 millimeter—circular piece of silicon material used to make semiconductor devices and integrated circuits.)

The extent to which physical constraints or cost pressures limit the industry's continued growth, however, will necessarily influence the industry's role in stimulating productivity growth in the broader economy.[9]

The Changing Industry

The semiconductor industry is becoming more specialized, meaning that some firms are dedicating their resources to particular points in the production process, especially design and fabrication.

Prominent elements of this emerging industrial structure are the *foundry model* and *design house*. Foundries are state-of-the-art fabrication facilities (sometimes called fabs) increasingly found in the US, Taiwan, and other Asian nations. Foundries produce semiconductors by contract with other companies; they do not design their own lines. Often aided by lower capital costs realized through direct government subsidization or favorable corporate tax structures, well-run foundries, such as those in Taiwan, offer substantial cost savings in producing new generations of chips. The parallel growth of design houses—firms that specialize in designing semiconductors, not in producing them—is yet another sign of specialization in the industry and functions congruently with the foundry model.

These trends reflect, in part, the industry's global scale and rising capital costs as well as the active industrial policies of leading East Asian economies. For example, the governments of Singapore and Malaysia contributed significant public funds and extended tax incentives to companies constructing fabs; Taiwan has approximately 100 design houses, some also supported by the government.[10]

This specialization poses significant challenges to US merchant manufacturers, who have traditionally housed both the design and production functions under one roof. The separation of design and production enhances the capacity of small firms to develop and rapidly produce new products—a potential source of innovation and efficiency.

In any event, US-based integrated producers face increasing challenges from the substantial capacity generated by government-supported fabrication facilities abroad.[11]

The Growth in National Programs

The belief that domestic high-technology industries are fundamental to state-of-the-art defense systems, technological competency, national autonomy, economic growth, and high-value-added employment is widespread among the US's major trading partners.[12] This belief has stimulated increasingly vigorous international competition, especially in those sectors that countries deem to be economically strategic—such as semiconductors.[13] Consequently, many governments have adopted policies to support nationally based firms in the hope of capturing the benefits of the industry for their national economies.

Although growing in scope and scale, such national programs are not new. As Laura Tyson noted in her 1992 study,

> "The semiconductor industry has never been free of the visible hand of government intervention. Competitive advantage in production and trade has been heavily influenced by policy choices, particularly in the United States and Japan. Some of these choices, such as the provision of public support for basic science, R&D, and education in the United States, have had general, not industry-specific objectives. But other choices, such as the provision of secured demand for industry output through military procurement in the United States and through preferential procurement of computers and telecommunications equipment in Japan, have been industry specific in intent and implementation."[14]

National research and development (R&D) programs focus on the semiconductor industry for several reasons. First, as mentioned earlier, semiconductors are an enabling industry—they serve as key inputs to numerous intermediate and final products and services.

Second, the semiconductor industry and its products are key contributors to economic growth. Performance increases and price decreases in semiconductor-based products are a boon not just for consumers; they also make lower-priced, higher-powered investment goods available for all sectors of the economy. Faster and cheaper information technologies, when successfully integrated into the production process, can increase worker productivity. Moreover, increases in semiconductor power drive more rapid advances in a wide range of information technologies.

Third, national programs supporting the semiconductor industry also seek to create high-wage jobs. In contrast, the manufacturing sector as a whole has witnessed a stagnation and slight decline of average pay over the past 30 years (see Figure 4).

