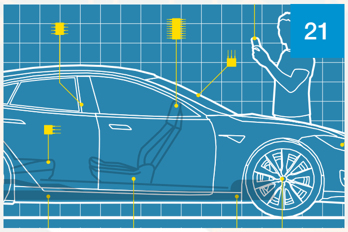
McKinsey&Company

McKinsey on Semiconductors

Number 6, April 2017

Highlights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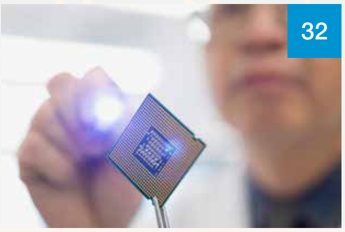
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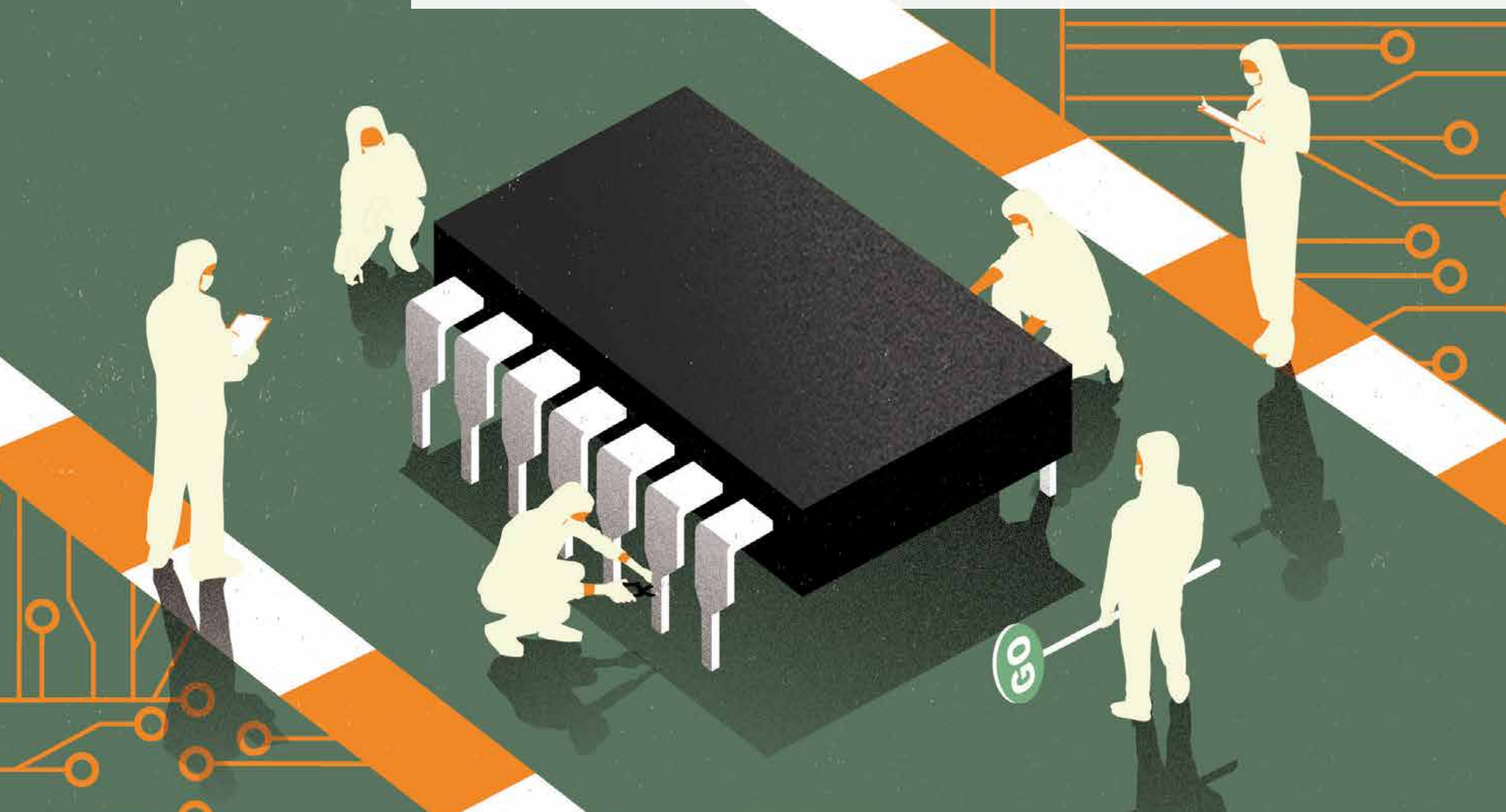

McKinsey on Semiconductors is written by experts and practitioners in McKinsey & Company's Semiconductors Practice along with other McKinsey colleagues.

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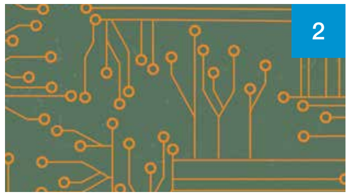
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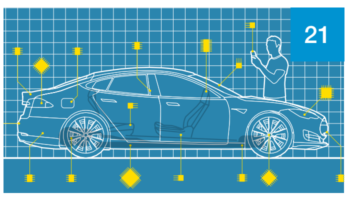
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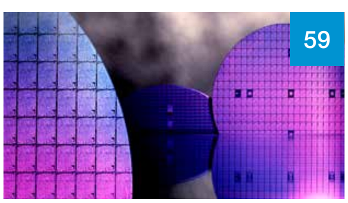
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Introduction

Welcome to the sixth edition of *McKinsey on Semiconductors*. This publication comes at an exciting time for the industry, with record semiconductor sales of $339 billion reported in 2016, and further growth projected for 2017. But it is also a time of transition, with new manufacturing technologies, marked shifts in demand patterns, and greater price pressures cutting into the bottom line. With the industry in flux, many semiconductor leaders are wondering if their familiar strategies still suit the evolving landscape.

Focusing on the theme of change, the articles in this issue examine major trends reshaping the market. “What’s new with the Internet of Things?” discusses obstacles that could limit the growth of the IoT and strategies for overcoming them. A second article, “Security in the Internet of Things,” takes a closer look at one obstacle: the absence of end-to-end solutions that protect IoT devices against hackers. This is a timely piece, since security concerns are growing and semiconductor companies are well positioned to resolve them.

Next, we look at disruptions in the automotive sector. “Mobility trends: What’s ahead for automotive semiconductors” explores how increased connectivity, automated driving, and other trends are shifting automotive revenue pools. It then describes how these developments will affect demand for automotive semiconductors, reviewing opportunities by device segment and application category. This sets the stage for a discussion of strategic issues that semiconductor leaders must consider as they adapt to the new automotive market.

Another article, “How semiconductor companies can win in China’s new product-development landscape,” examines why Chinese product-development centers want to develop more innovative products and increase exports. If they succeed, these centers could capture a much greater share of product-development activity—a shift that would increase their demand for semiconductors and other components. We explore how all semiconductor companies, both local and multinational, can prepare to capture business in this growing market.

Some of the most interesting changes within the semiconductor industry arise from the application of advanced analytics to manufacturing processes. “*Moneyball* for engineers: What the semiconductor industry can learn from sports” explores how advanced analytics can reduce costs and increase productivity when applied to engineering management. Another article, “Reimagining fabs: Advanced analytics in semiconductor manufacturing,” includes interviews with innovators who are developing new methods for improving chip production. Although each innovator offers highly specialized solutions and different technologies, they all focus on using data-driven insights to improve decision making and streamline manual tasks.

While advanced analytics could help usher in a new age of productivity in semiconductor operations, companies still need to consider other improvement strategies. The need is especially intense at back-end factories, many of which lag behind their front-end counterparts in productivity. "Optimizing back-end semiconductor manufacturing through Industry 4.0" describes how back-end factories can improve operational efficiency through a combination of traditional lean techniques and new strategies involving big data, advanced analytics, and an assortment of high-tech tools.

In the final article, we explore how semiconductor companies can effectively address a long-term issue: the need to expand their product offerings. "From hardware to software: How semiconductor companies can lead a successful transformation" describes a framework that can help companies increase their software capabilities—a task that many have struggled with in the past. This framework comes at a good time, since semiconductor companies are now under more pressure to expand beyond their core hardware business and explore innovative business models.

McKinsey on Semiconductors is designed to help industry executives promote the success and continued growth of their organizations. We hope that you find these articles helpful as you create new strategies and chart your future course. ■

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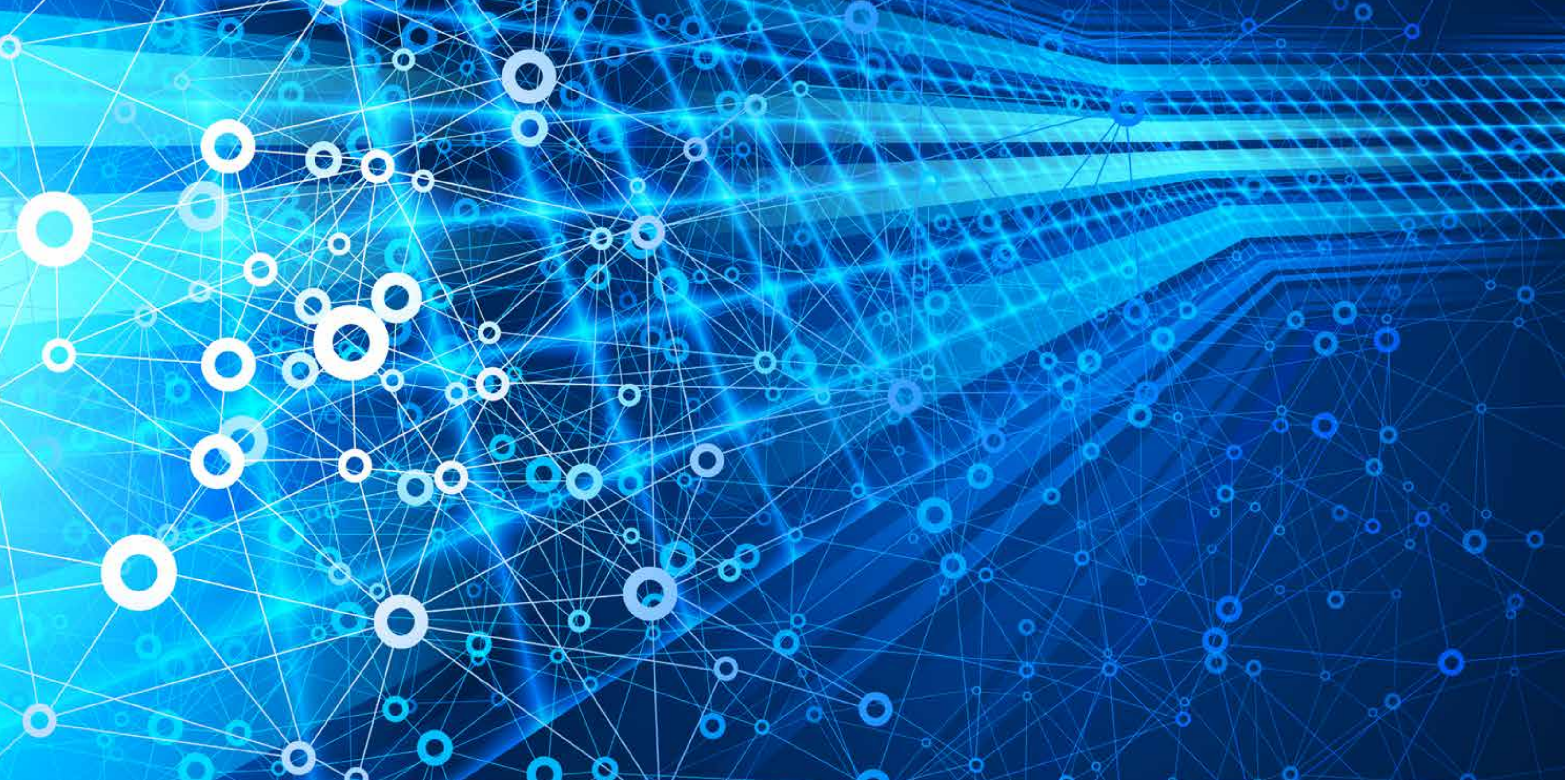

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What's new with the Internet of Things?

Adoption of the Internet of Things is proceeding more slowly than expected, but semiconductor companies can help accelerate growth through new technologies and business models.

Mark Patel, Jason Shangkuan, Christopher Thomas

Niccolò Machiavelli, one of history's great futurists, might have predicted the Internet of Things (IoT) when he wrote, "There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things." The IoT's early innovators, who have grappled with mixed overall demand, a lack of consistent standards, and other challenges, would agree that their road has been difficult. But, like other visionaries before them, they have persisted in establishing a new order because they see the promise ahead.

Both consumers and the media are fascinated by IoT innovations that have already hit the market. These "smart" devices have sensors that communicate seamlessly over the Internet with other devices or the cloud, generating data that make the world safer, more productive, and healthier. In just a few years, some IoT devices have become standard, including thermostats that automatically adjust the temperature and production-line sensors that inform workshop supervisors of machine condition. Now innovators want to enable more sophisticated IoT technologies for self-driving cars, drone-delivery services, and other advanced applications.

Although some analysts are excited about the IoT's potential, others have argued that it is overhyped. We take a more balanced view, based on our extensive research as well as our direct work with IoT application developers and their customers. Like the optimists, we believe that the IoT could have a significant, and possibly revolutionary, impact across society. But we also think that the lead time to achieve these benefits, as well as the widespread adoption of IoT applications, may take longer than anticipated. The uptake of IoT applications could be particularly slow in the industrial sector, since companies are often constrained by long capital cycles, organizational inertia, and a shortage of talented staff that can develop and deploy IoT solutions.

For semiconductor companies, which are looking for new sources of revenue, the rate of IoT adoption is an important concern. In this article, we will look at the case for optimism, as well as the reasons for more modest expectations. We will also examine new technologies that could accelerate the IoT's growth along with product-development strategies that semiconductor companies could implement to increase the appeal of IoT offerings.

Reasons for optimism: Increased connectivity helps the IoT

If we look at the IoT's recent growth, the optimists have reason to be encouraged. Consumers are more connected than ever, owning an average of four IoT devices that communicate with the cloud. Globally, an estimated 127 new devices connect to the Internet every second. A report from the McKinsey Global Institute (MGI) estimates that the IoT could have an annual economic impact of $3.9 trillion to $11.1 trillion by 2025 across many different settings, including factories, cities, retail environments, and the human body (Exhibit 1).[1]

The IoT is also benefiting from infrastructure improvements that have enhanced connectivity. For example, only 20 percent of the global population is now covered by low-power, wide-area networks (LPWANs) that allow long-range communications among connected devices while optimizing both costs and power-consumption requirements. By 2022, however, we expect that 100 percent of the population will have LPWAN coverage. Similarly, technological advances are reducing power requirements, decreasing costs, and promoting the development of more integrated IoT solutions. Consider lidar sensors, the laser-based sensor packages that scan and detect surroundings, which are essential for autonomous driving. Their price has declined more than 10-fold over the past eight years and is expected to drop more than 65-fold over the next two. This decrease, combined with the increased technological sophistication of lidar, is contributing to the development of fully autonomous cars, which could constitute 25 percent of all vehicle purchases by 2035.

Reality check: Industrial IoT adoption has been slower than expected

Many experts view the IoT's slower-than-expected growth within the industrial sector with particular concern. To gain more perspective, we investigated how industrial companies are using IoT applications and tried to estimate whether business-to-business (B2B) growth might accelerate. In addition to basic research, we interviewed and surveyed more than 100 leaders from various industries, including public sector and utilities, discrete manufacturing, oil and gas, mining, telecommunications, technology, media, healthcare, and pharmaceuticals.

Few large-scale IoT projects

Our interviews revealed that most businesses are adopting the IoT only to a limited extent. With the exception of oil and gas and mining, leaders from all industries reported that their companies often received real-time data from IoT sensors. However, most leaders reported that their enterprise deployments were still at proof-of-concept stage, and none have yet embarked on large-scale programs (Exhibit 2).

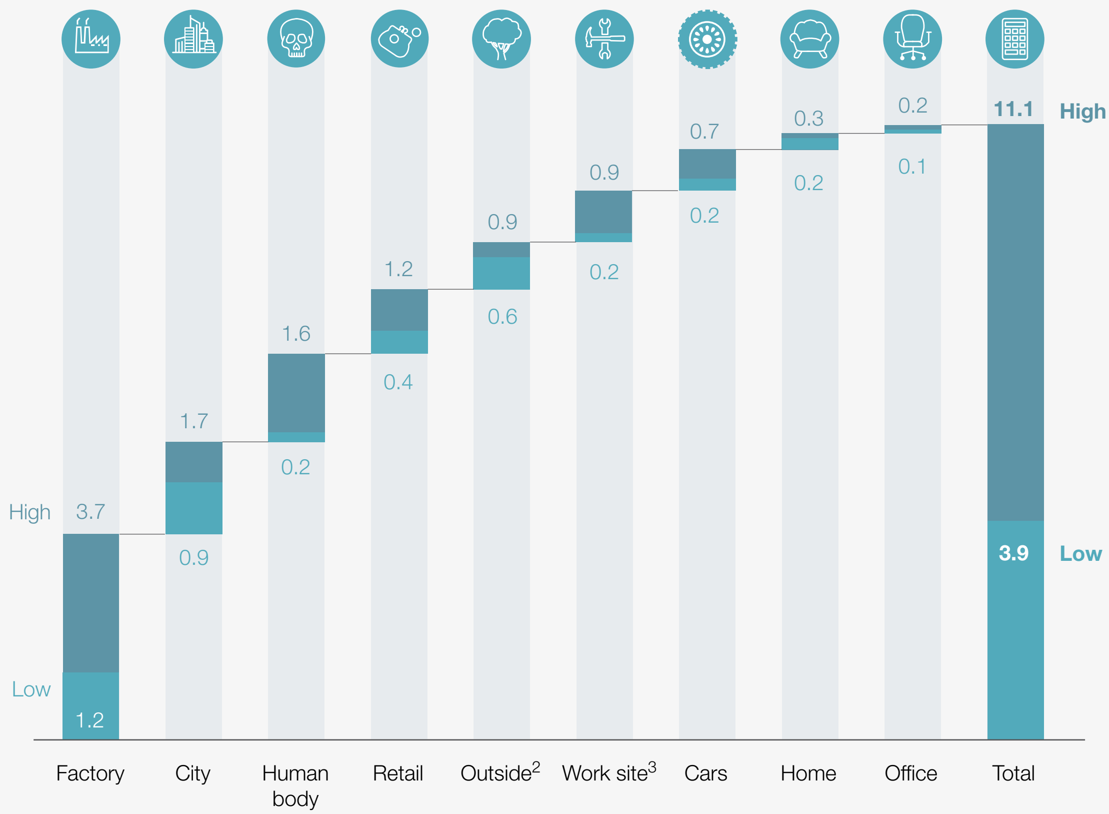
Limited use of IoT data

Although IoT sensors collect vast stores of data, a recent report from MGI showed that companies do

Exhibit 1

The Internet of Things has the potential to generate about $4 trillion to $11 trillion in economic value by 2025.

Potential economic impact by segment,[1]
$ billion (2015 dollars)

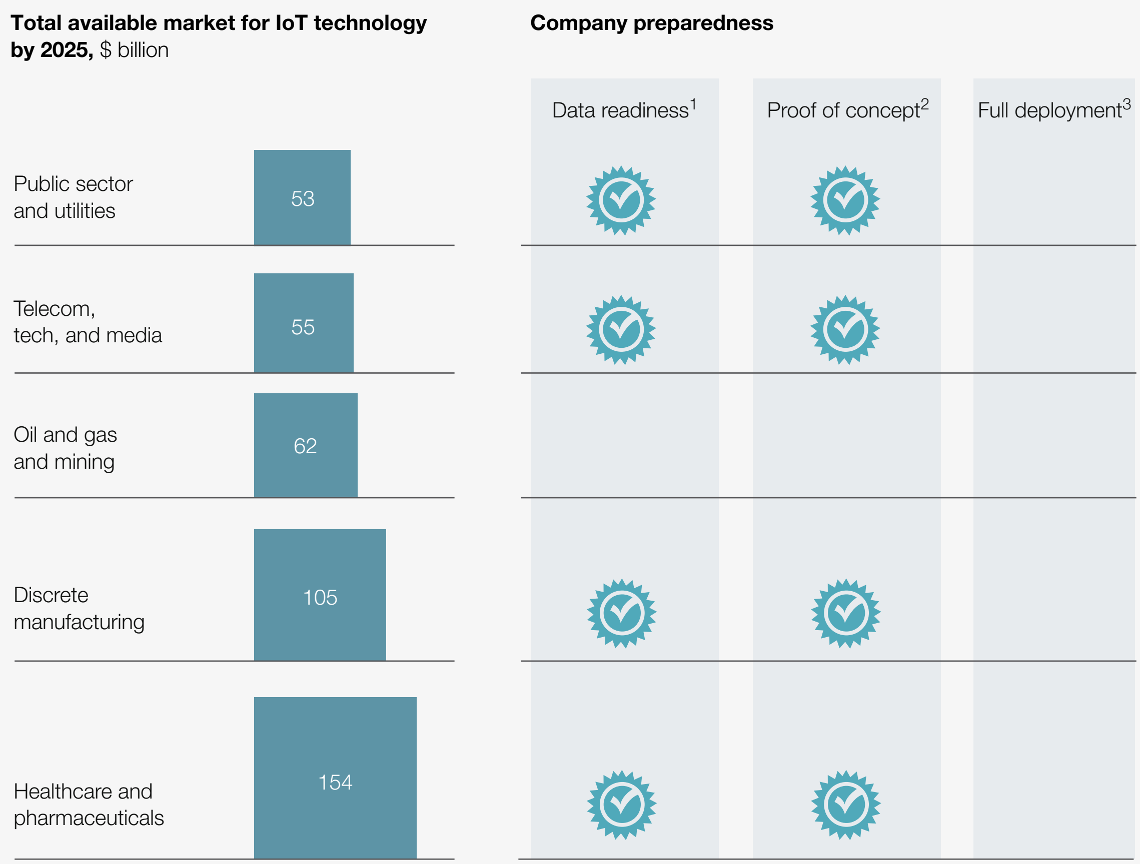


[1]For sized applications only. Numbers do not sum to total, because of rounding.
[2]Outside settings include outdoor environments, excluding those in urban settings.
[3]Work sites are defined as custom production environments.

Source: McKinsey Global Institute analysis

not analyze most of them.[2] For example, on an oil rig that had 30,000 sensors, managers examined only 1 percent of data. What's more, business leaders seldom consider information from IoT sensors when making important decisions, including those related to maintenance planning or automation procedures. Their reluctance to examine IoT data stems from several factors, including a lack of data-analytics staff, but the most important reason is simple: as humans, we prefer to consult other people for advice or to look back on our own experience when making decisions. Although hard data from IoT devices are more complete and objective, we tend to assign them less value. Before IoT data gain a more prominent role in corporate decision making, business leaders and other important managers—maintenance supervisors, field-service technicians, and retail

Exhibit 2 At most companies, Internet of Things applications are still at the proof-of-concept stage.



[1]Robust data, including real-time information from sensors.
[2]Small number of solutions with limited scale.
[3]Widespread deployment of Internet of Things solution across enterprises.

Source: McKinsey analysis

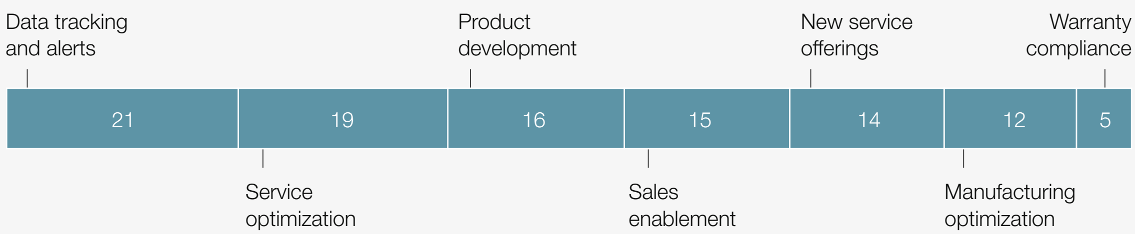
merchandisers, to name just a few—will have to appreciate their value.

A focus on simple IoT applications

In our survey, respondents favored simple use cases that enable tracking data and sending status alerts related to changes in the physical world (Exhibit 3). Some companies, for instance, have placed sensors in food packaging that track a product's location throughout the distribution supply chain. Simple tracking and alert functions are relatively easy to deploy because they do not require advanced analytics, complex algorithms, or data-science capabilities, allowing them to generate value quickly. Although some innovators are enthusiastic about IoT applications for optimization and prediction, we expect that most customers will remain focused on simple use cases, at least for the immediate future.

Exhibit 3 **Survey respondents favored simple Internet of Things use cases.**

What are your top priorities for Internet of Things solutions?, number of respondents (n = 102)



Source: McKinsey analysis

And that means they will not obtain full value from the IoT.

IoT security concerns

IoT devices, connected cars, and edge gateways are all potential entry points for a cyberattack—and we recently saw the full extent of this vulnerability. In the 2016 Mirai botnet attack, hackers targeted IoT devices, including appliances and routers, and disrupted many major Internet service providers. The attack, the most significant of its kind, was possible only because of human weakness—a failure to reset generic or default password and username combinations. This attack, and others like it, demonstrate that IoT vulnerabilities often result from a lack of basic care in managing and maintaining devices. Such weaknesses cannot be eliminated through encryption, attack-detection programs, biometric-access control, or other sophisticated technologies. That means companies that want to expand their IoT efforts will need to launch comprehensive security initiatives that address weaknesses resulting from both technological vulnerabilities and a lack of caution among those who use IoT devices.

Technology developments: IoT growth could accelerate

A few important, and potentially disruptive, developments could accelerate IoT uptake and create opportunities for semiconductor players.

Microphones and video: The ultimate IoT sensors

Video analytics—the application of sophisticated algorithms to video feeds—is spurring the creation of new IoT applications and use cases. For instance, data analysts can now examine customer demographics by applying sophisticated algorithms to videos taken as shoppers browse through merchandise.[3] Recent evidence also suggests that the IoT will benefit from audio captured on microphones.

The costs associated with video and audio feeds are falling, with sensors now embedded in devices at low cost—under $2 each. The data gathered from these feeds are extremely rich, diverse, and relevant to many widely used IoT applications. Lower data-communication rates, the growth of 5G data networks, and ongoing decreases in cloud-storage costs will continue to encourage developers to find new uses for video and audio.

