The Future of Work

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Introduction

A powerful, deep and far-reaching transformation is underway in industry. It is fundamentally changing the way we design and manufacture products, and what these products can do. It is making the complex supply and distribution networks that tie the global economy together faster, more flexible, and more resilient. It is empowering human beings to unleash more broad-based and distributed creativity and entrepreneurship. It is redefining the competitive landscape in multiple sectors, with far-reaching implications that will reverberate through international trade patterns and the distribution of global growth. And it is affecting each of our daily lives through major advances in health care, energy, transportation, and the way we work.

This transformation is the Future of Work. Three major forces are converging to shape it:

1. The meshing of the physical and digital world – the Industrial Internet
2. The development of new production processes and materials – Advanced Manufacturing
3. A reorganization of the networks linking together factories, workers, supply chains and distribution channels, which is enabled by advanced manufacturing and the industrial internet

The first driving force is the Industrial Internet. The lines between the physical and digital world are becoming increasingly blurred. The integration of cloud-based analytics ("big data") with industrial machinery ("big iron") is creating huge opportunities for productivity gains. As we have shown in previous studies,[1] the rapid decline in the costs of both electronic sensors and storing and processing data now allows us to harvest massive amounts of data from industrial machinery. Using advanced analytics, we can then draw insights that can increase efficiency.

Machines like gas turbines, jet engines, locomotives and medical devices are becoming predictive, reactive and social, making them better able to communicate seamlessly with each other and with us. The information they generate becomes intelligent, reaching us automatically and instantaneously when we need it and allowing us to fix things before they break. This eliminates downtime, improves the productivity of individual machines—as jet engines consume less fuel and wind turbines produce cheaper power—and raises the efficiency of entire systems, reducing delays in hospitals and in air traffic.

The second driving force is Advanced Manufacturing. At the core of the advanced manufacturing idea is the ability to digitally link together design, product engineering, manufacturing, supply chain, distribution, and remanufacturing (or servicing) into one cohesive, intelligent system—a Brilliant Factory. New production techniques like additive manufacturing, or 3D printing, allow us to

[1] Marco Annunziata and Peter C. Evans, "The Industrial Internet: Pushing the Boundaries of Minds and Machines", GE White Paper, November 2012; and "The Industrial Internet @ Work", GE White Paper, October 2013.

create completely new parts and products with new properties.

They also give us more flexibility to produce prototypes faster and at lower cost. Engineers can "print" one part, test it and, based on the test feedback, quickly adjust the digital design and reprint an improved version of the part—all using the same additive manufacturing machine. This accelerates the cycle of design, prototyping and production. Adjustments to the production process, as well as to supply chain and distribution logistics, can be calculated and enacted in real time.

This will turn the traditional factory into a Brilliant Factory. Risk-mitigation and resilience-enhancing strategies will be easier to develop, and will become an integral part of the Brilliant Factory's automatic response/adjustment system. Moreover, as we explore below, advanced manufacturing will accelerate a shift toward distributed production, micro-factories, and mass-customization.

The third driving force is the Global Brain. Technological progress and economic growth are contributing to a seismic shift in the role that human beings play in the production process. Technological progress, notably in High-Performance Computing (HPC)[2], robotics and artificial intelligence, is extending the range of tasks that machines can perform better than humans can. This may have painful short-term costs as some jobs are displaced and some skills made obsolete. But it dramatically augments the power and economic value of the areas where humans excel: creativity, entrepreneurship and interpersonal abilities.

Meanwhile, economic growth is extending to tens of millions more people. This growth is realized through both access to the Internet and the time to take advantage of it, since better access to food, clean water and health care free up precious hours. Millions more people will join the ranks of those who can both tap and contribute to the global stock of knowledge. The global brain—the collective intelligence of human beings across the globe integrated by digital communication networks—will grow bigger and more powerful.[3] The global brain is, in effect, the human version of HPC.

Open-source platforms and crowd-sourcing are two of the most effective ways to unleash the creativity and entrepreneurship potential of the global brain. Industry is increasingly relying on both in a trend that will deliver greater flexibility and greater rewards to both employers and employees—and redefine relationships between the two. Employers will gain access to a larger pool of talent, which could vary depending on the task at hand; and workers will gain greater entrepreneurial control over their skills and talents.

