

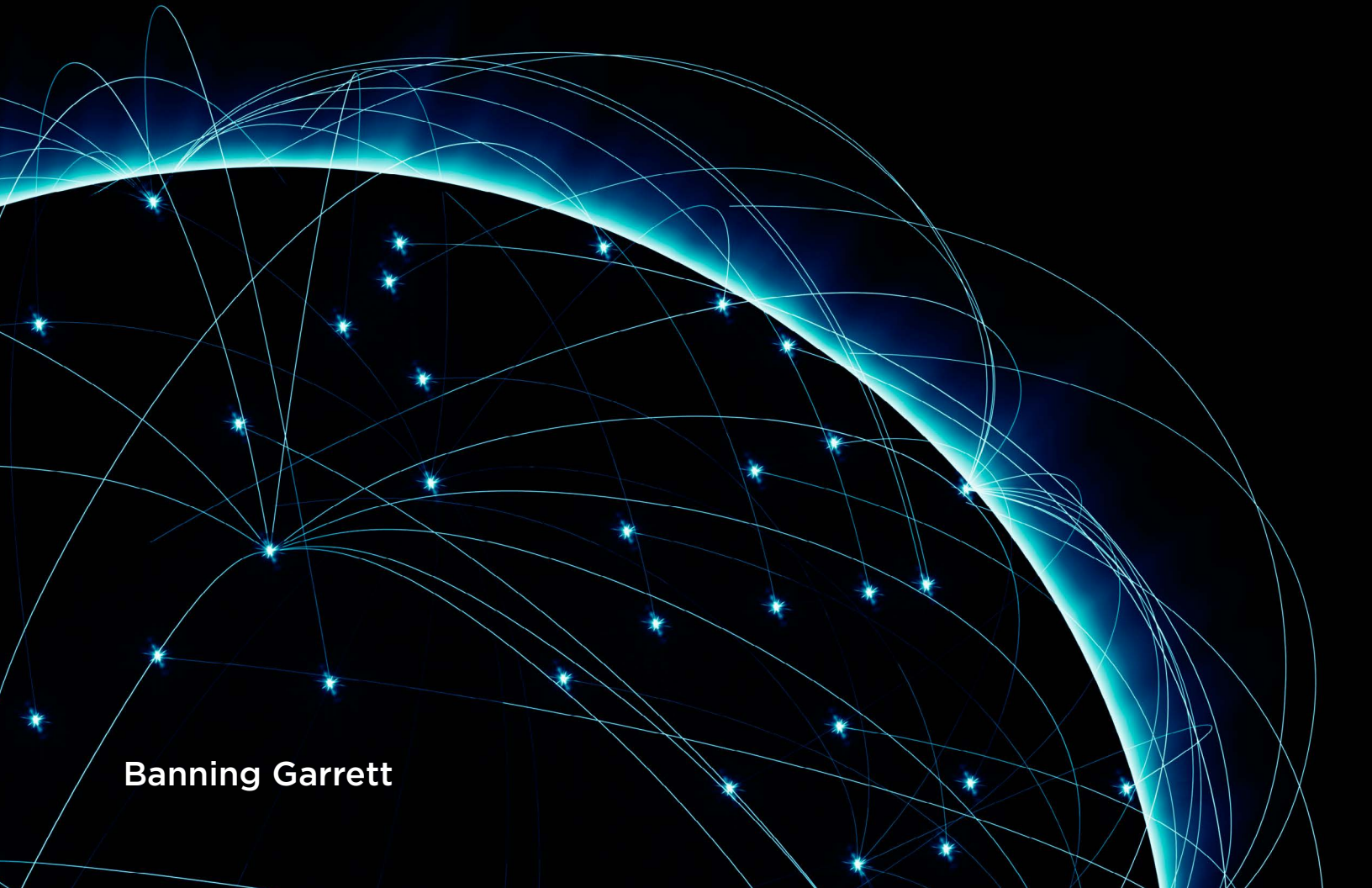


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# Technology Will Keep Changing Everything— and Will Do It Faster

Banning Garrett



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Atlantic Council  
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# TECHNOLOGY WILL KEEP CHANGING EVERYTHING—AND WILL DO IT FASTER

## Exponential Change

Imagine the world before the Internet. Hard to do, isn't it? Yet the Internet has been around for only two decades—just one generation—meaning that people in their thirties and older grew up in the pre-Internet era.<sup>1</sup> In that short time, the Internet has become nearly as pervasive as electricity. In much of the world, it is now a ubiquitous utility at home, in the office, and in the entire global fabric of economics, government, and politics.

Smartphones are even bringing the Internet to people without access to the electricity grid who charge their phones with solar power. It is even difficult to imagine the world without Google, Facebook, Twitter, and the hundreds of thousands of smartphone applications that have mushroomed within the last decade.

Many other astounding and influential technologies did not exist or were not widely disseminated two decades ago, including drones, advanced robotics, 3D printing, synthetic biology, a wide range of nanotechnologies, and new materials like graphene.

Imagine now that more technological change will affect our lives in the next twenty years than in the past half century. The pace of change in many areas of technology and the innovations based on those technologies is exponential rather than linear. Like “Moore’s Law,” whose prediction of computer chip power doubling every eighteen to twenty-four months has proven accurate for four decades of the computer revolution, the capability of many other new technologies is also doubling at a regular pace rather than increasing

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incrementally.<sup>2</sup> To visualize the difference, if you take thirty one-yard-long steps, the thirtieth step is also one yard long like the first step and you will find yourself thirty yards from where you started. If you doubled the length of each step, your thirtieth step would be about one billion yards long, or more than *twenty-two times* the circumference of the earth. The difference is more than just quantitative. It is a different world of change. Today’s smartphone has more computing power than the most powerful supercomputer in 1985, and hundreds of millions of people now carry around that computing power in their pockets.<sup>3</sup> The capacity of digital storage has similarly increased, and the cost has shrunk at an exponential pace. Think about that pace of change for another twenty years just in computing

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1 The World Wide Web went live on April 30, 1993.

2 Ray Kurzweil, *The Singularity Is Near* (New York: Penguin Books, 2005). Kurzweil argues that technology has been on an exponential path of development for centuries. See chapter 2, “A Theory of Technology Evolution: The Law of Accelerating Returns.” See the Performance Curve Database (<http://pcdb.santafe.edu/>) for data on some key exponential technologies. It should be noted that not all technologies have developed exponentially. The performance of the airplane and the internal combustion engine, for example, has not improved exponentially over the last century.

3 McKinsey Global Institute points out that the fastest supercomputer in 1975 cost \$5 million compared with \$400 for its computing power equal, the iPhone 4. James Manyika, Michael Chui, Jacques Bughin, Richard Dobbs, Peter Bisson, and Alex Marrs, *Disruptive Technologies: Advances that Will Transform Life, Business and the Global Economy* (McKinsey Global Institute, May 2013), p. 5, [http://www.mckinsey.com/insights/business\\_technology/disruptive\\_technologies](http://www.mckinsey.com/insights/business_technology/disruptive_technologies).



The LG stand at the Mobile World Congress 2013 in Barcelona, Spain. Photo credit: Jordiferrer/Flickr

power.<sup>4</sup> Significant exponential change is also taking place in many other areas of technology, including artificial intelligence and robotics, biotechnology and bioinformatics, energy and environmental systems, medicine and neuroscience, and nanotechnology.<sup>5</sup> The pace of new technology adoption has also been accelerating, from electricity and the telephone to the mobile phone and the tablet.<sup>6</sup>

In genomics, Moore's Law has been on steroids. The first sequencing of the human genome cost more than \$1 billion. Today, total personal genome sequencing

costs about \$1,000 and will likely fall to \$200 soon. This million-fold drop in price will help with custom medical diagnoses and, with access to big data analysis tools, help discover genetic links to specific diseases and disorders by analyzing millions of genomes and crowdsourcing analysis.

