

AN MIT SMR EXECUTIVE GUIDE

Seven Technologies Remaking the World

As the digital revolution rages on, every business leader must become technology literate. This guide provides executives with an introduction to the technologies that are transforming our world.

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To cite this article, please use:

A.H. Segars, "Seven Technologies Remaking the World," *MIT Sloan Management Review*, March 2018.

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GUIDE**
MARCH 2018

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Seven Technologies Remaking the World

Introduction

Once upon a time, business leaders could leave technology to the technologists. But today, we are at the starting line of a *universal* technological revolution — one that is fundamentally altering four key realms of our world: commerce, health care, learning, and the environment. Given the pervasive and diverse nature of this revolution, business leaders must understand the technologies that are driving it, the capabilities they offer, and their potential impacts.

This report provides executives with a lexicon to the revolution. It identifies seven core technologies — pervasive computing, wireless mesh networks, biotechnology, 3D printing, machine learning, nanotechnology, and robotics — and describes their implications for commerce, health care, learning, and the environment. Use it as a guide and a basis for strategic discussion as you and your team seek to understand today’s business frontiers and the opportunities that lie ahead.

Seven Technological Sparks

“You’re only given one little spark of madness,” said the late actor and comedian Robin Williams. “You mustn’t lose it.” Williams used his spark to ignite his comedic rocket and blast past the established boundaries of his craft. Technology provides a similar spark: It enables us to push beyond the established boundaries of our world.

The mechanized spinning of textiles, large-scale manufacturing of chemicals, steam power, and efficiencies in iron-making sparked the first Industrial Revolution (1760-1840). Railroads, the telegraph and telephone, and electricity and other utilities sparked the second Industrial Revolution (1870-1940). Radio, aviation, and nuclear fission sparked the Scientific/Technical Revolution (1940-1970). The internet and digital media and devices sparked the Information Revolution (1985-present). In each instance, the inflection point that marked the new revolution was the appearance of new technologies that fundamentally

reshaped key aspects of the world, such as commerce, health care, learning, and the environment.

Today, we see technological sparks everywhere. They are emerging from the digital, chemical, material, and biological sciences, and they are precipitating a revolution that is altering nearly every dimension of our lives.¹

But what are the dominant technologies driving this revolution? And how will they shape and reshape the world of commerce — and the world at large? These are critical questions for executives, and the answers will determine how value will be defined in the future, how businesses will be structured and managed, and where new opportunities for profitable growth may lie.²

To help executives answer these questions, I conducted two surveys of veteran technology entrepreneurs working in companies in a variety of sectors, analyzed the results, and then developed and assessed the validity of the findings in a series of individual interviews and field visits. The study revealed seven classes of technology that are driving

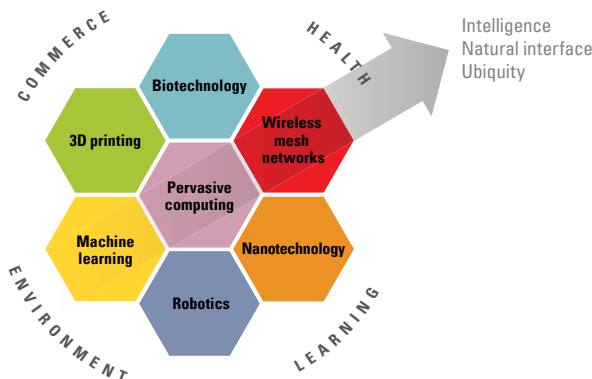
today’s universal revolution: pervasive computing, wireless mesh networks, biotechnology, 3D printing, machine learning, nanotechnology, and robotics. (See “Seven Technologies: A Strategic Framework.”)

Each of these technology classes exhibits three distinctive and rapidly evolving capabilities that are significantly different, more advanced, and larger in scope than the technologies of past revolutions.

- **Intelligence:** the ability to sense or predict an environment or situation and act on that knowledge. This extends far beyond knowing facts or rote learning; it is the ability to “make sense” of things.
- **Natural interface:** the ability to align with the actions, traits, and intuitive schemes of humans, as well as the physics of nature. It is the inclusion of voice, gestures, and other biomechanical cues in accomplishing digital tasks.
- **Ubiquity:** the ability to be omnipresent in previously discrete transactions, objects, machines, and people. These technologies can be embedded within everyday objects and surroundings.

SEVEN TECHNOLOGIES: A STRATEGIC FRAMEWORK

The author’s research reveals seven core technologies that are altering nearly every dimension of our lives.



What makes the seven technologies distinct and important is that each exhibits a universal impact in its own unique way. Individually, they are fundamentally changing the way we work and consume (commerce), our well-being (health), our intellectual evolution (learning), and the natural world around us (environment).

Beyond their individual impact, an intriguing and powerful aspect of the seven technologies lies in their potential as combinations. Today, we can draw distinct lines between the forms, capabilities, and evolution of these technologies. But already, the boundaries between them are beginning to blur. Soon, the synthesis of the technologies will give rise to new classes of super-technologies that not only transcend their discrete elements, but also offer rich opportunities to companies that can imagine and harness them.

In the sections that follow, I describe the seven technologies individually, explore their impact on our world, and offer innovative examples of their application. I will conclude the report with a glimpse of the impacts and opportunities ahead as the technologies combine.

While the content in this report is informed by expert technologists, it is intended for business executives and other nontechnical professionals. I encourage you to use it in whatever way suits you best. You can read it start to finish to understand all seven technologies and use it as a framework for creative discussion regarding how this emerging, universal revolution might reshape your company and your markets. Or you can dip into the report selectively and explore a specific technology as you encounter it in your work or life.

Pervasive Computing: Embedded, Proactive, Networked Digital Processors

What?