The Future of Work will substantially accelerate productivity and economic growth. In our Minds and Machines paper, we estimated the major economic benefits that can accrue from the Industrial Internet alone, based on a detailed assessment of sector-specific efficiency

[2] High Performance Computing leverages the power of "clusters" of interconnected computers, normally referred to as "nodes". The coordinated computing power of the nodes delivers much higher performance, enabling to solve large-scale high-complexity problems in business, science and engineering.

[3] The term "global brain" was originally coined by Peter Russell (1983) in his book "The Global Brain: speculations on the evolutionary leap to planetary consciousness." Los Angeles, JP Tarcher.

gains.[4] Some economists argue that modern innovations have nowhere near the transformative power and potential economic impact of the industrial revolution,[5] but **we believe the Future of Work will be as transformational as the industrial revolution, and possibly more.[6] This will bring major improvements to the quality of our lives.**

This transformation will not happen overnight. Its seeds were sown some time ago and have taken time to germinate. But we are now entering the stage where the changes we describe are set to accelerate decisively. To use an expression coined by Ray Kurzweil, we are entering into the second half of the chessboard—the phase where changes become all of a sudden a lot more visible, where science fiction more quickly turns into reality.[7]

This transformation will not happen by itself. We will have to invest in the new technologies and adapt organizations and managerial practices. We will need a robust cyber security approach to protect sensitive information and intellectual property, and to safeguard critical infrastructure from cyber-attacks. The education system will have to evolve to ensure that students are equipped with the right skills for this fast-changing economy. Continuous education and retraining will be needed to cushion the impact of transitional disruptions in the labor market. It will require time and investment, but this wave of technological innovation will fundamentally transform the way we live.

This paper is the first chapter of an ongoing research project and aims to lay out the framework for the Future of Work, exploring the three forces converging to shape it. In subsequent papers we will delve more deeply into how the Brilliant Factory works, discuss the evolving interaction of technology and the global brain, explore the potential of technological developments like robotics and artificial intelligence, and assess the implications for the competitive and macroeconomic landscape. Here we will more broadly describe the changes afoot. We will also strive to provide very concrete examples to bring these changes to life.

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[4] In "The Industrial Internet: Pushing the boundaries of minds and machines" we estimated that a 1% efficiency gain achievable through industrial internet technologies would yield savings of $90B in the Oil and Gas sector, 66B in the power sector, 63B in health care, 30B in aviation and 27B in rail transport.

[5] Robert Gordon, "The Demise of US Economic Growth: Restatement, Rebuttal and Reflections", NBER Working Paper 19895, February 2014; and ""Is US Economic Growth Over? Faltering Innovation Confronts The Six Headwinds", NBER Working Paper 18315, August 2012.

[6] The Industrial Revolution spanned a period of around 150 years beginning in the mid-18th century, and can be seen as divided in two distinct periods: the First Industrial Revolution, triggered by the invention of the steam engine, and the Second Industrial Revolution, starting around 1850, which saw a broader acceleration of technology, with the development of the internal combustion engine and electricity. Since the two revolutions developed along a continuum, we adopt the convention of "Industrial Revolution" to refer to both periods combined.

[7] Ray Kurzweil (2000), "The age of spiritual machines: When computers exceed human intelligence", Penguin.

1. The Industrial Internet

The lines between the physical and digital world are becoming increasingly blurred. The integration of cloud-based analytics ("big data") with industrial machinery ("big iron")—the Industrial Internet—is creating huge opportunities for productivity gains. Industrial machines are being equipped with a growing number of electronic sensors, which allow them to see, hear and feel a lot more than ever before—all while generating enormous amounts of data. Sophisticated analytics then sift through this data, providing insights that allow us to operate machines—and thus fleets of airplanes and locomotives, and entire systems like power grids or hospitals—in entirely new, more efficient ways.

We are entering a world where the machines we work with are not just intelligent, but brilliant.

Brilliant machines

Electronic sensors have been around for some time, but their cost is rapidly declining and, thanks to the advances of cloud computing, the cost of storing and processing data is rapidly declining as well. This is accelerating the scalability of the Industrial Internet.