Not only are individual technologies on an exponential curve of improvement, but the combination of key digital technologies is at an "inflection point," according to MIT researchers Erik Brynjolfsson and Andrew McAfee, who maintain that "we are entering a second machine age."<sup>7</sup> Brynjolfsson and McAfee note that the convergence of exponential technologies can surpass the expectations of science fiction: "On the *Star Trek* television series, devices called tricorders were used to scan and record three kinds of data: geological, meteorological, and medical. Today's consumer smartphones serve all these purposes; they can be put to work as seismographs, real-time weather radar maps, and heart- and breathing-rate monitors. And, of course, they're not limited to these domains. They also work as media players, game platforms, reference works, cameras, and global positioning system (GPS) devices. On *Star Trek*, tricorders and person-to-person communicators were

4 For a discussion of the cost curve on DNA sequencing falling faster than Moore's Law, see Aaron Saenz, "Costs of DNA Sequencing Falling Fast—Look at These Graphs!," May 3, 2011, <http://singularityhub.com/2011/03/05/costs-of-dna-sequencing-falling-fast-look-at-these-graphs/>.

5 This list was presented by Karen Myronuk, Singularity University, on April 15, 2013.

6 "It took 30 years for electricity and 25 years for telephones to reach 10% penetration but less than five years for tablet devices to achieve the 10% rate. It took an additional 39 years for telephones to reach 40% penetration and another 15 before they became ubiquitous. Smart phones, on the other hand, accomplished a 40% penetration rate in just 10 years, if we time the first smartphone's introduction from the 2002 shipment of the first BlackBerry that could make phone calls and the first Palm-OS-powered Treo model." Rita McGrath, "The Pace of Technology Adoption is Speeding Up," *Harvard Business Review*, November 25, 2013, <https://hbr.org/2013/11/the-pace-of-technology-adoption-is-speeding-up/>.

7 Erik Brynjolfsson and Andrew McAfee, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies* (New York: W.W. Norton, 2014), chapter 1.



separate devices, but in the real world the two have merged in the smartphone...”<sup>8</sup>

These emerging technologies could also have a game-changing impact on the developing world. Mobile phones have already played a critical role in boosting economic and social development in the developing world with, in many cases, huge productivity gains and innovations, such as the M-PESA mobile phone money transfer and microfinance system, developed in Kenya and launched by Safaricom in 2007.<sup>9</sup> Smartphones are now bringing broadband Internet access to hundreds of millions of people in the developing world, which could be virtually “wired up” by 2020, potentially producing huge additional economic and social gains. 3D printing could enable countries with little manufacturing capability and reliance on imports to produce many of their own goods without the need for advanced infrastructures and supply chains. Small local businesses could use local materials while providing employment and unleashing the entrepreneurial talents of the local population.<sup>10</sup>

## The First Step of Disruption

It is impossible to predict what the accelerating pace of change in technology will lead to in the next twenty years. However, one already can foresee some potential technological developments by building on current technologies and trends, such as faster computers, wider and more advanced use of 3D and 4D printing, more

ubiquitous robotics including autonomous vehicles, enhanced mobile computing with the individual at the center, widespread use of virtual and augmented reality, and creation of new designer organisms with biological building blocks. Far more difficult to predict are the second- and third-order, sometimes disruptive, effects of technology—social innovations and the implication of those innovations for society. For example, even after experts could foresee the vast expansion of the interactive Internet, they didn’t anticipate second-order effects such as Facebook or Twitter. Nor did they predict third-order effects like the use of those innovations for social movements and upheavals such as the Arab Awakening.

IN FACT, TECHNOLOGICAL DEVELOPMENTS IN THEMSELVES ARE RELATIVELY UNIMPORTANT IF SOCIETY DOES NOT UTILIZE THEM FOR INNOVATION.

In fact, technological developments in themselves are relatively unimportant if society does not utilize them for innovation. For example, the Internet had its humble origins in 1969 as ARPANET (Advanced Research Projects Agency Network), designed to connect a handful of computer research centers. The Internet only became an important factor in shaping society because people, businesses, organizations, and governments found it useful and then essential as innovators built on—and built out—the Internet platform and the web, resulting in the Internet’s integration into the lives of billions of people. Smartphones would just be cool gadgets for the rich avant garde if they did not appeal to millions and eventually billions of people and were not priced to make them accessible. Affordability, after all, is a dynamic of more demand, leading to cost reductions, which in turn lead to more demand and further cost reductions.

## Impact on Society Difficult to Forecast

Predicting how technology is developed and used—and the impact of that use—is inherently impossible and not a question of improved methods and information. Rather, it is dependent on the decisions of individuals—millions and billions of unpredictable, individual decisions. Thus, in forecasting the impact of new

<sup>8</sup> Brynjolfsson and McAfee, op. cit., chapter 2.

<sup>9</sup> M-PESA, currently the most developed mobile payment system in the world, allows users with a national ID card or passport to deposit, withdraw, and transfer money easily with a mobile device. Cecilia Kang, “For the Poor, Cellphones Can Offer Lifeline,” *Washington Post*, September 8, 2010, <http://www.washingtonpost.com/wp-dyn/content/article/2010/09/07/AR2010090706625.html>.

<sup>10</sup> A 2006 RAND study prepared for the US National Intelligence Council casts doubt on the ability of developing states to absorb advanced technology. The study’s key conclusions were that “scientifically advanced countries, such as the United States, Germany, and Japan, will be able to implement all key technologies assessed”; and that “countries that are not scientifically advanced will have to develop significant capacity and motivation before barriers to technology implementation can be overcome.” This 2006 study may have underestimated the ability of developing countries to adapt new technology and even leapfrog the advanced countries in innovation and use of new technologies, as seen so dramatically with the adoption of the mobile phone in the years since the study was conducted, heralding profound economic, social, and political change. Richard Silberglitt, et al., *The Global Technology Revolution 2020* (Santa Monica: RAND Corporation, 2006), [http://www.rand.org/content/dam/rand/pubs/monographs/2006/RAND\\_MG475.pdf](http://www.rand.org/content/dam/rand/pubs/monographs/2006/RAND_MG475.pdf).

## No Turning Back the Technology Clock

Envision the disappearance of the Internet from life today. It is not difficult to paint a picture of economic collapse, social disarray, political upheaval, military paralysis, and extensive conflict. The Internet's disappearance would cripple modern life, including most transportation systems, logistics and food provision, banking and financial transactions, all communications systems, and the infrastructure controlling water and electricity. In short, modern civilization would collapse into an unprecedented crisis. The world would not return to the pre-Internet era of twenty years ago but perhaps to a pre-industrial age.

The possibility of the Internet's sudden disappearance is not as farfetched as it may seem. Massive solar geomagnetic storms occur in less than one hundred-year intervals, the most recent one hitting the Earth in 1859, before the world was wired up. Such a storm could knock out satellites, the electric grid, and many sensitive electronic devices. "Until cures are implemented," the US National Intelligence Council's report, *Global Trends 2030: Alternative Worlds*, warns, "solar super-storms will pose a large-scale threat to

the world's social and economic fabric."<sup>1</sup> In July 2012, Earth experienced a near-miss of such a massive solar storm. Experts foresee a 12 percent chance of a direct hit in the next ten years.<sup>2</sup>

So as one considers the impact of technology on society and laments its downsides—from vulnerabilities of the digitally connected world to digital unemployment and new technologically enabled security threats—it is important not to lose sight of society's deep dependence on this technology. It is impossible to stop the science and technology train, and trying to dismantle today's technological society would be suicidal. Humans have always been a technological species since harnessing fire to cook food. Mankind must continue advancing science and technology while addressing critical challenges, such as climate change, that technology has helped create if it is to avert a total collapse of civilization.