Pervasive computing, also known as ubiquitous computing, delivers information, media, context, and processing power to us, wherever we are. This class of technologies is characterized by vast networks of connected microprocessors embedded in everyday objects.

The way information is shared across these devices is very different from the way it has been shared in the past. In contrast to data being recorded and updated in private, centralized databases, data is now embedded and continually reconciled in public networks. This makes it more difficult to corrupt data, and it has vast implications for workflow, commerce, and financial systems. Witness blockchains.

Pervasive computing is the technology driving the internet of things (IoT), but it is more accurate to

ABOUT THE RESEARCH

The research for this report included two surveys of U.S.-based technologists, entrepreneurs, and executives with a minimum of 10 years of industry experience. The respondents represent young companies (age 2 to 10 years) operating internationally in emerging and fast-evolving technology-based industries. More than 300 respondents participated in the surveys.

In the first survey, the respondents were asked to evaluate the impact of a list of specific technologies across the realms of commerce, health care, environment, and learning, and add and assess the impact of technologies of their choice. The survey responses were factor analyzed, yielding the seven technologies described in this report.

The second survey was conducted with the same respondents to assess the validity and impact of the seven technologies. It revealed very strong support for the seven technologies and their impact profiles. Subsequently, respondents were randomly chosen for Skype interviews and field visits to further assess the validity of the identified technologies and gather more context about their impacts.

think of it as the engine of the internet of everything. Unlike conventional computing platforms, pervasive computing networks are unseen, everywhere, and always available.³ The informational, exchange, and collaborative capabilities of these networks are not confined to any one device or fixed location; they are distributed throughout the world in which we live. Further, the form factor of pervasive computing can be mobile, wearable, or implantable.⁴

Why?

Pervasive computing is reforging established chains of business logic. This is particularly true of the logic of value creation, which governs the interchange between the beliefs, values, and expectations of customers and the products, value chains, and practices of companies. Ownership and exclusive use once governed this logic, but now they are giving way to the information and access enabled by pervasive computing.

Pervasive computing supports the creation of products with a strong informational component that

can engage and be shaped by customers. It enables the ongoing construction and deconstruction of products. Such products are capable of improving over time — a quality that may sound the death knell for the old logic of use and obsolescence. In the near future, in the new logic of pervasive computing, a used car with years of experience on the road might be more valuable than a new one!

To tap into the opportunities of pervasive computing, executives will need to consider how connected digital devices, networks, and creative and customizable palettes of media can be embedded in their company's processes, products, and extended value chain.

Where?

Pervasive computing produces new forms of commerce by generating information companies can use to create value across a variety of products, services, and assets. Uber Technologies Inc. used pervasive computing to unlock the idle value that resided in the unused capacity of automobiles. By adding three or four passengers to a single fare to the airport, an Uber driver better utilizes the capacity of his or her vehicle and earns more, while passengers pay less for a level of convenience that was not possible before.

Pervasive computing can also enable companies to vault the barriers that once separated functions such as design, manufacturing, and selling. Now, connected devices provide information flows that can be used to integrate and orchestrate these functions across the supply chain. In these ways and more, pervasive computing gives rise to new opportunities, businesses, and value-generation models.

In the realm of health care, pervasive computing can be embedded in wearable and implantable devices that monitor, maintain, and ensure our well-being. VitalConnect's VitalPatch MD is a biosensor worn on the forearm. It has three electrocardiogram electrodes that detect and record the wearer's heart rate, temperature, breathing, and movements. This data is delivered in real time to the servers, computers, and mobile devices of health care professionals.

Pervasive computing promises to revolutionize health care processes. Once medical devices are equipped to respond, they will be able to deliver precisely targeted care, eliminating many of the side effects of prescription drugs. They will be able to sense an emergency, summon help, and electronically deliver medical records and experts to the scene.

Surgical instruments will be equipped with pervasive computing technology, too. Such instruments will be able to detect changes in a patient's vital statistics, enhance precision, enable faster response, and expand the lifesaving options available in acute care settings. In these ways and more, pervasive computing could help address the great and as yet unmet challenge of health care reform: the need to lower medical costs while improving care quality.

Pervasive computing is transforming the realm of learning from the isolated and disjointed islands of the classroom and the library to a continuous, life-long pursuit that is integrated with our daily lives. Such technology allows us to access information in highly customized ways from a variety of sources and share it any way we please: one to one (in a text message), one to many (in a tweet), many to many (in a Facebook group), and many to one (on Yelp.com). The access, conversion, and flow of information results in very short cycles of recall, comprehension, and application of knowledge. It also leads to new and radical pedagogical approaches to learning. Khan Academy has transcended the borders of classroom education using interactive multimedia, peer-to-peer streaming, and social networks.⁵ The Amazon Echo and other smart speakers are embedding learning in our lives.

In the future, pervasive computing will increasingly transform learning into an Echo-like, ambient flow that attempts to engage all of our five senses by discreetly integrating learning into our environment and allowing it to flow seamlessly through and across our devices and everyday objects.⁶ MIT Media Lab spinoff Ambient Devices Inc. is working to free us from the rectangular computer screen by developing digital platforms that deliver a variety of

background information through glass (windows and windshields), sound (smart speakers), and light (projection). Taking this idea even further, flexible organic light-emitting diodes (OLEDs) will allow designers to build displays into paper, clothing, wallpaper — on virtually any surface.⁷ In short, pervasive computing is extending a broader range of educational opportunity to more and more knowledge seekers.

In the environmental realm, pervasive computing is giving voice to the natural world. Witness the World Resources Institute's Global Forest Watch, a web-based app that uses satellite, sensor, and user information to create customized maps of land use, deforestation, and conservation. Global Forest Watch makes the riddle about the sound made by a tree falling in the forest a moot point: It lets government officials remotely monitor woodlands in real time and helps supply chain managers ensure the origins and sustainability of purchased timber.