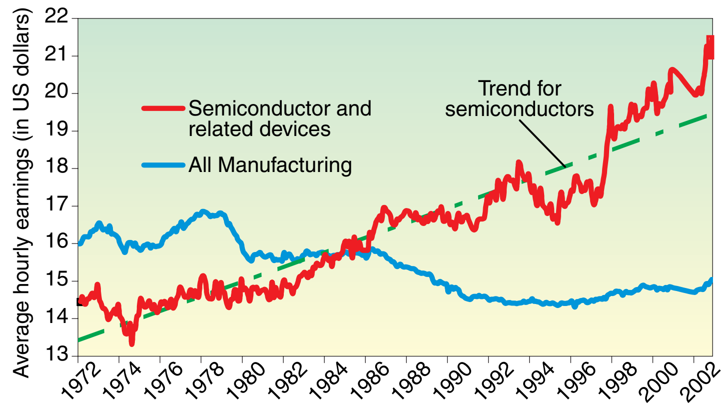

Figure 4. Average wages for workers in manufacturing industries. Between 1972 and 2001, hourly wages steadily declined for all manufacturing industries outside semiconductors. (Figure source material courtesy of the US Bureau of Labor Statistics and the Consumer Price Index.)

Lastly, semiconductors play an increasingly important role in national security. From the original Minuteman II missile to future wireless-network capable systems such as the battlefield-augmented reality system (BARS), semiconductor advances have direct consequences for improving defense against old and new threats.

A supportive policy framework. Although not often appreciated, the US government did in fact play a key role in the semiconductor industry's development, as Laura Tyson suggests, by providing early funding for both military and space-exploration programs. The government's subsequent role in assisting the commercial semiconductor sector, however, has been more controversial and restrained.[15]

This hands-off approach changed as a result of the near-crisis atmosphere in the US semiconductor industry during the mid 1980s. The government took several important steps to support the US industry, which was then under great competitive pressure from Japanese producers. In the 1970s, Japan's Ministry of International Trade and Industry (MITI), had made a systematic effort to promote a vibrant domestic semiconductor industry. Japan's vertically integrated semiconductor industry provided major advantages with respect to the capital-intensive investments required for manufacturing facilities. Japanese firms undertook a massive capacity build-up in the early 1980s, developed superior production techniques (often with the same technologies used by US firms), and used aggressive price cutting to gain market share in DRAMs, which was at that time the worldwide technological leader. As a result, the total DRAM market share of US industry sank from roughly 90 percent in the late 1970s to less than 10 percent by 1985, with many US firms exiting the DRAM market entirely.[16]

A key first step the US took in averting a deeper crisis was the 1986 Semiconductor Trade Agreement with Japan. Rather than closing the US market, this agreement ensured US manufacturers limited access to the Japanese market.[16] It also brought an end to the dumping by Japanese firms in the US and other markets. The next major step was the government's decision to work in partnership with a coalition of private firms to form a research consortium called SEMATECH. The purpose of SEMATECH was to help revive the weakened US industry through collaborative research and pooled manufacturing knowledge. The government provided $100 million a year, fully matched by industry funds.

Most importantly, neither trade nor technology policy can succeed in the absence of adaptable, adequately capitalized, effectively managed, and technologically innovative companies.

A powerful model of recovery. There is no single decisive public policy element in the US semiconductor industry's revival. It is, after all, companies that gain market share, not national programs. Yet, it is also true that a combination of private effort and public–private interactions helped US firms profit from shifts in demand—that is, away from DRAMS (where Japanese skill in precision manufacturing gave significant advantage) and toward microprocessor design and production (where US strengths in software systems and logic design aided the recovery).

We can think of the US industry's recovery as a three-legged stool: it is unlikely that any one factor would have proved sufficient independently. Trade policy, no matter how innovative, could not have met the requirement to improve US product quality. Similarly, even the most effective industry–government R&D consortium can be rendered useless in a market unprotected against dumping. Most importantly, neither trade nor technology policy can succeed in the absence of adaptable, adequately capitalized, effectively managed, and technologically innovative companies.

The US semiconductor industry's recovery has drawn the attention worldwide of policymakers seeking to emulate the model. The partial resolution of dumping (with the notable exception of DRAMs) has shifted the focus of international competition to R&D and regional subsidies. The perceived success of the SEMATECH consortium and the attendant focus on R&D cooperation has also meant that SEMATECH has become a widely imitated model. In some respects, the consortium approach has provided a vehicle for the traditional subsidy of targeted industries, yet it makes these subsidies less objectionable within the trading system—and arguably more effective in generating technical advances.