1 US National Intelligence Council, *Global Trends 2030: Alternative Worlds* (December 2012), p. 52, <http://www.dni.gov/index.php/about/organization/global-trends-2030>.

2 US National Aeronautics and Space Administration, "Near Miss: The Solar Superstorm of July 2012," July 23, 2014, [http://science.nasa.gov/science-news/science-at-nasa/2014/23jul\\_superstorm/](http://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/).

technology on society, the following points are important to keep in mind:

- The future is inherently unpredictable—society is not based on quantifiable and predictable Newtonian physics.
- The pace of technological change is accelerating, much of it at an exponential pace, which is likely to effect accelerated change in society.
- Much of the disruptive technological change is a result of many technologies coming together, such as those that make a smartphone smart. These range from the Internet and the web to touch screens, apps, and GPS.
- Although decision-makers and technology experts cannot predict the future, they can *forecast* trends in the development of technology and *envision* ways in which those technologies might be adopted and change society.
- It is useful to develop scenarios—alternative worlds—to envision how technology could affect society to prepare for or avert worst-case outcomes and to shape desirable outcomes.

To envision the potential impact of disruptive technologies on society, it is thus helpful to look at multiple levels of effects, each of which is more difficult to foresee than the previous level. Technology itself is just the "first-order" development that may or may not have a major impact on society. The disruptiveness of technology comes in the subsequent orders of impact and development. The "second-order" effect is how a particular technology, such as the personal computer, the Internet, or the mobile phone, is used. The "third-order" effect is the impact of using that technology on society—from economics, politics, and social relations to security, military affairs, geopolitics, and geoeconomics. A "fourth-order" effect is how the third-order effects of various technologies interact with each other to produce additional significant effects on society.

A new technology can make a previous iteration of the same technology obsolete, or it can create an entirely new category of technology, either of which may have major second-, third- and fourth-order social effects. The steam engine, the telegraph, the telephone, the Internet, and the microchip are just a few examples of broadly disruptive new categories of technologies and

technological applications that dramatically changed society with a broad range of knock-on effects.<sup>11</sup> The laptop, smartphone, and tablet all were disruptive but not entirely new categories of technology. Rather, they were built on a wide range of proven technologies. Yet, put together, they create a new socially disruptive reality of mobile computing. This mobility frees the individual from being tethered to a specific place, offering access to vast computing power, cloud computing and storage, the Internet and data on everything from the immediate physical and social environment, including geolocation, knowledge about any development in the world, and instant communication with others, similarly nearly anywhere else on the planet.

This capability has third-order effects as it interacts with other disruptive technologies and their second- and third-order impacts. For example, health systems, from diagnosis to provision and monitoring of health care, are likely to be disrupted. Hopefully, this disruption will be for the better, with cost reductions through wearable and ingestible sensors monitoring individual health, artificial intelligence-aided diagnostic, and new, patient-specific, and noninvasive treatments.

Some future technological disruption will be based on “proven technology” that is already changing society but is likely to have far greater impact in the decades to come. In addition, technologies under development, like quantum computing, are only in nascent stages of research and development but are likely to bear fruit.

The future development of technology is largely at the edges of different emerging technologies and combinations of existing technologies. Moreover, new technologies are most often built on the results of basic technological development that has been funded at least in part by government. This includes not only the Internet, but also a huge array of critical basic technologies from the GPS units on every smartphone for establishing geolocation and timing to autonomous vehicles and new drugs.<sup>12</sup>

11 The telegraph, which for the first time wired up the world for instant communication, had a dramatic impact on business models and government practice, as well as personal communication. See Tom Standage, *The Victorian Internet: The Remarkable Story of the Telegraph and the Nineteenth Century's Online Pioneers* (New York: Phoenix Books, 1999).

12 See Mariana Mazzucato on the twelve critical technologies in the iPhone that trace their origins to government-supported research. Mariana Mazzucato, *The Entrepreneurial State: Debunking Public vs. Private Myths in Risk and Innovation* (New York: Anthem Press, 2013), chapter 4.

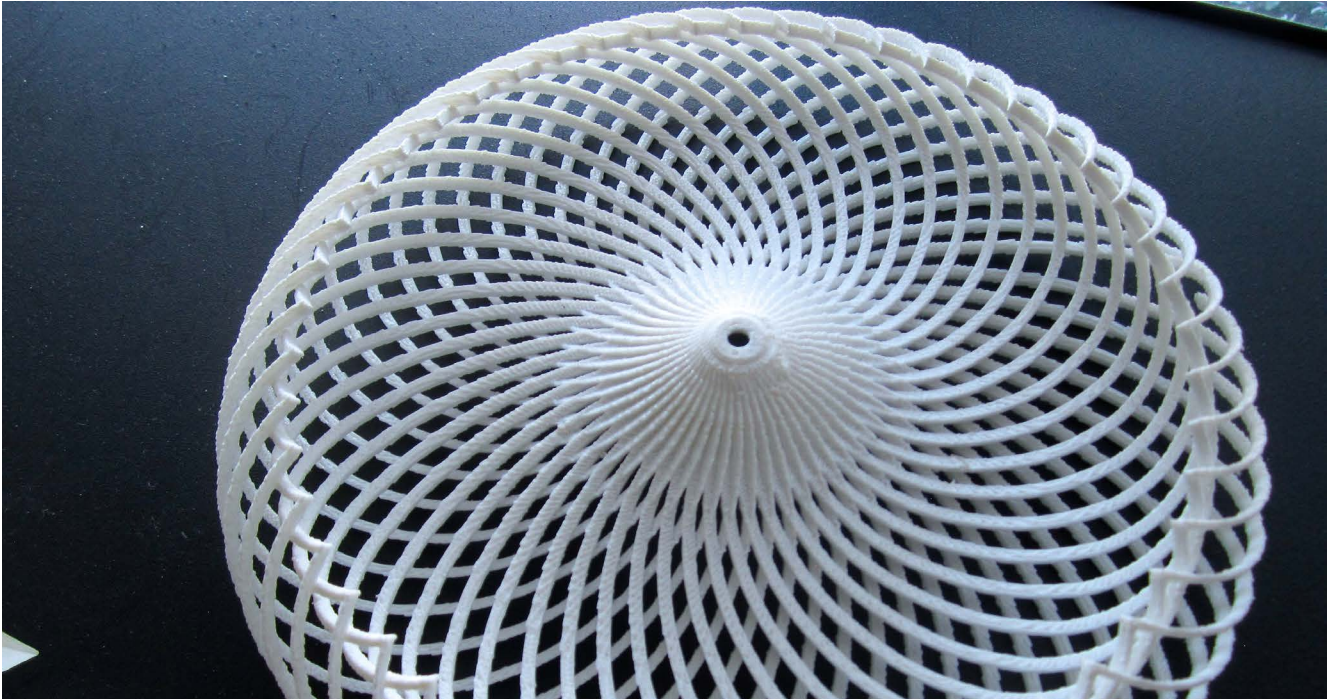
## Twelve Disruptive Technologies

Many efforts have been made to forecast the economic impact of disruptive technologies, most notably by the McKinsey Global Institute (MGI). In a May 2013 report, *Disruptive Technologies: Advances that Will Transform Life, Business and the Global Economy*, MGI examined twelve “potentially economically disruptive technologies”:<sup>1</sup>