Pervasive computing can provide complex data and analysis of ever-changing environmental conditions. Sensors enhance the detection of earthquakes, floods, fires, and other natural disasters, and improve the communication, coordination, and response of rescue and other professional personnel. They enable scientists and government planners to quickly assess scenarios involving natural phenomena, like hurricanes, and make much more accurate predictions.

In terms of consumption, pervasive computing supports the development of “smart” neighborhoods, where energy, water, and other resources can be efficiently and cost-effectively shared among residences. In smart neighborhoods, homes equipped with energy-efficient technologies, materials, and appliances are connected to a micro-grid of alternative energy sources as well as the traditional grid. The homes share performance data and energy use, which enables the delivery of new services to customers and more innovative energy management by utilities.

Wireless Mesh Networks: High-Bandwidth, Dynamic, Wireless, Smart Connectivity

What?

Wireless mesh networks (WMNs) are ad hoc loops of wireless connectivity in which only one device requires an internet connection. These are smart networks of wireless devices that can form, disperse, and re-form at the user's command. Because WMNs are created from the bottom up by connections between devices (versus top-down, inflexible network infrastructures), their self-forming — and self-healing — capabilities ensure robust and reliable communication anywhere, at low cost and without fixed infrastructure.⁸

WMNs extend the pervasive computing embedded in the IoT by making it more pluralistic and dynamic. In the United States, WMN initiatives tend

to be local and entrepreneurial. Examples include Meta Mesh Wireless Communities in Pittsburgh, Pennsylvania; SMesh in Baltimore, Maryland; NYC-wireless in New York City; TFA-Wireless in Houston, Texas; and WasabiNet in St. Louis, Missouri.⁹ On the global stage, the use of WMN tends to be more expansive and government sponsored. Some innovative examples of these networks are the Serval Project in Australia, Guifi.net in Spain, and Freifunk in Germany. All of these initiatives provide free and unfettered access to high-speed wireless communications. They hold great promise for communities that have been viewed as too remote to economically serve with fixed infrastructures.

Why?

Because WMNs alter the very definition of connectivity, they also will prompt a strategic reconsideration of the investment in and deployment of network infrastructure. For 20 years, the structure of connectivity has been based on a hub-and-spoke mentality in which devices connect through fixed points and are governed by the web's protocol. Now, devices can form their own networks off the grid. Thus, WMNs open a new frontier of high bandwidth and more efficient collaboration in processes that involve any sort of coordination between machines, people, enterprises, and products.

Where?

In commerce, WMN is transforming supply chain management. The previously passive RFID (radio-frequency identification) tag is now an active device that enables the remote tracking of products, people, and transportation assets. Ambient Systems, a Dutch company that was born out of a business accelerator at the University of Twente in Enschede, Netherlands, has developed and implemented a mobile tagging technology called smart points. Using mesh network technology — which is simpler, more reliable, and less expensive than Bluetooth or Wi-Fi — its interconnected sensors can check, track, and trace a wide variety of assets and environmental conditions.

In the future, WMN-equipped vehicles, drones, and devices will extend our geographic reach, increase access to information content, and expand business capabilities far beyond current network technologies. Already, Toyota Land Cruisers have been successfully used as WMN nodes to provide dynamic network capabilities in dense cities, as well as in Australia's vast Outback.¹⁰

WMNs will extend the reach of health care with wearable and implantable devices that can generate and receive off-grid signals. These devices enable new strategies around treatment, surgery, and everyday well-being.

Currently, telemedicine often uses low-bandwidth connections that cannot transmit complex images and

video, mainly because high-bandwidth wireless connections come with high operating costs and a high risk of network downtime. WMN technology solves this problem. Its intelligent, large-scale, and high-speed networks support telemedicine and telecare by reliably providing data, voice, and video communications over a large area. This type of connectivity enables clinicians to monitor patients remotely and give them timely health information, reminders, and support. Mesh networking between devices, machines, and people is creating a network of networks in health care that will help disrupt conventional notions of how, where, and when care is delivered.

The ability to self-organize into WMN-based communities and share resources will spawn new forms of collaborative learning. The web and the digitization of information have given us almost instantaneous access to knowledge. But, by and large, we are still bound by the traditional model of knowledge creation and dissemination: knowledge creators research and record their findings, and knowledge seekers use a digital or physical library to access those findings. The opportunity we're missing is the ability for creators and seekers to collaborate, share, and experience learning in the knowledge-generation process.

Using WMNs, traditional barriers to knowledge and information are removed, and creators and seekers can meet directly and efficiently anywhere knowledge is being generated, as it is being generated. WMNs allow the exchange of complex media, such as community-related resources, live broadcast of local events, and information about accidents, natural disasters, and crime. This can be done without burdening the grid and enable us to authenticate knowledge closer to its source.

In a remote learning environment (a forest, ocean, or mountaintop), a group of learners can connect their devices via a WMN to collaborate in ways that were once unimaginable. In contrast to traditional learning environments, these networks facilitate a new kind of learning capability that allows us to create, share, and consume knowledge anywhere, anyplace, anytime, and between any set of devices. This new

capability — which has implications for classroom learning, corporate training, and knowledge gathering of all kinds — opens up new pedagogical avenues to experience the world around us.