In short, notwithstanding the technical and human resource challenges and the global semiconductor market's pronounced cyclicality, many governments have increased their support for government–industry partnerships to promote the development of advanced microelectronics technology. As Table 1 shows, others steadily provide substantial incentive to add national industry manufacturing capacity. Some nations are also providing substantial incentives to attract native-born and foreign talent to their national industries to meet what some see as an emerging zero-sum competition for skilled labor.[10] In doing so, some national programs are altering the rules of global economic competition, with policies that differ in important ways from those of the traditional leaders.

New global players. State support for recent market entrants in Korea, Taiwan, and Malaysia has had a major impact on the semiconductor market. Lower capital costs or other incentives can provide significant special competitive advantages in the global market for semiconductors and other high-technology products.[12] Yet, there are other long-term trends. The emergence of China's growing and increasingly skilled workforce should generate significant competition, especially as technology and skills from Taiwan shift to the mainland.[17] At present, China accounts for roughly 1 percent of the world semiconductor market, but the country plans to add much new

Table 1. National programs that support the semiconductor industry.

Country	Project	Period of project	Level of funding (in US$)	Purpose
Japan	Next Generation Semiconductor R&D Center	2001–08	300 million (60 million in 2001)	Process and device technology for 70-mm generation
Japan	Future Information Society Creation Laboratory	2001–06	300 million	Small-scale, very short-term semiconductor production line
Japan	ASET	1995–	500 million	Lithography; semiconductor manufacturing technology
Japan	Nanotechnology Programs	1985–	350 million in FY 2001	Basic R&D nanotechnology including microelectronics themes
Taiwan	Astro	2000–	Government will fund half	Technology induction; upgrading of local industry
European Union	Medea	1997–2000	720 million (est.)	Process technology, design, and applications
European Union	Medea Plus	2001–09	1.350 billion (est.)	Systems on a chip, UV lithography
Germany	Semiconductor 300	1996–2000	680 million	300-mm wafer technology
France	Crolles I and II	1998–	136 million (est.)	Pilot 300-mm fab
US	MARCO	1997–	75 million over six years	Basic microelectronics R&D
US	National Nanotechnology Initiative	2000–	270 million in 2000	Basic R&D on nanotechnology including microelectronics themes
US	DARPA	Permanent	192 million in 2000 for advanced electronics technology	Advanced lithography, nanomechanisms, and electronic modules

capacity soon, as do other East Asian producers.[18] In Shanghai, for example, two new fabrication plants are under construction, another two are on the drawing board, and more than a dozen more are in the early planning stages.

Even during recent economic downturns, the semiconductor industry continues to grow throughout Asia. Malaysia has opened a US$1.7 billion wafer fab and plans to construct two more. In Taiwan, planners in mid 2000 envisioned a total of 21 new 300-mm fabs and nine new 200-mm fabs by 2010. Singapore's government has publicly set a goal of building 20 fabs by 2005. In South Korea, the government has worked with commercial banks to help finance the costs (and losses) of chip manufacturing by the country's family-controlled conglomerates.[10]

Markets are changing rapidly as well. Future market growth for semiconductors may not focus on areas where US manufacturers traditionally have been strong. Industry leaders in both Europe and Japan see the main semiconductor growth markets of the 21st century in the wireless, wired telecommunications, and digital home appliances sectors.[10] By contrast, US companies continue to dominate computer applications of semiconductors, in particular, personal computers, whose growth prospects could prove to be more limited in the future.[19] At the same time, major US design houses have shown great success in bringing new products to market.