For semiconductor companies, the increased importance of IoT video and audio feeds may create an opportunity to combine hardware with end-to-end approaches for analytics and control. They will have to move quickly to meet customer needs, however, since the technology related to advanced applications, such as those that use analytics to recognize faces, is evolving rapidly. Semiconductor customers may be particularly interested in products that integrate hardware and software more closely, as well as new architectures that optimize transmission, processing, and analytics on devices, in the network, and in the cloud.

Energy harvesting: Providing power to IoT devices

The advent of standards that truly support LPWANs, including LoRa, NarrowBand IOT, and Sigfox, will enable large-scale sensor deployment of IoT applications in many areas, including agriculture (analysis of soil conditions), safety (citywide monitoring of air quality), and productivity (real-time logistical tracking along the supply chain). But the growth of the IoT, combined with the increase in sensors and connectivity, will also make it more challenging to provide power to untethered devices and sending nodes. Even with long-life battery technology, many of these devices can only function for a few months without a recharge.

Energy harvesting, a process in which energy derived from external sources is captured and stored for use in wireless devices, might resolve power-related issues. Although solar energy could provide an answer for many IoT applications, semiconductor companies should also investigate other sources, such as wind, thermal energy (derived from heat), and kinetic energy (derived from an object's motion). Optimizing energy harvesting, management, and storage will require companies to create innovative designs, at both the silicon and system level.

Embedded intelligence and device analytics: Better power and storage

As the IoT expands, innovators are rapidly developing complementary architectures that combine two important features:

- the power of the cloud, which offers robust storage and greatly extensible computing power at low cost
- the ability to process and store data on a device (or edge), or within a network at gateways that connect multiple end devices to the cloud

Multiple IT architectures with these properties have already reached the market, each offering a compelling approach. But semiconductor companies have an opportunity to go further—and to make more rapid progress—in defining the future architecture of the IoT. In particular, they should focus on products related to video and audio sensors, since these devices are proliferating and generating significant amounts of data.

Many IoT applications require data to be processed on the devices themselves. For instance, applications for autonomous driving, surveillance, and security all have strict latency specifications that require systems to respond immediately after data input. To meet these requirements, the IoT devices that collect the data must process them and use the output to make decisions. Applications that require on-device processing are power hungry and include relatively expensive components, such as multiple application processors. Semiconductor companies could take the lead in optimizing on-device solutions for these applications. For instance, they could create edge-device solutions for autonomous control, facial recognition, and audio analytics, all of which have different hardware and software requirements with respect to computing performance, signal processing, and storage.

What needs to happen: How semiconductor companies and other players can capture IoT opportunities

Before any company explores IoT opportunities, it should take a new look at strategy, including the factors that it considers when developing solutions.

Focusing on outcomes (not technology)

Developers and business leaders often focus on the technological potential of the IoT, including its ability to collect and analyze vast stores of data. But technological advances alone will not make an IoT application more valuable or desirable to customers. Instead, developers should focus on outcomes—how a new application will improve safety, financial returns (for businesses), and convenience.

Consider, for example, the outcomes that one airplane manufacturer achieved by using IoT sensors to monitor jet-engine performance. By providing real-time data, the sensors immediately alert the manufacturer about potential problems, which makes it easy to conduct preventive maintenance and maximize uptime. Other sensors help with parts-inventory management. Together, these IoT enhancements have contributed to 9 percent revenue growth and a 30 percent increase in engine availability. That means airplanes spend more miles in the air and less time on the ground, consistently reducing overall operating costs.

To focus on outcomes, companies will have to coordinate activities across the value chain. In addition to providing the technology and data that enable the IoT, they will need to adapt their business models—a difficult process, in our experience, since incumbents often resist change. If they fail to evolve, a start-up or another disruptive player may take the lead in establishing a new approach to IoT application development, especially if new investors emerge to finance innovative ventures.

As companies shift their focus from technology to outcomes, they will need to provide incentives that encourage upstream vendors and customers to support the use of their applications.

Designing for people (not enterprises)

Just as IoT innovators tend to focus on technology, many IoT marketing materials try to appeal to customers by discussing the latest product upgrade, including better sensors, connectivity, computing power, and analytics. But our experience has consistently offered one clear insight: users, both personal and industrial, are more likely to adopt IoT technologies that generate a positive emotional reaction. Consider smart homes, where technology companies have recently won many customers by offering voice-based products—devices with basic conversational abilities that often respond to a name, just like a person. For instance, Amazon's Echo, a smart-home speaker, answers to the name Alexa and can respond to basic commands and questions. Such qualities may create an emotional connection between users and devices, and they could be partly responsible for the strong sales of voice-based products.

As technology companies develop new IoT offerings, they should ask digital designers to provide insights about customer behavior, since this information might help them create products that prompt strong positive feelings and accelerate adoption rates. As always, companies will also need strong technical and analytical capabilities.

Current IoT trends create an uncertain and sometimes confusing picture of the sector's future prospects. When we look at the evidence in total, however, we believe that the IoT is poised to serve as a major growth driver for semiconductor companies. Adoption rates have risen more slowly than expected, but that should not be a reason for pessimism, since many IoT technologies are immature or undergoing development. Semiconductor companies and other players can still undertake new strategies to accelerate IoT growth. Rather than focusing on technology upgrades, they could develop IoT products that truly improve customer outcomes for cost, performance, and other important metrics. They could also emphasize design-driven insights about customer needs, including the product features that generate a positive emotional response. This new approach to development will be challenging, but it will accelerate IoT adoption and help more customers, both personal and industrial, achieve benefits from this exciting new technology. ■

1 For the full McKinsey Global Institute report, see "Unlocking the potential of the Internet of Things," June 2015, on McKinsey.com.
2 Ibid.
3 For more, see Vasanth Ganesan, Yubing Ji, and Mark Patel, "Video meets the Internet of Things," December 2016, McKinsey.com.

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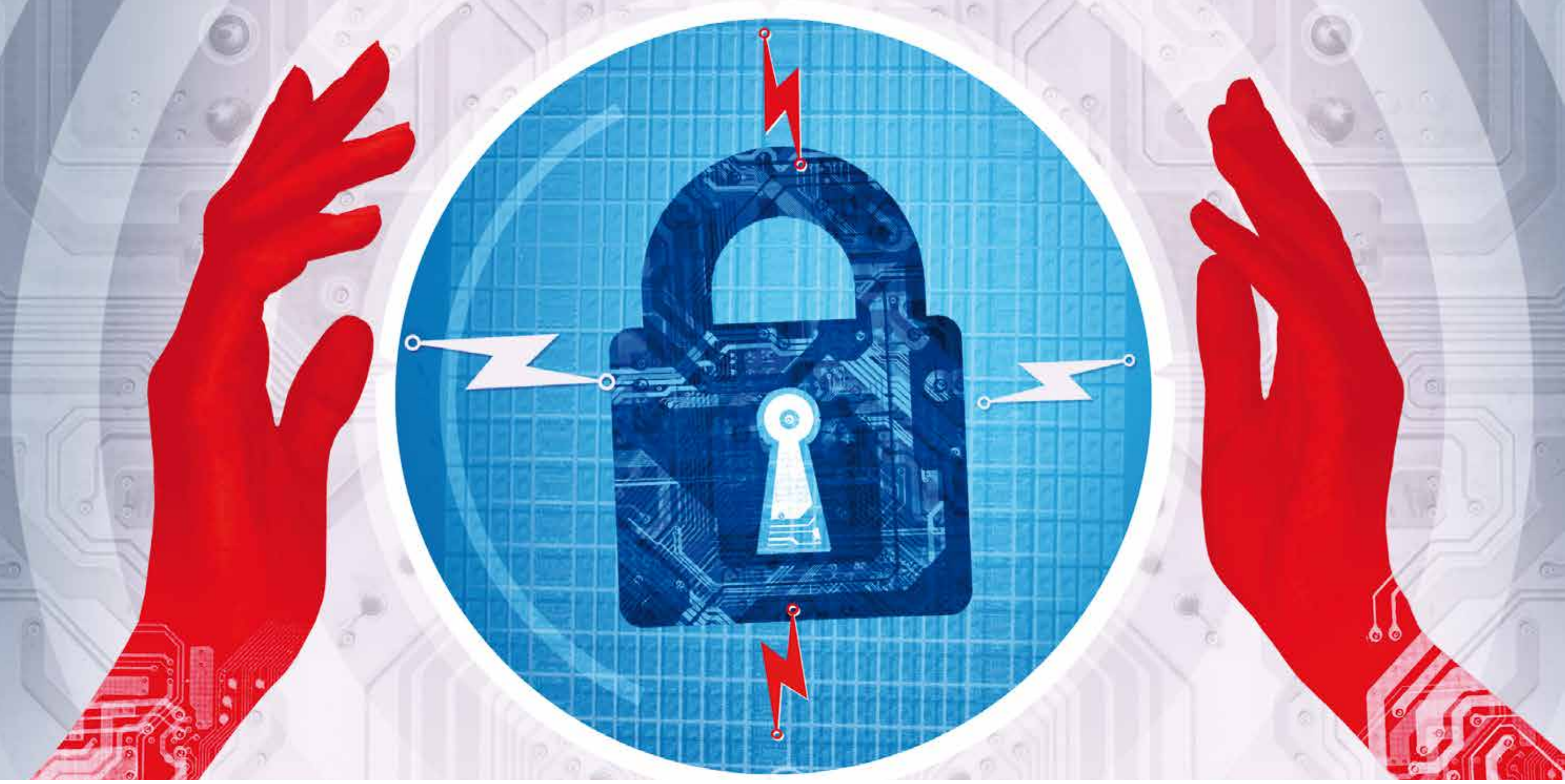


Security in the Internet of Things

Security issues may represent the greatest obstacle to growth of the Internet of Things. How can semiconductor companies help resolve them?

Harald Bauer, Ondrej Burkacky, and Christian Knochenhauer

Over the past few years, the Internet of Things (IoT) has captured headlines across the world, with newspaper and magazine articles describing its potential to transform our daily lives. With its network of "smart," sensor-enabled devices that can communicate and coordinate with one another via the Internet, the IoT could facilitate computer-mediated strategies for conducting business, providing healthcare, and managing city resources, among numerous other tasks. For the public, the IoT could transform many of our most mundane activities by enabling innovations as diverse as self-driving cars and connected refrigerators capable of sending pictures of their contents to shoppers in grocery stores.

Although the IoT is still a nascent phenomenon, with many aspects of its infrastructure under development, the McKinsey Global Institute predicts it could have an annual economic impact of $3.9 trillion to $11.1 trillion worldwide by 2025.[1] For the semiconductor sector, one of the many industries poised to benefit from the IoT's growth, the economic gains could be particularly significant.

The IoT's way forward may be complicated, however. As with any market in its early stages, growth projections could prove overly optimistic if innovators and business leaders are unable to overcome various technological, regulatory, and market challenges. In the case of the IoT, weak security may be the most important issue—a point underscored by a survey that McKinsey conducted in 2015 in collaboration with the Global Semiconductor Alliance (GSA).[2] When we asked respondents about their greatest concerns about the IoT, security topped the list.

Given the importance of IoT security to semiconductor companies, McKinsey and the GSA conducted an additional survey and interviews on this topic in 2016 (see sidebar, "Our research methodology"). The new research, which forms the focus of this article, revealed that respondents still view security as a major challenge to the IoT's growth. But they also believe that semiconductor companies can help overcome these problems and capture significant value by providing security solutions across industry verticals.

Our research methodology

The 2015 collaboration between McKinsey and the Global Semiconductor Alliance (GSA) involved the following research:

- interviews with 30 GSA members who were senior executives at semiconductor companies or at companies in adjacent industries that are part of the Internet of Things (IoT) ecosystem, such as network equipment and industrial automation
- a survey of 229 semiconductor executives at GSA member companies
- development of a fact base on the IoT, focusing on issues relevant to semiconductor companies

Our 2016 research, which focused on IoT security, involved interviews with 30 GSA executives, including some from our original study, and monthly meetings with a C-level executive steering committee. We also surveyed 100 executives within the semiconductor sector and adjacent industries, and interviewed McKinsey experts.

IoT security: A role for semiconductor companies

Hackers have already wreaked havoc by infiltrating connected IoT devices. Paradoxically, they usually aren't targeting device owners, who often remain unaware of security breaches. Instead, the hackers simply use IoT devices as starting points for attacks directed against another target. For instance, the 2016 Mirai attack used IoT devices to attack the Internet infrastructure, causing shutdowns across Europe and North America that resulted in an estimated $110 million in economic damage.

With the IoT installed base expected to increase by about 15 to 20 percent annually through 2020, security is simultaneously a major opportunity and a challenge. Semiconductor companies are therefore obliged to develop solutions that strengthen IoT security and also contribute to their bottom line. However, our recent research suggests that four major challenges may prevent them from capturing opportunities (Exhibit 1).

Challenge 1: Gaps in technical sophistication

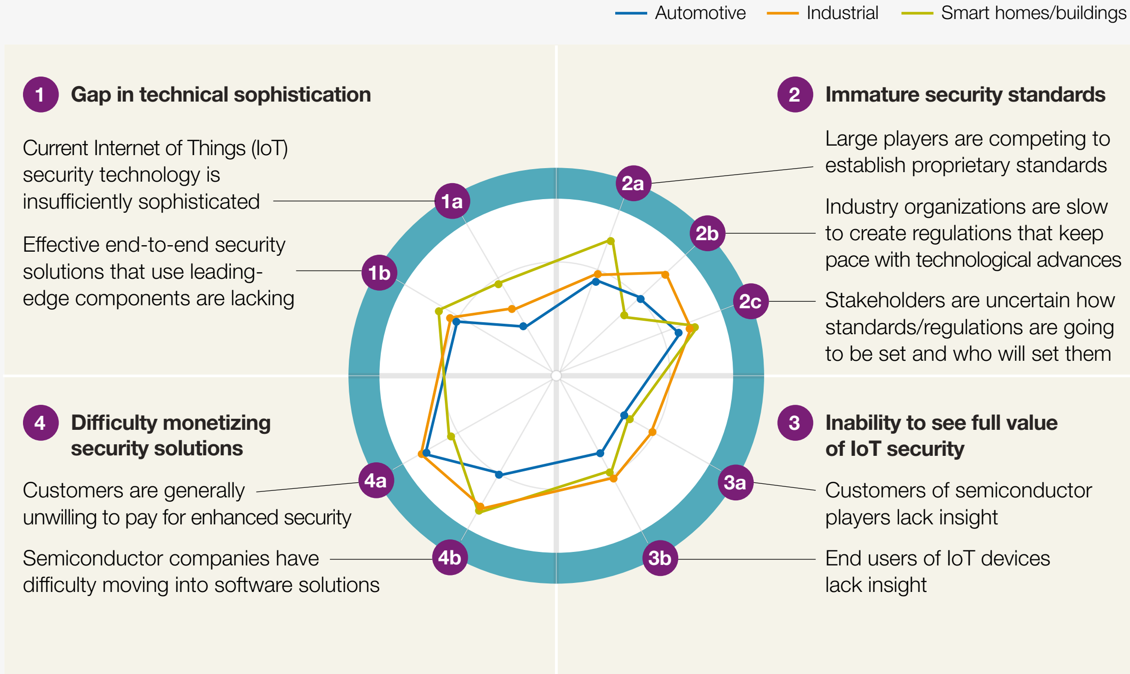
By nature, a complex system of connected devices opens many new attack vectors, even if each device is secure when used independently. Since a system's most vulnerable point determines its overall security level, a comprehensive, end-to-end approach is required to secure it. Such approaches are difficult to develop, however, because most hackers concentrate on breaching a specific element within the technology stack by using one methodology. By contrast, system operators or integrators must provide end-to-end protection against all possible attack vectors, dividing their attention and resources across the system.

It is not yet clear who will take the lead in developing end-to-end security solutions for the IoT. Component suppliers and OEMs are not well positioned to accomplish this task, since the IoT includes such a broad network of devices of different provenance.

Exhibit 1

Semiconductor companies see four main challenges in providing Internet of Things solutions.

Average rating of challenge and relevance on 0–3 scale[1]



[1]4-point scale where 0 = not challenging/irrelevant, 3 = most challenging/relevant. Center scaled to 1 in graphic.

Source: McKinsey/GSA Semiconductor Industry Executive Survey

Integrators are better positioned to provide solutions, but they often lack the necessary capabilities.

Challenge 2: Standards are absent or immature

The IoT lacks well-established overarching standards that describe how the different parts of the technology stack should interact. Instead, large players and industry organizations use their own solutions. Some segments, such as industrials, still rely on a small set of proprietary, incompatible technology standards issued by the major players, as they have done for many years. In other segments, such as automotive or smart buildings, standards are rudimentary. This lack of standards may slow IoT adoption or discourage device manufacturers and others from developing new technological solutions, since they do not know whether their innovations will meet the guidelines that eventually become dominant. In addition, IoT players will have difficulty developing end-to-end security solutions without common standards.

Challenge 3: Customers and end users view IoT security as a commodity

Our research confirmed that customers and producers consider security essential, but they also view it as a commodity—a basic feature that does not merit higher prices. This creates a fundamental disconnect between the desire for security and the willingness to pay for it. In our survey, 31 percent of semiconductor leaders claimed that their manufacturing customers want to try to avoid all security breaches at any cost; an additional 38 percent believed that their customers want security solutions that eliminate at least 98 percent of potential risks (Exhibit 2). Only 15 percent of respondents believed that their customers would be willing to pay a premium higher than 20 percent for the next tier of enhanced chip security. More than 40 percent indicated that their customers either are unwilling to pay any premium or expect security costs to decline.

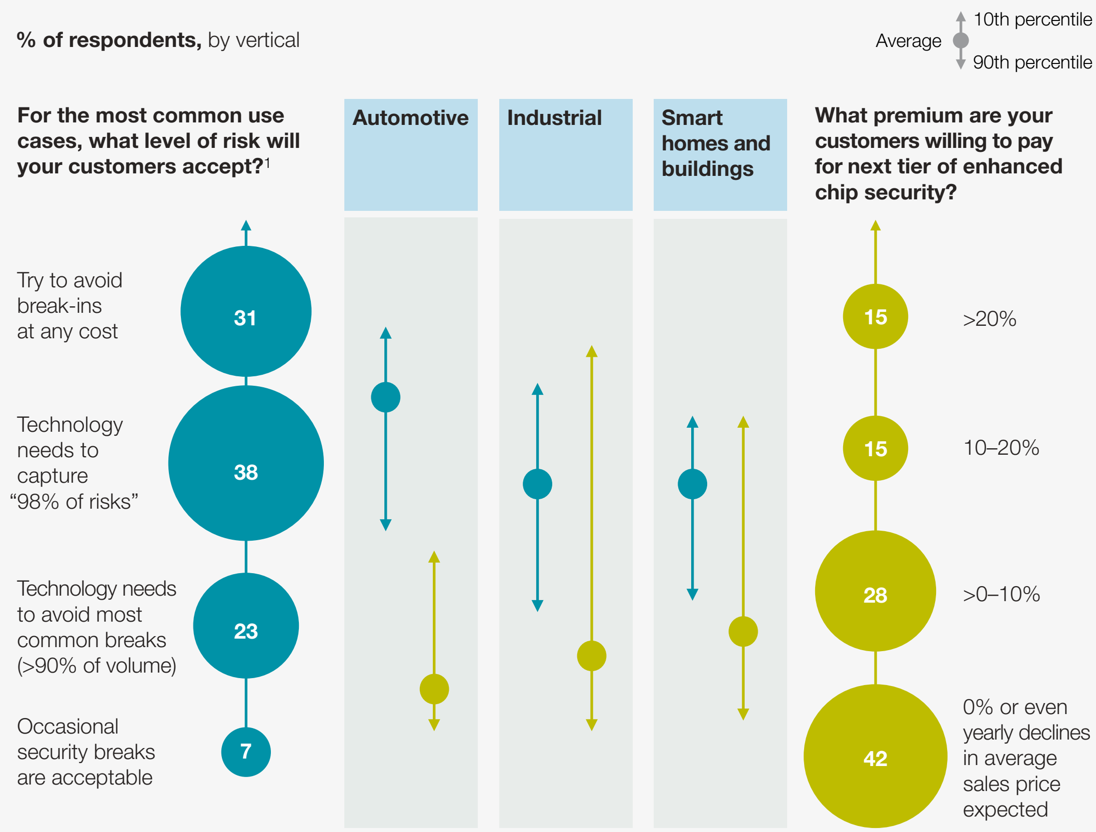
This disconnect could hinder technology progress and inhibit the growth of many IoT applications. Unlike challenges related to technology or standards, this issue can be resolved only by changing customer mind-sets—in other words, by convincing them that security is worth additional cost.

The implications of these findings for semiconductor companies are clear: they need to understand their customers thoroughly before developing security solutions, targeting those with a real willingness to pay, and then developing products that meet their specific needs.

Challenge 4: Semiconductor companies struggle to profit from security

With end customers and device manufacturers unwilling to pay for significant security measures, semiconductor companies are in a bind. In our survey, 38 percent of semiconductor executives

Exhibit 2 **Customers of semiconductor companies want security but are unwilling to pay a premium for it.**



[1]Figures may not sum to 100%, because of rounding.

Source: McKinsey/GSA Semiconductor Industry Executive Survey; McKinsey analysis said that it is highly difficult to make money by offering security solutions, and 40 percent said it is difficult. Their troubles may largely stem from the long-standing, widespread perception that software providers have greater security expertise. For those semiconductor companies that choose to create security software, or that are forced in that direction, the potential profits may not be commensurate with the effort required. After all, many semiconductor players have stepped up their software ventures in recent years, but most have been disappointed with their returns.

Challenges and trends in specific industry verticals

Since IoT industry verticals differ in many respects, their security challenges also will vary, as we discovered when we undertook a detailed examination of three important areas: automotive, industrial, and smart homes and buildings.

Automotive

According to our research on the automotive sector, semiconductor leaders are primarily concerned about how standards will evolve and who will set them, since there is still much uncertainty. Many respondents felt that major OEMs and industry consortia will move first in designing their own standards and technical solutions. However, some respondents also thought that other scenarios were plausible. For instance, a small group of OEMs might band together to take the lead, or reported new entrants to the automotive space, such as Apple, might gain enough scale and influence to establish de facto standards.

Semiconductor companies that want to pursue automotive opportunities may find it difficult to monetize solutions. While OEMs are concerned about security, they also need to keep material costs of the car's base model constant, even when introducing a new one, so they are often reluctant to pay more for security features. With this in mind, semiconductor companies should position their security offerings as part of optional features that are not part of a car's base price. For example, advanced driver-assistance systems (ADAS) currently generate an additional €3,000 to €5,000 in lifetime revenue for OEMs per car. But OEMs will not be able to develop these features any further unless they can ensure their safety—an imperative that gives them an incentive to pay for security. To obtain the additional €3,000 to €5,000 per car that ADAS features generate, our experts estimate that OEMs could spend an extra €50 to €150 per car on security solutions.

Industrials

Innovative industrial IoT applications ("Industry 4.0") are slowly gaining traction within factories and plants, helping companies pursue operational improvement. Despite those benefits, many companies have been slow to implement IoT use cases, often because of security challenges.

Insufficient security technology in industrials often relates to the large variety of legacy systems in the field, as well as a lack of standards. In many businesses, operations largely depend on older computer systems and dated machinery. When companies connect those legacy systems to the Internet, they often struggle to maintain end-to-end security or find it impossible.

To resolve the issues with legacy systems, our research suggests that IoT players should consider designing and implementing new solutions, such as completely ring-fenced networks or redundant sensor networks. Semiconductor companies could contribute to the development of such systems, allowing them to capture value from IoT security. The opportunities exist in two areas with different industry dynamics: common applications for mainstream-market equipment and niche applications for specialty equipment.

Within mainstream equipment, a few players have developed their own ecosystems of proprietary technologies and are significantly investing in end-to-end IoT applications and platforms. Since security is an essential part of the value proposition for mainstream-equipment ecosystems, semiconductor players should try to determine which company's ecosystem is likely to offer the most opportunities, and then develop security features that complement it.

Within niche applications for specialty equipment, OEMs typically create tailored solutions for their customers. In many cases, however, they have little incentive to provide security features that will drive up the cost of their solutions. In addition, specialty integrators and machinery OEMs often do not consider the total cost of ownership for IoT applications. The situation will not change until end customers specifically demand such applications and the security that goes with them—a trend that will take time to gain momentum.

Smart homes and buildings

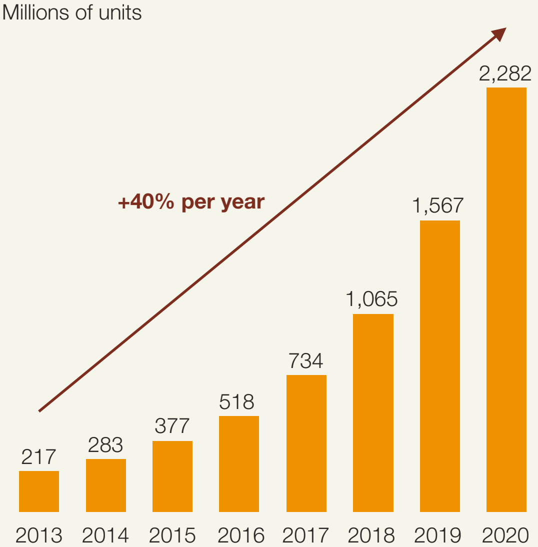
We have recently seen major growth in IoT applications for smart homes (private residences) and smart buildings (commercial use)—and this has also increased security issues.

Smart buildings. We expect the IoT installed base in the smart-building segment to grow by 40 percent until 2020, introducing a multitude of new attack vectors per building (Exhibit 3). Our research suggests that the smart-buildings segment is still in its infancy, with many players still developing applications and associated security solutions.

Exhibit 3 **Many professional building managers are not addressing Internet of Things security threats.**

Installed base of connected smart-building solutions is expanding rapidly …

Millions of units



… but most building managers have not addressed cybersecurity risks

% of building facility managers (n = 224)

78% **Do not feel knowledgeable** about cybersecurity issues related to building-automation systems

46% **Do not monitor** their building-automation systems **for cyberattacks**

45% **Have not involved their company's IT department** in implementing security measures

63% **Have not developed a response plan** in event of cyberattack

71% **Have not taken measures to improve cybersecurity**

Source: Gartner; IBM; smart-building facility-manager survey in *Building Operating Management*, Jan 2015

While this presents opportunities for semiconductor companies, it will take time until end customers deploy applications at scale. That means it could be the right moment for bold moves and investments in technology, but only for those willing to assume significant risks related to the lack of standards and uncertainty of demand. The payoff could be great, however, since our research suggests that professional building owners and managers feel unprepared for the threat ahead.