The initial environmental benefit of WMNs is their ability to operate remotely and within the context of the unexpected. When the state of South Carolina was hit with unprecedented flooding in fall 2015, drones, utilizing a WMN, were used to assess damage and help emergency personnel develop strategies for rescue and repair. This ad hoc network allowed the drones to efficiently survey large areas of terrain and transmit photographs and video to multiple sites. Similarly, after Hurricane Katrina hit New Orleans, the only working communication system in the city was a WMN, and it turned out to be a critical lifeline to the city.¹¹

Along with disaster relief, mesh technology in combination with pervasive computing is positively affecting water, air, and land quality through remote sensing, reporting, and intervention.¹² Already, sensors are being deployed for terrestrial and marine monitoring, but they require a base station node in each sensor cluster to relay data from the deployed sensors to a dedicated internet connection. Top-down architectures like this entail significant costs, data redundancy, excessive energy use, and delays in synthesizing measurement information — all of which limit deployment scale. Farmers, for instance, would need a complex and expensive infrastructure to collect data on soil moisture, temperature, and crop light exposure in multiple fields. A mesh network can serve as a bridge between the internet and geographically dispersed sensor clusters, enabling the sensors to coordinate with each other and other devices. The fields could be “self-managed,” reducing cost and complexity for farmers. This fundamental feature of mesh technology can be applied to many remote environmental monitoring scenarios.

Biotechnology: Technologically Created and Enhanced Life-Forms and Systems

What?

In essence, biotechnology is the use of living systems and organisms to develop or make products. Humans have been bioengineers for thousands of years, ever since we first planted and crossbred crops.¹³ Today, advances in digital technology, genetic engineering, informatics, cell technology, and chemical sciences are greatly expanding the boundaries of biotechnology.

The continuing development of the CRISPR-Cas system is a notable example. It enables geneticists and medical researchers to edit genes, bringing us closer to the day when Huntington’s, sickle cell, breast cancer, and many other genetic diseases can be treated *before* they attack the people who carry them within their DNA.¹⁴ The notion of engineering living cells and the emergence of the life sciences industry will radically change the boundaries of health care, agriculture, and chemicals.

Why?

Biotechnology has the potential to both expand existing industry boundaries and create entirely new industries, but it is easy to frame this technology too narrowly. An industrial goods manufacturer might see biotechnology as a life sciences technology, but if it did, it might miss a host of applications in recycling, energy production, pollution control, hazardous waste, and other areas. Likewise, life sciences companies that relegate biotechnology to product development would miss the same opportunities. The products, processes, and value propositions of companies across industries will be affected by the mash-up of technology, chemistry, and life sciences that is biotechnology.

Where?

In commerce, biotechnology is the basis for a new form of authentication: bio-identification, also

known as biometrics. Rather than keys, passwords, credit cards, and codes, biomarkers such as retinas, fingerprints, and voice are the new gateway to information access and commerce. As bio-identification continues to evolve, other unique biomarkers such as our ears, nose, body odor, and even the patterns of our veins will provide (or withhold) access to everything from automobiles to electronic devices.

Biomarkers will spawn industries of new products and services that are individually customized, and they will pose fundamental privacy challenges.¹⁵ Biometrics and bioinformatics (aspects of big data discussed shortly) will radically transform what we know and do not know about ourselves and our social communities. That new knowledge will give rise to new insights into how we perceive value, and it will lead to innovative new designs as wide-ranging as the media we consume to the offices in which we work. Swedish startup hub Epicenter, for example, now offers workers implants the size of a grain of rice that function as swipe cards, as well as payment systems for the company cafeteria.¹⁶

For years, The Walt Disney Co. has applied bioinformatics knowledge in the design of its theme parks.¹⁷ The immersive experience offered in the parks is based on full engagement of the guest's senses — from the sound of horses trotting on the Magic Kingdom's Main Street U.S.A. to the sudden drop in Hollywood Studios' Tower of Terror. Disney's Imagineers, the designers and engineers of its parks, have raised the task of understanding how Disney guests relate to the physical world to an art form. Moreover, the company has invested billions of dollars in technologies that help it create new designs. For instance, Disney now provides its guests with RFID-powered bracelets, called MagicBands, that not only streamline the guest experience, but also generate a continuous flow of data and feedback that is informing the design of new, even more immersive experiences, such as "Star Wars" and "Guardians of the Galaxy" attractions. Using this and similar technology, bioinformatic data such as heart and respiratory rate and movement of eyes, limbs, and torso will provide Disney with new avenues to engage park visitors through virtual reality. These

experiences will be lifelike, interactive, and unique to each guest.

The most obvious and prolific impact of biotechnology is within the realm of health care. Advances in the field of genomics are making it possible to treat, and, even more desirably, prevent disease at the level of our genetic instructions. Advances in stem cell research and technology promise radical new strategies in health care intervention: Imagine damaged organs that can repair themselves.

For example, a promising first step toward curing vision loss in patients with age-related macular degeneration (AMD) was realized by the London Project to Cure Blindness in 2015. In this trial, eye cells that were derived from stem cells were used to successfully treat a patient with severe visual loss. The operation, which lasted less than two hours, is now being developed as a widely available therapy for those who suffer from the debilitating disease. Gene therapy also has yielded promising results and may be another catalyst for treating AMD and other, more complicated forms of blindness.¹⁸ Although the ethical issues of cell editing and stem cell therapies are complex and not easily addressed, the science is marching on and revolutionizing health care technologies, educational pedagogy, processes, and treatment strategies.