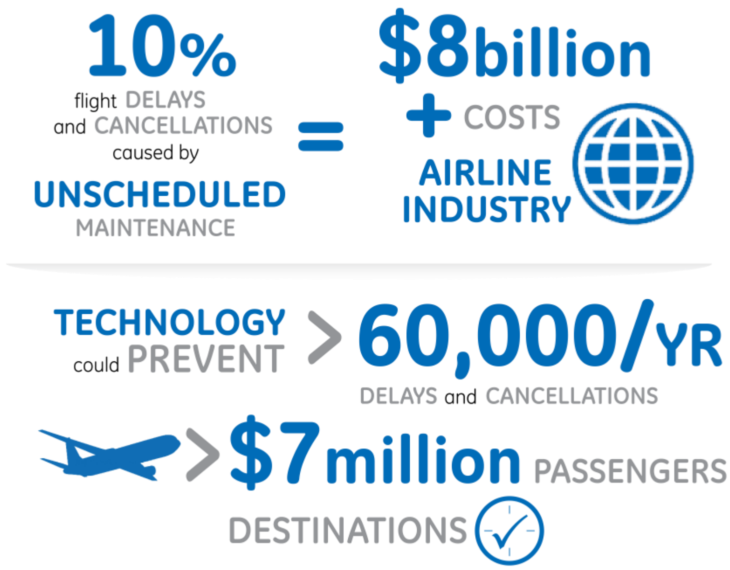
We are entering a world where the machines we work with are not just intelligent, but brilliant. They are predictive, reactive and social: airplane engines, locomotives, gas turbines, and medical devices are able to communicate seamlessly with each other and with us. Information is becoming intelligent; it reaches us automatically and instantaneously when we need it. We don't need to look for it.

While many industrial assets have been endowed with sensors and software for some time, software has traditionally been physically embedded in hardware in a way that the hardware needs to change every time the software is upgraded. We are beginning to deploy technologies like embedded virtualization, multi-core processor technology and advanced cloud-based communications throughout the industrial world. This new software-defined machine infrastructure will allow machine functionality to be virtualized in software, decoupling machine software from hardware and allowing us to automatically and remotely monitor, manage and upgrade industrial assets. In other words, the software of new-generation industrial assets can be upgraded remotely without changing any hardware at all—much like the software in our smartphones, instantly enabling new functionalities.

Zero unplanned downtime

This allows us to shift to preventive, condition-based maintenance. We'll be able to fix machines before they break rather than servicing them on a fixed schedule, and it will take us towards "zero unplanned downtime": no more power outages, no more flight delays, and no more factory shutdowns.

Ten percent of flight delays and cancellations are currently caused by unscheduled maintenance events, costing the global airline industry an estimated $8 billion—not to mention the impact on all of us in terms of inconvenience, stress, and missed meetings as we sit helplessly in an airport terminal. To address this problem, GE has developed a self-learning predictive maintenance system that can be installed on any aircraft to predict problems a human operator might miss. While in flight, the aircraft will talk to the technicians on the ground; by the time it lands, they will already know if anything needs to be serviced. For U.S. airlines alone, this system could prevent over



60,000 delays and cancellations a year, helping over 7 million passengers get to their destinations on time.

The health care industry also has huge gains at stake with the Industrial Internet; just a one percent reduction in existing inefficiencies could yield more than $60 billion in savings globally. Nurses today spend an average of 21 minutes per shift searching for equipment, which is less time spent caring for patients. Industrial Internet technologies allow hospitals to electronically monitor and connect patients, staff, and medical equipment, reducing bed turnaround times by nearly one hour each. When you need surgery, one hour matters; it means more patients can be treated and more lives can be saved.

Similar advances are taking place in energy, including renewables like wind. Remote monitoring and diagnostics, which allow wind turbines to communicate with each other and adjust the pitch of their blades in a coordinated way as the wind changes, have helped reduce the electricity generation cost in wind farms to less than five cents per Kwh. Ten years ago, the equivalent cost was over 30 cents—six times as much.

Platforms and collaboration tools

Industrial Internet tools and applications also help people collaborate in a faster and smarter way, making our jobs not just more efficient but more rewarding. Secure and reliable cloud-based platforms today allow teams of physicians and caregivers to quickly confer on patient cases, simultaneously access images and reports, and collaborate on diagnosis and treatment plans. By better leveraging each other's reports and expertise, health care professionals can deliver better health outcomes.

