REPORT TO THE PRESIDENT

Ensuring Long-Term U.S. Leadership in Semiconductors

Executive Office of the President

President's Council of Advisors on Science and Technology

January 2017

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EXECUTIVE OFFICE OF THE PRESIDENT
PRESIDENT'S COUNCIL OF ADVISORS ON SCIENCE AND TECHNOLOGY
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President Barack Obama
The White House
Washington, DC 20502

Dear Mr. President:

This letter transmits a report entitled *Ensuring Long-Term U.S. Leadership in Semiconductors*, prepared by a working group of technology industry leaders, eminent researchers, and former policymakers. The President's Council of Advisors on Science and Technology (PCAST) has reviewed and adopted the report. The report assesses the challenges and opportunities facing semiconductor innovation, competitiveness, and security, and outlines recommendations for action to address them.

Semiconductors are essential to modern life. Progress in semiconductors has opened up new frontiers for devices and services that use them, creating new businesses and industries, and bringing massive benefits to American workers and consumers as well as to the global economy. Cutting-edge semiconductor technology is also critical to defense systems and U.S. military strength, and the pervasiveness of semiconductors makes their integrity important to mitigating cybersecurity risk.

Today, U.S. semiconductor innovation, competitiveness, and integrity face major challenges. Semiconductor innovation is already slowing as industry faces fundamental technological limits and rapidly evolving markets. Now a concerted push by China to reshape the market in its favor, using industrial policies backed by over one hundred billion dollars in government-directed funds, threatens the competitiveness of U.S. industry and the national and global benefits it brings. The report looks at these challenges in greater detail.

The core finding of the report is this: only by continuing to innovate at the cutting edge will the United States be able to mitigate the threat posed by Chinese industrial policy and strengthen the U.S. economy. Thus, the report recommends and elaborates on a three pillar strategy to (i) push back against innovation-inhibiting Chinese industrial policy, (ii) improve the business environment for U.S.-based semiconductor producers, and (iii) help catalyze transformative semiconductor innovation over the next decade. Delivering on this strategy will require cooperation among government, industry, and academia to be maximally effective.

Sincerely,

John P. Holdren
Co-Chair

Eric S. Lander
Co-Chair

Table of Contents

Executive Summary

Semiconductors are essential to modern life. Progress in semiconductors has opened up new frontiers for devices and services that use them, creating new businesses and industries, and bringing massive benefits to American workers and consumers as well as to the global economy. Cutting-edge semiconductor technology is also critical to defense systems and U.S. military strength, and the pervasiveness of semiconductors makes their integrity important to mitigating cybersecurity risk.

U.S. semiconductor innovation, competitiveness, and integrity face major challenges. Semiconductor innovation is already slowing as industry faces fundamental technological limits and rapidly evolving markets. Now a concerted push by China to reshape the market in its favor, using industrial policies backed by over one hundred billion dollars in government-directed funds, threatens the competitiveness of U.S. industry and the national and global benefits it brings.

The global semiconductor market has never been a completely free market: it is founded on science that historically has been driven, in substantial part, by government and academia; segments of it are restricted in various ways as a result of national-security and defense imperatives; and it is frequently the focus of national industrial policies. Market forces play a central and critical role. But any presumption by U.S. policymakers that existing market forces alone will yield optimal outcomes – particularly when faced with substantial industrial policies from other countries – is unwarranted. In order to realize the opportunities that semiconductors present and to effectively mitigate major risks, U.S. policy must respond to the challenges now at hand.

Our core finding is this: the United States will only succeed in mitigating the dangers posed by Chinese industrial policy if it innovates faster. Policy can, in principle, slow the diffusion of technology, but it cannot stop the spread. And, as U.S. innovators face technological headwinds, other countries' quest to catch up will only become easier. The only way to retain leadership is to outpace the competition.

That does not mean that the U.S. government should be silent or passive in the face of Chinese industrial policies. We found that Chinese policies are distorting markets in ways that undermine innovation, subtract from U.S. market share, and put U.S. national security at risk. While stepping up the pace of innovation, the United States should also act in the short term to try to reduce this market-distorting behavior and its impacts. Our recommendations therefore focus on three approaches. First, the United States should attempt to influence Chinese behavior by working to improve transparency around Chinese policy through discussions in bilateral and multilateral forums, joining with allies to coordinate and strengthen inward investment security and export controls, and responding firmly and consistently to Chinese violations of international agreements. The United States also should calibrate its application of national-security controls in response to Chinese industrial policy aimed at undermining U.S. security.

Second, we find that a competitive domestic industry is critical to innovation and security. We therefore recommend policies aimed at developing and attracting talent, funding basic research and development that is critical to innovation, reforming corporate tax laws, and reforming permitting practices.

As noted above, however, a level playing field and a strong business environment are necessary but not sufficient. Our final set of recommendations focuses on driving transformative innovation. We propose a series of "moonshots"—such as developing game-changing biodefense systems and cutting-edge medical technologies—that have independent merit and would, if achieved, also deliver radical semiconductor advances of much broader applicability.

Delivering on such transformative innovation, as on our other recommendations, will require strong cooperation among government, industry, and academia to be maximally effective.

1. Challenges and Opportunities

Semiconductors are essential to many products used in modern life, from computers, cellular telephones, and solar panels, to medical diagnostics and self-driving cars. Progress in semiconductors has opened up new frontiers for devices and services that use them, creating new businesses and industries and bringing massive benefits to American workers and consumers and to the global economy. Cutting-edge semiconductor technology is also critical to defense systems and U.S. military strength, while the pervasiveness of semiconductors makes their integrity an important factor in shaping cybersecurity risk.

Today, the semiconductor industry faces challenges from technological barriers and rapidly shifting markets—trends that are now compounded by increasingly active Chinese industrial policy (see Box 1. The State of U.S. Industry). U.S. policy should aim to sustain and grow the contributions semiconductor technology makes to the economy and national security by promoting an environment that drives semiconductor innovation while protecting against specific national-security risks. Delivering on these goals requires sustaining a vibrant and competitive domestic semiconductor industry, but it will demand much more than just that.

Industry is a critical part of the semiconductor innovation system. In order to maintain and accelerate innovation in the semiconductor space, it is essential that companies have an open, market-based environment in which they have intellectual-property protection, access to affordable capital, access to leading-edge academic research and pools of well-trained engineers and scientists, and access to large markets. Industry requires an environment in which market power is not misused. This environment can be delivered through strong competition or by government-imposed restraints on abuse.

Innovation will benefit the U.S. economy regardless of where it occurs. Sustaining innovation, however, is far more likely if the United States itself has a robust semiconductor industry (along with a strong research community). The United States, in contrast with some major competitors, provides companies the ingredients necessary to innovate rather than simply cutting costs for existing technologies. Historically, U.S. government-sponsored research and development (R&D) has been essential to driving semiconductor innovation—but that support will be unsustainable if industry is hollowed out.

The innovation spurred by a robust U.S. semiconductor industry also creates a virtuous cycle: by helping U.S. producers stay ahead of competitors, it further strengthens U.S.-based industry, which in turn drives semiconductor innovation. This cycle will be most powerful when U.S.-based industry stays ahead through genuine comparative advantage, building on strong U.S. capital markets, talent, and research institutions. If the United States instead tries to keep its industry ahead by shielding it from legitimate foreign competition, innovation will suffer, ultimately leaving the U.S. industry less competitive and the U.S. economy worse off.

Economic strength is also fundamental to U.S. national security—increasing the urgency of getting the economic part of the semiconductor equation right. The United States faces a distinct set of specific, semiconductor-related national-security challenges. To maintain its advantage, the U.S. military needs access to leading-edge semiconductors that not all potential adversaries have. U.S. government purchasers of semiconductors, including the U.S. military, also need to be able to mitigate risks to their supply chains, with regard both to integrity and availability; moreover, mobile computing, automated vehicles, and the Internet of Things increasingly place similar demands on commercially used semiconductors, as a much broader civilian cybersecurity imperative.

A strong U.S.-based industry can mitigate some of these security concerns but is not a panacea for them. Risks to the integrity of the semiconductor supply chain, while lower when critical items are designed and produced domestically or on the territories of U.S. allies, cannot be assured through domestic manufacturing and design alone and therefore ultimately need to be mitigated through other means (such as integrity standards and testing and greater system resilience), regardless of where production is located. Moreover, if the United States attempted to ensure security by simply restricting the set of producers that was allowed to sell semiconductors to U.S. firms, it would slow innovation by fragmenting markets and reducing competition. The U.S. government and U.S. consumers would be increasingly unable to procure the cutting-edge chips on which the U.S. economy and national security depend.

Box 1. The State of U.S. Industry

U.S.-headquartered firms have the largest share of the global semiconductor market, as measured by revenue, but the semiconductor industry has steadily been globalizing over the last 40 years.

For approximately the past two decades, U.S.-headquartered firms have accounted for half of global semiconductor sales. Other leading firms are based in South Korea, Japan, Taiwan and Europe. No Chinese-headquartered company is in the top twenty.