Pronounced Shifts in R&D

All these challenges underscore the need for talented individuals—"architects" of the future—to devise new solutions. Unfortunately, the need is growing as the pool of available qualified labor is shrinking.[20]

Historically, the US government has supported human resources by funding basic research at universities. In this system, research grants to principal investigators are used to train graduate and postdoctoral students. The global semiconductor industry's uneven growth, however, has created wide swings in demand for skilled engineers, scientists, and technicians.

In recent years, federal funding for university research has regained a positive growth trajectory, with major increases in biomedical research. Yet, federal funding declined steeply in

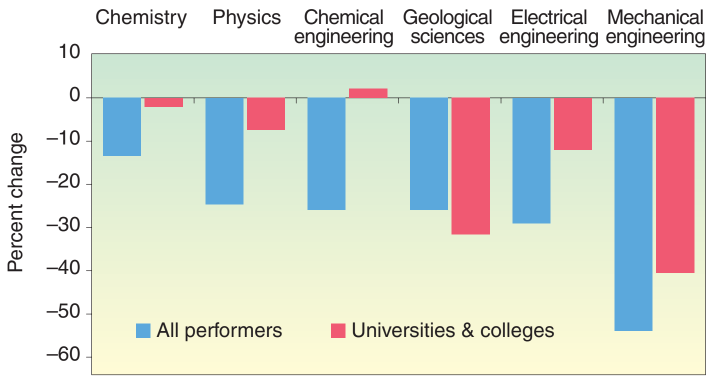

Figure 5. Real changes in federal obligations for research in fiscal years 1993 through 1999.

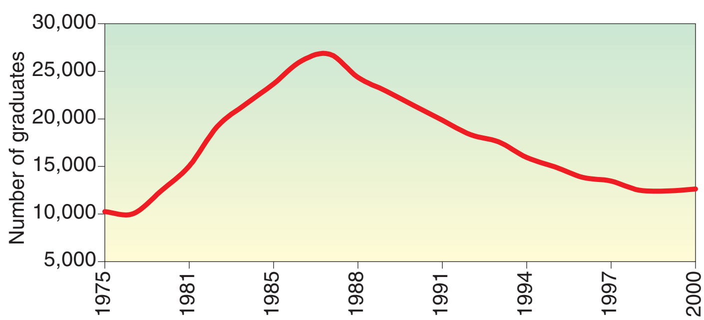

Figure 6. Electrical engineering graduates.

mathematics, physics, and engineering throughout the 1990s (see Figure 5).[21] These swings in demand and declines in funding have led, arguably, to a falloff in US production of engineers and graduates in disciplines such as chemistry and physics as fewer students are attracted to these fields.[20]

For more than a decade, US graduate schools depended on large numbers of foreign-born students and faculty to staff their laboratories and teach their programs. The US continues to attract foreign students as well as scientists and engineers who want to study, live, and work here. Increasingly, though, this group of highly skilled workers encounters significant inducements to return home.[10] The number of US students planning careers in science and engineering does not appear sufficient to take their place.[22]

One of the more disconcerting trends, from the US perspective, is that the number of individuals graduating from US universities with electrical engineering degrees has been declining since the mid 1980s (see Figure 6). In 1988, approximately 24,000 students graduated from US universities with BS degrees in electrical and electronic engineering. By 1997, this total had fallen below 14,000—a number not forecast to increase significantly in the near future.

This period witnessed other major developments in engineering schools, including new programs in computer science, which drew some students away from electrical engineering. Also, new advances in design methods over that period changed the way in which many problems in engineering were cast, requiring new engineering skills and competences. These developments notwithstanding, the drop-off in the number of electrical engineering graduates is disturbing, particularly in light of some estimates that put the production of scientists and engineers in China at about 465,000 per year.[23]

In the sheer production of engineers, the US lags current and future competitors in the microelectronics industry. Japan now produces about 63 percent more engineers per year.[24] Asia, as a region, produces more engineers per year than the US by almost a factor of six, whereas the European Union produces more than double the US output of engineers.[25]

These figures indicate broad trends and make no qualitative assessment. They also reflect, at least in some cases, the national priorities of countries willing to master the modern economy's technical requirements. Still, the disparities in the education of engineers are striking. Perhaps more of a cause for concern is that the declines in training for US students in these fields are not based on estimates of national need. Instead, they are the unplanned aggregate result of reallocations of resources by federal agencies, often resulting from post Cold War mission adjustments.