Systems like this are made possible by integrated digital software platforms that support a combination of information collection and storage, new analytic capabilities, and new modes of collaboration. These platforms can provide a standard way to run industrial scale analytics and connect machines, data and people. They can be deployed on machines, on-premise or in the cloud, and support technologies for distributed computing and big data analytics, asset data management, machine-to-machine communication and mobility—all in a secure environment that protects industrial data and safeguards access to machines, networks and systems.

2. Advanced Manufacturing

"The way we make things" is changing.

A wide-ranging wave of industrial innovations is changing every aspect of the production process. New techniques and materials mean we can make new things in new ways. We can use what we learn from data to reorganize the supply and distribution networks that tie an individual factory to its customers, distributors and suppliers in ways that enable greater speed and flexibility. The cycle that starts with design and prototyping, moving then to production, and on to customer use and servicing, is shortening and accelerating.

As the factory itself becomes intelligent—more than just intelligent, brilliant—it can predict, adapt and react more quickly and efficiently than ever before. Advanced manufacturing allows plant managers and engineers to simulate the impact of product design changes on the factory floor and reorganize supply chains and production processes in real time in response to unexpected events. Advanced manufacturing redefines the concept of scale, and enables a shift towards distributed manufacturing, micro-factories and mass-customization, which we will explore below.

Manufacturing redefines the concept of scale, and enables a shift towards distributed manufacturing, micro-factories and mass-customization.

New production processes and new materials

While it is not new, the process of additive manufacturing or "3D printing" has been grabbing media headlines—and it is easy to understand why. Besides the catchy moniker, additive manufacturing is at a stage where devoted amateurs can experiment at home or in a garage.

The technology has been around since the 1980s when Charles Hull first developed a process he called stereolithography (a much less catchy name than 3D printing!), creating a three-dimensional object from a digital blueprint by adding successive layers of specific materials. Over the subsequent three decades, the process has been refined, becoming more precise and allowing for the use of a wider range of materials. While the initial experiments used a UV laser-solidifying photopolymer, successive generations of 3D printers have used plastic and metal powders.

Some 3D printers are capable of handling multiple materials, so the objects they produce can possess a combination of different physical properties. Because of this, additive manufacturing can now be used to build medical implants and industrial components like parts for aircrafts and gas turbines—and perhaps even human tissue.[8]

Why is 3D printing so impactful? There are five major reasons:

1. Additive manufacturing enables the design and production of new parts and products that could not be obtained with traditional manufacturing techniques. Aircraft engine lean-combustion combustor components manufactured this way can combine more than twenty previous separate components into one. Additively manufacturing geometrically complex structures, such as aircraft engine brackets, substantially reduce the weight of these parts.
2. Additive manufacturing is fundamentally different from traditional "subtractive" techniques which rely on casting, cutting, drilling, milling and

[8]Anonymous: "Printing a bit of me", *The Economist, March 8, 2014.*

Additive manufacturing enables more localized, distributed, and reconfigurable production, which will completely change supply chains as we know them today.

joining materials. While subtractive manufacturing "wastes" up to 90 percent of the raw material, with additive manufacturing, almost all printed material is part of the final product.

3. Additive manufacturing enables the creation of an entirely new ecosystem of innovation through crowdsourcing of design. Crowdsourcing platforms, such as GrabCAD, allow manufacturers to post design challenges that are attacked by hundreds of engineers all around the world. GE recently conducted such a quest for an aircraft engine bracket and received close to 700 entries. The winning design (from Indonesia) reduced the weight by more than 80 percent.
4. Additive manufacturing is highly flexible since one can print very different parts on the same machine (albeit constrained by size and material).
5. Because of its flexibility, additive manufacturing enables more localized, distributed, and reconfigurable production, which will completely change supply chains as we know them today.

While additive manufacturing has captured the public's imagination, only 0.02 percent of all goods in the United States are produced using 3D printing[9]. Can the benefits of additive manufacturing be extended to large-scale "traditional" manufacturing? The answer is yes. **We project that by 2020 over 100,000 parts will be additively manufactured by GE Aviation**, which could reduce the weight of a single aircraft by 1,000 pounds, resulting in reduced fuel consumption.

Two major forces are spurring this progress: (1) High Performance Computing (HPC), and (2) the advent of "big data" to factories and supply chains. Together, these phenomena will enable vast improvements of manufacturing processes and systems, leading to a new paradigm in manufacturing.