- Mobile Internet—increasingly inexpensive and capable mobile computing devices and Internet connectivity
- Automation of knowledge work—intelligent software systems that can perform knowledge work tasks involving unstructured commands and subtle judgments
- The Internet of Things—networks of low-cost sensors and actuators for data collection, monitoring, decision-making, and process optimization
- Cloud technology—use of computer hardware and software resources delivered over a network or the Internet, often as a service
- Advanced robotics—increasingly capable robots with enhanced senses, dexterity, and intelligence used to automate tasks or augment humans
- Autonomous and near-autonomous vehicles—vehicles that can navigate and operate with reduced or no human intervention
- Next-generation genomics—fast, low-cost gene sequencing, advanced big-data analytics, and synthetic biology (“writing” DNA)
- Energy storage—devices or systems that store energy for later use, including batteries
- 3D printing—additive manufacturing techniques to create objects by printing layers of material based on digital models
- Advanced materials—materials designed to have superior characteristics (e.g., strength, weight, conductivity) or functionality
- Advanced oil and gas exploration and recovery—exploration and recovery techniques that make extraction of unconventional oil and gas economical
- Renewable energy—generation of electricity from renewable sources with reduced harmful climate impact

1 James Manyika et al., p. 4.





Complex designs at the Autodesk Gallery in San Francisco that demonstrates the ability of 3D printing to fabricate in a single process complicated geometries that are nearly impossible to produce using other manufacturing techniques. *Image credit:* Banning Garrett.

## 3D Printing Exemplifies Potential for Disruptive Social Change

3D printing has become a disruptive technology as a result of the coming together of a set of new technologies. Basic 3D printing was invented some three decades ago, but it reached a takeoff point as other technologies combined with the layered-printing capability of a 3D printer. These include computer-aided design, cloud computing, the Internet, new materials, and huge reductions in the costs of all these capabilities, including the printers themselves. Moreover, the 3D printing revolution is the result of a wide range of businesses and individuals pursuing these technologies. Global manufacturers such as General Electric, Boeing, EADS, and Ford are using expensive 3D printing machines and moving from rapid prototyping to producing critical parts for airplanes, automobiles, wind turbines, and other machines. From the bottom up, the 3D printing revolution has been driven by the “do-it-yourself” (DIY) movement, with tens of thousands of users buying personal 3D printers for experimentation or starting their own mini-manufacturing enterprises.

The 3D printing revolution demonstrates the potential second- and third-order effects of a disruptive

technology. As a general purpose technology, 3D printing is likely to transform everything from the construction industry, which will print buildings, to bioprinters fabricating human tissue and replacement organs. How will these disruptive technological changes affect social conditions?

One of the second-order effects in the long run could be a dramatic transformation of manufacturing. Instead of large-scale assembly of thousands of parts into millions of smartphones by tens of thousands of workers at a few factory complexes in China, small numbers of smartphones would be printed in thousands of locations near consumers around the world by a handful of workers in each local production facility. The third-order effects of this disruptive change could include massive “technological unemployment” at Chinese factories and a rebalancing of trade as fewer products are exported and more are produced at the point of consumption. This shift could, in turn, affect social and political stability in countries that are now manufacturing platforms. In short, the simple process of layering to make things (“additive manufacturing,” the more formal term for 3D printing) rather than carving them out of pieces of material (or “subtractive manufacturing”) could affect the fate of nations and the international order.

## The Next Wave: 4D Printing

On the horizon is 4D printing or “programmable matter,” in which the fourth dimension is time. This will be a world in which 3D printing produces material objects that are programmed to change their form (shape) and function (capabilities) after they are created. In some cases, they can even be commanded to disassemble into microscopic, “intelligent” particles or “voxels,” and then reprogrammed to become entirely different material objects. The potential of voxels can be understood by analogy to biological life, which is composed of twenty-two building blocks—amino acids—that are directed by DNA to assemble themselves in widely differing permutations to create different proteins and eventually life forms. Cornell University professor Hod Lipson and science writer Melba Kurman, coauthors of *Fabricated: The New World of 3D Printing*, explain that just as animals and plants “can consume each other and reuse the biological material because we are all made of the same relatively small set of just 22 building blocks,”<sup>1</sup> a relatively small number of types of voxels could assemble and disassemble themselves into objects of the nonbiological material world, based on software that performed a programming function similar to DNA. “In the same way a pixel is a building block of an image, a bit is a unit of information, and an amino acid is a building block of biological matter,” Lipson and Kurman note, “a voxel is a volumetric pixel (hence its name),” about the size of a grain of sand, that would

be the elementary unit of printed matter. “Just as amino acids are the low-level common denominator that enables nature to recycle materials perfectly, if all products would be made of a few dozen basic voxel types, products could be ‘printed,’ then decomposed, and reprinted into other products.”<sup>2</sup> Although voxels do not yet exist outside of the laboratory, Lipson and Kurman foresee that eventually everyday objects might be made of billions of voxels.

Potential applications of programmable matter might include airplane wings that change shape in flight; buildings that transform as desired for different functions, conserving space, cost, and the environment; infrastructure systems that adapt to loads or weather; furniture that is packaged flat but self-assembles after purchase; clothes that adapt to the user’s performance or the changing environment; and objects that disassemble for protection of private information, recyclability, or self-repair.<sup>3</sup> Envisioning the second-, third-, and fourth-order effects of such technology is only just beginning as the outlines of the potential of 4D printing indicate that it will take manufacturing—or the fabrication of the material world from the digital world—to a new level beyond 3D printing.

1 Hod Lipson and Melba Kurman, *Fabricated: the New World of 3D Printing* (New York: John Wiley & Sons, 2013), p. 276.

2 Ibid., pp. 277-8; Thomas A. Campbell, Skylar Tibbits, and Banning Garrett, “The Programmable World,” *Scientific American*, November 2014, pp. 60-65.

3 Thomas A. Campbell, Skylar Tibbits, and Banning Garrett, *The Next Wave: 4D Printing and Programming the Material World* (Washington, DC: Atlantic Council, May 2014); Lipson and Kurman, pp. 275-281.

## New Robotics: Out of the Factory

3D printing and forthcoming 4D printing are part of a Third Industrial Revolution that is changing the way the material world is designed, manufactured, and distributed. Another key technology contributing to this revolution is new robotics, powered by a set of technologies, including information and communications technology (ICT), artificial intelligence, the Internet of Things, big data, advanced algorithms, cloud computing and storage, and GPS. In fact, the new open-source Robotic Operating System (ROS), which operates sensors and actuators in the robot, relies on computation and data processing in the cloud rather than on an internal computer.