Smart homes. IoT security breaches are rising in residential applications. The fact that few end customers take extra steps to ensure security, such as updating firmware, suggests that many do not prioritize privacy issues. These factors may explain why end customers are extremely reluctant to pay for enhanced security.

Many companies have attempted to establish security standards for smart-home IoT applications, including OEMs, Internet players, and tech companies. The companies that become dominant within the nascent sector should prevail in setting standards, but it is not yet clear which these will be.

As with the automotive vertical, we believe that smart-home security could gain traction if developers link it with another feature that customers value, such as usability. For example, technologies or solutions that considerably simplify setup efforts and increase security could be in high demand. Since many smart-home devices have short replacement cycles, and since they require a limited investment per household, the market could experience healthy growth if stimulated by a major event, as described above. To benefit from this trend, semiconductor companies should place their bets now on the smart-home ecosystems that will become dominant.

Value-creation opportunities for semiconductor companies

When pursuing IoT opportunities—including those related to turning security solutions into an important new revenue source—semiconductor companies should choose among three core strategies, adapting them to suit their customers and industry (Exhibit 4):

- developing tailored security technologies for a broad range of customers
- formulating a sharper value proposition that draws attention to the benefits that security offerings bring to end customers
- creating security solutions that allow semiconductor companies to expand into adjacent business areas and develop new business models

Promoting tailored innovation

Semiconductor companies should develop a tool kit of security offerings that allows them to customize their products by vertical and customer segment. Some offerings will provide state-of-the-art security for applications requiring the most stringent degree of protection. But for standard applications, where customers consider security less important and are thus less willing to pay a premium, semiconductor companies must provide offerings with "good enough" security features that protect against only the most common threats. Ideally, such solutions will enable other features, unrelated to security, such as those that increase convenience or usability for end users.

Developing a sharper value proposition for security

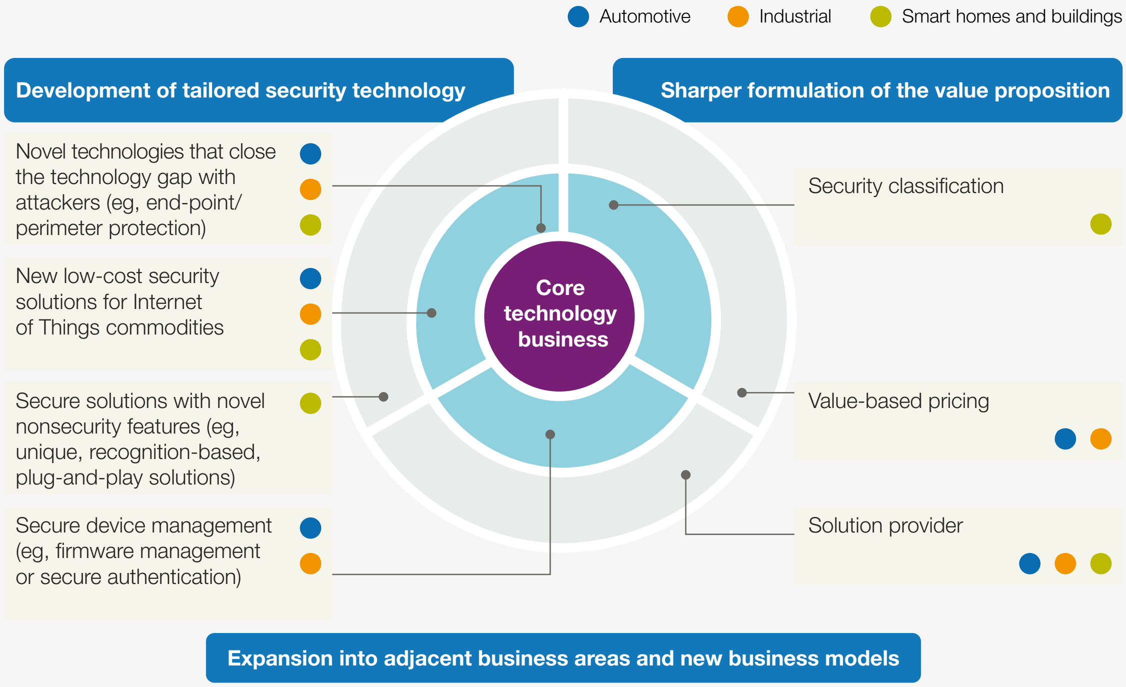
As we have noted, most companies do not view semiconductor players as potential partners in developing security solutions. To change that perception and increase the likelihood of generating profits, they will need to create a strong value proposition for their security offerings.

In consumer markets, companies often link value propositions that are difficult to understand for the end customer to ratings or other guidelines

Exhibit 4

Semiconductor companies need to create an Internet of Things strategy that involves three elements.

Strategy elements, positioned to show departure from semiconductor company's core technology business[1]



[1]Examples shown are not exhaustive. Items' position on target indicates how far they depart from semiconductor company's core technology business.

Source: Expert interviews; McKinsey/GSA Semiconductor Industry Executive Survey; McKinsey analysis

issued by a neutral third party. For instance, automakers have voluntarily developed vehicle-safety ratings and are actively publicizing their results to make consumers aware of features that might otherwise go unnoticed. With the IoT, the introduction of a "security seal" could increase awareness about the degree of protection that each device offers. Ratings from external sources might also help consumers appreciate the importance of IoT security.

In business-to-business markets, semiconductor companies need to go beyond ratings from external agencies to illustrate the value of their security offerings. Instead, they must create individual business cases for each customer—or their customer's customer—that quantify the benefits of their security features.

Expanding into new areas of the technology stack

The IoT security challenge may help semiconductor companies expand into new markets along the value chain. They may especially find opportunities within the middle layers of the technology stack, between application and hardware, such as software infrastructure, gateway communication, and communication protocols. However, this is new ground for most semiconductor companies and competition will be tough, since many other players, including start-ups and strong incumbents from adjacent markets, are trying to develop security solutions for these layers.

When pursuing opportunities in the middle segment, semiconductor players must have a clear strategy that considers their capabilities. Overall, success in obtaining value will require strong software and infrastructure-management expertise—areas where semiconductor companies may still be developing. Thus, partnerships and collaborations will probably be the preferred choice.

Semiconductor players should also continue to look for new business models along the value chain. For instance, they could help create end-to-end security offerings, which are essential to the IoT's success. Ideally, they should play a leading role when developing such offerings, to ensure that they obtain their fair share of value.

■ ■ ■

Despite the challenges ahead, we still believe that many IoT verticals present major opportunities for semiconductor companies to become part of the security solution and capture additional value. Our survey and interviews revealed that semiconductor leaders see the possibilities ahead. Those companies that act now may become leaders—and preferred partners—in securing the IoT. ■

[1] For the full McKinsey Global Institute report, see "Unlocking the potential of the Internet of Things," June 2015, on McKinsey.com.

[2] Harald Bauer, Mark Patel, and Jan Veira, "Internet of Things: Opportunities and challenges for semiconductor companies," October 2015, McKinsey.com.

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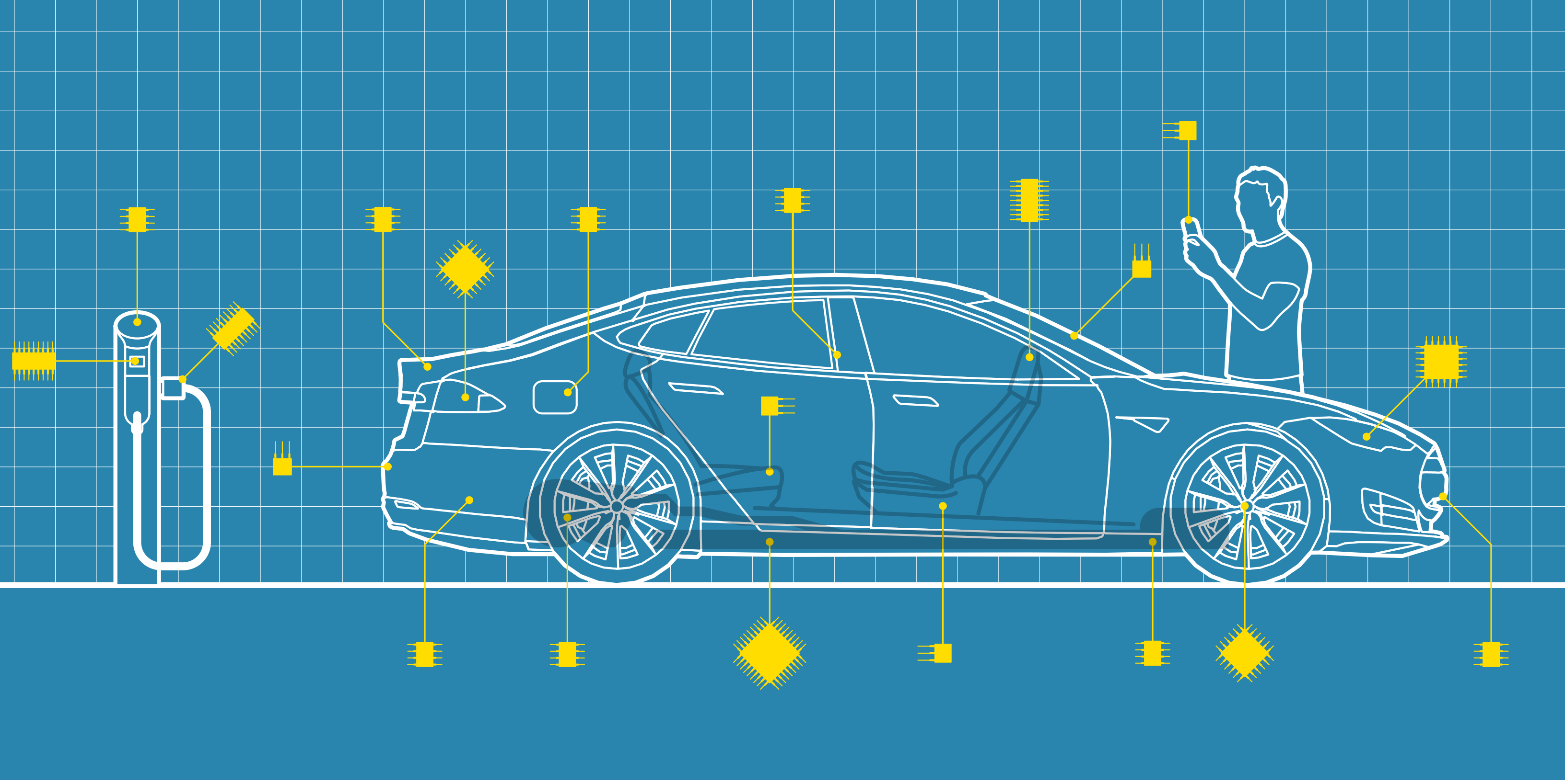


Mobility trends: What's ahead for automotive semiconductors

New mobility trends are diversifying demand for automotive semiconductors. Here's what companies need to know about new opportunities.

Stefan Burghardt, Seunghyuk Choi, and Florian Weig

Consumers who arrived in Las Vegas for the 2017 Consumer Electronics Show—one of the premiere exhibitions of new technologies for the general public—might have wondered if they were at an auto show. This annual conference, which attracts leading high-tech companies across sectors, featured more than 500 exhibits on mobility solutions for cars. Many global automotive OEMs and automotive suppliers participated, introducing innovative sensors, mapping applications, connectivity platforms, and other new technologies. These improvements, combined with the expansion of electric vehicles (EVs), will alter mobility—the market that includes public and private transport, as well as the transportation of goods. In the new environment, a car's electronic components and functionalities—already an important buying consideration—may become the feature that differentiates it from the crowd.

Semiconductors have enabled most of the recent innovations in automotive technology, including vision-based, enhanced graphics processing units (GPUs) and application processors, sensors, and DRAM and NAND flash. As cars become even more complex, demand for automotive semiconductors will continue to rise steadily and provide a major new long-term growth engine.

With many semiconductor companies aggressively pursuing automotive opportunities and forming partnerships along the value chain, players that move more slowly might be left behind. This article discusses three topics that all semiconductor companies must consider as they prepare for the future: trends shaping the automotive landscape, factors that affect demand for automotive semiconductors, and major strategic issues that players must address as they adapt to the evolving market.

The evolving automotive market

The automotive market has seldom experienced so many simultaneous disruptions. In the past few years, we have seen various technologies increasingly incorporated into the mass production of cars, including matrix LED lights, enhanced lidar sensors—those that use lasers to measure distance to a target—and better camera-based sensors. We have also seen improvements in 3-D mapping applications, EV batteries, and augmented-reality technologies, such as heads-up displays. And 5G networks—the next generation of mobility solutions—could soon be available. On the customer side, we are seeing new preferences and attitudes toward cars—for instance, a decrease in the number of consumers who consider vehicle ownership important.

In a 2016 McKinsey report, *Automotive revolution—perspective towards 2030*, we reviewed the major forces shaping the industry, focusing on four that we deemed particularly important.

Vehicle electrification. Excluding full hybrids—cars that can run using just battery power—EVs represented less than 1 percent of new-vehicle sales in 2016. Over the next decade, however, their sales could surge as technological advances address two major impediments to growth: high battery costs and limited charging capabilities. EVs could represent about 5 to 10 percent of car sales by 2020, depending on the extent to which they comply with emission regulations, and between 35 and 50 percent by 2030. The latter estimate is broad because it is difficult to predict many factors that affect growth, including the rate of technological advance, government regulations, and shifts in electricity and oil prices.

Increased connectivity. With hands-free mobile service and online navigation now standard in most new vehicles, automotive players have moved to the next wave of innovation in connected cars. New offerings include telematics services that rely on human–machine interfaces, including voice assistance (such as turn-by-turn audio instructions) and eCall (a program that prompts vehicles to make automatic calls to emergency services in the event of a crash). Both vehicle-to-infrastructure and vehicle-to-vehicle connectivity are increasing and will be supported by 5G networks by around 2020. For instance, BMW vehicles connect to smart-home services such as Deutsche Telekom's SmartHome app, which allows drivers to adjust their home's heating and lighting while they are on the road.

Connectivity strongly influences vehicle-purchase decisions and may have an even greater impact in the future. In a 2016 McKinsey survey of 3,000 consumers in three countries, 41 percent of respondents stated that they would switch to a new vehicle brand to obtain better connectivity.[1] The survey also showed that connectivity features are particularly important in certain countries. For instance, 62 percent of Chinese buyers stated that they would be willing to shift to a new brand to obtain the latest connectivity features, compared with 37 percent of drivers in the United States and 25 percent in Germany. As connectivity solutions become more important, the revenue they produce for OEMs could rise from about $30 billion today to more than $60 billion by 2020.

The growth of autonomous driving. Although OEMs have introduced many new advanced-driver-assistance-systems features, such as automatic braking and adaptive cruise control, highly autonomous vehicles—in other words, level 4 cars—are not expected to hit the road until sometime between 2020 and 2025 (see sidebar, "How are autonomous cars classified based on their driving capabilities?"). They could then experience steady growth, with McKinsey's most highly disruptive scenario for 2030 suggesting that 35 percent of cars sold will have conditional automation (level 3) and 15 percent will have high automation (level 4). The exact growth trajectory will depend on multiple factors, including improvements in core technologies, pricing, consumer acceptance of self-driving cars, and the ability of OEMs and suppliers to address fundamental concerns about safety and the potential for hacking.

Shared mobility services. While car-ownership rates have been increasing in developed markets, they are expected to slow or remain flat with the rise of shared mobility services and the rapid growth of car-sharing and e-hailing services such as car2go. In North America, for instance, membership in car-sharing services increased more than 400 percent between 2008 and 2015. Even greater gains are expected in the future. One McKinsey forecast suggests that e-hailing or ride-sharing services could account for 10 percent of vehicle purchases by 2030—a shift that is prompting many OEMs to increase their efforts to capture this market.

A shifting and diversifying revenue pool

Global automotive revenue now totals about $3.5 trillion annually, with the vast majority coming from new-car sales and the aftermarket (repairs and other services provided after an initial vehicle purchase) (Exhibit 1). Only $30 billion, or less than 1 percent of the total, can be attributed to recurring revenue—a broad category that includes proceeds resulting from e-hailing or car-sharing services, as well as those from data-connectivity services such as apps, navigation tools, in-vehicle entertainment, and software upgrades.

How are autonomous cars classified based on their driving capabilities?

SAE International, a global association of engineers and experts in the aerospace, automotive, and commercial-vehicle industries, created a classification system for autonomous vehicles that is standard throughout the industry. It divides cars into six categories based on the amount of driver intervention required during operation:

Level 0, no automation. Drivers control all vehicle functions, but vehicles may issue warnings about obstacles or other safety threats.

Level 1, driver assistance. The vehicle controls either steering or acceleration and deceleration, but drivers must be ready to assume control at any time. Drivers also control all other critical tasks.

Level 2, partial automation. Vehicles control accelerating, decelerating, and steering. Drivers can take control of these functions at any time, however, and still control other functions.

Level 3, conditional automation. Vehicles control all driving functions, but the system may request that drivers intervene in certain situations; without driver input, the vehicle will not perform appropriately.

Level 4, highly autonomous. Vehicles control all tasks. The system may ask drivers to intervene at some points, but it can still direct the car appropriately if there is no response.

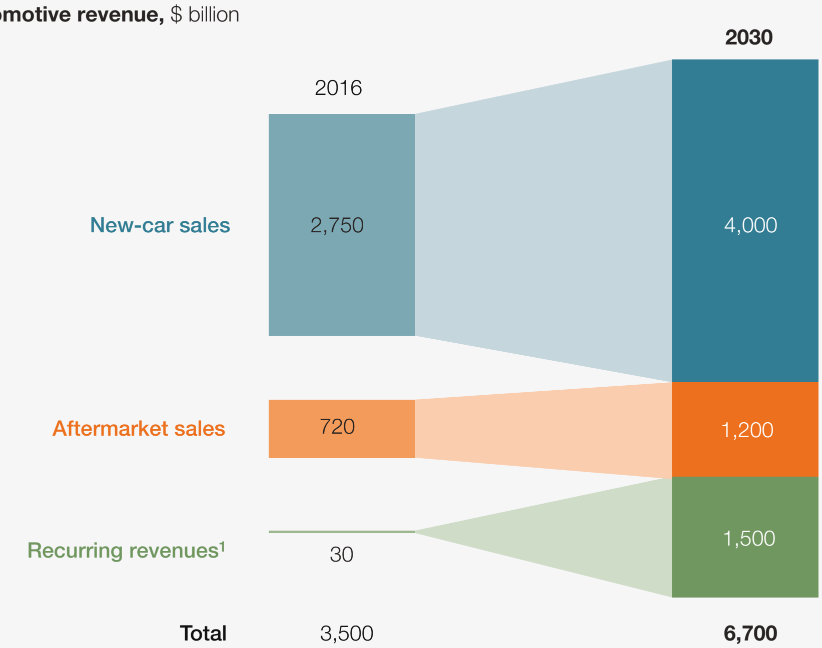
Level 5, fully autonomous. Drivers must start the car and establish the destination, but vehicle software makes all other decisions without further assistance.

The next wave of technology advances will allow vehicles to transition from level 3 capabilities to level 4.

Exhibit 1

Global automotive revenues could reach about $6.7 trillion by 2030, a growth rate of around 4.4 percent annually.

Global automotive revenue, $ billion



[1]Does not include traditional taxis and rentals.
Source: McKinsey analysis

We are about to see major changes in both the size and composition of the revenue pool, however. Under one highly disruptive scenario, it could total more than $6.7 trillion by 2030, with $5.2 trillion, or about 78 percent, coming from new-car sales and the aftermarket. Recurring revenue, expected to total more than $1.5 trillion, would account for the remaining 22 percent—a 50-fold increase from 2015.

The four trends just described will play an important role in the revenue pool's diversification and growth. The increase in recurring revenue that results from the rise of mobility services and greater connectivity is perhaps the most striking change. But the four trends will also affect other areas. For instance, autonomous vehicles (both levels 3 and 4) have high price points, which will increase revenue from new-car sales. Within the aftermarket, new mobility services will raise revenue, because shared vehicles have higher maintenance costs. However, there will also be downward pressure in the aftermarket, because EV powertrains are less expensive to maintain than those for conventional vehicles, and crash-repair costs for autonomous cars can be up to 90 percent lower. All of these shifts could change the source of demand for semiconductors and other components.

Implications for the automotive-semiconductor market

Despite the potential uncertainties, we expect demand for automotive semiconductors to increase over the mid- to long term as the industry tries to enhance safety, comfort, and connectivity features within vehicles. The move to automated-driving capabilities will be particularly significant. Over the long term, the growth of the EV segment will also accelerate growth, because hybrid EVs contain about $900 worth of semiconductors, while standard EVs have more than $1,000 worth—much higher than the average $330 value for the semiconductor content of conventional vehicles.

Between 1995 and 2015, semiconductor sales to automotive OEMs rose from about $7 billion to $30 billion (Exhibit 2). With this increase, automotive semiconductors now represent close to 9 percent of the industry's total sales. Current projections suggest that sales of automotive semiconductors will continue on their upward trajectory, increasing about 6 percent annually between 2015 and 2020—higher than the 3 to 4 percent growth predicted for the semiconductor sector as a whole. That would put annual sales for automotive semiconductors in the $39 billion to $42 billion range.

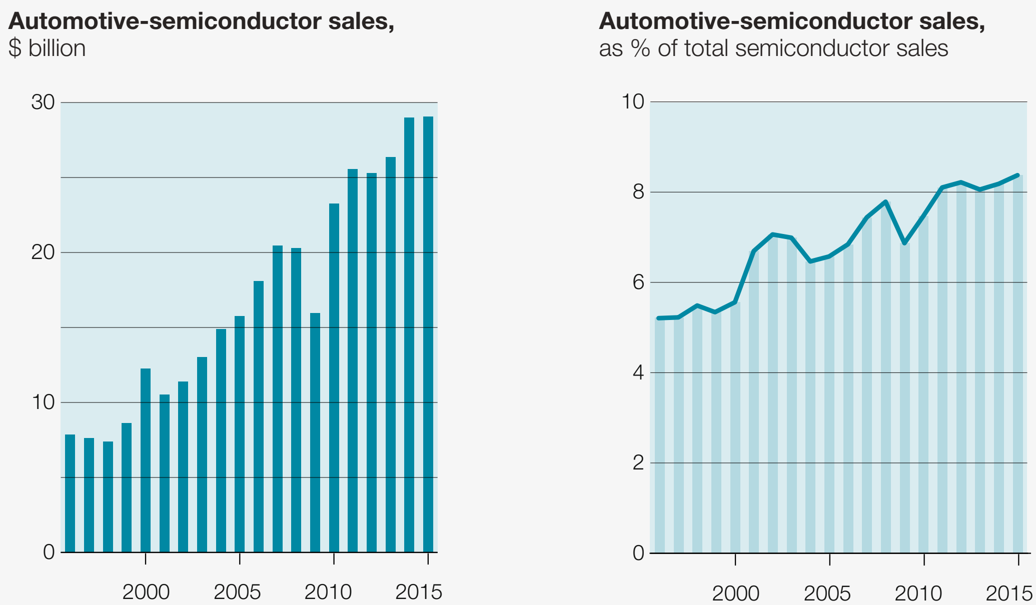
Although the opportunities ahead appear vast, our analysis of the automotive-semiconductor sector suggests that they will differ significantly by geography, automotive-application segment, and device segment. We have explored some of these variations to guide semiconductor companies in strategic planning.

Geographic growth: New forces rising in the automotive-semiconductor industry

Although the Americas and Europe account for most demand in automotive semiconductors, China now leads the world in annual sales growth, with average gains of 15 percent between 2010 and 2015 (Exhibit 3). China is expected to remain the world leader in sales growth, although average gains will fall to 10 percent through 2020, since the country's

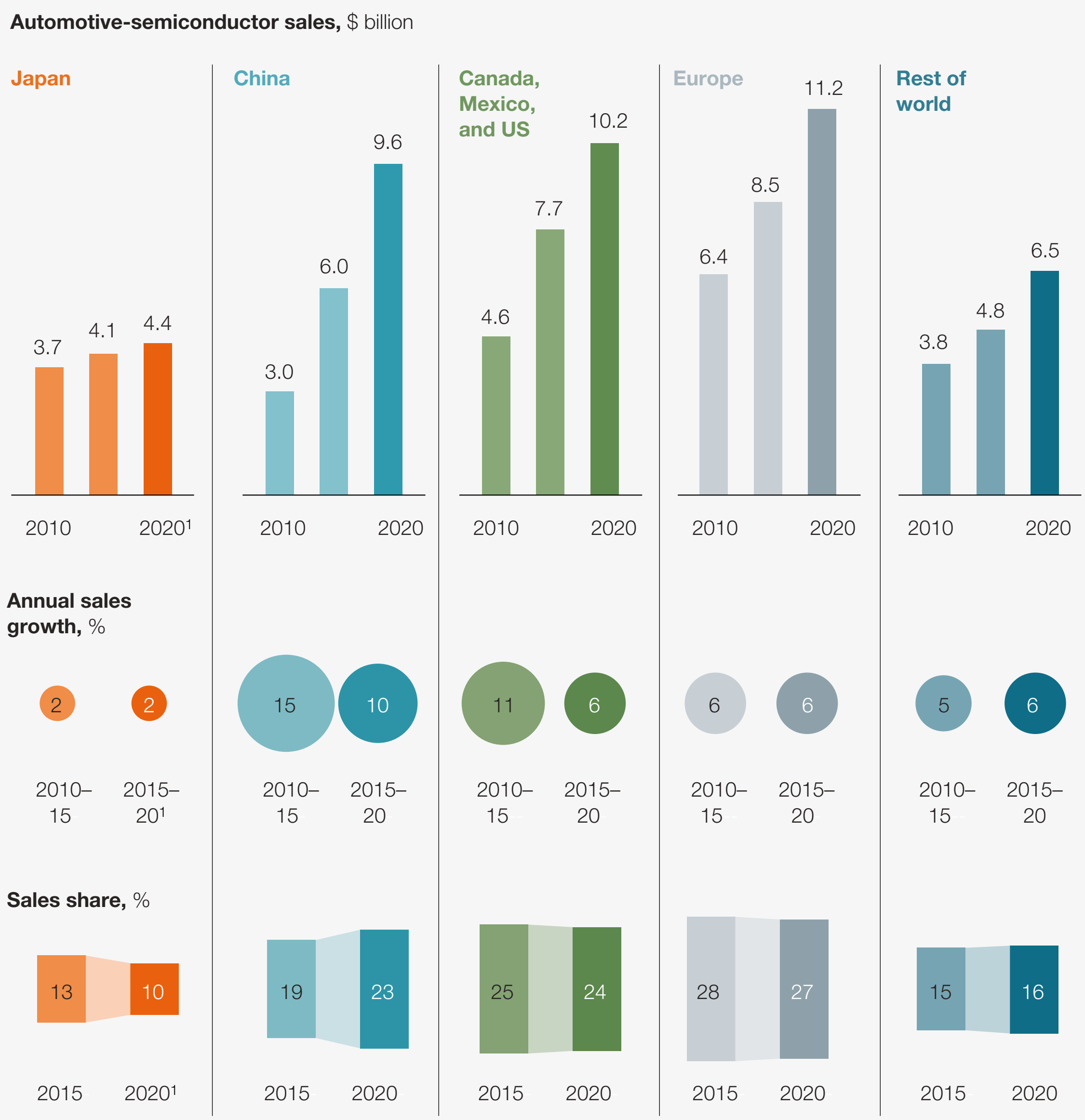
Exhibit 2

The automotive market increasingly generates a large portion of semiconductor sales.