How U.S.-based companies do business, however, has been changing. U.S.-headquartered semiconductor companies have increasingly moved fabrication facilities abroad or focused on design while contracting out fabrication (the so-called fabless business model). The share of worldwide fabrication capacity located in the United States fell to about 13 percent in 2015, compared to 30 percent in 1990 and 42 percent in 1980, though nearly half of planned global additions are U.S.-company-owned.[1] During the last four decades, the memory business has also largely shifted from the United States to Asia, with notable exceptions for cutting-edge technologies.

U.S. companies still earn the largest share of revenues in a host of critical areas. The United States has a majority of the global market for integrated circuits design and fabrication, which makes up over 80 percent of the global semiconductor market.[2] Within integrated circuits, the United States leads in logic and analog.[3] In particular, the United States has the clear lead in sales of high-end

[1] See: fas.org/sgp/crs/misc/R44544.pdf.
[2] Integrated circuits (ICs) are semiconductor devices (chips) composed of multiple electronic circuits. They are used for most electronic applications in which semiconductors are needed. They include memory, logic, and analog chips. The processor chip in a computer, for example, is an IC.
[3] Logic chips are central processing units (CPUs)—sometimes called microprocessors—that control and carry out computation; analog chips convert continuous signals such as sound or video that are found in the real world into

microprocessors, communication chips for smartphones and devices, and networking components for routers, the Internet, and landline exchanges. The top integrated device manufacturer (combining design and fabrication), the top three fabless companies, the top three Electronic Design Automation (EDA) companies, and two of the top three equipment manufacturers (all by revenue) are U.S.-headquartered.

Evolving Challenges

The global semiconductor market has never been fully free: it is founded on science that historically has been driven, in substantial part, by government and academia; segments of it are restricted in various ways as a result of national security and defense imperatives; and it is frequently the target of national industrial policies. Market forces play a central and critical role. But any presumption by U.S. policymakers that existing market forces alone will yield optimal outcomes – particularly when faced with substantial industrial policies from other countries – is unwarranted. In order to realize the opportunities that semiconductors present and to mitigate major risks effectively, U.S. policy needs to confront challenges from changing technology at the same time as it faces a new and aggressive set of Chinese industrial policies designed to shift the competitive dynamics in the global industry in favor of Chinese production and companies. We now turn to those challenges and threats.

Technology and Markets

The model for semiconductor innovation has long been simple, at least in principle. The semiconductor industry doubled the number of transistors on a chip, and hence performance, roughly every 18–24 months—the so-called "Moore's Law"—while maintaining or reducing cost. This trend has been supported by industry and customers aligned on a simple innovation goal—essentially faster computing—across the value chain and by a consistent, dominant focus on improving speed and density in CMOS technology.[4]

Maintaining this pace now faces two fundamental challenges. Because of physical limits, it is now harder—and will eventually be impossible—to shrink silicon-based transistors further. Progress has already begun to slow: the doubling time for the number of transistors on a chip has increased to roughly 30 months and continues to rise. In addition, as the range of major semiconductor applications has grown from traditional computing to include areas such as mobile devices, automotive advances, and data centers for the cloud, the appropriate emphasis of innovation is shifting and expanding, moving beyond mere processing speed to include progress on energy consumption, "system on a chip" functionality, and other dimensions. In the past, given that companies were largely working towards the same goal—doubling the processing power of chips while reducing or maintaining costs—private and public resources were concentrated on a shared goal. Now, companies are working on a more diverse range of technologies with different goals, making it harder to align strategies and investments across industry.

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digital data used by logic chips. They are used, for example, to convert the sound from a mobile phone into digital signals.

[4] CMOS stands for Complementary Metal-Oxide Semiconductor and has long been the dominant technology for constructing integrated circuits used in microprocessors, microcontrollers, memory chips, and other digital logic circuits.

The semiconductor industry is facing these challenges at a time of rising industry concentration. The top five global semiconductor suppliers now make up nearly 40 percent of the market, up from 32 percent in 2006.[5] Costs are driving this concentration. For example, to meet the technical challenges of speed and miniaturization, new advanced-logic, semiconductor fabrication facilities are expected to cost well over $12 billion in the United States.[6] Similar leading-edge fabrication facilities cost under $5 billion just 5 years ago. This escalation is driven in part by higher equipment costs, weaker economies of scale, and R&D costs associated with fundamental physics challenges. Venture-capital investment in the semiconductor industry has declined sharply, making it difficult for new companies to enter and compete.

High industry concentration has some benefits: firms with little competition can, in some cases, afford to invest more in long-term innovation. But concentration also comes with major risks. High market concentration means less competition—which reduces incentives for companies to lower costs, raise quality, and invest in new products and technology, while making collusion more likely. Higher concentration also raises the stakes for firm location: in the extreme case, if most or all production in an industry becomes controlled by a single non-U.S.-based company, that situation raises the odds that production or sales will be influenced by foreign-industrial or national-security policy to the detriment of U.S. interests. In contrast, in a highly competitive industry with a diverse production and ownership base, efforts by one country to distort markets—whether for economic or geopolitical purposes—are far less likely to have wide-ranging consequences.

Chinese Industrial Policies

Slowing innovation, changing markets, and rising concentration would be significant challenges by themselves. But Chinese industrial policies aimed at achieving a global leadership position in semiconductor design and manufacturing through non-market means, together with the steady growth in Chinese domestic semiconductor consumption, are now compounding those challenges. Chinese competition could, in principle, benefit semiconductor producers and consumers alike. But Chinese industrial policies in this sector, as they are unfolding in practice, pose real threats to semiconductor innovation and U.S. national security.

China's starting position in its quest for semiconductor prowess is well behind that of the United States. Chinese manufacturing of advanced-logic chips is significantly behind the state of the art in the United States, Taiwan, and elsewhere. China has many semiconductor foundry companies, but all are at least one-and-a-half generations behind the state of the art in volume production. In addition, there are currently no domestically-owned memory companies producing at commercial volume in China; all advanced-memory manufacturers in China are foreign-owned. Since the foreign companies have chosen to have no Chinese companies involved as joint venture partners, China is spending significant amounts of capital to develop its own indigenous memory industry. Similarly, China lacks a tier-one semiconductor equipment firm.[7] There is one tier-two semiconductor equipment company in China—

[5] See: technology.ihs.com/553230/preliminary-2015-semiconductor-market-shares and i.cmpnet.com/eetimes/eedesign/2007/chart1_031507.gif.

[6] See: http://semiengineering.com/10nm-fab-watch.

[7] *Tier* one companies are direct suppliers to equipment manufacturers (OEMs). *Tier* two companies are the key suppliers to *tier* one suppliers, without supplying a product directly to OEM companies.

AMEC—that makes manufacturing tools involved in the fabrication of semiconductors. The most likely avenue for Chinese growth will be acquisition of global players (or divisions of them) in the United States, Europe, or Japan; Chinese firms have been increasingly active in the acquisition space. China's brightest spot is its fabless semiconductor industry, which is booming. There are close to 400 companies, many of which are growing. But there is a technological gap between China's fabless semiconductor industry and those of other countries; at this time, most of China's fabless companies are focused on the low-end and mid-range parts of the market. Assuming that these companies continue to grow quickly—as they are making tailored products for the China market—that will provide motivation for foreign-owned fabrication companies to have a presence in China, which in turn may draw foreign-owned equipment makers.

The Chinese government, motivated by economic and national-security goals, has publicly asserted its desire to build a semiconductor industry that is far more advanced than today and less reliant on the rest of the world. After more than a decade of failed attempts to promote its semiconductor industry, in 2014 China promulgated "IC Promotion Guidelines" putting forth a new plan, including revenue targets and technology goals. This plan has been backed by the senior Chinese leaders (including President Xi Jinping according to public reports). One stated aim of Chinese policy is for China to be at an "advanced world-level [semiconductor capability] in all-major segments of the industry by 2030."

China's strategy relies in particular on large-scale spending, including $150 billion in public and state-influenced private funds over a 10-year period, aimed at subsidizing investment and acquisitions as well as purchasing technology. This figure is slightly smaller than the average of $23 billion spent annually on semiconductor mergers and acquisitions (M&A) by all U.S. companies over the past 5 years. Already multiple Chinese-government investments executed by investment firms are enabling this government-directed strategy. Consistent with its industrial-policy tactics in other industries, China also places conditions on access to its market to drive localization and technology transfer, according to public reports.[8] Chinese policy exploits headwinds currently facing semiconductor innovation: if the leading edge is advancing slowly, that makes it easier for China to use industrial policies to get technologically close enough to supplant the innovation leaders economically.

Chinese industrial policy can usefully be divided into two categories: subsidies and zero-sum tactics.

Subsidies

The Chinese government provides a range of subsidies to strengthen domestic production. These subsidies are driven in part by a desire to decrease reliance on foreign suppliers for technologies deemed critical to Chinese national security, and in part by a desire to capture market share for economic reasons. China's subsidies to the semiconductor industry include capital subsidies that encourage foreign companies to locate facilities in China as well as subsidized capital to domestic companies and investment firms to use in the acquisition of foreign companies and technologies. While China's subsidies are largely zero-sum in their impact on foreign semiconductor producers (companies, workers, or both) in the same market segment, they may not be zero-sum to other market participants

[8] See: www.minneapolisfed.org/research/sr/sr486.pdf.