The new robotics is no longer the encaged industrial

robot of the twentieth century, engaged in repetitive motions assembling vehicles and other heavy machinery. Robots are increasingly turning up everywhere from software agents in cyberspace to robotic cars on highways. Though still relatively primitive, these robotic platforms have evolved at a rate over the last four decades similar to that plotted by Moore’s Law for microchips. The future is one of ever smarter, more capable—and dramatically less expensive—robots inserting themselves into every corner of people’s lives.<sup>13</sup>

Self-driving cars, a form of robotic vehicle, are likely to

13 Robert A. Manning, “Rising Robotics and the Third Industrial Revolution,” Atlantic Council, June 2013, <http://www.atlanticcouncil.org/publications/issue-briefs/rising-robotics-and-the-third-industrial-revolution>.

be available commercially before 2020. Their impact on society could be a sharp reduction in driving accidents and fatalities, some 90 percent of which are due to human error. Second- and third-order effects could include a radical change in how humans use cars, as well as the transportation infrastructure and urban land use. Vehicles now use 60 percent of urban land for driving and parking, but cars on demand summoned by apps could be in constant use, drastically reducing the need for parking spaces as well as the overall number of cars. Today, for example, personal vehicles are idle 90 percent of the time. Even so, such personal-use vehicles taking people directly between desired starting and end points might be more efficient than the most efficient public transport. This could in turn lead to a redesign of cities

OVER TIME, ROBOTS WILL DISPLACE WORKERS IN CALL CENTERS, DRIVING TRUCKS, PICKING AND PACKING FRUIT AND VEGETABLES, MAKING MEDICAL DIAGNOSES, ANALYZING REAMS OF LEGAL DOCUMENTS, AND CARING FOR THE ELDERLY.

and a transformation of urban life styles.

Ever more capable robots will yield dramatic productivity gains that could eliminate countless blue-collar and white-collar jobs and possibly entire professions.<sup>14</sup> Over time, robots will displace workers in call centers, driving trucks, picking and packing fruit and vegetables, making medical diagnoses, analyzing reams of legal documents, and caring for the elderly. This constantly evolving ecosystem will dislocate as well as enhance lives, especially through “technological unemployment.” In what economist and technology expert Brian Arthur calls the “second economy,” jobs will disappear into the digital realm rather than being simply moved offshore.

14 Lydia DePillis, “Eight Ways Robots Stole Our Jobs in 2013,” *Wonkblog*, *Washington Post*, December 23, 2013, <http://www.washingtonpost.com/blogs/wonkblog/wp/2013/12/23/eight-ways-robots-stole-our-jobs-in-2013/>.

This trend could continue indefinitely, exacerbating other technological trends set in motion by the Third Industrial Revolution. A recent McKinsey report asserted that “advances in artificial intelligence, machine learning and natural user interfaces are making it possible to automate many knowledge worker tasks that have long been regarded as impossible or impractical for machines to perform.” Apart from low-level jobs, many mid-level jobs have also been eliminated by information and communications technology in the past two decades. More mid-level job destruction is likely in the future.

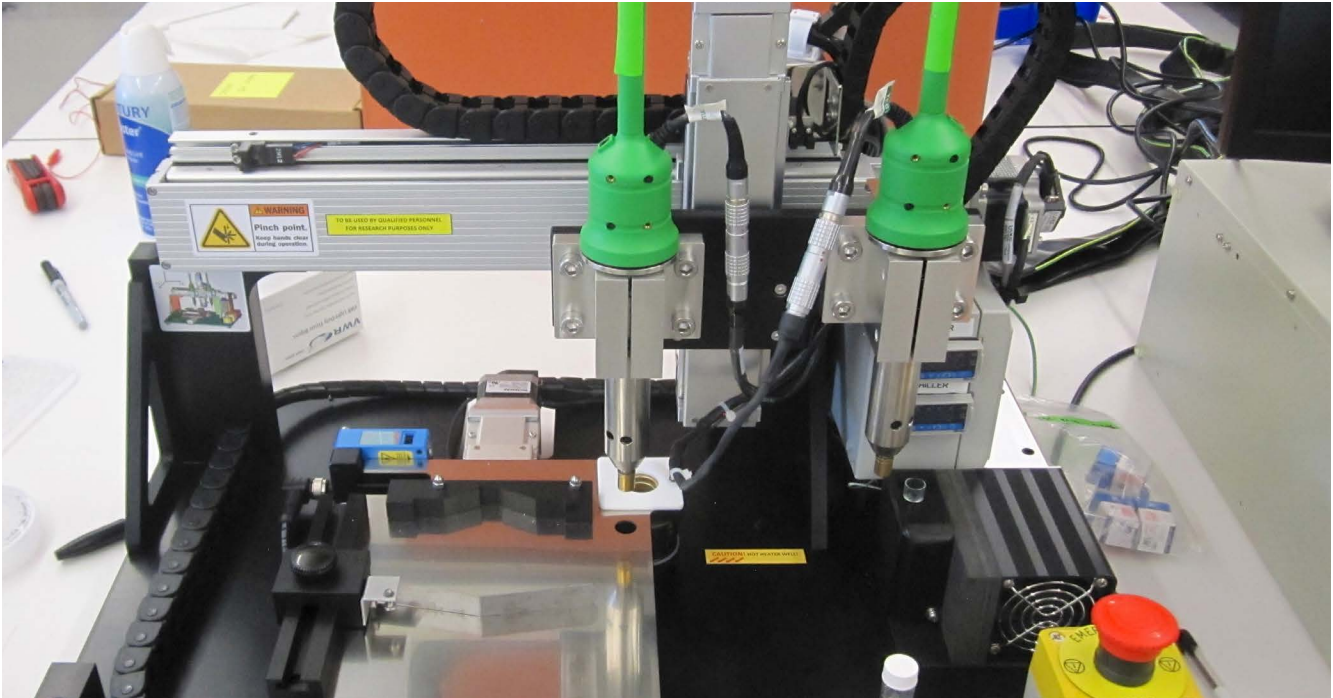
Will technological unemployment further exacerbate the wealth gap as the talented few supporting the automated, digital economy as well as company owners accrue an increasing percentage of the wealth, while the unemployed and underemployed of the middle class see their relative income fall? Some 80 percent of the 4 percent global decline in the share of gross domestic product (GDP) going to labor in the labor-capital split is the result of the impact of new technology.<sup>15</sup> Will this trend be reversed by the creation of far more good, high-paying jobs than are being lost? Or, will the great social issue before mid-century, at least in the developed world, be what will replace the notion of work as the central activity that provides citizens with income, health care, and, ultimately, meaning?

## 3D Printing Life: The Synbio Revolution

Synthetic biology and bioengineering also build on the convergence of a wide range of technologies leading to the development of new, previously unimaginable technological capabilities that likely will have a wide range of second-, third-, and even fourth-order effects on society. Advances in synthetic biology, like those in 3D printing, robotics, and so many other technologies, have been enabled by a combination of a wide range of other emerging technologies. A 2013 report by the National Research Council (NRC) and National Academy of Engineering (NAE) notes that “while synthetic biology arises from a century’s work in biology and related fields . . . its practice would not be possible without breakthroughs in such diverse fields as engineering,

15 The *Economist* cites a new Organization for Economic Cooperation and Development (OECD) study reporting that since the 1990s, labor’s share of GDP globally has dropped to 62 percent from over 66 percent, with 80 percent of the drop due to technology. “Labour Pains,” *Economist*, November 2, 2013, <http://www.economist.com/news/finance-and-economics/21588900-all-around-world-labour-losing-out-capital-labour-pains>.