From the US perspective, the relative ability to address future technical and structural challenges must be measured against the growth in foreign national programs. Given that the increases in productivity observed since 1995 have been associated with increases in semiconductor power characterized by Moore's law, a continuation of productivity increases could well depend on the ongoing benefits associated with the process of "scaling" in microelectronics.

In addition to predicting the pace of semiconductor technology advances, Moore's law also describes more broadly a set of expectations held by industry participants about the pace of competition. That is, each firm in the industry expects its rivals to develop and market a faster and cheaper product within the timeframe set by Moore's law. This expectation makes Moore's law a self-fulfilling prophecy. A shortage of engineering talent needed by firms in the industry to maintain this level of competitive vigor could thus pose a bottleneck in addition to technical challenges such as scaling.

Given the semiconductor's contribution to the economy and the fundamental technical and structural challenges facing the industry, US policymakers might need to rethink their support for the funding and research that underpins the US semiconductor industry.

First, US policymakers need to recognize the great benefits the country receives from a robust and internationally competitive semiconductor industry. Importantly, much of the US defense posture relies on semiconductors and related technologies—communications equipment, remote sensors, and smart weapons to name a few—all of which are made possible through the development and integration of information technologies. Essentially, US policymakers must consider these strategic benefits as well as the dynamic effects on the economy in formulating policies to support a US-based semiconductor industry.

Other countries have recognized the benefits offered by the semiconductor industry and have taken a series of steps to obtain them for their national economies. This has led to the substantial scale and continued growth in national and regional programs overseas. At this time, the US has no comparable national effort since its participation in SEMATECH in the early 1990s. Numerous steps, short of a formal partnership, could help.

Third, US policymakers should, at the very least, consider how to reverse the disturbing decline in public support for the basic research on which the industry ultimately depends. Encouraging partnerships among universities, industry, and national laboratories could help address the need for basic research in the disciplines related to the semiconductor industry. The government could, for example, contribute substantial federal matching funds to proven industry-funded programs such as the Semiconductor Research Corporation's MARCO program of university-led research. Moreover, US government entities other than DARPA could be encouraged to collaborate with the industry to jointly fund expanded research programs.

Finally, any US national effort to support R&D in the semiconductor industry does not diminish the need for international cooperation to meet common challenges. The nature of the technical challenges, the desire to share the costs and risks of heavy R&D expenditures, and the need to develop common standards all argue powerfully for international cooperation, such as that fostered by what is now International SEMATECH for the development of next-generation technologies.[26] Cooperation works best when all parties have vigorous research programs underway and can make comparable contributions.[12]

Essentially, US policymakers must consider these strategic benefits as well as the dynamic effects on the economy in formulating policies to support a US-based semiconductor industry.

Acknowledgments

The views presented here are my own and do not necessarily reflect the views of the US National Academies. I thank Adam K. Korobow, recently of the Board on Science, Technology, and Economic Policy's staff, for his many important contributions to this article and Thomas Howell of Dewey Ballantine for his original contributions concerning national technology programs to support the semiconductor industry.