(whether to participants in other parts of the semiconductor supply chain or to users of semiconductors).[9]

In the short run, Chinese subsidies can benefit U.S. consumers and firms that use semiconductors by reducing costs and lowering product prices. In the long run, however, subsidies to incumbent technologies tend to reduce innovation.[10] Depending on the initial state of the market, subsidies can also increase market concentration in China. This can increase national-security risks for the United States and other countries and, to the extent that Chinese policy allows firms to sell below cost of production, raises risks of overcapacity, which threatens direct competitors. Subsidies also, more directly, can erode U.S. market share, damaging industry employment as well as innovation.

Zero-Sum Tactics

China also employs a variety of tactics that are more broadly and unequivocally zero-sum. These are policies that shift business to China while raising, not lowering, costs. These policies are harmful because they hurt otherwise sound businesses without bringing countervailing economy-wide benefits, raise prices for consumers and other businesses that use semiconductors, and can deter innovation. Such policies also can create defense-related national-security risks by accelerating the spread of sensitive technologies. Chinese zero-sum activities include:

- *Forcing or encouraging domestic customers to buy only from Chinese semiconductor suppliers*. China is doing this both explicitly (e.g., in government contracts) and indirectly (e.g., through its proposals to implement "secure and controllable" requirements relating to cybersecurity concerns). Such practices reduce incentives for innovation across the board: non-Chinese companies see smaller markets, while Chinese companies face less competition. Given the size of the domestic Chinese market, these practices could also result in a high concentration of the global market in China over the longer run.
- *Forcing transfer of technology in exchange for access to the Chinese market*. This practice affects innovation by reducing incentives for R&D, including in the United States (since U.S companies sell into and compete with China), and by quickly turning leading-edge technologies into commodities that anyone can produce. It can also increase market concentration in China; conversely, as Chinese market concentration increases, so does China's ability to force technology transfer, creating a vicious cycle.
- *Theft of intellectual property*. This activity affects innovation in a similar manner to forced technology transfers. According to media reports, China steals intellectual property both covertly and overtly. Overt means using inspections for "secure and controllable" technology to gain access to detailed knowledge of semiconductor technologies.[11]

[9] Zero-sum tactics are those where one entity's gain is equivalent to another's loss, where instead of growing overall value, entities are taking from each other.

[10] See: economics.mit.edu/files/8790.

[11] See: www.nytimes.com/2016/05/17/technology/china-quietly-targets-us-tech-companies-in-security-reviews.html.

- *Collusion*. According to media reports, Chinese companies have colluded to lower the value of takeover targets before purchasing them in distressed situations.[12]

These behaviors sometimes violate international agreements but in other cases do not. Actions taken by other countries in response to Chinese industrial policy are described in Box 2.

Responding Strategically

In responding to these challenges, U.S. policymakers should be guided by six principles.

1. Win the race by running faster. There is often a strong temptation to respond to the challenges outlined above by focusing centrally on attempting to slow China down. But, even if that were possible, it would not be desirable. If the United States stays ahead in manufacturing but does not innovate, progress in semiconductors will cease to drive increased living standards or military strength; moreover, China will inevitably advance in semiconductors, even if the United States slows its progress. The most effective path to continued semiconductor leadership would focus centrally on sustaining U.S. innovation.

2. Focus principally on leading-edge semiconductor technology. Leading-edge semiconductor technology is central to economically transformative innovation. It is also critical to sustaining a national-security edge. Away from the leading edge, policymakers should focus sharply on major security risks, including continuity of supply and large violations of international trade and investment rules, rather than on broad leadership across the board in semiconductors.

3. Focus on making the most of U.S. strengths rather than trying to mirror China. The United States and China have very different views about the appropriate relationship between government and the private sector. In the United States, the role of the Federal government in the economy is largely to create the right environment for the private sector to succeed, including by funding pre-competitive innovation and acting as a trusted convener; the U.S. government role is not to allocate capital to particular firms or sectors. China has been far more willing to provide subsidies to mature firms and industries and to sustain that support even if it results in overcapacity and economic losses. The United States has also advocated for open global trade and investment, with some exceptions for national security. This stance has benefited consumers and the global economy. China has gained from global openness but has been less committed to sustaining it—and, in some cases, has worked against it, for example, by limiting or conditioning access to China's market. Now, globally, more countries are questioning the benefits of economic openness—a trend that will shape, and be shaped by, how the United States responds to challenges in the semiconductor arena.

4. Anticipate Chinese responses to U.S. actions. China will not stand still—and, in particular, will likely adjust what it does in response to U.S. policy. This is a particularly acute challenge for those areas in which the U.S. government had its greatest leverage over industry, e.g., U.S. investment review of Chinese companies seeking to buy U.S. companies and U.S. export controls, which are also those

[12] See: www.nytimes.com/2016/09/17/business/dealbook/china-germany-takeover-merger-technology.html.

areas in which U.S. policy changes would be most likely to influence Chinese policy (and Chinese corporate behavior) in turn.

5. Do not reflexively oppose Chinese advances. The U.S interest in promoting an open, competitive global economy, with its attendant economic and security benefits, will often outweigh the benefits of attempting to stop a specific undesirable market-based development, so long as that development is not driven by Chinese policies that breach international rules or accepted standards of fair behavior. At the same time, the U.S. government will need to identify areas in which the diffusion of particular semiconductor technologies, or control of particular companies, poses intolerable national-security risks that cannot be mitigated through steps short of stopping their acquisition and, therefore, should be stopped to the extent possible.

6. Enforce trade and investment rules. The U.S. government should oppose Chinese actions that violate rules of open trade and investment, even if those actions might appear to narrowly benefit the U.S. economy. This opposition should be active, drawing on the full range of tools available to the United States under international agreements, rather than merely rhetorical. It should also be done, in so far as possible, in coordination with other countries to increase effectiveness and reduce the risk of retaliation (see "Responses by Other Countries").

The semiconductor space is complex. As U.S. policymakers craft solutions, they should draw on industry expertise, in order to increase the odds that their policies have the desired impact.

Recommendation 1.1: Create new mechanisms to bring industry expertise to bear on semiconductor policy challenges. As the U.S. government further develops and executes a strategy to sustain semiconductor leadership and drive innovation, it will be important to be able to draw on cutting edge technological and markets expertise from within semiconductor producing and consuming industries. PCAST recommends that the Administration explore several (potentially complementary) options.

> The U.S. government could benefit from a standing committee of industry experts who are engaged on a continuing basis. This could be structured as a Department of Commerce Technical Advisory Committee (TAC), an arrangement that already exists for eight industry areas. It could also be structured as a PCAST subcommittee. It would be critical for committee membership to be broad, including industries that use semiconductors, in order to provide broad insight into how changes in the semiconductor space might affect the broader economy and national security. Regardless of where an advisory committee is housed, its expertise would need to be made available to the broader U.S. government.
>
> The U.S. government could also take steps to make it easier to access industry expertise on an *ad hoc* basis. This could include creating alternative processes to provide temporary security clearances to industry experts, as has been done for some aspects of cybersecurity. It could also include creating legal arrangements that make it possible for the U.S. government to consult responsibly with industry experts on commercially sensitive matters.

Promoting U.S. interests will ultimately require a strong focus on advancing semiconductor innovation. This demands a three-part strategy that pushes back against innovation-inhibiting Chinese industrial policy, improves the business environment for U.S.-based semiconductor producers, and helps catalyze transformative semiconductor innovation over the next decade.

Box 2. Responses by Other Countries

Japan, Korea, Taiwan, and Europe all have prominent roles in the global supply chain for semiconductors. Industries and governments across the world have reacted to Chinese industrial policy (in the semiconductor domain and others). Concern around the semiconductor industry is most pronounced in South Korea and Taiwan, but is also rising in Europe. In response, governments have used their trade rules, tightened their investment rules, and increased funding for semiconductor research and design. Specific responses include:

- **Taiwan** has taken steps to prohibit or heavily restrict Chinese acquisition of Taiwanese semiconductor technology by not approving any mainland Chinese acquisitions of, or investments into, any domestic semiconductor firms. The Taiwanese government has also launched a public-private partnership with industry to co-invest in R&D.
- **South Korea** has tightened its rules that restrict flow of critical semiconductor intellectual property to China. In addition, the South Korean Government and industry have partnered to launch a $175 million semiconductor start-up fund. The government has also created incentive programs to encourage its semiconductor engineering talent not to work for Chinese semiconductor firms.

2. Influencing Chinese Actions

The United States has a range of tools available to respond directly to Chinese activities. These include formal trade agreements, informal trade and investment norms agreed to with foreign countries, and unilateral tools such as scrutiny of acquisitions of potential national security concern by the interagency Committee on Foreign Investment in the United States (CFIUS). The current set of strategies pursued by the Chinese government through its policies brings the effectiveness of these tools, as currently applied, into question, however. The U.S. government should revisit its tools to ensure that they are sufficiently able to protect against actions that may unacceptably harm the country's economic and security interests. This section focuses on three foreign policy efforts that U.S. policymakers should pursue.