Source: IHS; McKinsey analysis

Exhibit 3 Sales growth for automotive semiconductors should continue.



[1]2020 is estimated.

Source: Strategy Analytics; McKinsey analysis economy is slowing and car sales, which have been surging, may flatten.

Demand by device and application segment: A shifting landscape

In addition to studying geographic trends, we explored how semiconductor demand might change for core automotive-application segments and device categories.

Identifying pockets of growth among diverse automotive-application segments. We examined growth patterns in the core-application segments: safety, powertrain, body, chassis, and driver information. Trends suggest that the greatest growth through 2020 will occur within the safety segment (Exhibit 4).

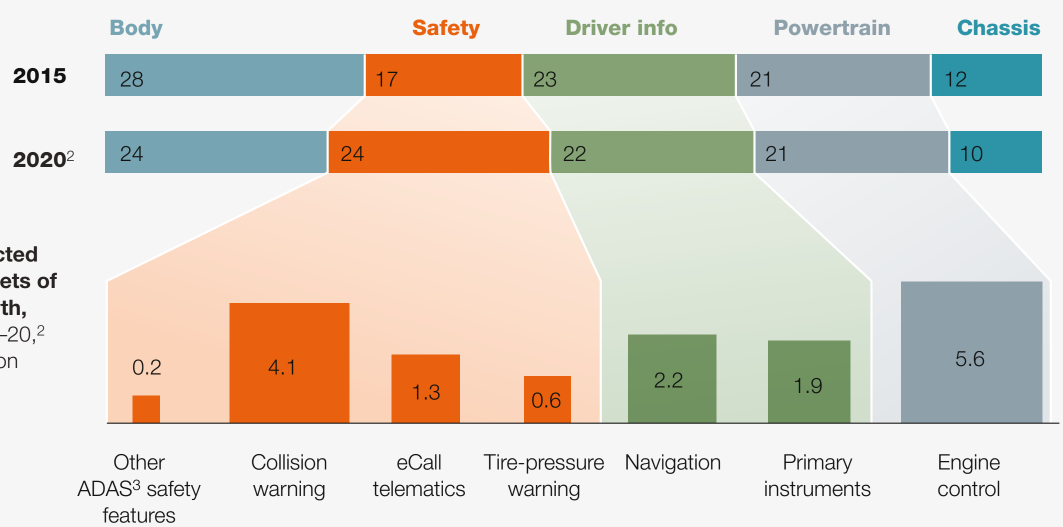
Within each core-application segment, some product categories will see much higher growth than others. For instance, within the safety category, collision-warning systems are expected to have a compound annual growth rate (CAGR) of 22 percent between 2015 and 2020, when sales will reach $4.1 billion. Looking at long-term developments after 2020, we expect continued growth in the engine-control segment, including e-motors and power electronics. We will also see more growth in integrated systems and solutions, such as engine-control units (ECUs) for fusion sensors and integrated-control systems that enable level 4 autonomous driving.

Understanding device growth. We also examined semiconductor demand across device segments: memory, microcomponents, logic, analog, optical

Exhibit 4

Within each core application segment, there will be pockets of growth.

Automotive-semiconductor demand by core segment, % of total[1]



[1]Figures may not sum to 100%, because of rounding.
[2]2020 is estimated.
[3]Other advanced-driver-assistance systems include safety features other than those mentioned in the chart above, such as parking assistance or drowsiness monitoring.

Source: Strategy Analytics; McKinsey analysis and sensors, and discretes. While some segments will see more growth than others, we do not expect any major shifts through 2020. Around that time, EVs will begin to proliferate. In addition to containing more semiconductor content than conventional vehicles, EVs also require different types of automotive semiconductors, which will shift demand patterns. For instance, up to 10 percent of automotive semiconductors in conventional cars are incorporated into discretes (power electronics). By contrast, about 35 to 40 percent of automotive semiconductors in hybrid EVs are in discretes, as are up to 50 percent of those in other EVs. Even though EVs are not expected to gain widespread popularity until around 2020, sales of these vehicles are already trending upward. That means demand for automotive semiconductors is already beginning to shift.

As with the core automotive-application segments, there will be pockets of opportunity within each semiconductor-device segment. For instance, with the microcomponent segment, the CAGR will be highest for microprocessor units (14 percent) and more moderate for microcontroller units (MCUs) (9 percent) and digital signal processors (3 percent) (Exhibit 5). After 2020, we still expect growth to continue in all core segments. However, the growth of autonomous driving and EVs will benefit some applications, such as GPUs and sensors, more than others.

Strategic questions and next steps

We have engaged in many discussions with semiconductor-industry leaders, as well as experts in the Americas, Asia, and Europe, about the challenges ahead in the automotive industry. Their critical questions include the following:

How can we differentiate our offerings?

Most leaders mentioned that a focus on hardware would not deliver the desired value in the evolving automotive industry. They all wanted to provide systems or solutions by adding software algorithms to their offerings, and some are also working with partners to differentiate their products in other ways. For example, NVIDIA recently announced that it plans to continue collaborating with the high-definition (HD) mapping player HERE. Together, they will develop HERE HD Live Map, a real-time mapping product for autonomous vehicles. Intel also announced the creation of the Intel GO Automotive 5G platform. This is the one of the first 5G platforms that would allow automotive manufacturers and tier-one suppliers to proof their designs for 5G.

If companies focus on systems, rather than the addition of individual chips, they can avoid intense price pressures. For example, NXP Semiconductors just launched a software-defined radio solution for in-vehicle infotainment (IVI) systems called the SAF4000. The company claims that this is the world's first one-chip system covering all global audio broadcast standards, including AM/FM, DAB+, DRM(+), and HD.

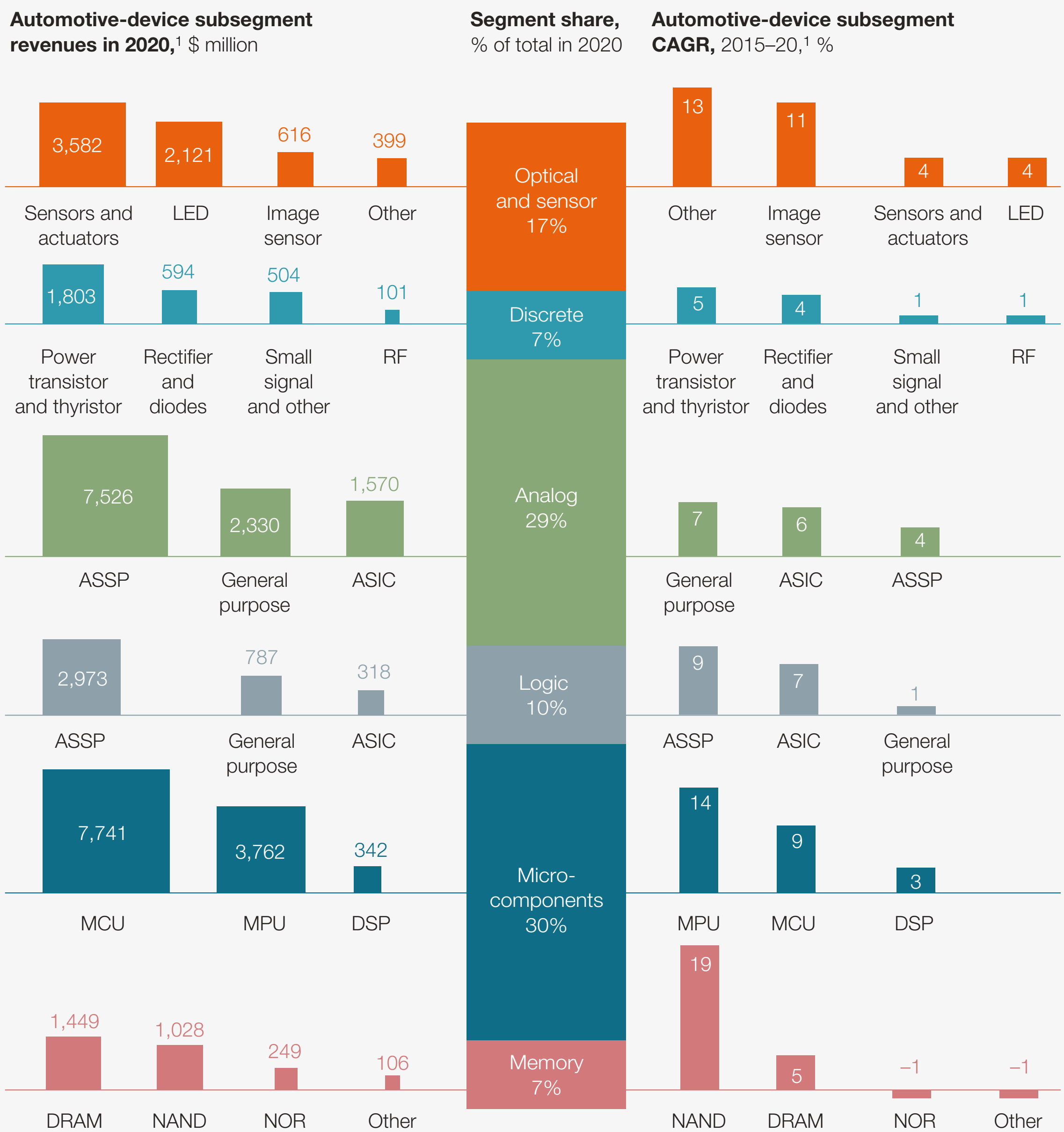
Will we see any changes regarding the life cycle of semiconductors in vehicles?

In the future, we may see OEMs purchasing chips at more frequent intervals, as long as a car is on the market. This trend will gain momentum as upgrades for optional features, such as IVI, are decoupled from other hardware upgrades, such as those related to powertrains.

How much integration is needed to reduce material costs while ensuring redundancy?

Some leaders are trying to build systems as an integrated unit, with multiple MEMS, MCUs, and other sensors, to ensure redundancy. In this context, redundancy refers to duplication of critical components or functions of a system to increase reliability of the system. For instance, redundancy may provide a backup or fail-safe. OEMs might also find that certain redundancies improve performance, such as the inclusion of additional ECUs. Some have also investigated the use of x-by-wire (electrical or electromechanical systems that

Exhibit 5 **All major automotive-semiconductor-device segments contain pockets of growth.**



[1]2020 is estimated.

Note: Acronyms in this exhibit include the following: ASIC = application specific integrated circuit; ASSP = application specific standard product; CAGR = compound annual growth rate; DSP = digital signal processor; MCU= microcontroller unit; MPU = microprocessor unit; NOR = nonvolatile memory (with NOR logic gates); RF = radio frequency.

Source: IHS iSuppli; McKinsey analysis

perform vehicle functions traditionally controlled by mechanical linkages) for braking or steering.

Questions remain, however, about how much redundancy is needed and when industry players will feel comfortable with less of it.

How should semiconductor companies collaborate with automotive OEMs and tier-one suppliers?

Semiconductor companies are increasingly working directly with both OEMs and tier-one automotive suppliers. For instance, BMW, Intel, and Mobileye announced that they have collaborated to create a fleet of about 40 autonomous test vehicles that will be on the roads by the second half of 2017. Similarly, Audi said that its continued collaboration with NVIDIA will introduce innovative features to its newest A8 luxury sedan, including systems that enable automated driving in complicated situations, such as those involving highways and traffic jams. Audi and NVIDIA have also formed a partnership to create what they have described as the "world's most advanced AI [artificial-intelligence] car," which they hope to have on the road by 2020.

For collaborations to succeed, semiconductor companies must first identify the areas where these opportunities bring complementary skills—for instance, a venture where their hardware expertise could benefit a company with strong software skills. They should then decide which form of collaboration—M&A deals, joint ventures, exclusive partnerships, or strategic partnerships—will best suit their needs.

How will the automotive landscape evolve and will this affect semiconductor companies?

Some shifts in the competitive landscape and the value chain could affect semiconductor players. Although leading global OEMs are expected to remain dominant within the global market, those that focus on the mass market may start to lose revenue share as disruptive players, including new Chinese OEMs, establish or expand their operations. Information and communication technology (ICT) players in other countries are also seeing demand grow for their products, including sensors and software, which could give them a larger role in the value chain. Finally, some tier-one automotive suppliers could gain bargaining power equivalent to that of less dominant OEMs.

How far should we expand into security offerings?

It will be critical for semiconductor companies to incorporate security features into chips, but this will not entirely address all safety concerns, including those related to hacking. In consequence, they should also consider developing other security solutions, especially in the neglected area of automotive connectivity. A few semiconductor players, such as NXP Semiconductors, are already working with automotive partners to develop end-to-end security solutions, and others may follow their example. As they embark on security ventures, semiconductor companies may find some inspiration from companies in other high-tech sectors that have created innovative offerings. For instance, Bosch recently announced a keyless entry and start product that allows drivers to access their vehicles securely, using only a smartphone that provides full encryption.

How should we address the China market?

Semiconductor companies should look at the China market from several angles. While it will be an important source of demand, the country could also become a major testing location for autonomous cars and EVs, partly because the consumer market has some unique characteristics. In the 2016 McKinsey survey of more than 3,000 car buyers in three countries, we found that Chinese consumers were more open to car-to-car data sharing—having vehicles exchange information about location, speed, and other factors—than drivers in Germany and the United States.[2] We also found that they were more willing to upgrade the IVI within their vehicles. Both of these factors might encourage automotive OEMs to test and market new automotive technologies in China, especially since car-ownership rates are rapidly growing.

China also provides semiconductor companies with a large and diverse pool of potential partners for automotive ventures. This fact was on display at the 2017 Consumer Electronics Show, where Chinese companies had more than 1,300 displays and accounted for more than 20 percent of the 500 exhibits on vehicle technology. As in the United States and other countries, some of the most promising partners may be new entrants into the automotive sector. For instance, Baidu, the Chinese web giant, is attempting to develop its autonomous-driving and EV technology through partnerships with global OEMs.

Semiconductor companies can also be optimistic about China—both as a market and a source of partners—because the Chinese government has launched several initiatives to support domestic manufacturing. For instance, the government's "Made in China 2025" policy provides subsidies and other incentives to local companies that upgrade their facilities and focus on innovation. Semiconductor companies may thus find that the pool of potential partners will become even more substantial in coming years. The Chinese government has also displayed a strong interest in promoting technologies for autonomous cars and EVs, as well as technologies related to the Internet of Things that enable many connected car features. The government's support has already encouraged more automotive and ICT players to establish a stronger presence in China.

■ ■ ■

Many semiconductor companies are moving quickly to develop automotive innovations, with some poised to become leading suppliers to OEMs that market autonomous vehicles and EVs. Other players, however, have been slow to form partnerships with automotive players or further invest in technologies that will meet their needs, perhaps because they are reluctant to assume the risks associated with an uncertain and rapidly evolving market. But those companies that hesitate to address strategic questions may now lose market share to more aggressive competitors, even if they take decisive action later. With the automotive market poised to serve as one of the semiconductor industry's greatest growth drivers, their lack of action is the real risk. ■

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[1] McKinsey connectivity and autonomous driving consumer survey, 2016.
[2] Ibid.

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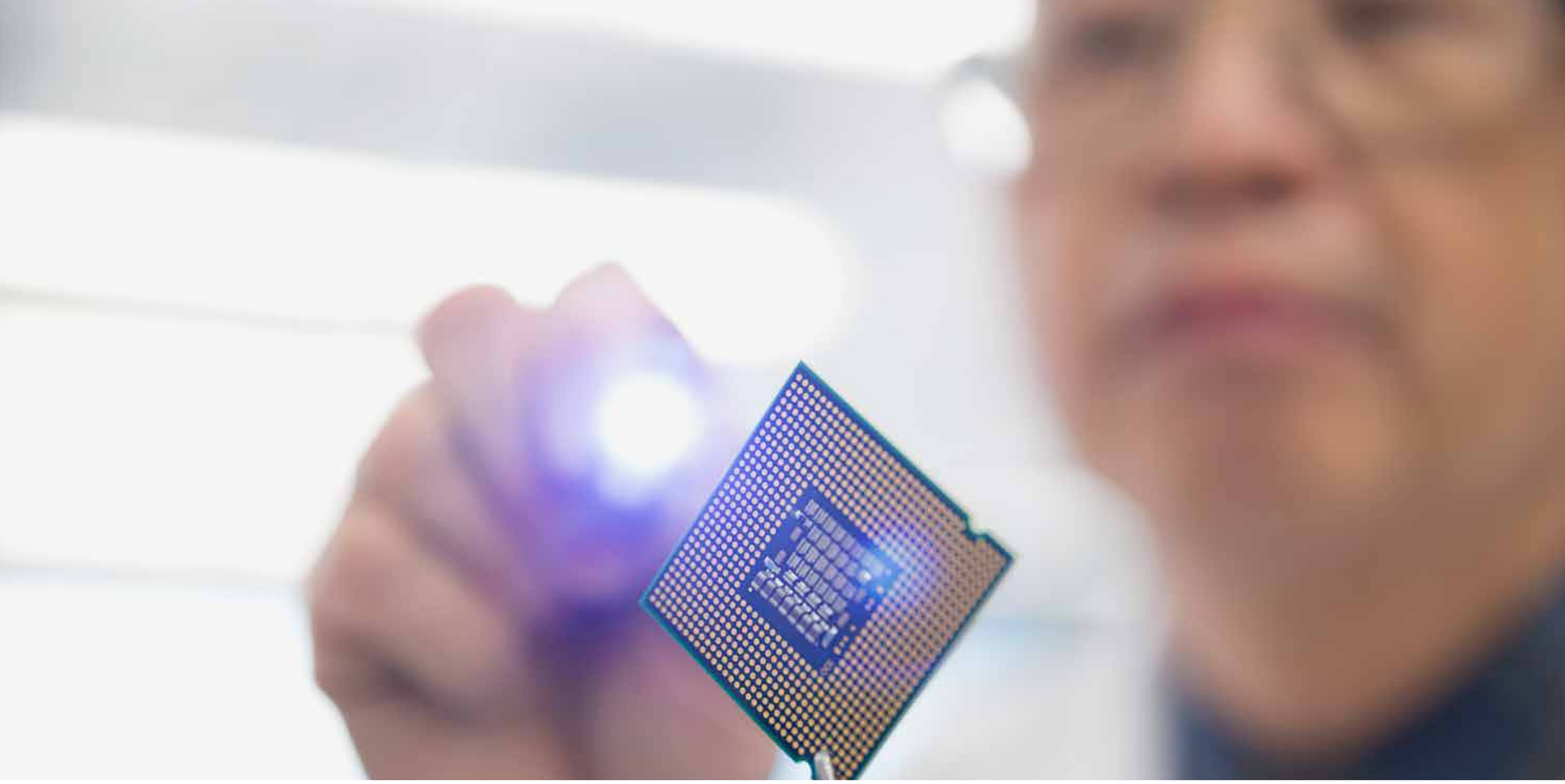

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How semiconductor companies can win in China's new product-development landscape

Product-design centers in China want to become stronger engines of global innovation. What does this mean for semiconductor suppliers?

Thierry Chesnais and Christopher Thomas

China has become an important center of R&D and global product development for many OEMs that semiconductor suppliers serve. With the country's strong economic performance until recently, its local universities graduating millions of engineers, and many OEMs eager to capture growth, China's ascent over the past decade was both predictable and understandable.

Hoping to take advantage of China's favorable environment, both Chinese and multinational OEMs have opened new product-design centers or expanded existing facilities throughout the country. The Chinese OEMs have traditionally asked their design centers to specialize in making products for the local market. Similarly, multinational corporations (MNCs) have focused their China-based design centers on customizing global designs for the Chinese market or on developing a narrow portfolio of China-focused products. Neither locally owned centers nor MNC-owned centers have emphasized innovation, because most products created for the Chinese market do not include leading-edge technologies, partly to keep costs low.

That will soon change, however. Chinese customers are becoming more discerning and increasingly want innovative products. In addition, the slowdown in the Chinese economy means that design centers must pursue more opportunities in other countries to maintain their momentum. These points were underscored by a survey we recently conducted of about 80 R&D and product-development executives at OEM China design centers[1] (see sidebar, "McKinsey survey of OEM China design-center heads: Methodology"). The survey respondents expect OEM China design centers to shift their focus to increasing exports and driving innovation over the next few years, a move that would allow them to capture a much greater share of global product-development activity. If our survey respondents' predictions play out, demand for semiconductors and other components at OEM China design centers could rise from $350 billion in 2016 to $500 billion by 2020. This growth would represent the single largest opportunity for component suppliers globally.

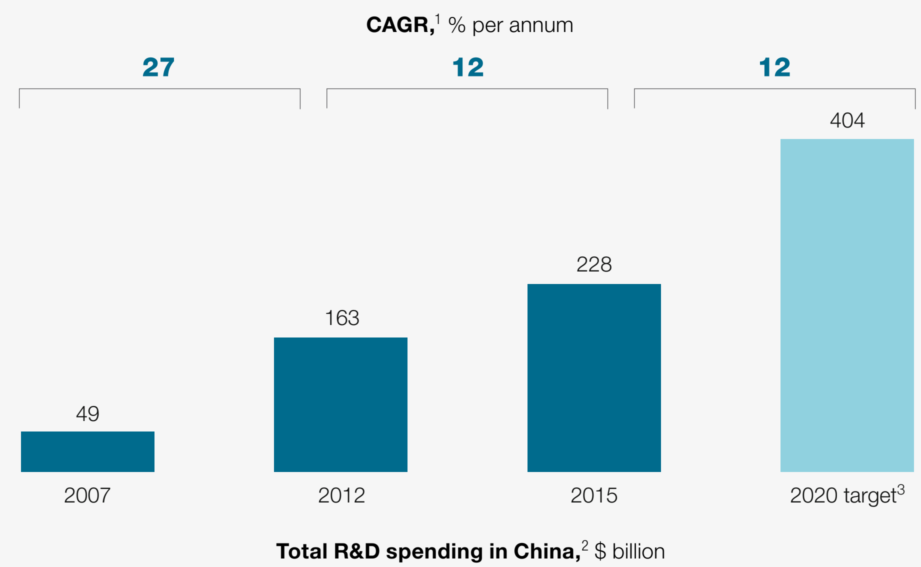
This article first reviews findings from the survey, discussing the evolution of OEM China design centers, their aspirations, and the government's role in promoting product development in China. It then focuses on strategic issues that semiconductor companies must consider when attempting to win business in China's thriving product-development landscape.

The growth of product development in China

Between 2007 and 2015, overall R&D spending in China rose more than fourfold across all companies and industries—the fastest growth among major countries or regions in the world (Exhibit 1). The increase was driven by both OEMs headquartered in China and MNCs with design centers there. Much

Exhibit 1 **China is an increasingly important component of global R&D and product development.**

R&D spending in China has seen double-digit growth since 2007



[1]Compound annual growth rate.
[2]R&D expenditures include current and capital expenditures (both public and private) on creative work undertaken systematically to increase knowledge or to apply knowledge to new applications. R&D covers basic research, applied research, and experimental development.
[3]Estimated from forecast of China GDP in 2020 ($16 trillion) and the Chinese government's target of R&D spending as % of GDP in 2020 (2.5%).

Source: International Monetary Fund; National Bureau of Statistics of China report; World Bank data; McKinsey analysis

McKinsey survey of OEM China design-center heads: Methodology

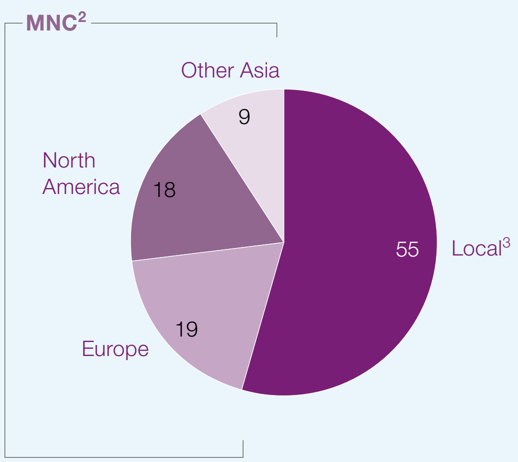
Throughout 2016, we surveyed about 80 R&D and product-development executives in OEM China design centers. All survey respondents were based in China, with 55 percent working for OEMs headquartered in China and the remainder employed by OEMs headquartered in Europe, North America, and elsewhere in Asia (exhibit). About half—54 percent—worked at companies that developed IT products, and the remainder were in other advanced industries, such as medical devices, industrial products, and automotive. Respondents averaged more than ten years' experience in China. The companies represented in the survey accounted for $1.6 trillion in global revenue and typically had three to five R&D sites in China. This survey follows a similar study that we conducted in 2012, and we compared our results with the previous findings.

Exhibit

Our 2016 survey included about 80 China-based R&D and product-development heads in nine industries.

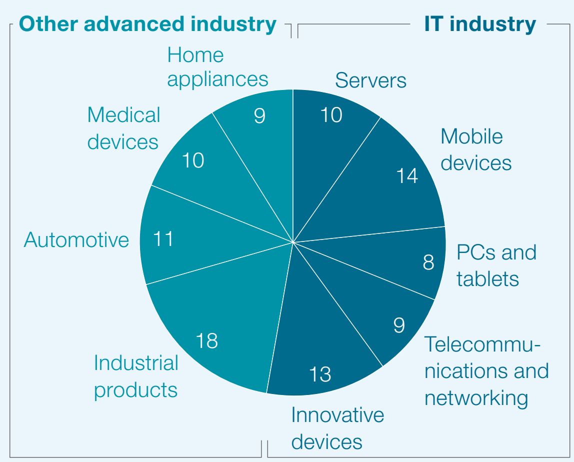
The survey covers companies from various regions . . .

Location of company headquarters, respondents, %[1]



. . . and various industries

Industry, respondents, %[1]



54% of respondents were in IT-related industries.