We call this new paradigm the Brilliant Factory.[10] [11] Many of the elements of the Brilliant Factory are not new,[12] but the systems integration and the feedback loops described below are novel. HPC and Internet-like data speeds in factories are enabling the modeling accuracy and real-time optimization of factories and supply chains.

[9] Wohlers Associates: "Additive Manufacturing and 3D Printing State of the Industry", Wohlers Report 2013, May 2013, wohlersassociates.com.

[10] Biller, Stephan: "GE's Brilliant Factory", *EmTech Conference 2013*, *MIT*, Cambridge, MA.

[11] Furstoss, Christine: "Digital Thread: Creating a Self-Improving, Brilliant Factory", *CIO Review, December 2013*.

[12] See for example www.smartmanufacturingleadershipcoalition.org

The Brilliant Factory

By creating a feedback loop from design to product engineering to manufacturing engineering to manufacturing and supply chain operation to services and back to engineering, factories can cut learning cycles between manufacturing and design, allowing for faster product development and flawless factory launches.

Just as in the case of the Industrial Internet, the physical and digital worlds are intertwining: every component of the value chain generates an increasing amount of data, which smart analytics quickly turn into insights instantly communicated across the relevant components of the system. The basic concept of the Brilliant Factory is simple: creating a digital connection, or "thread", across three major areas of the value chain: (1) manufacturing systems design, (2) manufacturing systems operations and (3) service operations (see Figure 1). By creating a feedback loop from design to product engineering to manufacturing engineering to manufacturing and supply chain operation to services and back to engineering, factories can cut learning cycles between manufacturing and design, allowing for faster product development and flawless factory launches.

The manufacturing process starts with design, which results in a digital blueprint. GE's Christine Furstoss explains:

Once a design has been determined, it is transmitted digitally to manufacturing engineering. Here the manufacturing processes are modeled and simulated. Are features producible? Will the manufactured part give a structure that will survive the stresses it encounters when in use? What trade-offs can be made to open up the tolerance to improve part yields? These are a few of many questions you can test and simulate. In addition, factory flow and layout, robots and manufacturing controls will be simulated and optimized prior to actual production.[13]

[13] Furstoss, Christine: *ibid*.