One of the most interesting aspects of biotechnology is its impact on learning. Biotechnology is giving us the capability to learn more about ourselves and how we coexist physically within our environment. Already, self-monitoring, personal fitness devices such as wearable trackers allow us to monitor basic vital statistics and our progress toward fitness goals. Tomorrow, it probably won't seem strange to electively implant devices that provide deeper insights into our physiology and whereabouts. And beyond that are glimmers of sophisticated implantable devices, such as brain implants that enhance or restore cognitive functions, including memory. Such devices promise to enhance human learning capacity or restore it in those who have lost the ability to learn as the result of aging, an accident, or physiological disorders.¹⁹

In the environmental realm, biotechnology already has radically altered farming and food production. Farmers in developing countries have realized significant gains in yields and income by planting crops that are insect resistant. Biotech crops have contributed to the reduction of greenhouse gas emissions and airborne pesticides. Bio-monitoring, bio-remediation, and the use of micro-organisms to treat solid, liquid, and gaseous wastes are key technologies and processes that are helping us create factories and other facilities that enhance rather than harm the environment.²⁰

Biotechnology also is playing an important role in the production of alternative forms of energy from algae and other plant and waste sources. (Perhaps the DeLorean automobile that ran on trash in the film “Back to the Future” is not that far off.) Meanwhile, biotechnical processes are transforming fossil fuels such as petroleum and coal into cleaner sources of energy by reducing the pollutants associated with their production and use, and reducing production and refining costs as well.²¹

3D Printing: Digitally Designed, Chemically Manufactured Objects

What?

3D printing is a revolution built on chemistry that is being amplified by continually evolving capabilities in digital and machine technologies. Also referred to as additive manufacturing, 3D printing transforms a digital blueprint of an object into a physical finished good. For example, rather than ordering a part from a supplier, 3D printing enables us to retrieve a digital rendering of the part and make it. It also enables us to create a digital rendering of a newly conceived product and immediately manufacture it in almost any material. 3D printing is manufacturing on demand, on the spot.

The capabilities of 3D printers — the machines that use successive layers of materials to bring digital

designs to life — are evolving rapidly. They have transcended their initially limited range of materials and tolerances. Now, they are mobile and can precisely print everything from concrete to living cells. And if current research bears fruit, in the future, 3D printers will operate at the molecular level. In other words, we will be able to print with molecules, combining them to create more complex molecules that will yield a host of new products, such as new forms of LED lighting and solar cells and truly personalized medicines.

Why?

3D printing upends the assumptions on which manufacturing is based. As the digitization of product designs, availability of 3D printers, and emergence of intermediaries accelerate, executives will rethink how their companies design and manufacture products and will reshape — or completely reimagine — their current supply chains and distribution systems.

Where?

3D printing will transform the realm of commerce. Customers will become intimately involved in product design and finished goods manufacturing. Value will shift from finished goods to the digital representations of goods. As the barriers to reaching production scale melt away, a flood of new entrepreneurial opportunities will become available to inventors and innovators, and the plants and machinery needed to manufacture goods will become unnecessary.

Even while the use of 3D printing is increasing, it is still in the early stages of its S curve, and the emergence of associated technologies, such as continuous liquid interface production (CLIP), demonstrate its promise far beyond current deployment. CLIP shapes an object from a pool of liquid photopolymer resin using ultraviolet light and oxygen. It is being commercialized in Carbon Inc.'s M1 3D printers, which can produce complex objects in minutes, compared with the hours needed by conventional, layer-by-layer 3D printers.²²

In the realm of health care, 3D printing is being used to create custom casts, custom replacements for bone,

and other structural prosthetics. It also is being used to create precise and structurally complex medical devices, such as integrated tissue-organ printers, that are dramatically changing surgical strategies.²³

Treatments derived from the application of 3D printing will not only change delivery systems, but also the price dynamics of new treatments. Many 3D printing solutions are coming to market at relatively low price points. For example, the first 3D implant made for children — airway splints that grow with babies being treated for tracheobronchomalacia — can be produced in a matter of hours at a cost of about \$10 per unit.²⁴ The promise of 3D products for everything from skin reconstruction and dental implants to bone repair and organ replacement suggests that 3D printing could help address the unsustainable increases in health care costs.

3D printing has many applications in the realm of learning. Most important, the technology allows us to visualize and experience objects as they are being designed. Rather than view an object on a screen, we can now quickly create it using 3D printing and better understand its mass and proportion. This use of 3D-printed models for rapid prototyping is changing the face of architectural design and engineering. Artifacts and objects that were once restricted to the pages of a blueprint can now be experienced in their full form and context, leading to more creative designs and more efficient proof-of-concept cycles. In many cycles of discovery, 3D printing, along with the growing inventory of digital 3D designs, can bring the creations of innovators to life quickly and cheaply. As such, new forms of design, testing, building, and collaboration will extend what we know and how we know it.

In and out of the formal classroom, 3D printing can help bring abstract concepts to life. More important, the addition of 3D printing to educational experiences promises to unlock a new avenue of innovation and entrepreneurship among learners. If a picture is worth a thousand words, imagine the value of a model that one can see, hold, and reshape or rebuild. This technology is having a powerful impact on learning effectiveness and will support the development of new experiential pedagogical approaches.

In the environmental realm, the waste reduction and recycling efficiencies of 3D printing will yield forms of manufacturing that make more efficient use of materials using less energy with lower levels of harmful emissions. One day, you may upgrade your mobile phone by throwing your old one into a recycler and using its remains to print a new one.

Beyond manufacturing, 3D printing technology will be used to create precise structures that occur in nature to preserve nature. An early example of this is the development of artificial reefs using digital technology, global positioning systems, and 3D printing. Teams of scientists and companies have designed and placed 3D-printed reefs to preserve marine life and protect threatened coastlines in the Mediterranean, the Caribbean, the Persian Gulf, and Australia.²⁵

Machine Learning: Augmented, Automated Data Analysis

What?

The next class of technology is machine learning. Machine learning covers a broad context of technologies and capabilities. Some scientists approach the domain purely from a perspective of computer programs that “learn.” A related perspective encompasses computer-based pattern recognition, statistical modeling, and analytics for decision-making. A third, and more holistic perspective, combines computer algorithms, statistical patterns, and artificial intelligence. Today, there are three principle technologies that when bundled together unlock key aspects of each perspective: cloud computing, big data, and artificial (augmented) intelligence (AI).