Recommendation 2.1: Boost the transparency of global advanced technology policy. Ideally, all countries should pursue fair, market-oriented policies toward the semiconductor industry, with reasonable exceptions for national security. Finding agreement with China around that goal, though, is likely to be difficult if not impossible. The United States therefore should aim to boost transparency around Chinese policy in advanced technology, including semiconductors.

> China is obligated under the World Trade Organization (WTO) Subsidies Agreement to notify other countries of all of its subsidy programs. While China has notified other countries of some semiconductor programs, the U.S. government believes that its subsidy notification is not complete. China also has obligations under the WTO to publish all trade-related legal measures in a single place and make translations available; it does not appear as if China has fully adhered to this obligation; moreover, in November 2016, in the context of the U.S.-China Joint Commission on Commerce and Trade (JCCT), the two countries asserted a joint commitment to a semiconductor industry that "operates in fair, open, and transparent legal and regulatory environments." China stated that its government has never asked for its investment funds to "require compulsory technology or IPR transfer," and the two countries agreed to continue to exchange information related to the sector.
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> Building on these foundations, the U.S. government, in consultation with industry, should identify specific areas where greater transparency could be mutually beneficial, and press for progress there. In doing so, it should be open to increasing transparency around its own activities. The United States should also seek to broaden support for increased transparency, whether by reinforcing it in other U.S.-China dialogues such as the Strategic and Economic Dialogue, multilateral forums such as the G-20 and Asian-Pacific Economic Cooperation (APEC), or new trade agreements that seek to set new, higher standards.

Recommendation 2.2: Reshape the application of national security tools, as appropriate, to deter and respond forcefully to Chinese industrial policies. The U.S. government has focused its semiconductor-related inward investment restrictions, export controls, and government procurement that requires domestic content on national security, rather than narrow economic objectives. It should continue to maintain that focus rather than expand these tools to pursue explicitly economic goals, a step that could easily backfire. That does not mean, though, that the United States should not respond forcefully to Chinese policies that distort the global market by limiting access of U.S. companies and U.S. exports to China's large and growing semiconductor market.

> The U.S. government should start by clarifying the types of measures that it believes are acceptable for protecting national security. (For example, restricting certain defense procurement to firms based in particular countries may be appropriate.) To the extent possible, it should do that in dialogue with China, with both governments agreeing in principle on what is and is not reasonable, much as the two countries have done in the area of cyberattacks. So long as China adheres to these norms, the United States should continue to implement its policies much as it has in the past. If, however, China acts (or continues to act) in ways well outside these bounds—for example through its "secure and controllable" rules for information technology—those actions should affect U.S. policy. One way to respond would be to tie U.S. assessments of the national-security threats posed by particular technology exports, investments, and contracts to Chinese policy. (For example, if China pursues a policy of undermining cutting-edge, defense-critical U.S.-based companies by flooding markets using government support, that should alter U.S. assessments of whether Chinese acquisitions of the capabilities required to do so are acceptable.) The main goal here should be to deter dangerous Chinese actions; this means that the United States will need to be more open and clear about how its investment and export restrictions actually work. If, however, this effort to deter fails, changes in U.S. national security threat assessments will presumably lead to changes in the specific exports and acquisitions allowed by the U.S. government.

Recommendation 2.3: Work with allies to strengthen global export controls and inward investment security. The United States dedicates substantial resources to export controls and inward investment security. The United States should work with like-minded partners to develop common principles (insofar as possible) for acceptable and unacceptable market behavior, and to help build their administrative capacity to effectively implement appropriate controls and pursue needed investigations, since many countries are currently far less capable than the United States in this regard. Led by the Departments of Treasury and Commerce, and by the Intelligence Community, this effort should provide global partners with technical assistance, training, and diplomatic support to identify risks and vulnerabilities and to remediate them.

> On export controls, the Departments of Commerce, Defense, Homeland Security, State, and Treasury work together to target export controls on national security priorities while facilitating legitimate commerce. To oversee investment security, CFIUS, chaired by the Treasury Department, plays a vital role in reviewing certain transactions with important national security implications involving potential foreign control of U.S. businesses.
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> The United States should not, however, carry this burden alone. Unilateral action is increasingly ineffective in a world where the semiconductor industry is globalized (though keeping the United States at the forefront of innovation allows it to retain some ability to be effective unilaterally). At the same time, when it acts unilaterally, the United States often raises suspicions (however ill-founded) among allies that it is motivated by economic-competitiveness concerns, rather than by national security.

3. Creating a More Supportive Business Climate in the United States

A U.S. semiconductor strategy needs to foster a supportive business environment in the United States. We focus here on sustaining a world-class workforce, boosting general-purpose scientific research, enacting prudent business tax reform, and responsibly speeding facility permitting. These are all areas in which U.S. companies, and many policymakers, have long called for action, and the ideas we outline below are largely not new. These policy areas are, however, particularly important to sustaining semiconductor innovation.

Recommendation 3.1: Secure the talent pipeline. Global businesses invest where the talent exists. With technological advances transforming existing facilities and with the growth of the so-called fabless model, the talent needs that are required to continue to drive semiconductor innovation and production are changing. The United States needs to strengthen its home-grown talent and attract talent from around the world.

> Thanks to the efforts of the government, the private sector, and academia, the share of science, technology, engineering, and mathematics (STEM) bachelor's degrees of total bachelor's degrees awarded has grown 12.3 percent since the 2008-2009 academic year. The U.S. government needs to double down on these collaborative efforts, continuing and expanding its investments in STEM education in partnership with the private sector and academia. As PCAST has noted in its 2012 report *Engage to Excel*, the first 2 years of college are the most critical to the recruitment and retention of STEM majors.[13] Ways to lift the Nation's game in this critical phase of STEM education are detailed in that PCAST report.
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> The United States also needs to attract talented scientists and engineers from abroad to live and work in the United States: immigrants play a critical role in U.S. high-tech businesses, 25 percent of which were founded by immigrants and provide jobs to immigrants and U.S.-born residents alike. The U.S. government should pursue steps that attract talented immigrants while expanding opportunity for all Americans. Some examples include giving STEM graduates from accredited U.S. universities fast-tracked, long-term visas; increasing the number of H-1B visas; and/or allowing existing visas to cover an employee's spouse and children.[14]

Recommendation 3.2: Invest in pre-competitive research. Pre-competitive research is essential to continuing to drive innovation in the semiconductor industry and broader economy. For example, recent advances in wide bandgap semiconductors—semiconductors that can withstand certain extreme environments—were originally driven by government-funded basic research, but have recently found widespread, important use in applications including electric vehicle charging and solar power. The U.S.

[13] See: www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-engage-to-excel-final_2-25-12.pdf.
[14] See: www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_future_research_enterprise_20121130.pdf.

government should increase its R&D spending, focusing in particular on collaborative pre-competitive R&D in science and technology areas outside the health sciences (which have received large increases in recent years). We recommend targeting a doubling of Federal non-health R&D spending.

> The semiconductor industry spends roughly 20 percent of sales on R&D; however, this investment is focused on competitive research and product development. A critical role of the U.S. government is to support pre-competitive research, where accelerated innovation would benefit the government, industry, and academia, but no one firm has sufficient incentive to invest alone.
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> Pre-competitive basic research will often not be specific to semiconductors, but rather build a broader foundation for innovation. For example, support for basic science related to carbon nanotubes was never aimed at any one particular application but has now led to advances that applied researchers are translating into cutting edge commercial applications to semiconductors and other technologies. Unfortunately, the U.S. government now spends less on R&D than in the past: as of 2012, it spent approximately 0.7 percent of GDP on R&D, down from 0.8 percent in 2008 and 1.8 percent in the 1960s. In particular, this pre-competitive basic research would fall into non-defense discretionary spending that is at a historic low as a share of Federal budget and continues on a downward trend.

Recommendation 3.3: Enact corporate tax reform. The U.S. tax system penalizes asset-heavy industries by discouraging capital investment. The semiconductor industry—particularly fabrication—is highly capital intensive. To encourage market-driven investment in the United States in the semiconductor industry, the corporate tax system should be reformed to create a more attractive environment for businesses to compete globally, while ensuring that the U.S. tax system as a whole is fair and responsible to all Americans.

> The United States has the highest statutory corporate tax rate, including Federal and State taxes, among the 34 members of the Organization for Economic Co-operation and Development (OECD), yet loopholes, tax expenditures, and tax planning strategies narrow this tax base. As a result, many U.S.-headquartered businesses are disadvantaged relative to foreign and domestic competitors. Comprehensive U.S. tax reform is particularly important for an industry like semiconductor manufacturing, given its capital intensity. The U.S. government should implement the actions that PCAST has previously recommended: (i) recognizing the importance of manufacturing through the tax code; (ii) strengthening R&D tax credits; and (iii) creating an internationally competitive corporate tax system. These recommendations are presented in and elaborated further in the 2012 report on the Advanced Manufacturing Partnership (AMP).

Recommendation 3.4: Responsibly speed facility permitting. Continuing to lead in semiconductors and other research-intensive, high-capital industries requires being constantly able to move beyond the current generation of technology. That, in turn, often requires building next-generation facilities in short time frames. Improving permitting could yield a step change in the pace of U.S. semiconductor foundry innovation.