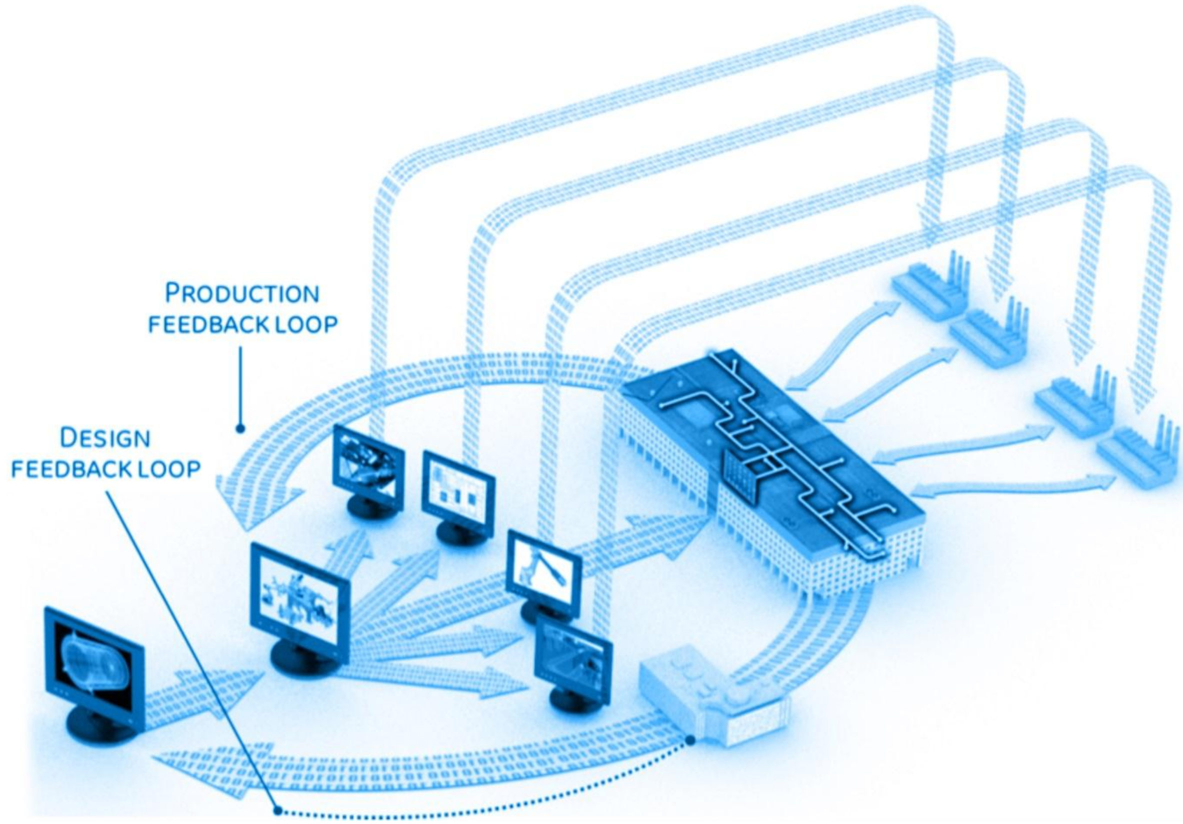


Figure 1: The Brilliant Factory

Once product design and manufacturing systems design have been virtually validated, manufacturing parameters and other programs and controls are transmitted to the factory floor. Intelligent machines then accept and translate the data to physically make that part or product.

The factory is digitally connected—machines to machines, machines to plant-floor execution systems, and factories to suppliers and sales force—and creates a completely transparent supply chain. Suppliers must also integrate into this thread to realize their innovation potential within this ecosystem.

Using HPC analytics, simulations, and algorithms optimizes production, logistics, inventory, and product offerings for factory, supply chain, and commercial operations in real-time. This is particularly important when unexpected failures occur; a robot might malfunction (or algorithms have predicted with high confidence that it will malfunction within the next 15 minutes), a supplier signals that parts will be delayed, or an employee is absent. Furstoss describes:

The Brilliant Factory will help adjust to problems with throughput, quality, and fulfillment, optimizing the extended enterprise in real time. In fact, utilizing predictive capability, the Brilliant Factory even reacts to problems that have not even happened yet, in a predictive and pre-emptive fashion, resulting in a factory that literally never stops. Knowledge gained from the manufacturing process can be fed back instantaneously to the virtual manufacturing stage to make modifications and improvements. Once tested, new and improved processes can be sent back to the Brilliant Factory to be implemented (production feedback loop). Once a product has been out with a customer for some time, it will need to be serviced. It is at this stage that a lot of new insights about the product's usage and shortcomings can be determined. In fact, servicing parts can be thought of as a failure mode and effects analysis for 100 percent of the products, which allows for improvements in the design and manufacturing process (design feedback loop). Both the production and the design feedback loop capture information and generate new knowledge for engineering and manufacturing of new and existing parts. This is the essence of GE's self-improving Brilliant Factory. What we are building is a truly open, collaborative innovation model that captures and acts on new information in ways that allow product design and manufacturing processes and systems to continuously improve. What's truly amazing is that we are rapidly reaching a point where machines will be able to make these optimizations themselves through real-time analytics and controls.[14]

Advanced manufacturing will also provide us with a genetic mapping of materials, production, use, and service history of each manufactured unit. Knowing perfect product genealogies will help engineers to identify with greater speed and accuracy the cause of any potential underperformance or quality issue—which can then be addressed with equally prompt and targeted actions. It also will provide an instant inventory of the exact products that might be affected by an issue, dramatically reducing the scale of product recalls.

Moreover, advanced manufacturing techniques can greatly expand the potential employment of re-manufacturing: the targeted replacement of broken or malfunctioning parts in a machine while keeping the basic design intact. Re-manufacturing can deliver up to 90 percent in energy savings over new manufacturing, with corresponding environmental benefits (by comparison, recycling energy savings in this context amount to less than 5 percent).[15]

The impact

Advanced manufacturing innovations present a veritable revolution in industry. New techniques are yielding new products with new features and properties. Eliminating the physical constraints of traditional manufacturing techniques expands the range of production possibilities. And when the products are industrial machines, these enhancements translate into efficiency gains and cost savings, like when lighter aircraft engines require less fuel to run.

Even more importantly, combining new manufacturing techniques with the data-driven power of the Industrial Internet allows us to tie together design, product engineering, manufacturing engineering, manufacturing, supply chain and distribution in one cohesive, intelligent digital thread—the Brilliant Factory.