An Organovo bioprinter used for printing human liver tissue for toxicity testing. Organovo, a startup public company based in San Diego, California, is engaged in research and development aimed at bioprinting human organ replacements using the patient's own cells to prevent rejection and to eliminate long waits for donor organs. *Image credit:* Banning Garrett.

computer science, and information technology.”<sup>16</sup> The report emphasizes that “progress in computer and Internet technology revolutionized the ability to process and transfer data and provided ideas and methods for how to manage complexity when engineering multi-component integrated systems. Calculations that only a decade ago would have taken weeks on a mainframe computer now take minutes: a gene sequence may be processed on a laptop.”<sup>17</sup>

In the new synthetic biology age, people will be able to edit their DNA like software in a computer. Craig Venter, who led the private effort to map the human genome and created the first synthetic organism, has termed this “digital life.”<sup>18</sup> The bioengineered digital file could represent the DNA of an existing organism,

an altered form of that organism, or an entirely new organism created from DNA. The NRC-NAE report explained that “synthetic biologists have the ability to design genetic code to elicit a specific function, pre-test the code for functionality using computer modeling, order the relevant genetic material from a commercial or open-source gene synthesis facility, and insert the material into a cell body in order to test real world functionality.”<sup>19</sup>

There will be no need to build a new organism from scratch. The 3D/4D printing process allows the designer of a synbio product to work with preexisting modules of the product. Synthetic biologists can work, for example, with BioBricks that can be bought and downloaded. BioBricks are DNA constructs of different functioning parts that can be assembled to create new life forms to

<sup>16</sup> US National Academy of Engineering and National Research Council, *Positioning Synthetic Biology to Meet the Challenges of the 21st Century: Summary Report of a Six Academies Symposium Series* (Washington, DC: National Academies Press, 2013), [http://www.nap.edu/catalog.php?record\\_id=13316](http://www.nap.edu/catalog.php?record_id=13316).

<sup>17</sup> Ibid, pp. 9-10.

<sup>18</sup> Roger Highfield, “J. Craig Venter Sequenced the Human Genome. Now He Wants to Convert DNA into a Digital Signal,” *Wired*, November 7, 2013, <http://www.wired.co.uk/magazine/archive/2013/11/features/j-craig-venter-interview>. Venter addresses this in greater detail in his new book, *Life at the Speed of Light: From the Double Helix to the Dawn of Digital Life* (New York: Viking, 2013).

<sup>19</sup> US National Academy of Engineering and National Research Council, *Positioning Synthetic Biology to Meet the Challenges of the 21st Century*, p. 10.

perform specific functions.<sup>20</sup> The building-block devised design can be sent to a bioprinter that will assemble the genetic material (plastics, metals, etc., in a conventional 3D printer) to create a new life form. The creator of the organism won't need to know how each of the BioBricks works—just as the designer of a 3D printed object does not have to be a software engineer—but only trained to use software to design the object on a computer and

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Perhaps even more astounding than the ability to digitize and bioprint life is that this digital life can be transmitted over the Internet and the organism recreated anywhere on the planet. Or, as Venter adds, digital life can be used to recreate organisms found on Mars by digitizing their DNA and transmitting the file back to Earth. And perhaps it might even be possible to send digital files of life-saving drugs to a future generation of human colonists on the Red Planet. In a global pandemic, synbio could both greatly reduce the time required to develop a vaccine and then send the digitized vaccine sequence around the world to be bioprinted for immediate use.

As the Internet and 3D/4D printing before it, synbio may dramatically change the world. Combined, these technologies will change what we can make, how we make it, where we make it, and what materials we use to make it. There are huge potentials for sustainability

(i.e., recycling amino acids). Drew Endy, a bioengineering professor at Stanford University, calculates that genetic engineering and synthetic biology already contribute about 2 percent to US GDP and predicts a near-term synbio-generated technological and economic boom comparable to the impact of the Internet earlier in this century.<sup>21</sup>

Craig Venter says genetically engineered organisms can be created for biofuels, water purification, textiles, food sources, and bioremediation. British scientist and architect Rachel Armstrong foresees synbio-developed “protocells” transforming architecture and cities to make them more resilient and even positive contributors to the environment.<sup>22</sup> “Instead of our buildings remaining inert, they could adapt to or respond to the seasons, like parks and gardens, with living coatings responding to the availability of more or less wind, sunlight and water.”

The ease associated with bioengineering—and the low cost and wide availability of materials and capabilities—has raised concerns about the potential dangers posed by synbio, especially the ability to alter viruses to become more deadly, or to create wholly new lethal microorganisms. Laurie Garrett, global health expert at the Council on Foreign Relations, noting that “the world of biosynthesis is hooking up with 3D printing,” points out that scientists in one city designing a genetic sequence on a computer can send the code to a printer somewhere else. The code might be the creation of a life-saving medicine or vaccine, Garrett asserts, “or it might be information that turns the tiny phi X174 virus . . . into something that kills human cells, or makes nasty bacteria resistant to antibiotics, or creates some entirely new viral strain.”<sup>23</sup> The challenge ahead will be to develop a security strategy that minimizes the dangers posed by dual use without undermining development of the field.<sup>24</sup>

20 The BioBricks Foundation (<http://biobricks.org/>) maintains a registry of a growing collection of genetic parts that can be mixed and matched to build synthetic biology devices and systems. BioBrick standard biological parts are DNA sequences of defined structure and function that share a common interface and are designed to be incorporated into living cells such as *E. coli* to construct new biological systems. Many of these parts are created through the International Genetic Engineered Machine Competition (iGEM) of young scientists and engineers.

21 Cited by Laurie Garrett, “Biology’s Brave New World—Be Happy—And Worry,” *Foreign Affairs*, November/December 2013, p. 36.

22 Rachel Armstrong, *Living Architecture: How Synthetic Biology Can Remake Our Cities and Reshape Our Lives*, (TED Books: February 6, 2013), Kindle edition.

23 Garrett, op. cit., p. 38.

24 Laurie Garrett, “Staying Safe in a Biology Revolution,” July 11, 2013, Council on Foreign Relations video, <http://www.cfr.org/technology-and-science/staying-safe-biology-revolution/p31087>. The availability of cheap polymerase chain reactions could lead to “home brewed” lethal viruses that could unleash a global pandemic for which there was no antidote or vaccine.





A do-it-yourself quadcopter drone at Singularity University, located at NASA Research Park, Moffett Field, California, that could carry a camera or a small cargo. *Photo credit: Banning Garrett.*

## The Individual Empowered by Mobile Computing Power and Connectivity

The individual is increasingly the focal point of technology, both as the target of marketing campaigns and surveillance by others, and as a collector and processor of data. The individual wields ever-increasing computing and communications power on mobile devices that provide tentacles of outreach to and input from almost the entire world.<sup>25</sup> While such power was unimaginable even a decade ago, it is only the beginning of what is likely to be possible in coming decades.

Moreover, the individual is increasingly enmeshed in a vast and rapidly evolving milieu of technology. Billions of devices, including computers, smartphones,

sensors, machines, and even the natural environment, are wired together and connected to people through the “Internet of Things.” This will affect nearly all aspects of life, although much of this interconnectivity will be invisible or “taken for granted.”<sup>26</sup> People are becoming hybrid beings for whom technology is increasingly an extension of themselves, through devices that are almost physical extensions of their bodies. These devices will become ever more “wearable” in the future with smart glasses, smart watches, and smart clothing. Google Glass has already demonstrated the potential power available “hands free” to the individual with the ability to access data available such as that on smartphones or specific information on a patient, technical procedure, or account. The information can be called up by voice command or a wink and be visible to the wearer superimposed on “reality.”<sup>27</sup>

Other companies are also developing wearable

<sup>25</sup> A UN report said that by 2014 there would be more than seven billion mobile phones, or more than one for every person on the planet. The report also predicted that by the end of 2013, there would be more than 2.1 billion mobile broadband subscribers, triple the number of fixed broadband connections. “Broadband is introducing new ways of doing things across our personal and professional lives, in the many and varied ways we communicate—integrating information infrastructure into the world around us through seamless, always-on connectivity delivering a range of services simultaneously.” Broadband Commission, *The State of Broadband 2013: Universalizing Broadband* (Geneva: September 2013), <http://www.broadbandcommission.org/Documents/bb-annualreport2013.pdf>.