> The permitting process provides important public benefits, examining projects to determine whether they meet public objectives, including minimizing environmental and community

impact, which companies are not always economically incentivized to do. The combination of the current Federal and state permitting and review processes, however, can be slow, unpredictable, and lacking in transparency.

Within the semiconductor industry, some executives identify current implementation of the Federal Clean Air Act (CAA) as the primary barrier to responsible and timely facility permitting. Under the CAA, two main permitting programs are likely to be relevant to the semiconductor industry: a preconstruction permit and an operating permit.[15] Each of these programs has specific applicability thresholds; however, generally, these permits are issued by State and local air agencies. In most circumstances, for both types of permits, the U.S. Environmental Protection Agency (EPA) has the opportunity to review a draft permit and provide any comments to the State or local permitting authority. For some large projects, the permitting process can take 12–18 months. This can create significant barrier to planning and building new manufacturing capacity in an industry where speed to market can be very important, given the pace of competition and innovation.

To responsibly accelerate facility permitting, we recommend simplifying the existing permitting process for high-technology facilities and carefully providing opportunities for speedier review:

1. The Federal government should review Federal permitting for high-technology facilities to identify important areas where regulations or procedures are redundant with state rules and might therefore be modified or removed. A first step would be for Congress to request that the Government Accountability Office provide an assessment of areas with significant overlap and identify any that have large impacts on semiconductor foundry investment.

2. EPA should create additional “fast track” permitting options and review existing ones to ensure that they are operating as intended. While the Federal government may need to conduct a more thorough review for brand new facilities, “fast track” options could focus on companies building new fabrication facilities at existing sites. States are leading the way here—for example, the State of Oregon has developed a Plant Site Emissions Limit (PSEL) program, which assigns to all facilities in the state an emissions cap that they must operate under for all CAA-covered pollutants. As long as a facility remains under its cap, it can make many types of operational changes, including expansions, without significant oversight by the State or EPA. Indeed the EPA has already adopted provisions similar to the Oregon PSEL program in the Federal New Source Review (NSR) rules as part of a 2002 reform. EPA should consult with industry to verify that these reforms are functioning as intended, make modifications as appropriate, and identify additional fast track approaches that might be appropriate.

3. Congress should provide funds to increase staff capacity at EPA and other relevant agencies to handle the permitting process. While some applications need significant review, a major bottleneck in the permitting review process can be insufficient capacity.

[15] See: www.epa.gov/sites/production/files/2015-12/documents/20090925fs.pdf, www.gpo.gov/fdsys/pkg/FR-2009-10-06/pdf/E9-23794.pdf, and www.epa.gov/sites/production/files/2015-09/documents/eval-implementation-experiences-innovative-air-permits.pdf.

4. Developing a "Leapfrog" Strategy for Continuing U.S. Leadership

The United States will not remain a semiconductor leader if it confines its efforts to making it cheaper and easier to build today's semiconductors and opposing damaging Chinese industrial policy. Ultimately, to maintain a strong and globally competitive semiconductor industry, the United States needs an economic and policy environment that fosters innovation and keeps the U.S. industry at the technological frontier.

The United States last faced a major challenge to semiconductor competitiveness and innovation in the 1980s. The U.S. government responded through technology policies that focused on continuous improvement in computing speed based on existing technology fundamentals (which required significant technological innovation). A successful strategy today must be different for the two reasons described in Chapter 1—looming limits to CMOS technology and fundamental shifts in the semiconductor market—that now emphasize other performance dimensions beyond processing speed. Additionally, the diversity of computing systems has blossomed dramatically in the last 30 years, revealing a greater variety of solutions beyond today's CMOS technologies that are capable of whole new paradigms of computing.

These circumstances mean that the role of government will need to be supporting rather than central. Government procurement is only a small part of the semiconductor market—not enough for government to cause a wholesale change to how semiconductor technology is pursued. While total U.S. government spending on all non-defense R&D was $65.9 billion in 2015, the semiconductor industry alone nearly matched this level of R&D spending at $55.4 billion. But U.S. policymakers can help a diffuse set of players in academia, industry, and government laboratories organize around important common goals and support catalytic activities that remove obstacles to fundamental technological and industry progress. This approach lies somewhere between "top-down" and "bottom-up:" government should set ambitious and clear goals, rather than assuming that all progress is equally useful and support only key activities, rather than trying to comprehensively dictate all activities. In short, semiconductor innovation should not be viewed as an independent goal—rather, it must be part of broader innovation in the ways semiconductors are used.

Focus Areas

We recommend that U.S. policymakers carefully select ambitious challenges, which we call "moonshots," as focal points for industry, government, and academic efforts to drive computing and semiconductor innovation forward together. These moonshots are aspirational goals with society-wide benefits—like developing affordable desktop semiconductor fabrication capabilities that could take the place of a billion dollar fabrication facility and allow the production of small batches of structures; using 3D printing at the nanoscale to connect "hard" electronic materials with "soft" biological materials, which could be the foundation of a zero-day bio-threat detection network; or a commercial, gate-based quantum computer to work on large-scale problems.[16] The purpose of selecting a goal is that it will catalyze activity that will accelerate innovation and create new technologies and systems that can then be used more widely. The Apollo program itself—the original moonshot—did just this: it captured the imagination by setting a big, important goal that ultimately drove fundamental technological advances of much broader value.

Our recommended approach to designing the moonshots is driven by the fact that the future of semiconductors and computing lies in innovating along multiple dimensions: new ways of performing calculations (such as non-von Neumann and approximate computing), utilization of materials other than silicon (such as carbon nanotubes and DNA for computation and storage), and novel approaches to integrating semiconductors into the devices we use (such as embedding into fabrics and the Internet of Things). (For further discussion of opportunities for innovation, see Appendix A, particularly Table A1.) This contrasts with the traditional approach associated with Moore's Law of focusing most innovation into regularly doubling the number of transistors on a chip. A focus on innovating along multiple dimensions, many of which are novel, also plays to capabilities where the U.S.-based innovators are particularly strong. The specific moonshots are therefore crafted with an eye toward capturing the imagination and driving innovation along multiple dimensions, which should attract a wide range of players.

Government should loosely coordinate industry, government, and academic efforts around solving these moonshots, with an aim to drive innovation with broader payoffs. Government will also almost certainly need to back these efforts with significant, catalytic funding to overcome the risks associated with radical innovation. Four principles should guide the design and selection of moonshots to strengthen semiconductor competitiveness and innovation:

1. Applications-driven approach. Policymakers should take an application-driven approach to innovation. This means that each moonshot that policymakers select should be chosen with the goal of motivating progress in one or more semiconductor-enabled applications of significant economic or strategic importance that currently lack adequate technological solutions. Put another

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[16] A zero-day bio-threat detection network is infrastructure to catch undisclosed software vulnerabilities that may enable biological or chemical weapons. A zero-day bio-threat detection network is infrastructure to detect previously unseen biological threats that may result from chemical or biological weapons. A quantum computer is one that runs on qubits, and is the quantum analog of classical computer that runs on classical bits. Similarly, quantum gates are analogous to classical logic gates, which implement Boolean functions, but in the case of quantum computers these quantum gates form quantum circuits which perform the manipulations of the quantum information state.

way, these moonshots should be selected so that the process of attempting to solve them can be expected to yield major general-purpose advances in semiconductor technology and related computing innovation. The R&D should integrate efforts from top-level applications through component technologies. This approach can provide coherence to a sprawling space, is more likely to attract sustained funding and buy-in from the agencies that will ultimately be responsible for carrying the work out, and can motivate individual scientists and engineers to develop new advances. It also reflects the fact that developing such applications can be broadly beneficial to society in ways that are not reflected in profits they generate for those who develop them.

2. Ten-year time horizon. Policymakers should focus on projects where the right technological approach could, in principle, yield a breakthrough solution in less than ten years. This means that this effort will need to focus on strategies to move existing research to market.

3. Compensate for weak industry investment. Key application domains (clusters of applications) can be broken down into those with stronger and weaker interest from industry. Certain areas—like big data analytics, artificial intelligence, and autonomous systems—have strong industry interest, as they are more easily monetized in conjunction with their existing business interests. These are likely to receive adequate funding and industry-led support by companies to develop leapfrog technologies for their own business reasons within ten years. For these domains, the government should simply help accelerate where appropriate, on an *ad hoc* basis, primarily as a funder of foundational research and as an early adopter of these new systems. Other domains—such as advanced materials science, advanced manufacturing, and modeling and simulation—are critical to the U.S. economy and would be widely utilized by industry, but the consuming industries lack the capabilities to build these leading-edge systems as part of their own business strategies. In these cases, in addition to funding research, the government should play a more active role coordinating early purchases and facilitating industry collaborations on moonshots that accelerate progress in these domains to ensure that promising technologies are ultimately commercialized. A table with more detailed examples is included below.

4. Reduce design costs. The cost to design complex integrated circuits is increasing rapidly, stifling the ability to design systems that focus on tailored applications. The Federal government should invest in R&D that makes it as easy to design hardware as software. For example, the government could support the development of tools akin to the modern computer-aided design tools that emerged in the 1980s, with the goal of reducing design costs by one to two orders of magnitude. These tools will also enable the same design to be used for a range of technologies.