- **Cloud computing** is the on-demand access to computing resources, including software applications, storage, network, and other services. The advent of the cloud signaled the separation of storage and pro-

cessing from the device, thereby creating ubiquitous access to software and data. It also gave rise to creative forms of collaboration (witness Pokémon Go).

- **Big data** is the generation and collection of massive amounts of structured and unstructured data in the search for new insights and new responses to challenges that organizations and decision-makers face.
- **AI** is the programming and algorithms that allow digital devices to access, combine, and share data to learn, explain, and forecast events, processes, and trends.

Although these three technologies are often described as distinct, they rarely stand alone. Together, they have marked effects beyond the typical domain of information technology. This impact is driven by (1) the availability of data in many forms and from many sources; (2) the ability to access it in many places and from many devices; and (3) the capability to efficiently analyze data and apply it effectively.

Why?

Data and the ability to access, organize, interpret, and distribute it is the lifeblood of the modern company. But today, data is bigger than ever before. It is sourced from inside and outside the boundaries of the company. Further, it is both structured (a transaction, invoice, or receipt) and unstructured (a tweet, a video, a blog post). This chaotic flow of data can seem like a threat or inconvenience on the surface, but it harbors an enormous opportunity to gain valuable insights into the operation of a company and the larger ecosystem that includes its customers, suppliers, and stakeholders.

In fully developing the machine learning capabilities of their companies, corporate leaders need to expand their analytical range from monitoring and control (operational analytics) to forecasting and planning (strategic analytics). In addition, they must extend their explanatory reach from highly predictable decision-making (noninterpretative) to

dynamic and unpredictable decision-making (interpretative). (See “A Strategic Portfolio of Analytics.”) The full promise of machine learning is its ability to be a new and collaborative source for decision-makers in addressing complex chains of cause and effect, as well as rendering a potential solution set of traditional and novel paths for moving forward.

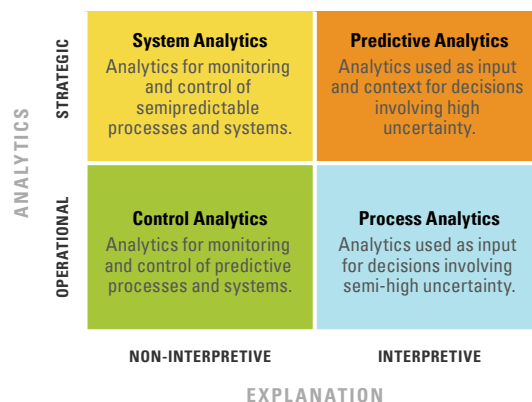
Companies that are anchored in control analytics are exposed to competitive risks, particularly within volatile, competitive industries. But those that harness the power of machine learning and expand their capabilities to include systems, processes, and predictive analytics can gain access to deeper insights and accelerate their decision cycles. The question for leaders: Where is your company currently positioned, and what investments are needed to improve its position?

Where?

Big data and analytics are rapidly eclipsing other sources of value in the realm of commerce. Businesses have used data to build profiles of buying habits, prices, and other retail contexts to better tar-

A STRATEGIC PORTFOLIO OF ANALYTICS

Corporate leaders must expand their analytical range from monitoring and control (operational analytics) to forecasting and planning (strategic analytics).



get products to consumers. For example, data from store loyalty programs and credit card purchases are now used to anticipate shoppers' needs ahead of time. In the grocery industry, data analytics are used to determine how often shoppers buy milk, condiments, or other products, and then send each household coupons based on specific purchasing habits. Across many industries, this has led to methods of product and service design that are less linear and more focused on the dynamic aspects of supply and demand, as well as the dynamic nature of customer experiences and outcomes.

IBM's Watson project bundles big data, cloud computing, and AI into a machine learning technology that is greater than the sum of its parts. Watson combines natural language processing with retrieval, reasoning, and learning algorithms to search, link, and reconcile structured and unstructured data to understand the questions humans ask it and provide answers they can understand and justify.²⁶ IBM calls this "augmented intelligence" instead of "artificial intelligence" to emphasize the way in which Watson enhances, as opposed to replicates, human intelligence. Elements of Watson have already found their way into apps that run on devices like the Apple Watch, where it answers users' questions about exercise, diet, and health — and even offers unsolicited advice.²⁷

In the future, many forms of emerging technology will feature augmented intelligence. Andrew Moore, dean of Carnegie Mellon's School of Computer Science, estimates that 98% of AI researchers are focused on engineering systems that will help people make better decisions versus simulating human consciousness.²⁸ The interface between machine learning and human intelligence is fast becoming the Holy Grail of the high-tech industry.

In health care, the emergence of machine learning promises a dramatic shift in treatment and diagnosis strategies. Rather than wait for troublesome symptoms to appear, physicians now can continuously monitor the vital health markers of patients, starting at a much earlier age. This enables preventive measures and more timely interventions.

Big data and augmented intelligence support the move toward evidence-based medicine, in which treatment strategies based on judgment and heuristics are being replaced by strategies based on the aggregation and analysis of a patient's data, clinical trials, and other research. The result is a personalized plan of action that takes into consideration individual nuances, genetic factors, lifestyle, and potential threats and issues that have occurred in patients with the same condition. In turn, medications and therapies can be custom designed for best effect.

Learning in all its myriad forms is the core outcome of this technology. Many of the assumptions underlying learning theory are shifting as data availability, access, and analysis technologies continue to evolve. Simulations, virtual reality, and other tools offer learners a more complete understanding of complex systems, such as the environment and the human anatomy.