<sup>26</sup> Banning Garrett, “Big Data Is Changing Your World...More Than You Know,” Atlantic Council, August 2013, [http://www.atlanticcouncil.org/images/publications/Big\\_Data\\_is\\_Changing\\_Your\\_World.pdf](http://www.atlanticcouncil.org/images/publications/Big_Data_is_Changing_Your_World.pdf); Neil Gershenfeld and JP Vasseur, “As Objects Go Online,” *Foreign Affairs*, March-April 2014, <http://www.foreignaffairs.com/issues/2014/93/2>.

<sup>27</sup> For an example of this capability in action, see Klint Finley, “Google Glass Does Solar Panel Installs in the California Sun,” *Wired*, December 23, 2013, <http://www.wired.com/wiredenterprise/2013/12/sullivan-solar/>.

## Oculus Rift



Oculus Rift went from a crowd-funded Kickstarter concept to a \$2 billion Facebook acquisition in the space of just over eighteen months. This photo shows video screen displays of the images for each eye seen in an Oculus Rift headset. By streaming two simultaneous instances of video with slightly offset images through the Oculus' two display pieces (one for each eye), the wearer's entire field of view is immersed in 3D virtual reality. *Photo credit: Banning Garrett.*

computing devices. Intel, for instance, unveiled Edison, a “full Pentium-class PC in the form factor of an SD card.” It is used to power a monitoring system that can be clipped to an infant’s clothing to track heart rate, breathing, and movements, and transmit the data at regular intervals as status updates.<sup>28</sup> And as individuals interact with others and the environment, smart devices could also be actively interacting and exchanging information with other smart devices.

As with all things connected to the Internet, the ever-lurking threat of the malicious hacking of the Internet of Things hangs over these devices, especially cheap sensors or wearable gadgets that have virtually no built-in security measures to protect them. Individuals or small groups could reprogram these devices—including control systems in (driverless) cars, planes,

and drones—for destructive or nefarious purposes.<sup>29</sup> No sooner had Amazon.com founder Jeff Bezos announced plans to deliver small packages via drones, when a well-known hacker released technical plans for an interceptor drone capable of hijacking other drones.<sup>30</sup>

Although new technology gives the individual unprecedented and increasing power and knowledge, corporations and governments can also use this same technology to violate individuals’ privacy and civil rights. Companies like Google and Facebook provide free services to individuals, but the price for these services is the acquisition of massive amounts of personal

28 Sebastian Anthony, “CES 2014: Intel Abandons Smartphones, Focuses on Wearable Computing and Tablets,” *ExtremeTech.com*, January 7, 2014, <http://www.extremetech.com/extreme/174168-ces-2014-intel-abandons-the-smartphone-ship-focuses-on-wearable-computing-and-tablets>.

29 Peter Haynes and Thomas A. Campbell, “Hacking the Internet of Things,” *ScientificAmerican.com*, August 13, 2013, <http://www.scientificamerican.com/article.cfm?id=hacking-internet-of-everything>.

30 Matthew J. Schwartz, “Hardware Hacker Demos Zombie Drone Hijacker,” *InformationWeek.com*, December 2013, <http://www.informationweek.com/security/vulnerabilities-and-threats/hardware-hacker-demos-zombie-drone-hijacker/d/d-id/1112913>.



data, often unwittingly.<sup>31</sup> The state, too, has access to technology that lets it gather information on specific individuals. This capability ranges from increasingly ubiquitous closed-circuit television (CCTV) powered by enhanced facial recognition software to massive data gathering on individuals by the National Security Agency (NSA).

Today, government agencies use powerful algorithms to target individuals by discovering connections between telephone calls, bank account records, tweets, Facebook postings, Google searches, YouTube videos, and physical movements tracked by GPS applications on their smartphones. In extreme cases, the state can—as the US government already has done—target individuals or small groups for elimination through kinetic attacks by drones. The tension between individual privacy rights and government information-gathering and surveillance is likely to continue indefinitely, with the two sides often engaged in a virtual arms race as citizens and companies try to prevent government snooping, and with the government employing more technology and resources to maintain and increase its access.

## The Future Is Unevenly Distributed

“The future is already here—it’s just not very evenly distributed,” science fiction writer William Gibson famously quipped two decades ago.<sup>32</sup> He made an important point: disruptive technologies and their multiple orders of impact on society develop at different paces within societies and globally. Electric vehicles (EV), for example, are already on the road. The all-electric Tesla Model S is the highest rated automobile by *Consumer Reports* in history.<sup>33</sup> Tesla currently produces only a handful of cars per year, and they cost anywhere

from \$60,000 to \$100,000—far too expensive for most consumers. However, the Model S may be the harbinger of future personal transportation throughout the world over the next two to three decades.

The widespread use of EVs—and eventually self-driving vehicles—may have a profound impact on society. The auto industry’s transformation could create new winners and losers of corporations and workers. Reduced demand for gasoline will hurt not only the oil industry from well to pump, but also the economic and geopolitical status of oil-producing countries, possibly leading to the fall of autocratic regimes. Demand for electricity production, smart grid connections, and distributed solar and wind power would all likely rise. The reduction in carbon emissions could slow the trajectory of global warming and pressure societies to transition faster to electric-vehicle production.

THE ALL-ELECTRIC TESLA  
MODEL S IS THE HIGHEST RATED  
AUTOMOBILE BY CONSUMER  
REPORTS IN HISTORY.

But then again, maybe the future is not the EV, which could remain a niche player with a slow increase in demand as major auto companies do not follow Tesla’s lead and special interests that have everything to lose in the transition oppose government assistance to the nascent EV industry. Moreover, other technology could slow the pace of EV development. Gas prices may remain low due to new technology enabling capture of previously unrecoverable shale oil. The extraction of this previously inaccessible oil is already occurring and is likely to continue for years if not decades. New technology in one area—energy extraction—could affect the deployment and impact of technology in another realm—electric vehicles.

A more serious “uneven distribution” of the future could be in the area of human augmentation, including cognitive enhancement. There is concern that this would add a new layer of technological capabilities to enhance the power and income of those already privileged. New technologies could potentially be monopolized by a “ruling class” that seeks to use its advantages to further enhance its position, further widening the growing inequality gap in nearly all countries.

31 Jaron Lanier, in *Who Owns the Future?* (New York: Penguin Books, 2013), maintains that users should be paid for the data they provide Google, Facebook, and other Internet companies whose business model and profits are based on use of the massive amounts of accumulated user data.

32 “Science Fiction Writer William Gibson,” *Fresh Air*, NPR, August 31, 1993.

33 “Slipping behind the wheel of the Tesla Model S is like crossing into a promising zero-emissions future. This electric luxury sports car, built by a small automaker based in Palo Alto, California, is brimming with innovation, delivers world-class performance, and is interwoven throughout with impressive attention to detail. It’s what Marty McFly might have brought back in place of his DeLorean in *Back to the Future*. The sum total of that effort has earned the Model S the highest score in our Ratings: 99 out of 100.” “Tesla Model S Review,” *Consumer Reports*, July 2013, <http://www.consumerreports.org/cro/magazine/2013/07/tesla-model-s-review/index.htm>.

On the other hand, human enhancement technologies may rapidly spread throughout societies globally, just as the PC democratized computing, the mobile phone democratized communication, and smartphones are democratizing Internet access. New ICT capabilities that will further augment humans through access to information, communications, sensors, location, computing power, etc., may spread so rapidly that any advantage of the rich is both relative and transient. In this scenario, technological change would neither reinforce class divisions nor strengthen the political power of the wealthy.