Table 1. Examples of key application domains that will benefit from advances in semiconductors.

Strong Industry Interest *(Government Support)*	Weak Industry Interest *(Government Leadership)*
• Big Data Analytics[17] • Artificial Intelligence and Machine Learning[18] • Biotechnologies, Human Health Technologies[19] • Robotics, Autonomous Systems[20] • Telepresence, Virtual Reality, Mixed Reality[21] • Machine Vision[22] • Speech Recognition and Synthesis[23] • Nanoscale Systems and Manufacturing[24] • Ultra-High Performance Wireless[25] • Holistic Secure Systems[26]	• Computational Chemistry[27] • Advanced Materials Science and Manufacturing[28] • Modeling and Simulation[29] • Space Technologies[30]

Recommendation 4.1: Execute moonshot challenges. The National Science and Technology Council (NSTC) should form a Subcommittee on Semiconductor Moonshots under its Committee on Technology to coordinate the selection, development, and execution of moonshot challenges. The membership should include officials from the Executive Office of the President (National Economic Council, Office of

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[17] Big Data Analytics: Local real-time data analysis and visualization enabled by advances in security, low-power computation, and processor specialization.

[18] Artificial Intelligence and Machine Learning: Supervised and unsupervised machine learning enabled by new processors, including low-power processers, graphics processing units, and quantum computers.

[19] Biotechnologies, Human Health Technologies: Medical implants that are capable of ultra-low power processing, communications, and wireless charging.

[20] Robotics, Autonomous Systems: Speech and image recognition for mobile computing.

[21] Telepresence, Virtual Reality, Mixed Reality: Local real-time sensory input, such as video and graphics.

[22] Machine Vision: Imaging-based automatic inspection and analysis for applications such as process control and robot guidance.

[23] Speech Recognition and Synthesis: Portable systems enabling recognition and artificial production of human speech.

[24] Nanoscale Systems and Manufacturing: Democratized, small-batch fabrication structures at the nanoscale using a variety of material classes. For example, point-of-use nanoscale 3D Printers may provide desktop-sized fabrication capabilities for rapid prototyping novel interfaces between traditional “hard” electronic materials and “soft” biological materials.

[25] Ultra-High Performance Wireless: Wireless systems with very low latency and extremely reliable communications, for example, between autonomous vehicles.

[26] Holistic Secure Systems: hardware-based defense in-depth, such as tamper resistant hardware that electronically authenticates software integrity.

[27] Computational Chemistry: Design of novel solutions for catalysis, low-temperature nitrogen fixation, etc.

[28] Advanced Materials Science and Manufacturing: Simulation of solid state materials, etc.

[29] Modeling and Simulation: Efficient exascale computing to enable advanced earthquake prediction (CMOS-based high-performance computing capable of 1-10 exaflops), high-fidelity weather modeling (superconducting-based hyperscale computing capable of 10-100 exaflops), and optimization problems (quantum computing).

[30] Space Technologies: radiation hardness through circuit design and technologies (e.g., wide-bandgap electronics) rather than special manufacturing processes (e.g., insulating substrates or shielding).

Science and Technology Policy, National Security Council) and relevant Agencies (Department of Defense, Department of Commerce, Department of Energy, Department of Health and Human Services, Department of Transportation, Department of Homeland Security, National Science Foundation).

> This interagency group would coordinate the selection and prioritization of the moonshots across the U.S. government. For each moonshot, the group would identify: (i) a lead agency to host the moonshot, (ii) the resources required for achieving the moonshot, and (iii) the timeline for execution. The group should focus on moonshots that have common commercial and U.S. government interests. In each case, the moonshot should be chosen remembering that the goal is to drive advances in systems and component technologies that not only solve the particular problem, but also provide a general capability that can be subsequently used to address other problems without completely new breakthroughs.
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> In addition, for each moonshot, an advisory group across industry, government, and academia should be established. The purpose of this group would be to help identify the right people and resources to address the moonshot. The group would help identify companies and people to engage, determine sources of funding and other resources, and provide additional feedback and support to the lead agency throughout the process. A similar approach was used by the National Nanotechnology Initiative to launch a Grand Challenge for Future Computing.[31]
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> The Subcommittee, along with the lead agency, would determine the appropriate government tools for achieving the moonshot. A standard approach is government acquisition, where agencies contract mission-relevant products or services, and the contractor performs applied research and development to bridge the gap between off-the-shelf products and the mission requirements. In many cases, the technologies developed to meet the mission requirements are also valued by other agencies and the commercial marketplace. While the development of new technologies is often incidental to product acquisition, new methods are emerging that explicitly recognize technology development. For example, the "progress payment" model specifies incremental payments when technical milestones are reached, which may be beneficial for semiconductor-related technology development. For several additional ideas, see Box 3. Tools to Reach Moonshots.

The following three examples of moonshots show further how such an effort could catalyze semiconductor innovation. These examples illustrate the integration and application of the guiding principles, and have been developed with the goals of capturing the imagination, motivating ambition, and catalyzing innovation along multiple dimensions. They are offered as examples and starting points for discussion and debate—including over the feasibility of executing the moonshots within the next decade—and for creative thinking about additional moonshots.

1. <u>Development of a zero day bio-threat detection network</u>, which would identify previously unknown threats (for example, some unexpected types of biological or chemical agents). This would require innovation in the following areas: (i) design of advanced and low-cost bio-sensors, (ii) real-time data

[31] The goal of the Grand Challenge is to "create a new type of computer that can proactively interpret and learn from data, solve unfamiliar problems using what it has learned, and operate with the energy efficiency of the human brain."

analytics based on classic and machine learning algorithms to detect threats and anomalies, (iii) ultra-secure and encrypted communications including methods such as post-quantum cryptography, and (iv) real-time communications through this sensor network for rapid dissemination of threat information.[32] This effort could be sponsored by Department of Homeland Security (DHS) (lead agency), National Institutes of Health (NIH), and Defense Advanced Research Projects Agency (DARPA). The challenge could involve engaging with established and startup companies through prizes and procurements of products for both domestic and battlefield monitoring of bio-threats. While the ability to identify all zero-day bio-threats is unlikely to be achievable in the next ten years, that should not deter innovators from driving toward transformative progress on that problem. The technologies developed here could ultimately be applied more broadly in healthcare, battlefield sensing and communications, and population health surveillance activities.

2. Development of a high efficiency, domain-focused architecture to produce a system for 1-kilometer-resolution Global Weather Forecasting that consumes less than 5 megawatts (i.e., has unusually low power needs); is not CMOS-based; includes non-Von Neumann computing elements that allow for parallel processing (non-von Neumann architectures) and/or approximate computing methods; and can be designed and programmed using high-level programming models.[33] (Prescribing a set of technological solutions here would help ensure that this effort yields more broadly valuable advances. Recall that the goal is to yield innovative, generally reusable component technologies and systems, and not a hard-coded machine to do weather forecasting.) This could be sponsored by the National Oceanic and Atmospheric Administration (NOAA) (lead agency), Department of Energy (DOE), and Department of Defense (DOD). The challenge could involve engaging with Federally Funded Research and Development Centers (FFRDCs) and National Labs along with university and corporate teams to design competitions with prizes and subsequent procurement with progress payments to actually deploy the winning concept. This project would have many potential benefits, both as a result of fine-grained weather event forecasting globally, but also the ability to deploy this regionally and perhaps even aboard ships in a reduced capability way. New programming architectures developed here could also be applied to other important problems, potentially reducing cost, power and time-to-market for those solutions.

3. Development of commercial quantum computers capable of handling computational chemistry and materials science problems needed to develop and deploy a pilot version of a high-scale, zero-carbon, cost-competitive energy system to power a large government base or National Lab.[34] This work could be sponsored by DOE (lead agency) and DOD and build on existing interagency efforts,

[32] Post-quantum cryptography covers methods that are secure against attack by a quantum computer.

[33] Non-Von Neumann computing elements are computing elements that allow for data-driven parallel processing; Existing efforts should build on prior work, including: www.dhs.gov/health-threats-resilience-division, www.dhs.gov/biowatch-program; www.dtra.mil/Research/Chemical-Biological-Technologies; and www.dtra.mil/Portals/61/Documents/CB/BSVE%20Fact%20Sheet_04282015_PA%20Cleared.pdf.

[34] Such a quantum computer should be gate-based (i.e., have a quantum analog for the classical logic gate in a conventional digital circuit), providing for the general purpose programming of quantum circuits to implement arbitrary algorithms. The physical qubits (the quantum analog of the classical bit, which tend to have impractically short lifetimes) could have various constructions, but after error correction should provide a minimum of 100 logical qubits and grow exponentially larger as the technologies mature.

including the National Strategic Computation Initiative. The challenge could involve engaging with FFRDC and National Labs along with university and corporate teams to design competitions with prizes and subsequent procurement with progress payments to actually deploy the winning concept. Relatively small, commercial quantum computers would be able to solve modeling problems in physical systems that cannot be solved by even the largest traditional computers. The underlying technologies would lead to advances in chemistry and materials that could have broad application across the economy, including in energy storage, generation, transmission, and pollution-related issues This exemplifies the concept of a moonshot in that it is driven by a big problem that matters, and fundamental semiconductor innovations, given that, to the best of our knowledge, these problems cannot readily be solved by current technologies or envisioned extensions of current technologies, . This would also allow the beginning of the process of developing a cadre of technologists and scientists who will lead the world in the challenges associated with using these radically different forms of computation. Quantum computers are also likely to have application in machine learning and artificial intelligence applications.