Machine learning technologies allow educators to mold content and outcomes to meet diverse needs in teaching pedagogy. For example, educators will be able to understand how students interpret and apply concepts through patterns revealed by their actions, decisions, and interactions with other students. This will lead to the development of novel "paths" that meet the cognitive predispositions of learners. This will also enable us to personalize educational experiences, as well as provide unique contexts and avenues of team collaboration. In this way, the promise of machine learning extends beyond learning generation to the provision of tools for analysis, simulation, and experimentation that can enhance learning effectiveness.

Big data and machine learning contribute in many ways to the preservation of the environment. They enable the creation of real-time geospatial maps that offer valuable insight into conditions, trends, and risks involving climate, air, and water quality, as well as animal and plant life. This information provides business and governmental leaders with critical information on the potential impact of development on the environment. Machine learning also enables companies to reduce waste, conserve energy, and understand the environmental impact of their entire value chains.

For example, global databases are being used by coalitions of producers and customers to monitor the manufacturing of goods to ensure they are being made under fair labor and environmental conditions. In a similar vein, the Global Partnership for Sustainable Development Data is a coalition of governments, companies, and other global organizations that achieve sustainability goals by pooling their data sets. As data-focused collaborations between corporations, nonprofits, and governments continue to evolve, we can expect to see remarkable progress in mapping risks involving natural resources, labor practices, and a host of other areas.

Nanotechnology: Engineered Atoms, Super-Materials

What?

Nanotechnology, which encompasses molecular engineering, is a new and radical engineering science that is designing and manufacturing incredibly small circuits and devices that are built at the molecular level of matter, typically 1 to 100 nanometers. To put this in perspective, there are 25.4 million nanometers in 1 inch.

Dry-fit clothing, drug delivery patches, water-repellent shoes, and antibacterial bandages are all consumer product applications of nanotechnology. But they only scratch the surface of what promises to be a revolutionary leap in material capabilities. As we slip into our odor-repelling nano-silver socks, molecular engineers are pioneering new ways and new tools to see and manipulate the atoms that make up food we eat, the clothes we wear, the places we dwell, and even the air we breathe.

Why?

Combinations of nanomaterials like graphene, tungsten diselenide, and boron nitride may usher in a new

era of Moore's Law, bringing us computers and other devices with heretofore unattainable processing power, memory, and display characteristics. These devices could be readily manipulated into various dimensions to meet different requirements, confounding and transforming the form and function assumptions that currently govern computing hardware.

With nanotechnology, all sorts of media and materials that have had no information processing and delivery capabilities can become new portals of commerce and communication. A window in your home could display not only the view, but also the weather forecast, news headlines, an incoming video call, and your email inbox. From electricity to chemicals to metals, nanoengineered materials will take on new physical properties that are far different from and more useful than the physical properties of their natural states.

Where?

In the realm of commerce, nanotechnology is already producing a huge wave of new product development. Nanomaterials are used in a range of products from golf balls to gaming consoles, imbuing these products with previously unattainable capabilities. Golf balls treated with nanomaterials fly straighter by channeling the energy from the club head to correct for mishits and drift. Gaming consoles deliver dramatically improved graphics using micro-scale optical wires that accelerate the transmission of data between microprocessors.

Nanotechnology and sports science have combined to create an entire industry of technical fabrics and apparel that help professional athletes enhance their performance and help the rest of us look more like professional athletes when we exercise — and when we sleep, too. Performance apparel maker Under Armour Inc. recently introduced “recovery” sleepwear lined with a bioceramic print that absorbs body heat and reflects back far infrared radiation, which has been shown to stimulate cells and tissue.²⁹

In the realm of health care, nanoparticles are being developed to ferry drugs, heat, light, and other sub-

stances to human cells. Researchers at Harvard Medical School recently made an “origami nanorobot” out of DNA to transport a molecular payload to cancer cells. The team successfully delivered molecules that triggered suicide in leukemia and lymphoma cells.³⁰

In the future, nanotechnology will support the development of molecular structures that replicate living cells. These molecular structures will be the foundation for the regeneration or replacement of body parts that are currently lost to infection, accident, or disease.

The most immediate impact of nanotechnology on learning will likely be enhancements in learning environments and tools such as pencils, paper, whiteboards, and even the walls of classrooms and conference rooms. For example, note-taking is being transformed by electronic paper displays that use positively and negatively charged particles on thin film to replicate the look and feel of ink on paper. Unlike backlit displays, these devices use power only when an image is being created or modified.

The angular learning surfaces of today’s computing devices and classrooms are likely to give way to curved and domed surfaces as the structural laws of energy use, form, and function are altered by nanotechnology. Flexible displays that can be stretched and curved to surround us will provide new tools for better visualizing and thus understanding complex phenomena, such as the weather and the human body, and for designing innovative solutions.

In the environmental realm, nanotechnology is both learning from nature and helping to preserve it. Using nanostructures derived from nature, scientists have developed products such as Kevlar (inspired by silk), adhesives (inspired by geckos and mussels), and coatings (inspired by lotus leaves). Meanwhile, molecular engineers are developing new kinds of structures, such as iron nanoparticles that disperse in a body of water and decompose organic solvents that cause pollution. Similarly, they are using silver nanoparticles to significantly reduce the amount of pollution that occurs in the manufacture of plastics, paint, detergents, and other materials. These types

of particles can also rid the air of viruses and other harmful antibodies. In the future, nanotechnology may enhance the efficiency of solar panels and serve as the basis for power storage that makes smart energy grids even smarter.

Robotics: Precise, Agile, Intelligent Mechanical Systems

What?