[1]Figures may not sum to 100%, because of rounding.
[2]Multinational corporations have headquarters outside China.
[3]Local companies have headquarters in mainland China.

Source: McKinsey China product-development survey, 2016

of the spending was related to system-level, end-product design in IT and advanced industries, the sectors that formed the focus of our survey. R&D spending in China is expected to continue on its upward trajectory through 2020.

According to McKinsey research, roughly 15 to 20 percent of OEM product development in IT and advanced industries took place in China in 2016. (This is at an aggregate level; China's share of global product development varies substantially by industry subsegments.) China's share of the global end market for IT and advanced industries is also about 15 to 20 percent. Locally owned centers account for 70 to 80 percent of product-development spending in China, with MNC-owned centers accounting for the remainder.

Survey respondents expect their OEM China design centers to increase their share of global product development over the next five years by about ten percentage points. If this growth materializes, China will account for 25 to 30 percent of worldwide product development. This shift would realign the global product-development footprint, with $150 billion to $200 billion in annual product-development spending moving to OEM China design centers. Growth estimates varied somewhat by industry, but all respondents believe that locally owned centers will account for almost all of the increase in product-development spending in China.

Despite recent economic challenges in China, growth of the country's end market will continue to outpace the global average and is expected to have an aggregate value of $3.5 trillion by 2020. But even with this above-average growth, China will represent only about 20 to 25 percent of the global end market. This means that China-based product-development activity might grow more rapidly than the Chinese end market.

For component suppliers of OEM China design centers, the stakes are high. Managers at the location where an end product is designed and developed generally make important "design-in" decisions about its components, including semiconductors. If OEM China design centers gain ten incremental points of product-development share (and associated design-in), they could account for an additional $150 billion in component sales—another substantial realignment of the global footprint.

Aspirations of OEM China design centers

How can OEM China design centers gain a greater share of the global market and become exporters of product designs? In the view of survey respondents, the path to this goal involves globalization and innovation.

> As the global market becomes more important and local customers increasingly focus on innovation, OEM China design centers must produce leading-edge products. To achieve this, nothing is more important than talented engineers.

Going global. Our survey showed that OEM China design centers, both local and MNC, would like to increase the number of products that can be exported outside China. Respondents from locally owned centers, regardless of industry, realize that this will necessitate a more global outlook. Currently, their initial designs only consider the needs of domestic customers. They then either modify the product for export to the global market or try to sell it internationally without modification. In the future, however, locally owned centers plan to consider input from both Chinese and global customers during the initial design phase, increasing the number of products with international appeal.

For MNC-owned centers in advanced industries, the goal of increasing exports is also relatively straightforward, since they already consider the needs of both global and Chinese customers and want to continue this approach. For MNC-owned centers in IT, however, the situation is more complex. Although they now consider the needs of Chinese and global customers during product design, our survey showed that they wanted to more closely emulate the locally owned centers' design model to gain an advantage with local customers. But like all other design centers, they also want to increase the number of products for export. These dueling ambitions could be difficult to achieve.

Creating leading-edge product designs. OEM China design centers want to create more leading-edge products that use the latest microprocessor architecture, connectivity technology, or software platforms. At MNC-owned centers, survey respondents hope to increase the percentage of leading-edge designs from 50 percent to 90 percent; respondents at locally owned centers hope to move from 30 percent to 85 percent. This obviously requires the development of better end-to-end capabilities.

Can OEM China design centers achieve their aspirations?

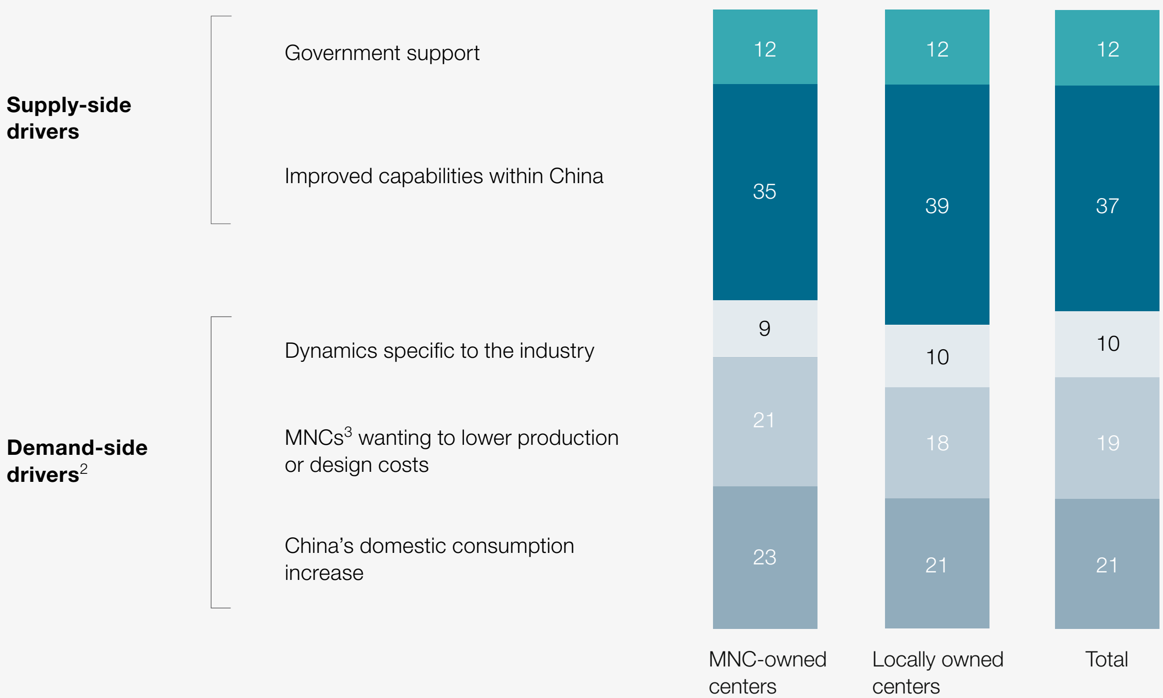
When we asked survey respondents if they were optimistic about the future of product development in China, 55 percent stated that OEM China design centers were already on par with, or superior to, leading global centers. However, 45 percent felt that they would never achieve best-in-class status. These divergent opinions are unsurprising, since there's evidence in support of both viewpoints.

Optimistic view: OEM China design centers will become global innovation leaders. As the global market becomes more important, and as local customers increasingly focus on innovation, OEM China design centers must produce leading-edge products. To achieve that goal, nothing is more important than the presence of talented engineers. Some of our survey findings indicated the OEM China design centers have a wealth of talent, with respondents stating that improved capabilities are the most important driver of increased product-development activity in China (Exhibit 2). Respondents also stated that they'd seen capability improvements across disciplines, especially software architecture, mechanical engineering, and electrical engineering. These upgrades have helped OEM China design centers continue to increase productivity despite wage inflation, including average annual increases of more than 10 percent in engineering salaries over the past five years.

An opposing view: OEM China design centers will take longer to achieve aspirations, or fail to do so. If we look at our 2012 survey, there's reason to be concerned about the ability of OEM China design centers to achieve global growth with leading-edge products. Back then, most respondents predicted that their design centers would become global leaders. But when we measured progress against these aspirations via our 2016 survey, these objectives were not reached:

Exhibit 2 **Product design is moving to China because of the increased capabilities of Chinese companies and engineers.**

"What are the main reasons your industry is increasing product development and design work in China?,"
% (respondents allocated 100 points[1])



[1] Figures may not sum to 100%, because of rounding.
[2] China's domestic consumption has recently declined as the economy has slowed. Wages have been rising, which has decreased China's cost advantage.
[3] Multinational companies.

Source: McKinsey China product-development survey, 2016

- MNC-owned centers did not achieve their goal of becoming leading "global centers of excellence." Instead, they became more focused on selling to the China market, possibly because domestic demand was growing so strongly and innovation was not as much of a priority for local customers during that time.

- Only 41 percent of products coming out of MNC-owned centers in China were described as "mostly new designs" (rather than lower-cost or derivative designs) in 2016—down from 48 percent in 2012. For locally owned centers, new designs decreased from 54 to 28 percent. This again may reflect an increased focus on the local market, which had not yet shifted its focus to innovation.

- Between 2012 and 2016, the share of products created specifically for the global market dropped from 70 percent to about 35 percent at MNC-owned centers and remained at about 30 percent at locally owned centers as domestic demand surged.

These findings indicate that OEM China design centers increased their resources, spending, and portfolios rapidly between 2012 and 2016, but they did so by focusing on the China market's overall desire for "value for money," which generally (but not always) involves derivative or lagging-edge designs.

Some other findings from the 2016 survey also raise concerns. For instance, only 55 percent of respondents believe that China's current engineering productivity is greater than the global average. Further, one out of five respondents stated that OEM China design centers are now less productive than those in other locations. A few more years of double-digit cost inflation, combined with a lack of corresponding productivity improvements, will make China a high-cost location for design.

There are also some concerns about engineering capabilities, despite the obvious gains made in recent years and the optimism expressed by many respondents. For instance, locally owned centers are less likely than MNC-owned centers to employ expatriates, China natives with overseas experience, or engineers who are proficient in English (the global language of product development). All of these factors may interfere with the dual goals of globalization and innovation. The lack of engineers with international experience may become a greater issue, since survey respondents at locally owned centers think that their engineering staff will include a greater percentage of China natives in the future.

The impact of new government policies on OEM China design centers

Over the past few years, the Chinese government has indicated that greater innovation in manufacturing and product development is a national priority. For instance, the "Made in China 2025" policy, implemented in 2015, aims to upgrade Chinese industry across sectors, with a focus on improving quality and helping local companies achieve a greater role in the global supply chain. Most of our survey respondents—53 percent—believe that new government policies will have a major impact and increase product development in China. For instance, agencies granting government contracts might favor companies that are headquartered in China or whose products contain many components made in China.

Our survey also revealed that OEM China design centers believe that the government will provide more incentives, including subsidies, for companies to create products that can be considered Chinese in origin. For locally owned centers, this is not an issue, since their products will be Chinese by default. MNC-owned centers, by contrast, will need to take additional steps for their products to be considered Chinese. Many respondents stated that branding and manufacturing strategies, such as forming a partnership with a company headquartered in the People's Republic of China (PRC), could make a product local in the eyes of government or state-owned entities (SOEs). Others felt that engineering-based approaches, such as using software-source codes from PRC-headquartered companies, would help. Only 25 percent of respondents believe that the inclusion of core components from PRC suppliers will increase the likelihood that a product is classified as Chinese. However, 61 percent stated that the inclusion of components from PRC-headquartered companies will be important within five years—and that has major implications for the semiconductor suppliers that serve OEM China design centers.

The $500 billion treasure hunt for semiconductor and component suppliers serving OEM China design centers

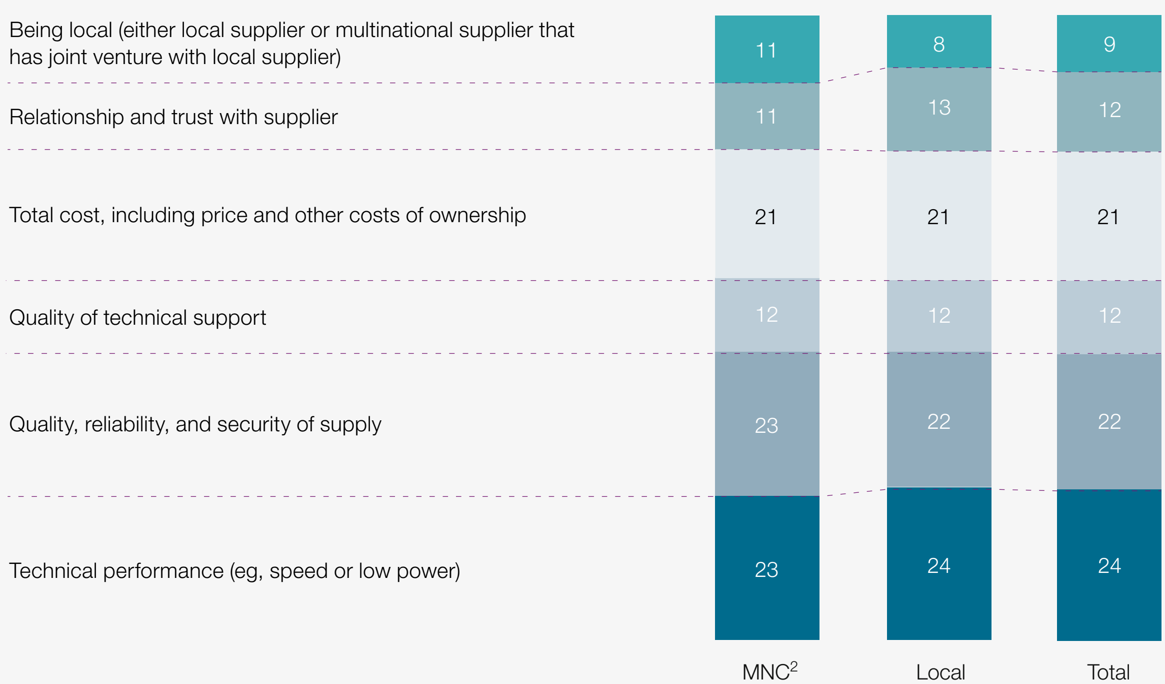
For component suppliers aiming to win the next generation of OEM designs in IT and advanced industries, the stakes are high. If our respondents are right and China adds ten percentage points to its global share of product development by 2020, OEM China design centers could control $500 billion worth of design-in decisions for critical end-product components, including semiconductors, up from roughly $350 billion in 2016. This growth could represent the single largest opportunity for component suppliers globally in the next five years.

To win, component suppliers will have to understand the rapidly changing market. For instance, McKinsey research indicates that locally owned centers now account for about three-quarters of demand for semiconductors and other components in China, largely because they have complete freedom when making purchase decisions. By contrast, 49 percent of survey respondents at MNC-owned centers stated that they had little or no influence over the choice of core components for leading-edge designs, instead following decisions made at their headquarters. That may soon change, however, since two-thirds of MNC respondents believe that their Chinese design teams will have primary or equal control over component selection for their designs by 2020. That means both MNC-owned centers and locally owned centers could represent important opportunities.

Shifting customer priorities could also have a major effect on component demand. Our survey indicates that OEM China design centers, both local and MNC owned, now select core components based on classic considerations such as technical performance, price, and quality (Exhibit 3). The location of a supplier's headquarters is of relatively little

Exhibit 3 **MNC-owned and locally owned centers care about the same factors in selecting core components.**

"Please indicate the relative importance of key buying factors for choosing core-component suppliers,"[1]
% (respondents allocated 100 points)



[1] Figures may not sum to 100%, because of rounding.
2 Multinational company.

Source: McKinsey China product-development survey, 2016

importance. This may soon change, however, since many MNCs want to indigenize their supply chains. That means they'd like to include more core components from PRC-headquartered suppliers so that the government and SOEs will consider their products local. In our survey, MNC respondents indicated that the share of core components purchased from PRC-headquartered suppliers could rise from 22 percent today to 32 percent within five years (Exhibit 4). For the total bill of materials, MNC-owned centers could increase sourcing from PRC-headquartered suppliers from 30 percent to 40 percent. If this happens, up to $50 billion of the servable market would shift toward PRC-headquartered suppliers.

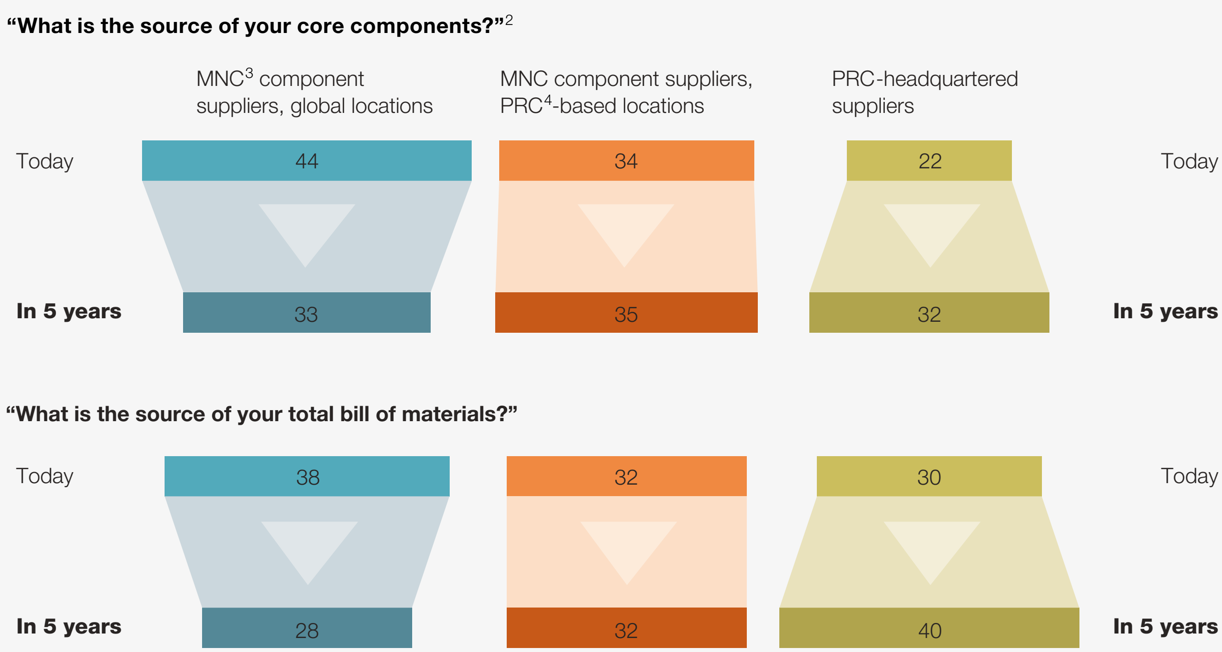
How can MNC and PRC-headquartered semiconductor suppliers succeed in this rapidly changing environment? What strategies will help them grow along with OEM China design centers and ensure that their components are incorporated into new global, leading-edge designs?

As in any market, strong execution will be critical to winning. But the size and complexity of the China opportunity may create some additional complications. For instance, component vendors may have difficulty determining which locally owned centers represent the best opportunities, since many are still developing the capabilities needed to compete globally and produce leading-edge products.

Exhibit 4

MNC-owned centers aspire to source more core components from PRC-headquartered suppliers in the future.

% (respondents allocated 100 points)[1]



[1] For core components or bill of materials, % shown represents share of total component spending that MNC-owned centers gave to each type of supplier.
[2] Critical, high-value components that drive system architecture, such as hard drives and software-operating systems.
[3] Multinational corporation.
[4] People's Republic of China.

Source: McKinsey China product-development survey, 2016

In addition, the local OEM market is incredibly dynamic, especially in emerging growth sectors, such as electric vehicles, the Internet of Things, and smart devices. In the past year alone, China-based appliance makers, Internet companies, television-content players, and solar-panel manufacturers have all announced plans to become electric-vehicle OEMs. Although many of these players will enter the market with great hype, the hot company one year can be an also-ran the next. Such uncertainty can complicate investment decisions when suppliers are contemplating their options.

Strategic considerations for MNC component suppliers

It can be difficult for MNC component suppliers to create a coherent China strategy because they often have a fragmented view of opportunities and challenges within the market. Their local country leadership, CEOs, heads of business units, and global function managers may hold different perspectives based on experience and their own priorities. To avoid conflict, MNC component suppliers should invest in building a common and aligned fact base to accelerate decision making, such as information on customers that might point to the best opportunities. They'll also need to address some basic questions, such as how important it is for them to win in China, whether they're poised to succeed, and the extent of the competitive threat from PRC-headquartered component suppliers, many of which are rapidly improving their technological capabilities.

Customizing for China. Our survey, as well as discussions with project-development executives, suggest that OEM China design centers—both locally owned and MNC owned—appreciate suppliers that have a personal touch. In other words, they like to partner with companies that consider how their needs might differ from those of design centers in other locations. Suppliers might gain a particular advantage with OEM China design centers by tailoring their products, pricing, business arrangements, and technical support to the Chinese market. This could involve the following activities:

- designing components from the ground up for OEM China design centers, focusing on their desired performance and price points
- providing rapid turnaround on pricing and product road-map requests (without long reviews at headquarters)
- fulfilling orders through local distributors and system integrators
- providing physical and online technical materials in Chinese that target engineers with less global experience

These practices are straightforward to implement, but they may differ, in minor and significant ways, from a company's global processes. To implement them successfully, MNC component suppliers will have to shift some authority and road-map control to their local China teams. Empowering teams requires a delicate balance and may be one of the more challenging issues for MNC component suppliers to resolve. If they move too little authority and control, more nimble PRC-headquartered component suppliers will outhustle them for business. If they move too much, they might fragment their engineering function, wasting precious resources.

Increasing local investment. MNC component suppliers have to make hard decisions about increasing their "on the ground" investment in China—the amount they spend improving their local operations or forming partnerships with local investors, component suppliers, or other companies. A partnership could involve something as simple as providing technical support, or a more substantial

Winning in China will require MNC component suppliers to make some hard trade-offs and undergo operational restructuring across regions and functions.

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commitment, such as a minority investment. When evaluating their options, MNC component suppliers will need to identify the key buying factors for each of their target customer segments and determine if a greater investment in China would help them fulfill these needs. For instance, MNC-owned centers that conduct most of their business with PRC government entities are more likely to prefer PRC-headquartered suppliers so that their products will be considered "local." In cases like that, MNC component suppliers might not gain any benefits by forming a partnership with a Chinese player.

If MNC component vendors do move forward with partnerships, they should remember that OEM China design centers now have the same high expectations for technology, cost, and reliability as their global counterparts. A partner that falls short in any of these areas could thus make it difficult to win business. Whenever MNC component suppliers discuss increasing local investments, all options should be rigorously tested with a war-gaming mentality. For instance, they'll need to consider whether forming a partnership with a Chinese company will help if their other global competitors are doing the same thing.

Restructuring for success. No matter what path they choose, winning in China will require MNC component suppliers to make some hard trade-offs and undergo operational restructuring across regions and functions. For instance, they might need to move some decision-making authority out of headquarters to managers within China. To succeed, they'll need just as much support from home-country development teams as the local China team. Since it would be hard for these trade-offs to be driven from the bottom up, the MNC component supplier's senior-management team will need to orchestrate any actions.

Strategic considerations for PRC-headquartered suppliers

For PRC-headquartered suppliers, many of the most important strategic challenges involve their engineering capabilities. Most of these suppliers now win business from locally owned centers by offering low component costs and rapid time to market. In the future, however, locally owned centers will place more importance on finding partners with strong technological skills that can help them create innovative products for the global market. In our survey, respondents from locally owned centers stated that MNC technology and component suppliers are now their first choice for third-party partnerships, favoring them over other OEMs, Internet companies, and Chinese start-ups. To compete with their global rivals and prepare for long-term success with locally owned centers, PRC-headquartered suppliers will need to begin enhancing their capabilities now. They could take various routes to achieve this goal, ranging from hiring new engineers with the desired technological skills to acquiring leading-edge companies.

Improved technological skills will also help PRC-headquartered suppliers win business from MNC-owned centers, which have long focused on obtaining leading-edge components when selecting suppliers. If these centers increase sourcing from PRC-headquartered suppliers, as our survey suggests, new opportunities will open up. As with locally owned centers, those PRC-headquartered suppliers that offer the most innovative products could capture the largest share of new business.

■ ■ ■

Despite tremendous past success, OEM China design centers need to take their game to the next level by developing innovative products that will allow them to compete globally. They will need support from technology partners to achieve this goal, and both PRC-headquartered and MNC semiconductor suppliers are well positioned to provide it. The sheer scale of the opportunity to serve OEM China design centers, combined with the unique requirements of these customers, indicate that semiconductor suppliers cannot follow their traditional approach to the Chinese market. Instead, they must smartly and proactively build a new strategy that allows them to help OEM China design centers—especially the likely winners—meet their aspirations on the global stage. The stakes are huge. ■

[1] In this article, we use the phrase "OEM China design center" to refer to all design centers located in the country, both multinational and local. If we are specifically referring to centers owned by Chinese companies or multinationals, this will be specified.

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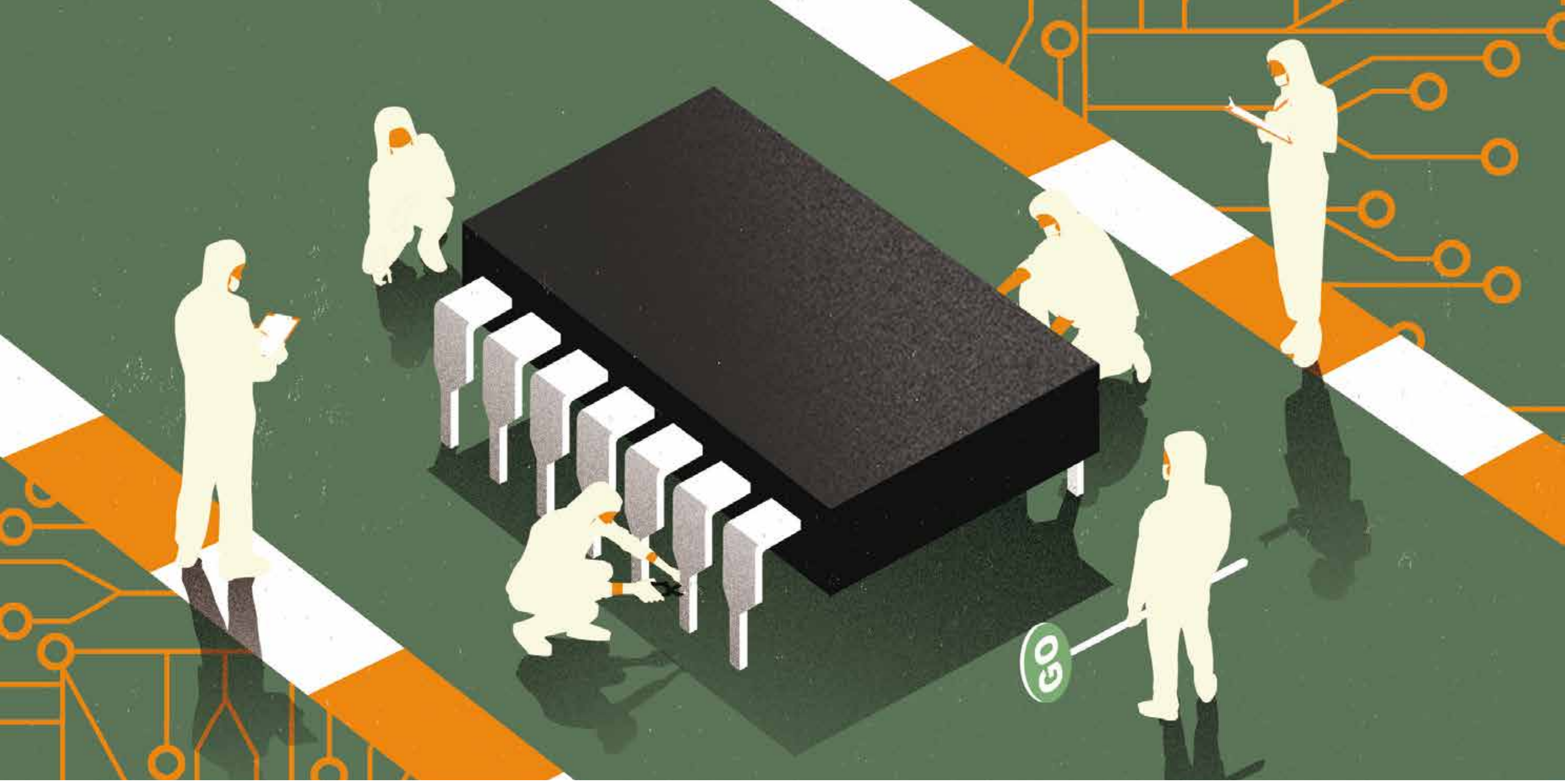

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Moneyball for engineers: What the semiconductor industry can learn from sports

R&D leaders can boost productivity by using advanced analytics to create stronger, faster engineering teams.