Box 3. Tools to Reach Moonshots

There are a number of best-practice models that have already been tested within the government and can be used to reach moonshots. While a typical tool used is government procurement, here are four additional tools that could be drawn on:

1. Incentive Prize. An agency could host an incentive prize to encourage teams across industry and academia to solve a moonshot that agency is hosting within a timeframe. The winning team of the incentive prize should be rewarded in a way that allows them to actually deploy the winning concept – such as through funding or a government procurement agreement. This model has been used by many U.S. government agencies to address a wide variety of technology challenges, including to accelerate the development of technologies for self-driving cars, automated cybersecurity, and overcoming spectrum scarcity.
2. U.S. Government Fellowship. Once moonshots are selected, the Subcommittee on Semiconductor Moonshots could bring on two fellows per project—one from industry and one from academia—for 1-2 years to work together on assembling and running a team to tackle the moonshot and on coordinating external resources (such as funding and research).
3. Collaborative Institute. The government could create a collaborative institute that brings together resources from industry, academia, and government. These shared facilities could support a range of activities, including early-stage research, small-batch production and implementation, technology transfer, and loosely coordinated R&D. An example model is the Manufacturing USA Institutes, which the U.S. government developed based on a PCAST recommendation.
4. Industry-Led Venture Capital Consortium. The number of Series A deals for chip-only ventures has been declining over the last 15 years due to the long time to revenue, the relatively large investment required, few IPO successes, and less investment from traditional sources. Industry could increase venture funding by creating a venture consortium that invests collectively in next-generation technologies. If necessary, the U.S. government could make anti-trust exceptions as it did in the 1980s for SEMATECH. The U.S. government could also consider co-investing through organizations such as DARPA and the Advanced Research Projects Agency-Energy (ARPA-E).

5. Conclusion

Semiconductor innovation long has been an engine of U.S. economic prosperity and national security. Today it faces major technological, market, and geopolitical challenges. A concerted effort in partnership among the Federal government, State and local governments, industry, and academia is critical to fully meeting those challenges.

This report has focused mainly on recommendations for the U.S. Federal government; however, important parts of what it proposes—particularly around long-term innovation—can be pursued by industry, non-Federal government, and academia without Federal government involvement, albeit with less success. Our proposal for loose coordination around moonshots, for example, could be led by non-profit consortia that include industry and academic participants if the Federal government chooses not to lead. Federal money, organization, and diplomatic influence can often fill gaps that private efforts will never meet—but, in other cases, leadership from outside government can be just as effective.

That said, we strongly recommend a coordinated Federal effort to influence and respond to Chinese industrial policy, strengthen the U.S. business environment for semiconductor investment, and lead partnerships with industry and academia to advance the boundaries of semiconductor innovation. Doing is essential to sustaining U.S. leadership, advancing the U.S. and global economies, and keeping the Nation secure.

Appendix A. Moonshots – Methodology and Exemplars

This appendix expands the moonshot concept introduced in Recommendation 4.1 in the body of this report. The methodology section provides context for how the moonshots were developed and a roadmap for creating additional moonshots, either industry-led or government-led. The remainder of the appendix provides additional example moonshots.

A.1 Methodology

Each moonshot vertically integrates technologies across the entire compute stack, from the top-level application down to the component technologies, in order to sufficiently nurture transformative ideas and create a more sustainable competitive advantage for the United States. The technology stack has the following traditional layers (from top to bottom):

1. Ultimate Software Application
2. Application Programming Model
3. Platform Software Services
4. Platform Programming Model
5. Operating Systems Services
6. Computer System Architectures (processing, storage, and interconnect at every scale)
7. Component Technologies

Traditional CMOS semiconductor technologies and von Neumann system architectures have dominated system development. This has been driven by the economic and performance implications of Moore's Law, and a robust ecosystem of consistent tools and a large workforce which has developed in support. As performance gains in CMOS semiconductor technologies become more elusive, newer technology options are more compelling than in the past, but the supporting ecosystem is often lacking. Moonshots based on combinations of new technologies can jump start the development of the corresponding ecosystem.

A.1.1 Overall Approach

PCAST's methodology assumes an application-driven approach to fostering innovation. Desired progress in a particular application domain provides concrete goals for a particular moonshot, but the resulting advances in the underlying technologies are almost universally more broadly applicable. Application domains considered by PCAST are summarized in Table 1 in the body of the document. Moonshots are chosen so that at least some experts in the field believe that achieving them within ten years is feasible.

After identifying a promising application domain, PCAST considered potential options for realizing the technology stack described above. They considered options on three distinct dimensions: computing systems architectures, computing modalities, and component technologies (Table A1). Ideally, a moonshot envisions solution which requires a technology stack requiring interdependent innovations along one or more of these axes, and which helps spur innovation beyond the current technology base. The goal is for these moonshots to result in innovations that can be used for other general scientific, engineering, or economically valuable advancements.

A.1.2 Computer System Architectures

- **Von Neumann:** Changes in technology to accommodate post-Moore's Law realities, such as multi-core CPUs with different, complex memory hierarchies, will demand new engineering paradigms across the existing range of traditional Von Neumann architectures for digital computation.
- **Quantum:** Quantum Computing has the potential to substantially advance our compute capabilities and solve currently intractable problems. There are several quantum architectural approaches which may support different strategic domains, and along different timelines. These approaches, in rough order of likely deployment, are: analog quantum simulation; adiabatic quantum annealing; and circuit-based quantum computing.
- **Bio/neuro-inspired (neuromorphic computing)**: Biologically-inspired power consumption and "topology" of the circuitry (using three dimensions, more like the brain), analogous to how radio networks are now designed in the post-Shannon Limit era.
- **Analog computing:** Analog computing approaches predate digital computing and in theory can solve some problems that are intractable on digital computers. In practice, digital computing techniques have overtaken analog computing, but advances in noise minimization could allow solutions in some areas.
- **Special purpose architectures:** Field-programmable gate arrays, graphics processing units, and deep learning/machine learning accelerators, including for edge computing.
- **Approximate Computing:** Performing bounded approximation instead of exact calculations for error-tolerant tasks (such as multimedia processing, machine learning, and signal processing), significantly increasing efficiency and reducing energy consumption.

A.1.3 Computing Modalities

- **Embedded systems**: Specialized semiconductors, ranging from high-volume/low-cost for applications like Internet of Things (IoT) devices to low-volume/high-cost semiconductors for robotics or defense systems. Power efficiency requirements will vary by application (harvesting energy from the ambient environment versus dedicated power sources, respectively). Flexibility and agility in fabrication and design will be needed to maintain profitability.
- **Personal/Portable systems**: Desktop, mobile, and wearable computing devices. These are frequently battery-powered computational devices, which will be optimized for performance, price, and power efficiency. General purpose computing will be augmented by accelerators, sensor add-ons, and other function augmenting ICTs.
- **Hyperscale systems***:* Supercomputing devices for "remote" computation that will be aggregated to form the most powerful systems that can be produced in each architectural class. These systems are expected to solve otherwise intractable problems; or, for classical architectures, to maximize performance within practical power constraints. Emerging architectures providing new capabilities and domain-specific optimizations will become increasingly important as performance increases lag and practical power limits are reached in traditional computing architectures.

Table A1. Selected component technology vectors that have a high probability of deployment in ten years *(* denotes more speculative deployment within this timeframe)*

Component technology vector	Time-frame to first commercial products	Approach to achieving and retaining competitive advantage
Neuromorphic Computing	Available now	Continued R&D into new architectures coupled with 3D technologies and new materials, Deep Learning accelerators (for mobile and data center applications), and applications for true brain-inspired computing
Photonics	Available now	Foundries for tools and materials R&D; integrate photonics with CMOS and other materials
Sensors	Available now	Foundries for tools and materials R&D; integrate new types/classes of sensors with CMOS and other materials
CMOS (sub 7nm node size or new 3D structures)*	Advances in thermal management available with new process nodes	Deep understanding of transistor physics and chipset architecture and related design know-how; foundries and labs for transistor and materials R&D
Magnetics	1-2 years (MRAM as eFlash), 3 years (as DRAM), 5-7 years (as SRAM)	Foundries for tools and materials R&D; integrate magnetics with CMOS and other materials
3D	2-3 years (wafer-to-wafer stacking), 4-5 years (die-to-wafer stacking), 5-7 (Monolithic 3D)	Deep understanding of applications space and benefits associated use of 3D technologies and design know-how; foundries for tools and materials R&D; design automation tool R&D
Data-flow based architectures	3-4 years	Continued architecture R&D, coupled with materials, integration, and manufacturing; build an ecosystem for solutions using data-flow based architectures
Ultra-high performance wireless systems	3 years (5G), 10-12 years (6G)	Continued R&D in new materials and processes, antenna design advances, chipset manufacturing, and integration
Advanced non-volatile memory as SRAM	5+ years	Deep understanding of applications space and chipset architectures
Carbon nanotubes and phase change materials*	5-7 years	Foundries/labs for materials R&D for hardware architectures; chipset designs to leverage these technologies
Biotech/human health	5-10 years	R&D towards low power, highly integrated, high performance processing, high-data rate communications, wireless charging; couple R&D with clinical research to create, build, and evaluate on new materials and interfaces
Quantum Computing	< 10 years	Pre-competitive R&D labs for new materials; foundries for new materials and hardware architectures; tools for quantum algorithms and software programming with various architectural paradigms
Point-of-Use Nanoscale 3D printing	Available now	Desktop fab capabilities for rapid prototyping, additive manufacturing, moving beyond silicon and interfacing with soft matter, and small batch production
DNA for compute and storage*	10+ years	Multi-disciplinary basic research in efficiently and reliably reading and writing and retrieving DNA strands

A.2 Sample Moonshots

A.2.1 Bioelectronics for sensory replacement and implantable neuro-stimulation for control of chronic conditions.