Bridging the disciplines of mechanical engineering, electrical engineering, and computer science, robotics is the design and development of mechanical systems (a frame, electrical components, and code) that can operate autonomously or semi-autonomously. Robotics isn’t a new technology in and of itself, and if the technology were relegated to performing narrow ranges of repetitive tasks, it wouldn’t merit our attention. But in the past decade, robotics has undergone a radical transformation driven by three traits:

- **Precision:** the ability to accomplish extremely exacting and detailed tasks accurately.
- **Agility:** the ability to accomplish a variety of tasks quickly and easily.
- **Intelligence:** the ability to acquire and apply new knowledge and skills.

Why?

Robotics has transcended its roots in cost reduction and automation. Now, it is being applied to reimagine processes throughout the business, including IT, sales, and customer service, and to open new frontiers in business innovation.

Robots are helping customers find and purchase products and check in at airports, and they are tak-

ing and delivering room service orders. Robots are an essential element in the new workforce, where they assist employees with a wide range of operational, service, and managerial tasks. And they are rapidly coming to define the future of transportation on land, sea, and air.

Where?

In the realm of commerce, robots are assembling increasingly complex products and augmenting human performance. They are collaborating in activities involving troubleshooting, scheduling, and setup. For instance, the robotic platforms currently being built by Kuka Robotics Corp., ABB Inc., and Rethink Robotics Inc. are lighter in weight and adaptable, and able to sense when parts are fitted correctly. Platforms like this will enable faster setup cycles, instant repurposing, and easy reconfigurations in manufacturing. Robotics will deliver — at a much lower cost — manufacturing efficiencies once reserved for investments in heavy industrial machinery.³¹

In addition, robots are interacting with humans in a variety of new ways that may well presage the development of new relational bonds. Scientists at Nanyang Technological University in Singapore have created a receptionist robot named Nadine that greets visitors, smiles, makes eye contact, and shakes hands. Nadine also recognizes returning visitors and sparks up conversations based on previous chats with them.³² As robots become our companions, helpers, and tutors, the human-technology interface is bound to evolve in unexpected ways.

Within the realm of health care, robotics is revolutionizing surgery. One example is the da Vinci Surgical System, which allows physicians to translate their hand movements into precise movements of small instruments inside the patient's body. A high-definition, 3D vision system and tiny-wristed instruments provide surgeons with enhanced visualization, greater dexterity, as well as greater precision and ergonomic comfort. For the patient, a da Vinci procedure may offer all the potential benefits of a minimally invasive procedure, including less pain and blood loss.³³

In the learning realm, robots can serve as proxies for human instructors, lowering educational costs and extending educational reach. Robots can be used to ensure that children with disabilities or illnesses are not left behind, while providing the sense of presence that enhances the learning experience.

New forms of robotics will allow educators to create more meaningful and more humanized forms of online learning. Moreover, robotics-based simulations can create educational contexts that enable complex learning without the associated risks. Robotics and digital simulations are being used to create entirely new educational experiences in everything from driver's education to complex surgery.

Within the environmental realm, robotics is enabling the design and installation of complex solar arrays, wind turbines, and wave/current energy. Advanced forms of recycling, environmental monitoring, and energy exploration are also driven by robotics.

Outer space has long been the most celebrated domain of robotics. We have learned much about the universe using such technology in Mariner 4, Viking lander, and Voyager missions. Advanced robotics will continue to help us not only improve this knowledge, but also harvest the universe's resources. Currently, the California Institute of Technology and Northrop Grumman Corp. are developing a dynamic, robotic technology that will capture sunlight from outer space, convert it into radio-frequency power, and beam it to ground stations on earth, where it will be converted into electricity.³⁴

The Rise of Super-Technologies

The seven technologies described in this report will change our world in more ways than we can imagine. But the most intriguing and far-reaching of these changes are likely to result from combinations of their capabilities. Together, they will give rise to even more powerful super-technologies.

Super-technologies will open new digital frontiers. New forms of digital information and new methods for using it will further alter how we live. The integration of digital technologies with the materials, chemical, and biological sciences may alter life itself.

Consider health care. Pervasive computing technologies, such as blockchain, will keep health care data decentralized and closer to the patients who generate it. Other relevant data will be kept in blocks close to health care providers. Machine learning can be added to the blockchain to break down the traditional sequence of clinical trials and treatment. Patients, researchers, pharmaceutical companies, and physicians can collectively use this data to run trials and realize benefits that are customized and available more quickly. When 3D printing capability for drugs and medical devices is added to this smart chain, a whole new form of health care technology will be born, one that radically changes the traditional chain of treatment and prevention.

Similar super-capabilities that enable instantaneous creation, flow, and updating of data — along with the ability of machines to interpret, synthesize, and intelligently act upon it — are already changing the face of financial systems, commerce, product development, how we vote, and more.³⁵

It is these types of combinations that hold the greatest potential for remaking the traditional systems of commerce, learning, health care, and our environment. It is also the reason that this wave of technology is so different from those of the past. The universal nature of this technological revolution carries with it greater weight in its power to both do good and cause harm.

We hear dire warnings about technology — how it could lessen the role of humans and even supplant us. But I believe it is more likely that the seven technologies and their symbiotic combinations will enhance the human experience. This is a good news story. These technologies will lead us to significant inflection points in health care, commerce, learning, and the environment. They will save lives, improve the planet, advance our intellectual capacity, and drive new forms of industry.

This technological revolution will also challenge many of our long-held assumptions, beliefs, and conventions. I offer this report to today's executive strategists as a means of launching a structured dialogue about how technology may alter the future of value generation and exchange, products, and marketplaces. Almost every industry will be touched by these seven technologies, and when that happens, disruptive change — even more disruptive than what we are experiencing today — may come fast and in unexpected ways. My goal is to provide introductory context for the new technological frontier and urge you toward the “spark of madness” needed to seize upon the opportunities it will offer. If this marks the beginning of your journey to understanding the next wave of technological change, don't let it be the end.

Reprint 59370.

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