On the contrary, in this future, technology would help level the playing field. Many of these technologies may be extremely cheap and plentiful, and much if not most of the information they access and produce is “free” due to the marginal cost of information distribution in the digital age. When one downloads a document, there is no additional cost of production other than the amount already invested in a computer and the cost of Internet access. A million electronic copies cost no more to make than ten electronic copies. But in the material world, every additional item produced has costs in materials, production, and distribution. Although the rich have an advantage when it comes to the acquisition of material goods such as big houses and expensive cars that others cannot afford, they have no such advantage in access to “free” information available to virtually everyone. So perhaps the initially uneven distribution of the future in the area of human augmentation could produce a future characterized by more equal distribution of knowledge and power.<sup>34</sup>

The uneven distribution of the future extends to the developing world where new technology innovations are transforming economies. In many poor countries, relatively underdeveloped and outmoded infrastructure could spur new technology-enabled innovations that allow countries to leapfrog old technologies, as the mobile phone has spread rapidly, bypassing the stage of wired telephone systems. The new technology-enabled teaching models, such as the Khan Academy, Udemy, and the many university-sponsored MOOCs (massive open

online courses), often free or inexpensive, will enable countries to rapidly educate their populations without the huge investment and time-consuming construction of “bricks and mortar” educational institutions and the transport infrastructure needed to get students physically to the place of education. As they seek out of necessity to exploit these technologies to leapfrog stages of development in education infrastructure, these countries may also become a source of new innovations in education that are exported back to the developed world.

ALTHOUGH THE RICH HAVE AN ADVANTAGE WHEN IT COMES TO THE ACQUISITION OF MATERIAL GOODS SUCH AS BIG HOUSES AND EXPENSIVE CARS THAT OTHERS CANNOT AFFORD, THEY HAVE NO SUCH ADVANTAGE IN ACCESS TO “FREE” INFORMATION AVAILABLE TO VIRTUALLY EVERYONE.

In the future, transportation infrastructure, 3D printing,<sup>35</sup> and new energy technologies also may find their most innovative uses in developing countries. Developing world efforts to harness new medical technologies and innovations to provide better health care at lower costs may provide models for addressing ever-higher global healthcare costs. Some developing world innovations have already found their way to the developed world, such as Ushahidi, a website initially created in the aftermath of Kenya’s disputed 2007 presidential election. Ushahidi (Swahili for “testimony” or “witness”) collected eyewitness reports of violence

34 Jeremy Rifkin, *The Zero Marginal Cost Society: The Internet of Things, the Collaborative Commons, and the Eclipse of Capitalism* (New York: Palgrave Macmillan, 2014). Rifkin argues that the world economy is moving toward zero marginal cost production not only in the digital realm but also in energy production such as solar power, which is marginally free, and even production of goods via 3D printing and other mechanisms. See also comments on Rifkin’s thesis by Banning Garrett, “Moving to Zero,” *Huffington Post*, April 3, 2014, [http://www.huffingtonpost.com/banning-garrett/moving-to-zero\\_b\\_5079238.html?1396528010](http://www.huffingtonpost.com/banning-garrett/moving-to-zero_b_5079238.html?1396528010).

35 Peter Diamandis and Steven Kotler suggest that with 3D printing, powered by cheap cloud computing, design, and manufacturing, can be globally democratized. “Suddenly an invention developed in China can be perfected in India, then printed and utilized in Brazil on the same day—giving the developing world a poverty-fighting mechanism unlike anything yet seen.” *Abundance: The Future is Better Than You Think* (New York: Free Press, 2012), p. 70. See also “3D Printing Brings New Promise for Developing World,” *Techtonics* (blog), *Voice of America*, December 20, 2013, <http://blogs.voanews.com/techtonics/2013/12/20/3-d-printing-brings-new-promise-for-developing-world/>.

reported by text message and placed incidents on a Google map. Today, Ushahidi's platform is widely used not only throughout the developing world, but also in the United States and Europe for a wide range of purposes, from election monitoring and protest organizing to disaster relief coordination. The uneven distribution of the future may result in new uses of emerging technologies with accompanying innovative business models that spread from South to North and South to South as well as from niches to the broader society within both developed and developing countries.

## Alternative Futures

Experts can foresee the trajectories of some technologies with a certain level of confidence. Computers will become faster, smaller, more connected, and more ubiquitous. Robots, of both the physical and digital varieties, will be increasingly ubiquitous in people's economic and personal lives. Both the individual and the organization (whether business or the state) will have access to more digital power. 3D printing will empower the individual to become a digital-to-material creator, and the same technology will transform manufacturing and many other industries. Synthetic biology will not only impact health care and medicine but also industry and the environment. Nanotechnology will continue to improve the ability to manipulate matter at the molecular level across almost all areas of material invention.

**3D PRINTING WILL EMPOWER THE INDIVIDUAL TO BECOME A DIGITAL-TO-MATERIAL CREATOR, AND THE SAME TECHNOLOGY WILL TRANSFORM MANUFACTURING AND MANY OTHER INDUSTRIES.**

More generally, technological convergence will spur new, unexpected developments, while new scientific discoveries will likely further upend our technological future. One of those “upending” technological breakthroughs is likely to be quantum computing, which will transform people's ability to understand the world and solve problems currently insoluble by even the fastest conventional computers crunching numbers for

hundreds or thousands of years.<sup>36</sup>

In short, we can already identify the outlines of a huge array of technological developments, although we cannot predict with certainty whether these will come to fruition as major innovations and, if they do, when that would occur. It is even more difficult to foresee how societies will use new technology and its second-, third-, and fourth-order effects. Will new technology be harnessed to meet global challenges such as climate change and energy transition and growing demands for food and water? Will new technology create more jobs than it destroys? Will it lead to more wealth for all or further exacerbate growing inequality? Will individuals, groups, or governments use it for destructive purposes, including bioterrorism, cyber warfare, and robotic attacks? Will it advance democracy or authoritarianism? Will it enhance prospects for global prosperity and cooperation or lead to new conflict and zero-sum competition?

These questions about technology's impact on society underscore the inherent unpredictability of the future, which depends on decisions not yet made by individuals, groups, and governments. In short, the future does not passively “happen” but is the result of choice—billions of individual and collective choices. An infinite number of alternative futures can be chosen and shaped.

Preparing for the uncertain and unevenly distributed future puts great demands on governments, businesses, organizations, and individuals. One relative certainty is that the future will not simply be a continuation of the present. Surprising and abrupt changes will be increasingly commonplace. Preparing for the disruptive and unexpected—and shaping the future we want—will require agility, resilience, and anticipation of alternative futures.

<sup>36</sup> Quantum computers will not just be faster, but will approach problem solving in a fundamentally different way. Instead of decryption, where billions or trillions of possible combinations need to be tested sequentially, a quantum computer could try all combinations simultaneously to find the key. One simulation by Microsoft indicated that a factoring problem that would take 31,000 years to solve on a conventional computer could be resolved in a matter of seconds on a quantum computer. When quantum computers become available, much, if not most, current encryption, including on the Internet, will be subject to nearly instantaneous decryption. Quantum computers could also mark a new age in solving intractable problems. A quantum computer could simultaneously explore thousands of possible molecular combinations for a new material or drug to find the best combination in short order. These could include such challenges as creating a room temperature superconductor or accurately and in detail modeling climate change. Although the first quantum computers will be very large, they could eventually be very small and provide immense new power to individuals and the Internet of Things.



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