Eoin Leydon, Ernest Liu, and Bill Wiseman

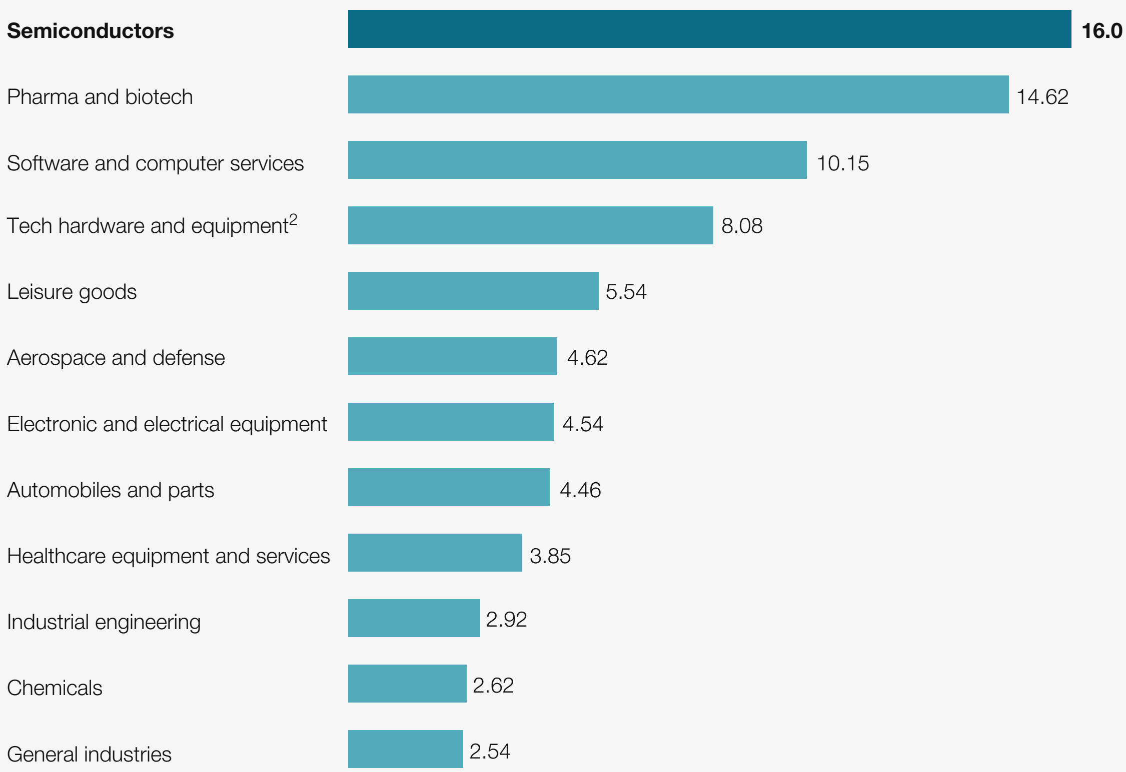
Semiconductor R&D budgets are growing by about 6 percent annually, and the drivers behind the soaring costs are easy to pinpoint. On the technology side, Moore's law is getting harder to maintain, while business models have increasingly shifted toward systems and solutions that require more complicated development processes. Organizationally, large internal software groups are now the norm as engineers grapple with increased complexity, especially in coding, testing, and verification. Given these developments, it's no surprise that semiconductor companies rank above those in other S&P 500 industries in R&D expenditures as a percentage of overall sales (Exhibit 1).

Semiconductor companies have already embarked on ambitious programs to decrease costs and boost productivity through advanced data analytics. But most of their efforts have focused on streamlining basic engineering tasks, such as chip design or failure analysis, rather than on improving management activities. Without automated tools to sort data, engineering managers have difficulty obtaining fresh insights and identifying patterns that might lead to better strategies. By default, they rely on the same management systems and performance metrics that they've used for years.

With costs continuing to rise, it's time for semiconductor companies to reexamine how advanced data analytics could benefit engineering management. Although they could find some inspiration by looking at data-driven strategies in similar industries, we believe they also have much to learn

Exhibit 1 Considered as a percentage of revenue, R&D spending is highest in the semiconductor industry.

R&D as a share of revenue in 2014,[1] %



[1]2014 data on the world's top 2,500 companies.
[2]Excluding semiconductors.

Source: EU industrial R&D investment scoreboard, IC Insights

from elite sports. The greatest lessons may come from baseball, where advanced analytics came into vogue after data scientists turned California's struggling Oakland Athletics into a top competitor, in 2002. The now-ubiquitous use of data science to select baseball players and design teams also contributed to the Chicago Cubs' historic World Series win in 2016.

How can semiconductor management learn from the advanced analytics used in baseball?

You don't need to understand baseball to appreciate the Oakland Athletics' transformation, which Michael Lewis described in his 2003 book, *Moneyball: The Art of Winning an Unfair Game*. The force behind the change was Billy Beane, the team's manager, who had a much smaller recruitment budget than major-league powerhouses, such as the New York Yankees. Since Beane couldn't afford to recruit stars with the best batting averages or other well-known performance measures, his statisticians investigated whether other metrics were equally or more effective in identifying talented players. One question was at the core of every analysis: What are the true drivers of winning teams?

To handle the massive volumes of baseball statistics, the team's analysts relied on tools that incorporated pattern recognition and machine learning. They could therefore sift through multidimensional data sets with greater precision and accuracy than a manual process would provide. Their research revealed that the teams whose players scored high on common metrics were not always the most successful. On the contrary, the statisticians discovered that certain overlooked metrics, such as on-base percentage combined with slugging percentage, had the highest correlation with a baseball club's success.[1]

Armed with these facts, Beane recruited players who scored best on these offbeat metrics and could be acquired for reasonable salaries when he assembled the 2002 team. His strategy paid off that season: the Oakland Athletics achieved a club record 103 wins, on par with the Yankees but with a much smaller budget.

Although the Oakland Athletics stopped short of a championship that year, the analytics-led approach has taken Major League Baseball by storm. It paid off notably in 2004, when Theo Epstein, then general manager of the Boston Red Sox, used data analytics to help his team win its first World Series in 86 years. After Epstein moved to the Chicago Cubs, in 2011, he again made data analytics part of his core strategy. In 2016, after a five-year transformation, the Cubs won the World Series for the first time since 1908.

Similar strategies have been applied in sports as diverse as European football (analyses to predict the likelihood of injury) and basketball (finding the best pairs of players, not just the best players). It may seem like a leap, but semiconductor managers might also benefit from using advanced analytics to determine which metrics—including unlikely ones—are correlated with success in R&D for both individuals and teams.

How do advanced analytics work in semiconductor engineering?

Over the past two years, several organizations—including an electronics manufacturer; pharmaceutical, oil and gas, and high-tech companies; and an automotive OEM—have taken a cue from Billy Beane to improve management techniques in complex engineering environments. The "*Moneyball* for engineers" approach, which relies on pattern recognition and machine learning, has uncovered counterintuitive insights, typically delivering productivity gains of 20 percent or more for engineering groups. With some fine-tuning, it is equally effective in all industries, including semiconductors. For more information on the origin of this approach, see the sidebar, "Lessons from Formula One racing."

You can't use batting averages: Where do semiconductor managers start when applying advanced analytics to engineering?

In baseball, statisticians have been compiling detailed data for many decades, and the fact base is easily accessible for anyone who wants to conduct an analysis. But most companies can't consult existing repositories that contain information on individual engineer performance, or even comprehensive data on project performance. Instead, they have bits and pieces of information scattered in siloed databases throughout the organization. For instance, separate databases usually track the following data:

- information on individual employees, such as current position, job grade or level, salary, prior employers, prior performance reviews, degrees, and patents

- project information, including team assignments, engineering time charges, milestones or stage gates, metrics on quality from design reviews, and the number of on-time tape outs and re-spins

Lessons from Formula One racing

Although we've been focusing on baseball analogies, the approach described in this article was first applied to another sport—Formula One racing, where milliseconds can determine the winner. When a racing team wanted to prioritize car-development projects that would improve performance on the track, it looked at available data within its IT systems, including email traffic, project-management records, human-resources information, and time vouchering. With this information, the team identified important performance drivers for developing cars and uncovered some counterintuitive findings that helped the company develop a better early-warning system for projects, so it could identify potential problems before investing large sums. The overall R&D yield increased by 18 percent.

- product information, such as customer-support logs, sustaining-engineering logs, bug-tracking logs, documentation, app-note authorship, and app-note downloads
- collaboration information, including communication patterns (such as the number of meetings in an employee's online calendar and the frequency of emails to other group members); simulations; and analysis-system log-ins
- customer information, such as documentation, troubleshooting requests, and complaints

Companies following the *Moneyball*-for-engineers approach combine the information from these databases into a central repository, or data lake. The criterion for the inclusion of individual data sets should be their perceived relevance—specifically, whether a variable appears to influence engineering performance. Companies should also consider their confidence in the data (whether information is accurate and reliable), completeness (including whether long-term findings are available), and the level of detail. Within the data lake, they can link data sets by using tags, such as employee- or project-identification numbers (subject to the caveat below).

Evaluating individual performance: What's the equivalent of slugging percentage in semiconductor engineering?

It's easy to examine baseball statistics for on-base percentages or total bases and then identify the individual players who have scored highest on each. With engineers, however, individual performance may be more difficult to assess, since the metrics tend to be less straightforward. Another problem is that the typical engineering group is much larger than a baseball roster. All chief technology officers know who their five best people are but may be unfamiliar with the remaining staff, including most of their top 100 engineers.

Lacking information about individual capabilities, managers may have trouble identifying either problematic or exceptionally strong employees. They might therefore overlook opportunities to address performance issues and support professional development. Equally important, managers who do not have clear insights about their employees might create unbalanced teams with too many top or low performers.

Advanced data analytics can help identify talented people by uncovering patterns that may not be immediately obvious when companies look at individual performance. For instance, it might reveal which engineers consistently serve on projects that meet their release dates. One company that used analytics to assess individual performance segmented design engineers into one of three categories:

- top performers, who were two times more productive than the average engineer as measured by factors such as project costs and person-days

- project coordinators who tended to have significant communication issues (for instance, more than one standard deviation from the average email response time)

- the remaining staff

After this segmentation, the company adjusted the composition of its teams to improve their performance: for example, it ensured that top performers were allocated to separate teams so that more projects could benefit from their leadership and expertise. Dividing them among different teams also eliminated or reduced several problems, including potential clashes between experts about the best path forward. The company then discussed communication issues with project coordinators who appeared to be struggling and appointed additional staff to assist them or to serve as their backups, thus alleviating backlogs.

There's one caveat to this approach: in some countries, an analysis that focuses on individual performance might violate privacy laws or create problems with unions or workers' councils. In such cases, companies should use advanced data analytics only to identify and measure the drivers of team performance as described below, while keeping data about individuals anonymous.

Optimizing team performance: How do you assemble the best roster of semiconductor engineers?

We have conducted research to explore whether certain factors, such as geographic spread, influenced team performance, by looking at data from past analyses. We found that shifting certain staffing parameters, such as team size, could significantly increase productivity. While managers have long known that such factors could affect team performance, our analysis found that some of them have a far greater impact on outcomes than expected. These five are particularly important:

- *Team size.* Companies typically achieved the best results when project teams had a maximum of six to eight engineers, since they often had difficulty coordinating larger groups.

- *Team-member fragmentation.* Conventional wisdom says that engineers should focus on one or two projects to maximize productivity. But our analysis showed that productivity increased when engineers worked on more projects. For example, mechanical engineers in one organization did best when they worked on three projects simultaneously, and their productivity didn't drop until they were

> Advanced data analytics can help identify talented people by uncovering patterns that may not be immediately obvious when companies look at individual performance.

assigned to a fourth or fifth. By contrast, firmware engineers benefited from much higher levels of fragmentation, with teams seeing productivity gains when their members were spread across seven or more projects.

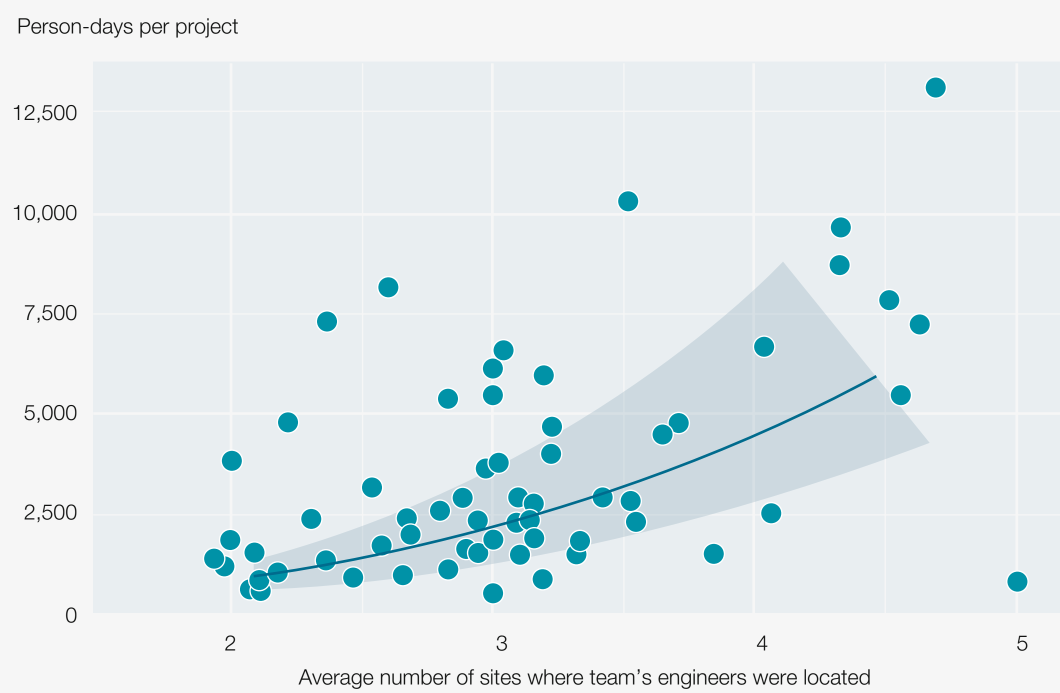
- *Collaboration history.* Strong group dynamics among team members who have worked well together in the past can raise productivity by 7 to 10 percent. There are some limits to this finding, however. In closed networks, where individuals tend to work with the same people on project after project, some teams may see performance decline, which can hurt overall quality, cost, and timelines. Companies can combat these trends by shaking up the membership of such teams.

- *Individual experience.* We analyzed how various personal attributes affected team performance in workplaces requiring high skills. Experience was the strongest performance driver, surpassing education level and other factors. Companies should therefore strive to have some experienced members on every team—and should also make greater efforts to retain them.

- *Geographic footprint.* Managers have long known that a diverse geographic footprint—team members based in multiple locations—can make teams less productive. Many, however, might not be aware of the extent of the problem. In our analysis, we found that adding an additional site to a team's footprint can decrease productivity by as much as 10 percent (Exhibit 2).

Exhibit 2

Dividing team members among multiple geographic locations tends to reduce productivity.



Source: QuantumBlack; McKinsey analysis

How do you track performance data for engineering productivity?

Typically, semiconductor companies track the performance of teams simply by looking at end results—metrics such as overall costs and person-days, as well as whether timelines were met. That's a bit like looking at a baseball team's wins for a season but not determining what contributed to them.

Our approach can help companies track performance at a more detailed level. For instance, companies can use advanced data analytics to determine how they performed on individual tasks that contribute to product quality, rather than just looking at the overall quality rate. The performance-analysis process is also automated—a big improvement from past practices, which required managers to comb through data manually, enter relevant results in spreadsheets, and create charts for various metrics. All performance information is displayed on dashboards, in real time, using simple visuals. The information is also retained after each project, giving current and future teams an easily accessible record of effective strategies and past mistakes.

■ ■ ■

With multiple challenges ahead, semiconductor companies are looking for new ways to decrease costs and increase productivity. If they apply advanced analytics to management, as they have to many basic engineering tasks, they can upgrade individual performance and create high-functioning teams. In addition to providing a competitive edge, these changes will help their employees gain greater satisfaction and more enjoyment from their jobs. It's a win for all. ■

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[1] On-base percentage is a measure of how often a batter reaches base (not counting bases achieved because of catcher interference or several other factors unrelated to a player's batting ability). Slugging percentage is a popular measure of the power of a hitter. It is calculated as total bases divided by the number of times a player is at bat.

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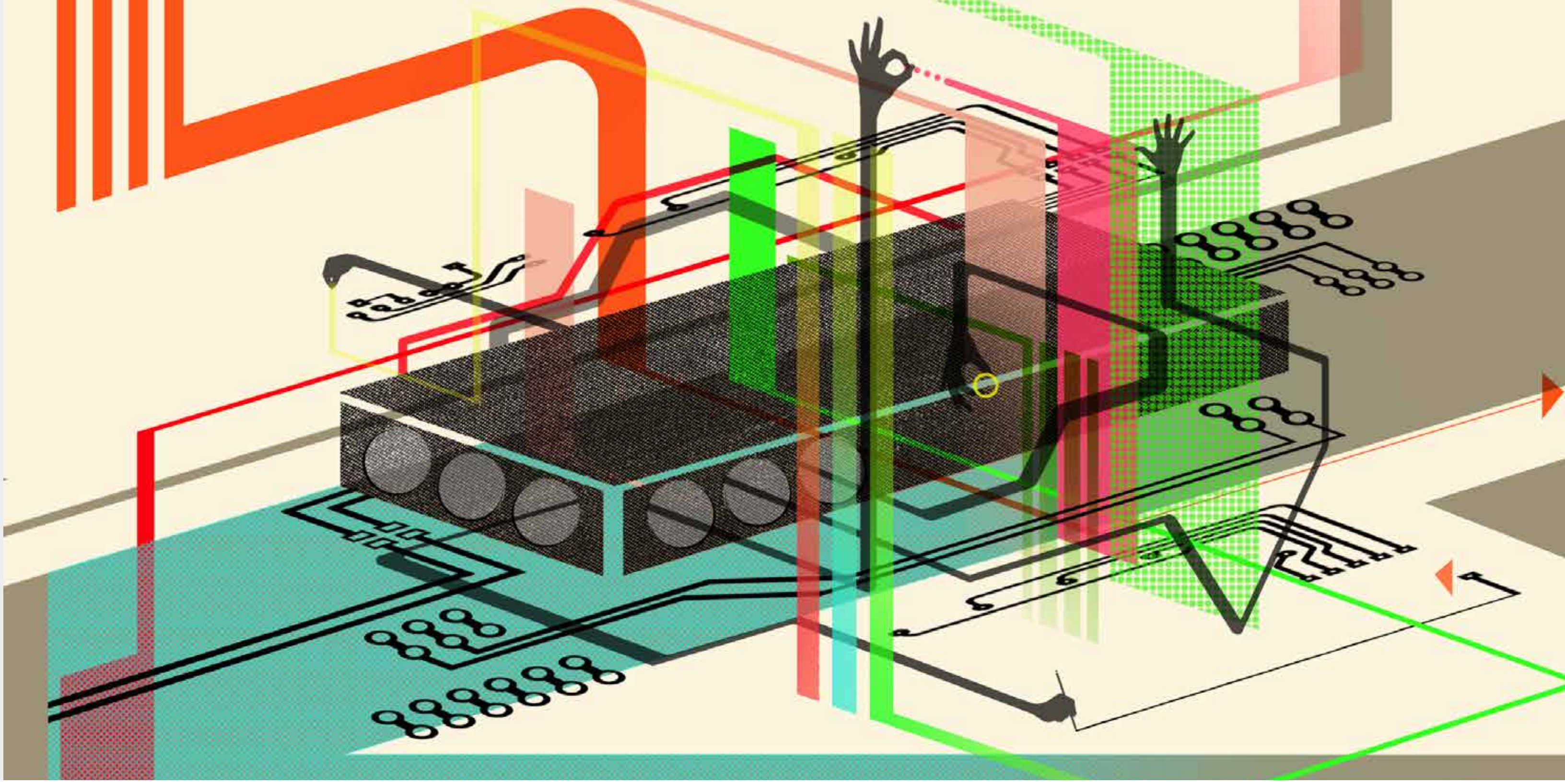

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Reimagining fabs: Advanced analytics in semiconductor manufacturing

Fabs want to streamline the end-to-end process for designing and manufacturing semiconductors. Will innovative analytical tools provide the solution they need?

Ondrej Burkacky, Mark Patel, Nicholas Sergeant, and Christopher Thomas

Across industries, the application of advanced analytics, machine learning, and artificial intelligence is disrupting traditional approaches to manufacturing and operations. While semiconductor companies have been somewhat restrained in applying these technologies, that may soon change—and with good reason. Lead times for bringing integrated circuits to market have been gradually rising with each node. New design and manufacturing techniques account for some of the increase, but more complex inspection, testing, and validation procedures also create delays.

A quick look at the semiconductor value chain shows that fabs need help in multiple areas (exhibit). There has been a 50 percent increase in test and verification time during the design process over the past few years, and new-product introduction and ramp-up now generally involves 12 to 18 months of debugging. Similarly, 30 percent of capital expenditures during assembly and testing relate to tests that do not add value. The problems don't stop after chips enter the market: customers may encounter unexpected performance issues and ask semiconductor companies to help resolve them—a difficult task, since there's no way to trace a chip from design through use. What's more, many fabs don't have efficient processes for recording problems encountered during production, or the steps they took to resolve them.

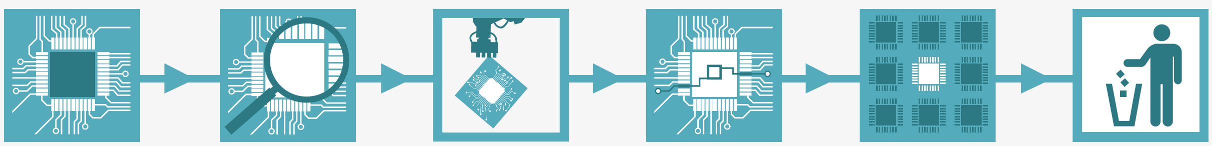
In many cases, problems arise because important tasks still require frequent manual intervention, despite having some degree of automation. To

Exhibit

Fabrication plants are struggling to manage increased complexity along the semiconductor value chain.

Current state of semiconductor value chain

Integrated-circuit design, process development, and factory setup	**New-product introduction and ramp-up**	**Wafer manufacture**	**Assembly and functional testing**	**System integration and after-sales**	**End of life**
50% increase in time in test and verification over the last few years	About **12–18 months** of iterative debugging	**80–90%** utilization and **85–95%** integrated yield	About **30%** of capital expenditures relate to testing that does not add value	**No end-to-end traceability** at device level	**Lack of feedback loop** at end of life



improve the process, many technology companies are now creating analytical tools that can help fabs replace guesswork and human intuition with fact-based knowledge, pattern recognition, and structured learning. In addition to reducing errors, streamlining production, and decreasing costs, these tools might even help fabs discover new business models and capture additional value.

Although analytical tools are just beginning to gain traction at fabs, semiconductor players already have many options from which to choose, since many technology players have recently developed specialized solutions to streamline the chip-manufacture process. We chose three companies from the large pool of innovators to serve as representative examples of nascent disrupters, interviewing their business and technology leaders to gain further insights into their capabilities.

Our goal here is not to endorse companies selectively but to provide diverse examples of emerging solutions for semiconductor companies that might be unfamiliar with the new offerings.

Optimizing yield by preventing errors proactively

Advanced data analytics now offers fabs an opportunity to test and flag possible points of failure in virtual or digital-design files. Companies can then correct errors in physical designs and improve yield and reliability without running a single wafer or making a mask. Fabs can also use the same techniques to generate and run virtual and actual test chips, allowing them to identify and eliminate marginalities while simultaneously optimizing processes. Finally, advanced data analytics allows fabs to combine numerous inputs from sensor and tool data with extensive process-level information to create a rich, multivariate data set. They can then rapidly isolate and amplify possible sources of chip or equipment failure, giving them an early warning of potential problems. The tools can learn from prior designs and enhance their ability to detect failures over time. To gain more insight about new tools that may prevent errors, we spoke with Bharath Rangarajan, CEO of Motivo, an advanced-analytics company that has enhanced the approach to predictive analytics by using proprietary algorithms, machine learning, and artificial intelligence to provide greater insight into diagnosing and preventing complex chip failures.

McKinsey: *Can you talk about some of the problems we're seeing with chip production, particularly error detection?*

Bharath Rangarajan: Each fab has thousands of process steps, which, in turn, have thousands of parameters that can be used in different combinations. With so many factors in play, we see a lot of chip failures or defects. But the frequency of each error tends to be very low, since the parameters are seldom aligned in exactly the same way during design and production. That makes it difficult for even the strongest engineering teams to predict where and when problems will occur.

Since fabs have traditionally had few analytical tools, they've tried to find high-frequency errors by making masks, running test wafers, and performing basic analytics. In other words, they changed a design or process to see if that eliminated a common error. That approach reduces some high-frequency problems in cases where only a few parameters need to be changed, but it doesn't help fabs identify low- and medium-frequency errors, which are much more common. It also doesn't identify the high-frequency errors that can only be resolved by changing numerous parameters—and those are the ones that often decrease yield.