References

1. D. Jorgenson, "Information Technology and the U.S. Economy," *The American Economic Rev.*, vol. 19, no. 1, 2001, pp. 1–32.
2. D. Jorgenson and K. Stiroh, "Raising the Speed Limit: U.S. Economic Growth in the Information Age," *Brookings Papers on Economic Activity*, vol. 1, no. 1, 2000, pp. 125–211.
3. S. Oliner and D. Sichel, "The Resurgence of Growth in the Late 1990s: Is Information Technology the Story?" *J. Economic Perspectives*, vol. 14, no. 4, 2000.
4. B. Martin and Z. Wahhaj, "The Shocking Economic Impact of B2B," *Global Economic Paper 37*, Goldman Sachs, 3 Feb. 2000.
5. G.E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, vol. 38, no. 8, 1965.
6. B. Doering, "Physical Limits of Silicon CMOS and Semiconductor Roadmap Predictions," to be published in *Productivity and Cyclicality in Semiconductors: Trends, Implications, and Questions*, C.

Wessner, ed., Nat'l Academy Press.

7. C.C. Mann, "The End of Moore's Law?" *Technology Rev.*, May/June 2000, www.imakenews.com/techreview/e_article000003598.cfm.
8. *2001 Ann. Databook: Rev. Global and U.S. Semiconductor Competitive Trends, 1978–2000*, Semiconductor Industry Assoc., 2001.
9. G. Scalise, *Productivity and Cyclicality in the Semiconductor Industry*, Nat'l Academy Press, 2001.
10. T. Howell, "Competing Programs: Government Support for Microelectronics," *Regional and Nat'l Programs to Support the Semiconductor Industry,* to be published by the Nat'l Academy Press, 2002.
11. "The Great Chip Glut," *The Economist*, 11 Aug. 2001.
12. Nat'l Research Council, *Conflict and Cooperation in National Competition for High-Technology Industry*, Nat'l Academy Press, 1996.
13. A. Wolff et al., eds., *Conflict Among Nations: Trade Policies in the 1990s*, Westview Press, 1992, p. 528.
14. L.D. Tyson, *Who's Bashing Whom?* Inst. for Int'l Economics, 1992, p. 85.
15. K. Flamm, *Mismanaged Trade? Strategic Policy and the Semiconductor Industry*, Brookings Institution Press, 1996.
16. L. Tyson, "Managing Trade and Competition in the Semiconductor Industry," *Who's Bashing Whom?* Inst. for Int'l Economics, 1992, pp. 85–113.
17. K. Bradsher, "Taiwan Is Trying to Limit Its Engineers' Work in China," *The New York Times*, 26 Apr. 2002.
18. G. Johnson, "Is China's Semiconductor Industry Market Worth the Risk for Multinationals? Definitely!" *Cahners In Stat Group*, 29 Mar. 1999, www.instat.com/insights/semi/1999/china42999.htm.
19. "From Stagnation to Growth: The Push to Strengthen Design," *Nikkei Microdevices*, Jan. 2001.
20. Nat'l Research Council, *Capitalizing on New Needs and New Opportunities: Government-Industry Partnerships in Biotechnology and Information Technologies*, Nat'l Academy Press, 2002.
21. Nat'l Research Council, Trends in Federal Support of Research and Graduate Education, S.A. Merrill, ed., Nat'l Academy Press, 2001.
22. J. Kelly, "Three Critical Needs," to be published in *Regional and National Programs to Support the Semiconductor Industry*, C. Wessner, ed., Nat'l Academy Press.
23. "High Tech in China," *Business Week*, 28 Oct. 2002, p. 80.
24. Nat'l Science Foundation, *Science and Engineering Indicators 2000*, Nat'l Academy Press, 2000.
25. M.L. Good, "Scientist's Call to Action: S.F. Conference Opens with Plea for Cabinet Position," *San Francisco Chronicle*, 16 Feb. 2001.
26. D.A. Irwin and P.J. Klenow, "Learning-by-Doing: Spillovers in the Semiconductor Industry," *J. Political Economy*, vol. 102, no. 6, 1994, pp. 1200–1227.

Charles Wessner is the director of the National Academies Program on Technology and Innovation with the Board on Science, Technology, and Economic Policy. Contact him at cwessner@nas.edu.