The result is a tremendous gain in speed and efficiency: a faster feedback look between design, prototyping, production and customer experience that enables the entire production process to adjust in real time, automatically, to unexpected circumstances, guaranteeing "zero unplanned downtime" at the production system level. In the Brilliant Factory, risk-mitigation and resilience-enhancing

[14] Furstoss, Christine: ibid.

[15] See John W. Sutherland, Daniel P. Adler, Karl R. Haapala and Vishesh Kumar, " A Comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production", CIRP Annals – Manufacturing Technology, 2008.

strategies will be easier to develop, and will become an integral part of the Brilliant Factory's automatic response/adjustment system.

Because different parts can be built from the same additive manufacturing machine, additive manufacturing can also change the nature of economies of scale. Traditionally, a factory would need to produce a very large number of identical units with each machine to achieve the benefits of economies of scale. Because additive machines are more flexible, factories can reach the same degree of capacity utilization while manufacturing a number of products with different features. If economic efficiency no longer hinges on the mass production identical units, it then becomes possible, from a profitability standpoint, to significantly increase the number of different versions of a specific product that can be churned out by the same production facility. Bespoke becomes nearly as easy and cost-efficient as mass-produced. Advanced manufacturing will enable mass-customization.

Advanced manufacturing also brings greater flexibility at the level of the factory and the entire manufacturing system. Scale remains extremely important, but will become increasingly distributed with greater reliance on smaller-scale manufacturing plants, or micro-factories. This would deliver a number of additional advantages:

A greater ability to co-locate research, design and manufacturing, accelerating the innovation process.

A greater ability to bring production closer to the market and optimize the production chain against factors like transport costs or local content requirements (though the optimal location of production facilities will ultimately depend on a number of key factors, including the availability of talent, the quality of infrastructure, and the overall business environment including regulation and taxation).

The flexibility to create jobs in areas where the necessary talent is available but suffers from constrained geographical mobility. During the slow recovery from the 2008 recession, for example, U.S. job growth has been hampered in part by reduced labor mobility as people were tied to underwater mortgages and unable to move to states with better job opportunities. Micro-factories could allow the jobs to come to them.

3. The Global Brain

New digital communication and analytical tools are powering greater flexibility and interconnectivity of machines. Similar changes are transforming the human side of the equation. Technological progress will push a growing share of the workforce toward creativity and entrepreneurship, where humans have a clear comparative advantage over machines. The global brain—the collective intelligence of human beings across the globe integrated by digital communication networks—will grow bigger and more powerful as tens of millions more people gain access to education and to the Internet, becoming able to both tap and contribute to the global stock of knowledge. Open-source platforms and crowdsourcing are two of the most effective ways to unleash the full creativity and entrepreneurship potential of the global brain. Companies are increasingly relying on both of these to deliver greater flexibility and greater rewards to both employers and employees—and redefine relationships between the two.

Technology breeds creativity and entrepreneurship

From the mechanization of agriculture to the early automation in industry, the shifting of tasks from humans to machines has gradually unburdened us of a number of physically arduous or mind-numbingly repetitive tasks. This process is ongoing: we delegate to machines the jobs they are better suited to perform with greater power, consistency and precision, and focus on the ones for which humans have a comparative advantage.

As machines and factories become brilliant, education and skills become more valuable. The last several decades have seen a rise in the "college premium," or the difference in the average wage of college graduates and high school graduates.16 This happened while the number of college graduates increased, so even as the supply of high-skills workers increased, the demand for their services increased even faster. Technological change has increased the productivity of high-skilled workers, making them more valuable and more sought-after. This is what economists call "skill-biased" technological progress. [17]

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[16] See for example Daron Acemoglu, "Technology and Inequality", NBER Reporter 2003; Acemoglu notes that this new kind of innovation, where new technologies are complementary to high skills workers, increasing their productivity and wages, stands in contrast to the technological change of the 19th century, which tended to replace skilled workers through automation.

[17] Jan Tinbergen, "Substitution of Graduate by Other Labor", Kyklos 27, 1974, first referred to a race between education and technology: technological innovation raises the productivity of skilled workers and hence the value of education, but if education increases the number of skilled workers above their demand, their wages will drop. For a more recent treatment, with a detailed discussion of implications for the US, see Claudia Goldin and Lawrence F. Katz, "The Race Between Education and Technology", Harvard University Press, 2008; and the review by Daron Acemoglu and David Autor: "What does Human Capital Do? A review of Goldin and Katz's The Race Between Education and Technology", Journal of Economic Literature, 2012.