Another problem with the traditional approach to finding errors is that it's hard to learn from past experience. As I mentioned, fabs have been able to eliminate defects by adjusting multiple parameters. That helps them with the current batch, but their tests don't give them insights about what caused the problem. By that, I mean they don't show the exact change that produced improvement, so it's possible they may repeat the same errors in the future. Fabs have also had some communication problems that lead to errors, since many design teams and process engineers aren't accustomed to describing problems in the same way, or even sharing data, including information about past failures. I can understand why that happens—a lot of times, the design and process people aren't even located at the same site, they speak different languages, and some of them might not even know about a problem.

McKinsey: *How do your tools work?*

Bharath Rangarajan: First, we analyze a customer's physical design—typically a graphic-database system II or Open Artwork System Interchange Standard file—those are the current industry standards for data exchange of integrated-circuit layout. Our tool extracts all features and combinations, from simple geometric patterns to complex structural patterns. Then we determine how these are linked.

After processing this information, we can identify a single point, or node, of failure on a topological network map, as well as the factors that contribute to the failure. For instance, the map will show how a failed node connects to causal nodes, providing a possible point of origin. Our map also helps customers determine what features and nodes to measure and test, which helps optimize yield. That's an improvement from the current practice of randomly selecting points, and it helps increase productivity for metrology and testing. You end up with superior metrology statistics.

There's still a role for some older, physics-based models in finding errors, but none of them can predict all possible complications or outcomes for advanced manufacturing processes. And they won't be sufficient as chip complexity increases.

McKinsey: *What sort of results can fabs expect in the field?*

Bharath Rangarajan: With advanced data analytics, we have the potential to alter the current paradigm dramatically. Right now, fabs run multiple batches of wafers and go through multiple costly iteration cycles to eliminate problems. That approach is also time-consuming because of the long cycles needed to process silicon wafers. If companies look more broadly at chip designs, they could reduce the lead time for yield ramps and the number of iterations required to eliminate problems with new products and processes by tenfold. That would have a big impact on timelines and silicon costs. In pilots, two semiconductor companies discovered failures and related failure modes in weeks versus a few quarters.

Enhancing wafer inspection

The inspection tools for semiconductor design and manufacture have become increasingly specialized, with their use limited to one narrow part of the end-to-end process. Fabs may need ten or more large, costly machines to accomplish the hundreds of steps that occur during wafer production, straining capital budgets and floor-space requirements. But what may be most notable are the tools' technological limitations: it can be difficult to transfer data from one device to another, import additional design layers, or program equipment to detect new errors. At many steps, manual inspectors must often review data from the tools—a process that may require the transport of hundreds or thousands of wafers to the inspection and metrology bay, increasing the risk of damage and making it impossible to capture process control and yield data in real time. To learn about new techniques for wafer inspection, we spoke with two officers at Nanotronics, a company that builds automated microscopes that incorporate artificial intelligence: chief revenue officer Justin Stanwix and chief technology officer Julie Orlando.

McKinsey: *Tell us about the use of your technology in chip inspection.*

Julie Orlando: Our microscopes combine nanoscale, micro, and macroscopic imaging with machine learning and artificial intelligence. They can find new defects automatically and share this information across the network. That eliminates the need for image tagging and other tasks that are usually completed manually and are inherently error prone. There's also a convenience factor with our microscopes, since fabs can use them for crystal growth, lithography, etching, and other processes rather than using different tools for these steps, as they've been doing. Another change is that the microscopes can inspect transparent, semitransparent, and opaque chips, as well as microprocessor units, MEMS [microelectromechanical systems] devices, and packaged wafers.

McKinsey: *Can you describe differences from manual inspections in a little more detail?*

Julie Orlando: Our microscope might analyze 100,000 chips within minutes, while a manual inspector could require 30 minutes to look at 50. Fabs can also inspect more layers if they use our microscopes, rather than manual inspections. We worked with one company that inspected 25 layers manually but increased that to 300 with our microscopes. Then there's the improvement in yield and throughput—fabs also see increases when they move from manual inspections to our microscopes.

McKinsey: *How does your software help microscopes share data?*

Justin Stanwix: Our software connects all the microscopes in the fab or fab network, so engineers can develop new algorithms to find correlations between defect-identification data and process-tool parameters. Then, they can incorporate the new algorithm into the microscope network immediately by updating the software. Our open-software platform and API make this possible, since they allow our microscopes to connect to other tools, including those that a fab might already have.

Connecting the semiconductor and electronics supply chains

Product engineers that want to improve quality often hit an important roadblock: difficulty in obtaining data from other players along the value chain. All too often, they collect only incomplete or piecemeal information about chips within systems or applications, leaving important pieces of the puzzle missing. We discussed better strategies for sharing information with two executives at Optimal Plus, a company that specializes in software for big data analytics: Michael Schuldenfrei, chief technology officer, and Yitzhak Ohayon, vice president of business development.

McKinsey: *Tell us a little about your technology.*

Michael Schuldenfrei: We created a cross-industry platform for connecting OEMs to semiconductor companies along the supply chain. It can track all data for individual products, including where and when they were manufactured, every piece of information from functional and electrical tests, data about the equipment that manufactured them, and usage conditions—things like humidity levels or operating threshold. So, basically, engineers get an end-to-end view of information about the product and its components, making it easier to spot problems. Our platform also allows engineers to pair and match devices coming from specific manufacturing environments. That can really improve reliability in a lot of critical end-user applications.

McKinsey: *Can you tell us about how your platform works?*

Yitzhak Ohayon: For the first step, we clean and normalize data. It has to be complete, accurate, and consistent across all locations and products. Then we enter the data into the platform, where it helps overcome one of the most important data disconnects: the lack of information exchange

> "With advanced data analytics, we have the potential to alter the current [semiconductor manufacturing] paradigm dramatically."

between the chip manufacturers that conduct wafer-sort testing and the electronic OEMs—either board or system customers—that conduct final testing. After comparing data from these tests through our platform, electronics vendors and semiconductor suppliers that agree to exchange data can determine if the results are highly correlated for a particular chip—a clear signal that it will probably function well—or if discrepancies exist. For example, a chip manufacturer can use data from its electronics customers to determine which test signals predict failure downstream and which signals don't affect the final product. This means that the chip manufacturer can fine-tune its quality screens to optimize yield. In other words, improving the screens reduces the number of devices with borderline quality.

McKinsey: *What sort of results have you seen with your platform?*

Yitzhak Ohayon: In 2016, we analyzed more than 50 billion chips. We've seen improvements in time required for testing, operational efficiency, yield, and test escapes.

In one case, we worked with an electronic-equipment OEM that wanted to bring a board-level design to market quickly. The company had encountered a lot of problems with chips and offered to give suppliers any board data they wanted in exchange for limited chip information. After correlating the board test data with the chip data from the original component supplier, we were able to find signatures in the chip-test data that predicted the eventual board failures. These findings reduced the amount of time it took the customer to analyze the failures. The result was a dramatic improvement in yield and time to market.

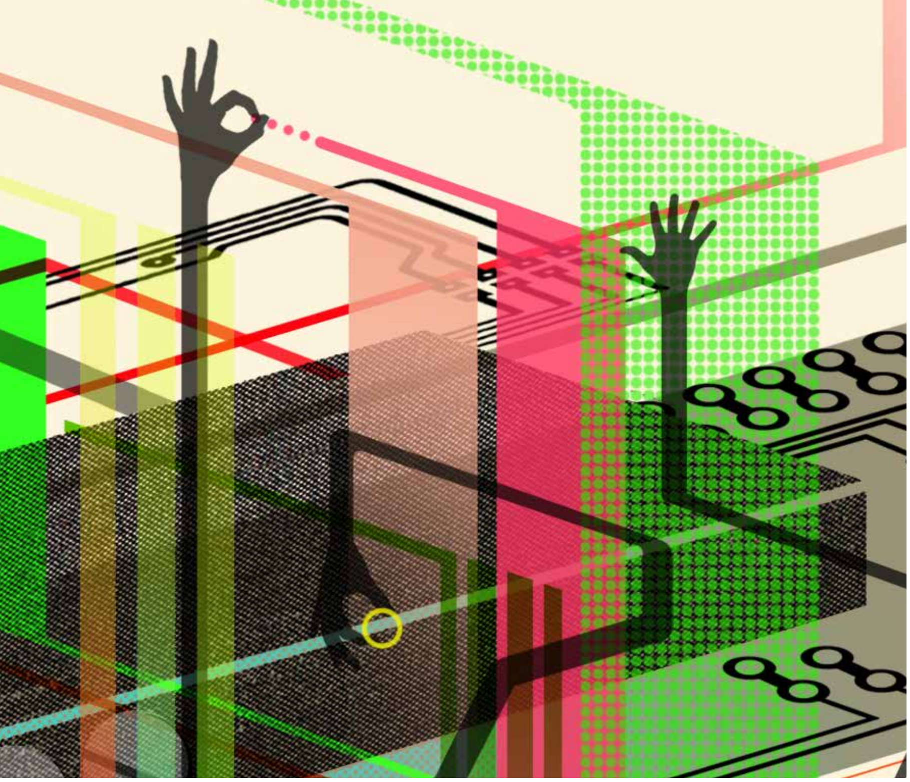
Using the same techniques, an electronics OEM reported that it has decreased the time required to achieve acceptable shipping quality by half. It also decreased the number of "faulty" chips with no trouble found on retesting by 50 percent. Those are the chips where customers report problems, often when they're used in combination with other chips, but that work fine when the manufacturer retests them on their own. The amount of time needed to understand product failure dropped from three months to one week. The new techniques also improved testing efficiency, since the number of chips the OEM had to test intensively dropped quite a bit.

McKinsey: *Do you see any barriers to using your technology or similar technologies?*

Michael Schuldenfrei: There are some barriers related to information exchange. For this aspect of our technology to work, semiconductor companies and their customers will have to share information more freely than they do now. It may be difficult to convince suppliers to share information, since they might wonder if customers will use their product data against them during negotiations. Hopefully, our platform can reduce some of those concerns by serving as a kind of third-party intermediary between suppliers and customers. They won't have to exchange information directly, and when we share data, it's all very controlled. We only release information when problems arise—typically, quality issues—and that keeps data exchange to a minimum. We've also seen some situations where electronics companies circumvent the problem by reversing the process and providing board-test data to their suppliers, so that's another possible solution.

What it will take to move forward

The aspirations are clear: faster translation of product and process into the fab environment, shorter time to market for new chip designs, lower overall cost resulting from higher and more predictable yields, and traceability through the



supply chain and later use for individual chips. Making this a reality will require technical innovation that is now well within our capabilities. But in our view, the semiconductor industry also has to go further by undertaking real work on at least four dimensions.

Talent

We are experiencing a talent drought in semiconductors. Few new graduates with data-analysis capabilities name semiconductors as their chosen field, and fewer still understand the incredible opportunity to innovate and deliver groundbreaking technology improvements. Consider the situation in North America, which has fewer than 10,000 recognized data scientists. Of these, the vast majority work in or in support of a limited number of application areas, most of which involve improving the personalization of advertising or marketing content. This skewed distribution creates problems for semiconductor companies that want to apply machine learning and advanced analytics to their operations. To attract and retain the right talent, semiconductor companies will have to create compelling working environments, where data science is recognized, rewarded, and given the same respect as other technical capabilities.

Organization

Functional and organizational boundaries provide clarity, but they can also hold companies back. For instance, many fabs are struggling to optimize chip design and process technology, but they lack an end-to-end view of manufacturing processes, making it difficult to spot problems and support faster yield ramps. They need to break down boundaries by bringing design and development organizations closer together, under common leadership, to align on goals. Otherwise, even the most compelling approaches to advanced analytics may not deliver the desired results.

Investment

Engineering is at the heart of fabs and chip-design organizations, not data science. That's why fabs are making only a limited investment in advanced analytics, despite the billions of dollars at play. And when semiconductor companies do create data-analytics groups, they tend to incorporate them into the realm of information technology or manufacturing technology, rarely recognizing them as a function in their own right. This needs to change. If semiconductor companies do not significantly invest in analytical capabilities, including the application of machine learning and artificial intelligence, the sector will fall behind.

Collaboration and partnership

Analytics and machine-learning vendors are often hesitant to enter the semiconductor market. In addition to fears that the customer base is consolidating, many believe that semiconductor companies like to develop solutions in-house, alone. This perception may persist because few software or analytics companies now collaborate with semiconductor players, especially in design and operations. In the future, semiconductor players must form active partnerships with technology and research companies to prompt new ideas, applications, and ways of thinking. In the past, the semiconductor sector has enhanced manufacturing and process technologies through collaborative partnerships, such as the one involving International SEMATECH and IMEC, an international research center. It is time that we created an equivalent model for advanced analytics, machine learning, and artificial intelligence.

■ ■ ■

The semiconductor industry presents a unique opportunity to innovate and experiment with advanced analytics, since no other sector creates as much in-process data, which provide insights leading to improvement along the entire value chain. Many new companies, including those discussed in this article, have recognized the opportunity and are bringing real data science to semiconductors. The use of such tools, combined with an increased appreciation for data analytics at the leadership level, could turn semiconductor companies into analytics leaders. ■

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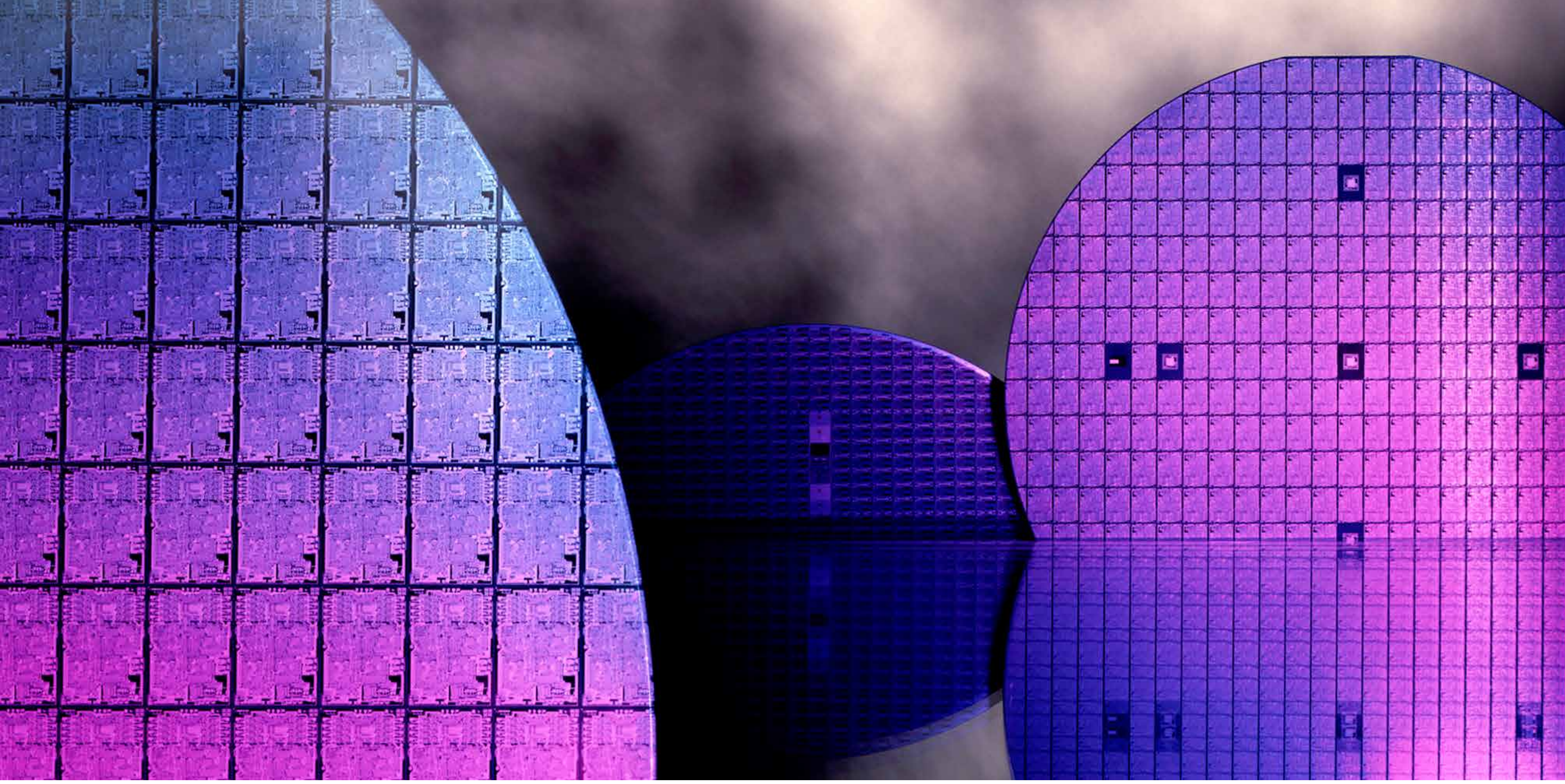

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Optimizing back-end semiconductor manufacturing through Industry 4.0

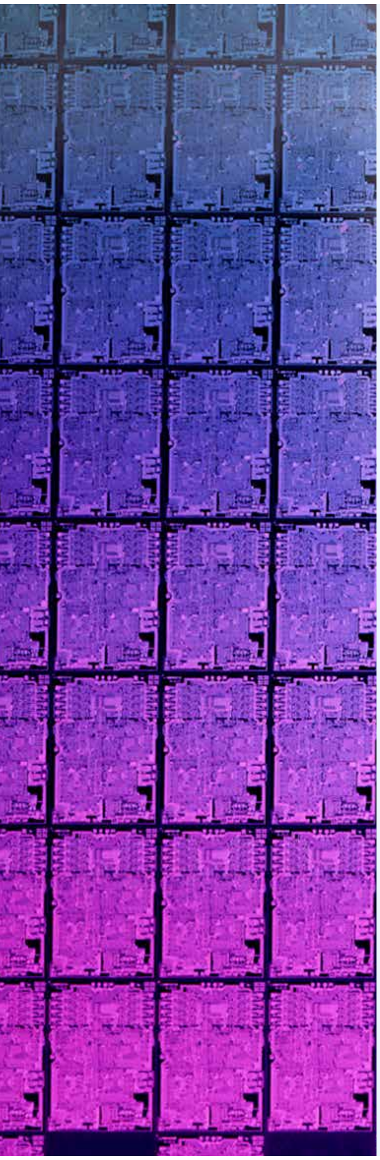
Can Industry 4.0 tools help back-end semiconductor factories capture elusive gains in productivity, throughput, and quality?

Koen de Backer, Matteo Mancini, and Aditi Sharma

It's a challenging time to be a semiconductor manufacturer. Wages and energy prices have been rising in traditionally low-cost manufacturing locations, while capital expenditures have increased. Meanwhile, competition is intensifying, with many new companies entering the market over the past few years. Industry players are rightfully concerned about these developments and have been undertaking a record level of M&A activity, hoping to capture the next wave of productivity improvements.

To remain competitive in this environment, front-end fabs—those that produce wafers—have focused on improving operational efficiency through a combination of lean programs and Industry 4.0 techniques. While lean initiatives are well known for their ability to reduce waste and promote continuous improvement, Industry 4.0 is an emerging concept that involves the increased digitization of the manufacturing sector—everything from big data analytics to increased automation (see sidebar, "What is Industry 4.0?").

Most back-end factories, which are primarily located in emerging markets, are far behind front-end factories when it comes to technology. They have not yet applied Industry 4.0 techniques to their major tasks, which include the dicing of wafers and the assembly, testing, and packaging of individual semiconductors. In fact, many of these facilities



What is Industry 4.0?

Industry 4.0 will introduce a new era of automated production and data exchange in factories—a shift that will change how they optimize operations and interact with other companies in their ecosystems. Under some definitions, the 4.0 in its name refers to the fact that it represents the fourth major disruption in modern manufacturing, following the lean revolution, increased outsourcing, and the first wave of automation. An alternative definition takes a longer-term view of manufacturing history, claiming that the first three disruptions involved the use of steam power, the discovery of electricity, and the introduction of computers in the workplace. In either case, Industry 4.0 represents a major advance that will change how we manufacture goods.

Industry 4.0 is a fairly recent innovation, and it wouldn't be possible without some recent technological advances: increased data volumes, computational power, and connectivity; the emergence of big data, analytics, and automated knowledge work; better human–machine interactions, such as those involving collaborative robots; and advanced production methods, including 3-D printing (exhibit).

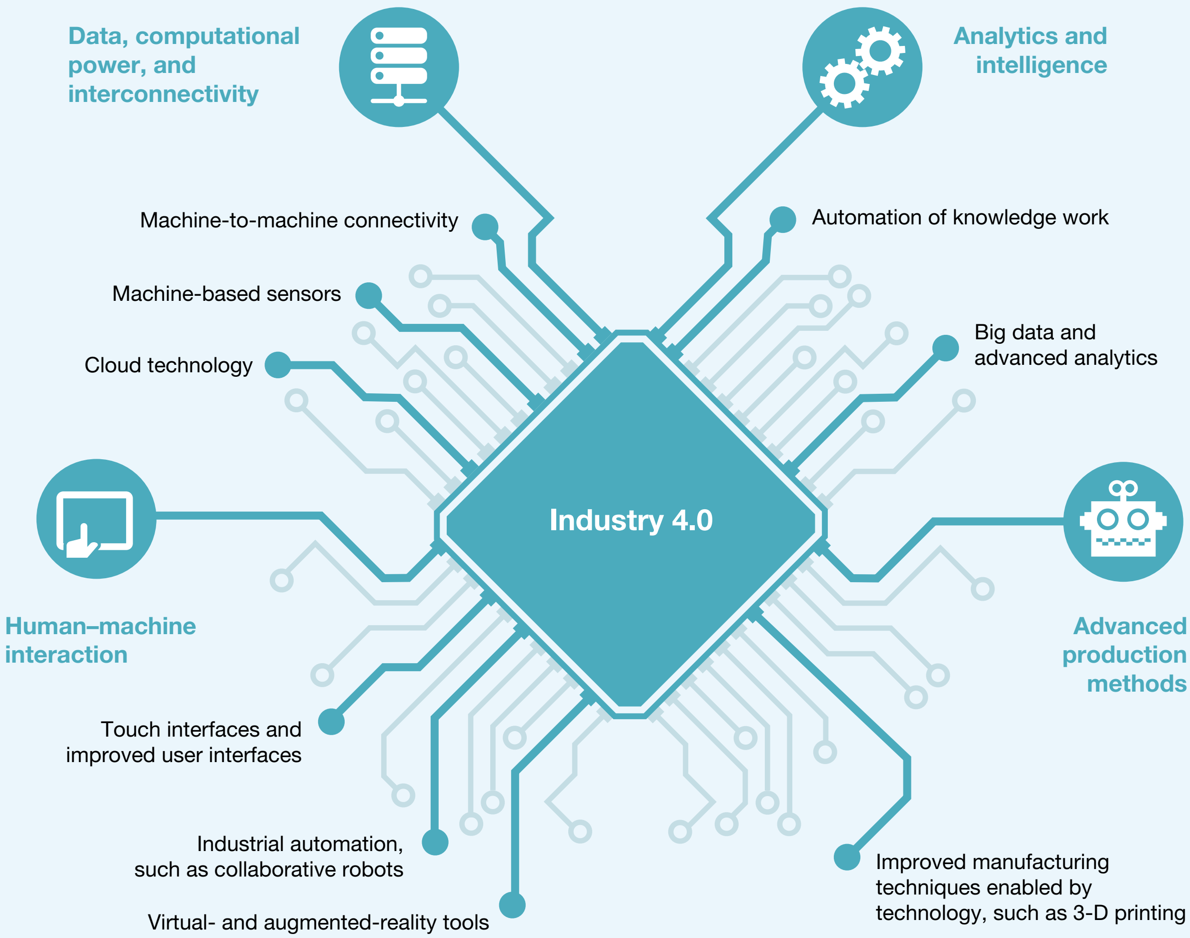
Although Industry 4.0 techniques are relatively new to front-end fabs and almost unknown at back-end factories, we've already seen some impressive results. The availability of low-cost automation options and advanced robotics is making it easier for chip manufacturers to reduce human error or accelerate production. Likewise, the use of sensor-enabled equipment and big data analytics lets semiconductor companies predict when plant equipment may need to be repaired or replaced ahead of any breakdowns. And better connectivity among products and machines gives managers more visibility into production steps, which helps them detect and address potential errors earlier in the process.

are still struggling to implement the lean techniques that are routine at front-end fabs. Even when back-end factories do achieve some benefits from lean programs, they often have difficulty sustaining improvement.

With cost pressures increasing, it's time to reverse this situation. Our experience with 20 back-end factories in Asia shows that a more disciplined approach to lean, combined with the introduction of Industry 4.0 techniques, can help companies attain the same benefits that front-end factories have long enjoyed by accelerating and sustaining improvement in labor costs, throughput, and quality. The potential increases from these technological improvements are significant. Factories can typically realize productivity gains of 30 to 50 percent for direct labor and gains of 10 to 20 percent for maintenance productivity. They can also anticipate average improvement of 10 to 15 percentage points in overall equipment effectiveness (OEE), increases of 1 to 3 percent in yield, and a 30 to 50 percent decrease in customer complaints.

Exhibit

Industry 4.0 results from the emergence of four technologies that are disrupting the manufacturing sector.



Making the most of labor

At back-end factories, operator touch time—that is, the amount of time an employee spends handling material or operating a machine—accounts for 30 to 50 percent of all labor. For the rest of the workday, employees are often idle while they wait for machines to finish their production cycle. Even if a line is not operating at full capacity, employee-to-machine ratios are fixed, which increases the amount of time that employees aren't directly engaged in work.

Some back-end factories have managed to improve labor productivity by applying standard lean techniques, such as adjusting worker–machine ratios based on operator touch time, or by introducing flexible staffing to ensure that the number of employees on the floor is appropriate for a factory's current capacity. These initiatives have produced some improvements, but they're difficult to sustain—and that means back-end manufacturing is still very labor intensive.

With labor costs continuing to escalate, it's clear that back-end factories need to step up their lean programs. But they also need to consider Industry 4.0 solutions that can complement and support their efforts. For instance, some factories have equipped machines with sensors that monitor performance. In some cases, engineers analyze the data in a central control room and adjust process parameters as needed; in others, Industry 4.0 tools make the adjustments automatically (exhibit).

Industry 4.0 tools may be particularly helpful for some of a factory's most labor-intensive tasks, including the loading or unloading of machines, or final packaging. For instance, factories could use collaborative robots with camera-equipped hands to pick and place parts precisely. Since the robots incorporate machine-learning technology, employees can "program" them simply by moving the robot arms and hands to new positions.