Context: Implantable medical devices are currently used for treatment of a limited set of conditions, such as Parkinson's disease, but their application is limited by size, power consumption, and inefficient electronic-biological interfaces.

Goal: With a concerted effort by the electronics and semiconductor industry, clinicians, surgeons, and neuroscientists, we can develop implantable medical devices for important new classes of conditions, including:

- Restoring sight or hearing to someone with sight or hearing loss by connecting implantable devices for vision and sound to the visual or auditory cortex
- Alleviating chronic conditions, including pain and all auto-immune conditions, with tiny implants and non-invasive surgery

Challenges/Innovation: Achieving these goals would demand simultaneous advances in semiconductor technologies:

- Ultra-miniaturization to enable non-invasive surgery and enable implanting in the brain or on the peripheral nerves
- Enhanced processor performance to enable executing complex algorithms such as those based on machine learning or sophisticated signal processing in the implant
- Ultra-efficient electronics to enable implants powered by energy harvesting or fast and extremely convenient wireless charging (such as through ultrasound)

These advances would need to be paired with application-specific innovations, including:

- Materials for improved neuron/nerve interfaces and power transfer between the electronics and the brain/nervous system
- Advanced robotic surgery and surgical tools, to handle the small implant reliably

Key Government Stakeholders: The National Science Foundation (NSF) and Health and Human Services (HHS). Potential supporting roles for Defense Advanced Research Projects Agency (DARPA), Intelligence Advanced Research Projects Activity (IARPA), and National Institute of Standards and Technology (NIST).

Other Potential Applications: Advances in sensors may support "smart dust" technologies, where microscopic sensors that float in the air record and transmit basic measurements for environmental control or enhanced weather prediction. Enhanced processor performance and efficiency would likely benefit hyperscale systems, which maximize performance within practical power constraints. Advanced materials may also apply to neuro-inspired computing platforms. Advances in robotics will support a broad range of national needs, including advanced manufacturing, logistics, services, transportation, homeland security, defense, medicine, healthcare, space exploration, environmental monitoring, and agriculture.[35]

A.2.2 Threat Detection Network

Context: The technology to develop and deploy biological, chemical, and nuclear threats has become increasingly accessible, but our ability to detect these threats has not kept pace. Smart phones and IoT devices, in combination with cellular service and the Internet, form a vast sensing and communication network that could offer early detection and efficient warning for these threats.[36]

Goal: Develop a high-speed biological, chemical, and/or nuclear threat detection network through deployment of electronic devices that incorporate chemical, bio-chemical, spectral imaging, and radiation sensors in addition to sensors for primary functions, that would cut detection times by an order of magnitude. Benefits would include:

- Early detection of toxic biological, chemical, and/or nuclear materials could facilitate intervention by first responders before deployment and ensure medical personnel are appropriately equipped for an evolving event
- Ubiquitous sensing and robust communications after a nuclear event would facilitate appropriate guidance to the public based on location (e.g., whether to shelter in place, or safest escape routes) reducing casualties from fallout

Challenges/Innovation: Achieving these goals would demand simultaneous advances in semiconductor technologies:

- Advances in special purpose processor design to support real-time data analytics based on classic and machine learning algorithms in edge devices to detect biological threats
- Ultra-Secure cryptographic algorithms to simultaneously authenticate sensor data and protect privacy of device owners

These advances would need to be paired with application-specific innovations, including:

- Design of advanced and low-cost sensors (chemical, biochemical, multi-spectral imaging, and others) that are also easily integrated into devices such as smartphones, automobiles, buildings, security cameras, and other IoT devices
- Real-time communication protocols for rapid dissemination of threat information

Key Government Stakeholders: The Department of Homeland Security (DHS) and NSF. Potential supporting roles for DARPA, IARPA, and NIST.

Other Potential Applications: The sensor advances developed in this moonshot would also contribute to the realization of "smart dust" technologies (see moonshot A.2.1 for details). Advances in special purpose processor design to support real-time data analytics and machine learning in edge devices would offer significant benefits in autonomous systems such as self-driving vehicles.

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[35] See: www.whitehouse.gov/blog/2011/06/24/developing-next-generation-robots.
[36] See: www.darpa.mil/news-events/2016-08-23.

A.2.3 Distributed Electric Grid

Context: Renewable energy offers significant benefits to society, but these sources amplify long standing electrical grid challenges such as balancing demand and supply. Traditional power plants generate power efficiently in a steady state, but are costly to bring on- and off-line. A decentralized power system, where distributed generation meets local demand, or distributed electric grid has the potential to better leverage the complete portfolio of power technologies.

Goal: Through a suite of advances in novel power generation methods and energy storage (e.g., batteries), application of artificial intelligence and machine learning to energy management, standalone energy systems, local energy distribution, and real-time communications protocols, technology advances would accelerate the realization of distributed electrical grid that would:

- Efficiently leverage renewable energy resources, including cost-effective storage when supply exceeds demand
- Rapidly and efficiently add power from storage traditional technologies when renewable energy sources are not available

Challenges/Innovation: Achieving these goals would demand simultaneous advances in semiconductor technologies:

- Advances in special purpose processor design to support real-time data analytics based on classic and machine learning algorithms in edge devices to optimize electrical usage and minimize cost
- Design of advanced power electronics, utilizing wide bandgap semiconductors, for inverters, frequency control and voltage stability

These advances would need to be paired with application-specific innovations, including:

- Energy storage technologies with greater energy density and cost efficiency
- Standalone energy systems with a mix of sources to counter unpredictability of energy generation (and integration of energy generation and consumption with as co-generation and electric vehicle-to-local grid)
- Local energy distribution grid and related communication network

Key Government Stakeholders: The Department of Energy (DOE) and Nuclear Regulatory Commission (NRC). Potential supporting roles in energy management for the Federal Energy Regulatory Commission (FERC) and in semiconductor technology research for NSF, DARPA, IARPA, and NIST.

Other Potential Applications: Advances in special purpose processor design to support real-time data analytics and machine learning in edge devices would offer significant benefits in autonomous systems such as self-driving vehicles. Advanced electronics for inverters, frequency control and voltage stability would likely benefit advanced manufacturing facilities. Advances in energy storage capacity would benefit electric vehicles and a myriad of consumer products.

A.2.4 Global Weather Forecasting

Context: Due to the longstanding success of Moore’s Law, the computing and semiconductor industry are optimized for a world where general purpose microprocessors provide dependable performance increases and cost reductions to von Neumann based applications. As maintaining Moore's Law becomes more difficult, industry must look to new sources for performance increases and cost reduction.

Goal: Develop a global weather forecasting system with a fidelity of 1 km and power consumption less than 5 MW using an innovative, high-efficiency, domain-focused architecture. This level of fidelity would support explicit inclusion of cumulus clouds in weather simulation and modeling. Advances in systems architecture, along with new design methods and tools for hardware and software development, required to field such a system would also offer:

- Alternative component technologies to achieve the performance increases but with much lower power than historically provided by Moore's Law-advances.
- Support innovation through integration of radical computer architecture, and attendant software technologies while retaining the potential for re-use in other applications.

Challenges/Innovation: Achieving these goals would demand simultaneous advances in the following semiconductor technologies:

- Advances in theory and tools for system architects to create domain-focused architectures
- Advances in design tools that reduce the cost and time for hardware design (e.g., special purpose processor design) to parity with software development
- Advances in hardware design tools that enhance portability so that existing weather mode designs and related software algorithms can move to radically new underlying technologies, greatly accelerating our ability to bring new integrated circuit technologies to the market

These advances would need new programming approaches that are less dependent on architecture or hardware but fully leverage the performance of the underlying system

Key Government Stakeholders: The National Oceanographic and Atmospheric Administration (NOAA) and Department of Defense (DOD).

Other Potential Applications: Tools for rapid and portable hardware design will support innovative hardware design for all strategic domains and will accelerate the adoption of emerging integrated circuit technologies. New programming approaches that ease programming of special purpose devices will accelerate their adoption in low cost (e.g., IoT) devices, accelerating a shift to processing in edge devices. New programming approaches that are less dependent upon system architectures would also benefit traditional supercomputing, alleviating workforce shortages and reducing the cost of porting software to successive generations of systems.

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