Exhibit

Remotely monitoring and adjusting machines from a central control room improves labor efficiency and increases yield.

1. Sensing hardware captures data

Machines collect and monitor data on process parameters

2. Software analyzes data and facilitates decisions

Models determine optimal process-parameter settings based on historical data

3. Users can steer processes remotely

Parameters are adjusted remotely by operators, or automatically in real time

In addition to automating many processes, Industry 4.0 tools make workers more effective at the tasks remaining under their remit. One tool, designed for maintenance staff, shows all actions these employees have completed related to a particular task, provides progress updates, and notes when problems have been escalated. The tool also captures photographs to supplement written reports, such as images of machines under repair.

Taking a more thoughtful approach to throughput

When assessing OEE, most back-end factories focus on absolute measures of uptime—equipment is either available or unavailable—and ignore nuanced findings such as minor stoppages that don't result in a complete shutdown. What's more, back-end factories track production losses through a manual process that only identifies general trends over time. These high-level findings don't provide engineers with a detailed fact base about the factors contributing to production issues, making it difficult to craft improvement strategies.

Some back-to-lean basics are necessary to combat such problems. For instance, factories could create continuous-improvement teams to set priorities and identify the root cause behind throughput shortfalls. These teams are a fixture at many companies, but they're far from universal at back-end plants. But lean improvements, by themselves, are not enough; factories also need to consider applying Industry 4.0 tools to accelerate the discovery and resolution of throughput issues.

Consider one straightforward innovation: machines could be equipped with sensors to record important events that affect OEE, including production slowdowns or equipment malfunctions. Operators would then use a touchscreen interface to enter contextual information, reducing the time spent on manual data input and providing engineers with a richer level of detail. More sophisticated Industry 4.0 solutions could take automation a step further by using problem-solving tools to examine machine-log data. These tools first analyze historical information and conduct automated data analyses to identify the root cause of problems. They then suggest solutions or automatically execute them.

Preventive maintenance, another essential element of efficient throughput, could benefit from Industry 4.0 tools that use advanced analytics to assess machine function in real time, with the goal of predicting failures before they occur. Typically, the tools collect information from multiple sources, rectifying any gaps or inconsistencies that might mar the analysis. They then search for patterns across multiple data sets, allowing them to create explanatory models and map performance drivers. With this information, engineers can create interventions that keep machines running.

Enhancing quality without slowing the line

If there are spikes or losses in yield, or unexpected quality issues at back-end factories, engineering teams must examine the machine data and speak to colleagues on the manufacturing line to identify the particular production steps that are causing losses. But engineers may collect the data only once a week, long after problems first arise, making it more difficult to identify root causes. Delays can be especially problematic if engineers need to interview production-line staff for information, since the workers may recall few relevant details about tool parameters or other operating conditions.

A better approach would involve establishing dedicated yield- and quality-improvement teams that have daily lean "huddles." These structured conversations can help engineers understand issues related to the stability and variability of outputs—knowledge that can drive improvements. The discussions will be even more valuable if participants receive insights from Industry 4.0 tools. Consider a few examples:

- *Yield tracking.* Analytical tools can generate automated yield reports that identify the major categories of quality rejects on each day of production, the reasons for product loss, and the machines or workstations where rejected units were processed. The information is quantified—for instance, the tools show the percentage of rejects associated with a particular machine or production problem—and displayed on a dashboard in real time.

- *Traceability throughout production.* Currently, back-end factories trace production units at the batch level, making it difficult to conduct detailed analyses that identify the specific source of quality problems. Industry 4.0 tools, by contrast, allow traceability at the individual-die level throughout production. Consider the case of a factory that was having serious issues with die cracks. Following traditional processes, engineers couldn't narrow down the source of problems or even determine whether the problems arose during front-end or back-end production. After applying Industry 4.0 tools, they could identify the front-end fab where rejected units originated, as well as all machines and operators involved in their manufacture.

- *Root-cause analysis.* Once companies have compiled data on individual production units and obtained yield information, they can use Industry 4.0 tools to conduct sophisticated multivariate analyses. For instance, the company that was having trouble with die cracks analyzed quality outcomes for all possible tool paths. It then determined that wafers processed using a certain combination of machines were much more likely than others to have problems. Another multivariate analysis revealed that wafers manufactured at a particular front-end fab were more likely to be rejected. This information helped the factory design interventions that improved yield by 5 percent within four months.

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The semiconductor industry is a leader in data collection; the problem is that companies use only a fraction of their information. Industry 4.0 tools can help factories mine their vast stores of knowledge for the first time, providing the detailed, practical insights needed to identify solutions. Equally important, Industry 4.0 tools automate many time-consuming tasks that back-end factories now complete manually. Together, these improvements help managers implement their lean programs more quickly and efficiently, with some companies capturing real improvement in costs, throughput, and quality within months. By leapfrogging over players who are taking a more traditional approach to lean, the back-end factories that embrace Industry 4.0 technologies may emerge as the winners in the increasingly competitive semiconductor sector. ■

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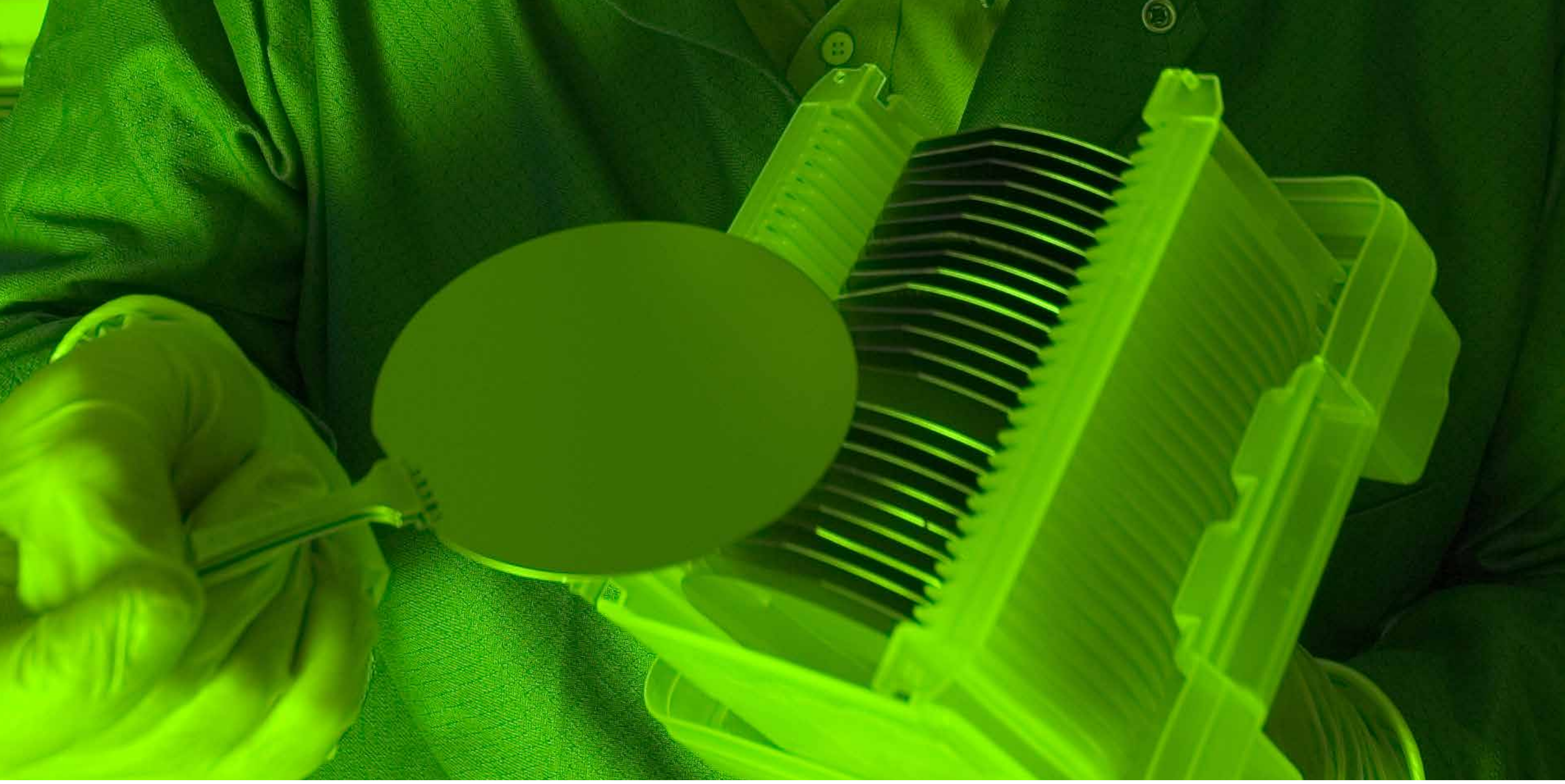


From hardware to software: How semiconductor companies can lead a successful transformation

Many semiconductor companies struggle when attempting to transition from hardware to software. How can they improve the process?

Harald Bauer, Ondrej Burkacky, Jörn Kupferschmidt, and André Rocha

It's a familiar scenario: a semiconductor company sees profits drop as core hardware products become commoditized. In response, it tries to move into embedded software and associated application software. The transformation begins optimistically, with the company projecting strong software sales, but difficulties quickly emerge. Timelines increase, the project hits snags, and software revenues fall below expectations. Instead of improving margins, the new business creates even more financial stress.

Despite these problems, we expect more semiconductor companies to increase their software capabilities over the next few years, attracted by the potential for high profits. To their credit, many players have acknowledged that previous transformation attempts were subpar and have made some improvements—for example, by taking a new approach to talent recruitment or streamlining product development. These efforts have helped, but they only address a few parts of the puzzle. No company has yet developed a comprehensive approach for navigating all stages of a software transformation.

We've tried to fill this gap by developing a framework based on our work with numerous companies in high-tech and advanced industries, including semiconductor players. It focuses on ten recommendations designed to optimize both strategy development and execution (Exhibit 1). Although the framework aims to create a thriving software business, the recommendations will also help companies enhance their core hardware business, which will always provide some of their revenues.

Software strategy: Keeping the focus on value

Traditional hardware players will be on unfamiliar ground when creating a software strategy. With a limited knowledge of the competitive landscape, customer needs, and effective pricing models, they may have difficulty developing a targeted approach. The following steps can help.

Creating a detailed transformation plan and incorporating it into the existing corporate strategy

Many semiconductor companies assume that their existing corporate strategy will serve them well for software. But software customers are fundamentally different from their hardware counterparts, requiring more frequent product upgrades and greater ongoing support. To reach them, companies will need a specific plan.

As with hardware, the software strategy will include a few basic elements—product offerings (including the main business opportunity for

Exhibit 1 There are ten core elements of strategy and execution for software transformations.

Strategy	Creating a detailed transformation plan that links to corporate strategy
	Involving board members in strategy development from day one
	Taking advantage of innate strengths, rather than imitating digital natives
	Capturing critical control points and network effects to create a competitive advantage
	Exploring multiple pricing options for software, rather than providing it for free
Execution	Appointing a high-profile software leader from another industry
	Taking a more strategic approach to talent recruitment
	Giving software groups independence, including their own governance bodies
	Maintaining separate processes for hardware and software development, but ensuring that groups communicate
	Considering the acquisition of a software company

Source: McKinsey analysis

each one), sources of differentiation, and specific goals, such as the time frame for becoming a market leader. The best strategies will go beyond this, however, by considering market research about common pain points and inefficiencies that a strong software product could resolve. For instance, Intel developed a high-performance software suite to assist with advanced analytics after research revealed that customers wanted help with such tasks. In some cases, companies may also gain a sense of a customer's software priorities and preferences through interactions on the hardware side.

Finally, the software strategy should support the existing corporate strategy. That means executives need to consider goals for the core hardware business—a segment that will always contribute to a company's bottom line, especially in the early days of a transformation, when it may be difficult to take market share from digital natives with strong customer ties. For instance, NVIDIA created deep-learning software based on its latest-generation graphic-processing unit, hoping that the new product would encourage sales of existing devices. It's also important to support the brand image articulated in the corporate strategy. Consider the auto manufacturer Daimler, which has a reputation for producing leading-edge hardware. To maintain its image as a technology leader, the company recently invested in building the digital capabilities needed to create sophisticated software offerings.

Involving board members in strategy development from day one

At many semiconductor companies, IT middle managers develop software strategies. This approach was appropriate when software was a secondary offering, but today's disruptive transformations, which see businesses shifting their focus from hardware, require board-level oversight from day one. Without central guidance, individual business units may create a mélange of small-scale programs that use different tools and platforms. In addition to generating low returns, these programs prevent companies from realizing synergies resulting from scope and scale.

Given that semiconductor companies have traditionally focused on hardware, board members will need to gather extensive information on the software value chain before creating a strategy. They may be able to gain customer insights by analyzing how their competitors moved into software, since this could help them identify popular products and services.

As with any strategy, many board members will have firm opinions about the best direction to take. Some, for example, may want to focus on becoming the top software provider in the semiconductor industry, while others view software as a lever for increasing hardware sales. Boards may be able to avoid these differences by closely involving all members in strategy development from the earliest stages. In some cases, it may help if the board creates a fact base that members can consult when making decisions, especially if leaders have limited software experience.

Taking advantage of innate strengths, rather than imitating digital natives

Semiconductor companies may be tempted to venture into areas where software start-ups are flourishing. Such moves may be challenging, however, since they typically lack the agility and speed of start-ups, as well as their highly specialized software skills. As an alternative, we suggest that semiconductor companies focus on opportunities where they can leverage their existing assets, such as a strong customer base, brand loyalty, a broad hardware portfolio, and domain knowledge.

Consider, for example, a semiconductor company that wants to develop network-communication software. If a start-up already offers data-visualization software that charts network efficiency, it could be difficult to create a competitive offering. A better strategy might involve developing a software program that delivers additional insights based on the semiconductor company's proprietary data, such as the reasons why a network access point had less data throughput on a certain day.

Semiconductor companies should also draw on their long-standing and powerful partnerships with suppliers, IT companies, and connectivity providers as they expand into software, since this will help them achieve scale more rapidly and efficiently. In some cases, they may even benefit from forming alliances with their traditional competitors. For instance, Audi, BMW, and Daimler—normally rivals—jointly acquired HERE, a data-mapping company, from Nokia. In addition to reducing the risks for each company, the acquisition increased their ability to compete with established mapping players.

Capturing critical control points and network effects to create a competitive advantage

Across industries, many companies have become software leaders by capturing control points—business segments that they can dominate because they offer unique products or services such as software programs based on proprietary data or algorithms. For instance, Siemens captured a control point by creating innovative automation hardware and software for manufacturing industries. The company now dominates this segment and serves 80 percent of OEM manufacturing lines, as well as 14 out of 15 major automotive OEMs.

In some cases, companies may attempt to strengthen their control points by giving their unique assets to other companies. The hope, of course, is that these companies will develop complementary products for use in a single system. NVIDIA takes this approach with its software-development kit for deep learning, which it provides free to start-ups interested in machine learning.

In addition to helping companies win control points, a strong product may generate a network effect—the phenomenon by which it becomes more valuable as more people use it. And once the network effect occurs, it may create new sources of income. For instance, Apple was able to generate significant revenues from its app store after the iPhone's ascent.

A product with a network effect may also boost a company's reputation for knowledge and expertise, allowing it to shape industry standards. For instance, Qualcomm was able to drive standardization efforts for 3G wireless technology because its telecommunications equipment was so popular. Since many of these standards are based on the company's own products, Qualcomm now derives one-third of its revenues and two-thirds of its profits from licensing royalties.

Exploring multiple pricing options for software, rather than providing it for free

Semiconductor players typically give customers free software in combination with a hardware purchase, hoping to encourage additional sales. Some companies also offer free software as a stand-alone product to attract customers that do not need new hardware. When companies do charge for software, many default to a one-time license fee because it provides guaranteed revenue at time of sale and allows them to sell additional services or charge for maintenance after a product warranty expires.

While free software and one-time fees are sometimes appropriate, semiconductor companies should not automatically revert to these models. Instead, they should evaluate several innovative pricing options, including the following (Exhibit 2):

- Under the "freemium" model, software is free, but customers must pay for improved features or functionality.

- With on-demand subscription services, customers pay only when they use software. Companies typically charge for any necessary hardware, since software revenues vary greatly under this model and may not cover their costs.

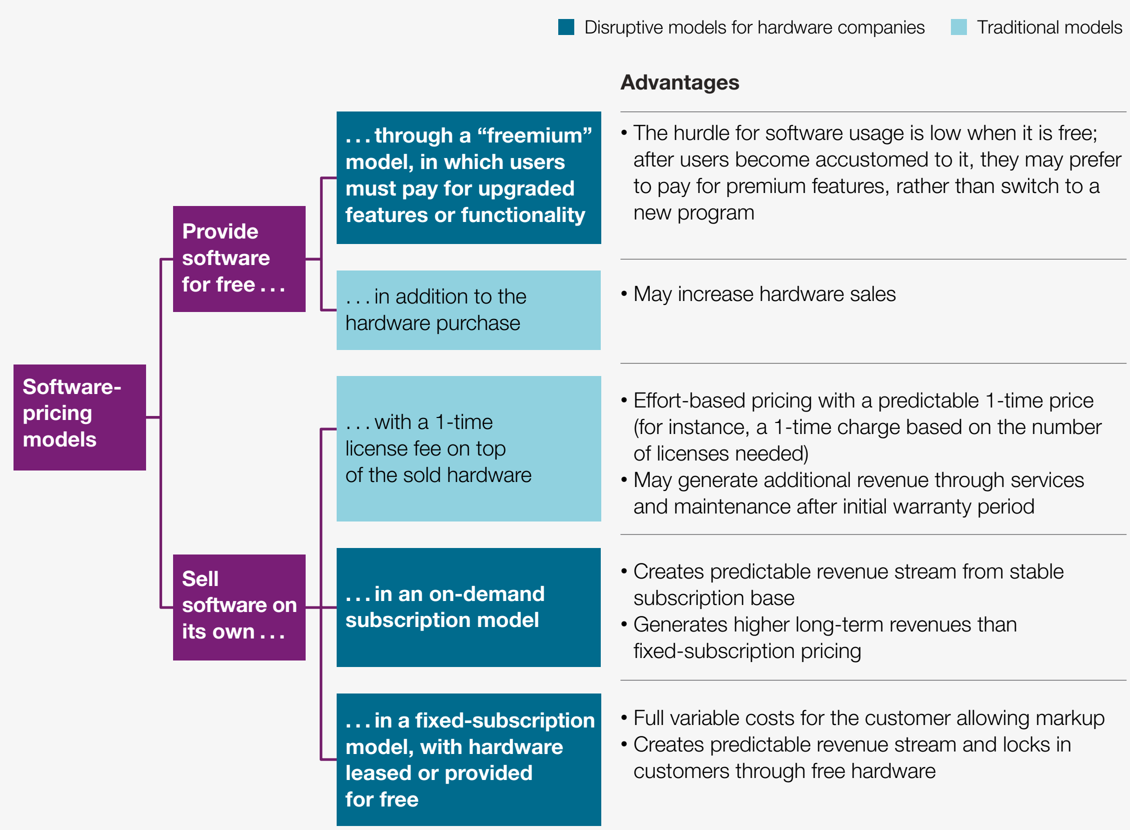
- With fixed-subscription services, customers pay a regular fee, regardless of how often they use software or receive upgrades. They lease hardware or receive it free.

Semiconductor customers may object to buying software, since they are accustomed to receiving it for free, so companies will need to create compelling products. For instance, semiconductor companies could provide software that allows multidevice configuration management or secure over-the-air flashing.

Software strategy: Optimizing execution

During each software transformation, semiconductor companies embark on extensive hiring campaigns to attract the talent needed for execution. While they begin optimistically, expecting the same enthusiastic response they receive when recruiting hardware experts, their efforts often falter. Company culture is one obstacle. Many software engineers do not believe that a traditional hardware

Exhibit 2 **Companies may select from several different pricing models for software.**



Source: McKinsey analysis

player can create an environment that promotes the development of leading-edge software products. Some also fear that their career opportunities will be limited. To address these concerns, semiconductor companies need to take a more innovative approach to talent recruitment and retention, both for top executives and midlevel managers. They also need to show their commitment to software by transforming both their company culture and organizational structures.

Appointing a high-profile software leader from another industry

Semiconductor companies that lack top software talent should recruit experienced leaders from other industries, rather than asking an internal hardware expert to manage the transformation. Unlike lower-level managers, many of these executives view software transformations as an exciting challenge, particularly if they began their careers in hardware. To attract the best talent, companies must emphasize that they will reward leaders for building the software business. They should also give leaders some freedom to shape the transformation—for instance, by allowing them to develop their own road map of improvement initiatives.

The appointment of a well-known software executive sends a clear message that software is central to a company's goals, both internally and externally, and it may prompt other talented engineers to investigate job opportunities. Experienced software leaders will also have numerous industry contacts and can reach out to talented colleagues if an appropriate position opens.

Taking a more strategic approach to talent recruitment

Semiconductor companies will need to be more aggressive and strategic when recruiting midlevel managers and entry-level software staff, given their reluctance to consider traditional hardware companies. First, they need to understand what high-tech employees truly value. Some of these are obvious, such as high pay, but others are more subtle. Drawing on our experience with high-tech companies, McKinsey has created a framework that classifies the factors contributing to employee satisfaction into four dimensions: compensation, job, company, and leadership (Exhibit 3). For instance, we found that employees were more satisfied when they could work on leading-edge content with up-to-date technology.

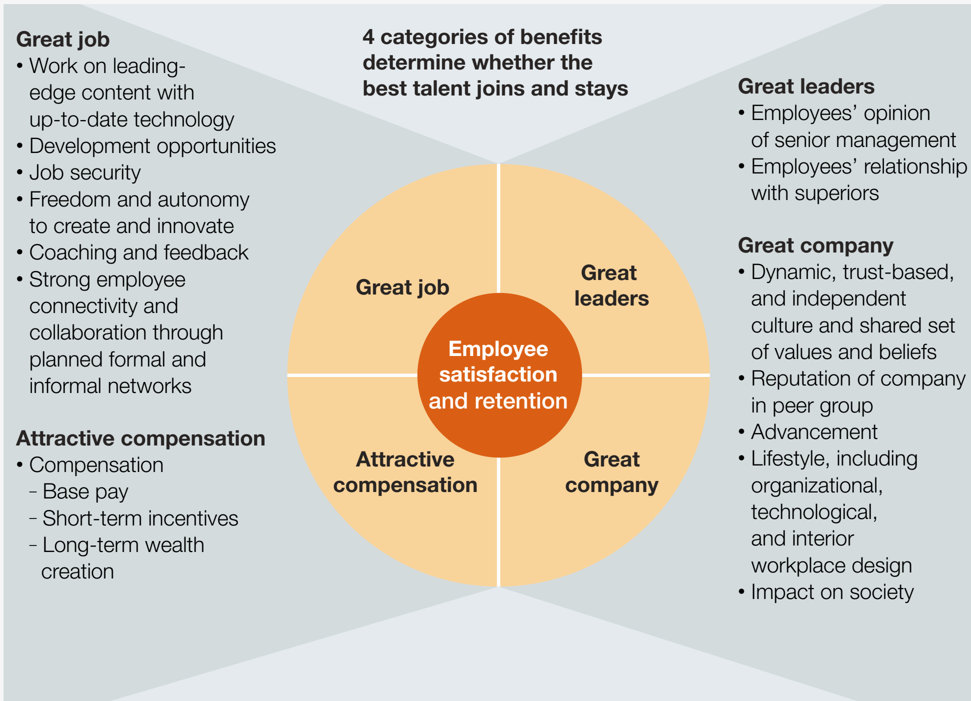
While it may be tempting to hire any talented engineer who becomes available, semiconductor companies should initially focus on recruiting the software and systems architects who handle interface specification and other crucial tasks during early development. These employees are in extremely high demand and are often difficult to find, but teams will make little progress without their guidance.

Companies based outside tech hubs like Silicon Valley face additional recruitment hurdles because of the small local talent pool. To attract a greater number of qualified applicants, including recent software graduates, their leaders should consider opening a new site in a location with a thriving technology culture. Software engineers often gravitate to such areas, knowing that they will have multiple job options and can strengthen their professional networks. The benefits associated with improved recruitment will outweigh the drop in productivity that often occurs when companies expand their geographic footprint.

Giving software groups independence, including their own governance bodies

Software engineers differ from hardware experts in how they think, work, and behave. Their projects are more likely to require collaboration with coworkers, for instance, and their products go through more frequent testing and revision cycles. Such differences mean that a well-intended effort to integrate software engineers into the existing organization could backfire, with new employees leaving because the company's culture is unfamiliar.

Exhibit 3 **Understanding why the best talent joins and stays is key.**



Source: McKinsey analysis

The solution to this dilemma is simple: semiconductor companies must adapt their organizational structures, rather than expect employees to change how they work. Executives should consolidate software staff into a single group that has its own governance body and decision-making power. For instance, software leaders should be able to establish their own processes for product testing and version control. As an added benefit, the group's scale, combined with its independence, will signal that software is central to a company's goals. Consolidation will also ensure that software employees use the same processes and tools, something that might not happen if they were scattered across multiple departments.

Maintaining separate processes for hardware and software development but ensuring that groups communicate

Many companies follow sequential development processes, always creating a hardware product before they devote any attention to software. This strategy may seem logical, since software has to run on devices, but it often leads to excessively long development timelines and potential synchronization problems.

As an alternative, companies should pursue a parallel development strategy enabled by leading-edge tools. Under this model, software development begins before hardware is available, with engineers testing their programs on virtual prototypes and making revisions. In some cases, they may finish their work before the hardware team has a final product. For this approach to succeed, hardware and software teams must discuss their progress at critical points, especially during hardware releases with tape outs, in order to reach consensus about goals, timelines, and desired features.

Considering the acquisition of a software company

If companies have an aggressive timeline for building their software capabilities, or if they are having difficulty finding an adequate number of engineers, they should consider acquiring a software company. This strategy could help reduce attrition, since team members who have a good working relationship with their colleagues are less likely to seek opportunities elsewhere. Established teams are also more productive from day one, since they have a shared understanding of development processes and procedures. On the downside, acquisition costs for a software company can be two to five times higher than those for hardware companies.

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The journey from a traditional, hardware-focused company to one with strong software offerings—either stand-alone or within other products—is long and difficult. This transformation is not a choice but a necessity, since companies that focus solely on hardware will see their margins continue to deteriorate, especially as customer preferences continue to shift toward integrated solutions. The ten recommendations outlined here are not a magic bullet, since transformations will always involve unexpected issues and company-specific challenges, but they may eliminate the most perplexing problems on the road from strategy to execution. ■

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