The picture is more complex and subtle, however. The U.S. and Europe have each experienced a polarization of jobs and wages since the 1990s, where the numbers of high-education, high-wage jobs and low-education, low-wage jobs have both increased relative to middle-level jobs. Both high- and low-range wages have also risen relative to middle-range wages. In other words, technology is displacing repetitive, routine white- and blue-collar jobs, but it is also creating more demand for creative high-skill jobs (managerial, professional) and for low-skill jobs that require adaptability and interpersonal skills.[18]

This trend is set to continue. As brilliant machines become better able to communicate and self-regulate, they will require less routine human intervention. Gradually, robotics, artificial intelligence and High-Performance Computing are expanding the abilities of machines, extending the range of tasks that they can perform more efficiently, or less costly, than we can. Smart grids are a reality, our homes are becoming smarter, and self-driving cars might be a common sight on our roads sooner than we think. More and more jobs that are repetitive or that can be tackled via data mining techniques will be efficiently assigned to machines.

A larger share of the human workforce will correspondingly shift toward tasks that leverage greater creativity. Creativity in this context is the ability to think independently, to identify new solutions—an ability which is boosted by the availability of more powerful technology.

The transition will not be painless. Technological progress is disruptive, and as tasks get reallocated between humans and machines, there will be jobs that get displaced and skills that become obsolete. This implies a real human, social and economic transition cost that needs to be addressed with a combination of retraining and social safety measures.

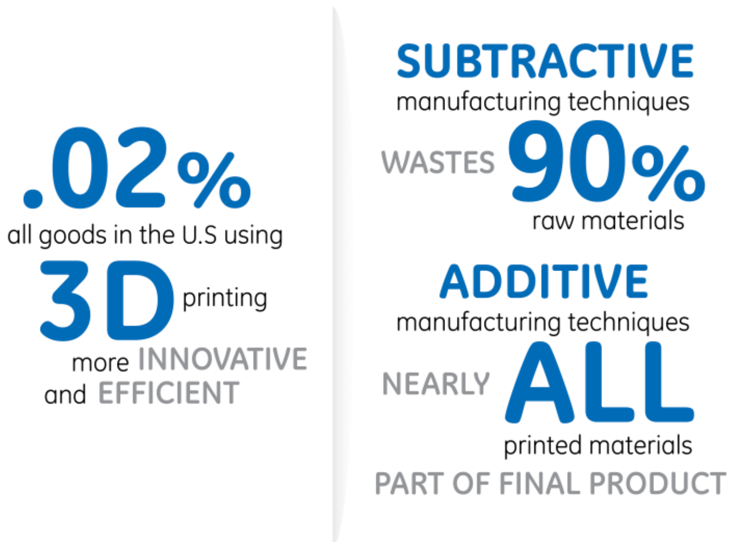
But technological progress will continue to create job opportunities and better incomes at both ends of the skills distribution. Technological progress does boost productivity and economic growth, and thereby creates greater purchasing power; this, in turn, translates into greater demand for new goods and services.[19] This process should be monitored closely to ensure that the education systems and company-sponsored training programs keep the supply of skills closely aligned with the shifting demand.

Indeed, a key trend is the emergence of new kinds of jobs. Mechanical-digital engineers, who understand both the physical machine and its relevant data,

[18] See Daron Acemoglu and David Autor, "Skills, Tasks and Technologies: Implications for Employment and Earnings", NBER Working Paper 16082, June 2010; Daron Acemoglu and David Autor: "What does Human Capital Do? A review of Goldin and Katz's The Race Between Education and Technology", Journal of Economic Literature, 2012, and David Autor, Frank Levy, and Richard J. Murnane, "The Skill Content of Recent Technological Change: An Empirical Exploration." Quarterly Journal of Economics, 2003.

[19] The key role of technological innovation as a driver of productivity and economic growth has been long recognized, and most famously and influentially formalized by Robert Solow, "A Contribution to the Theory of Economic Growth", Quarterly Journal of Economics, 1956, which spawned a vast theoretical and empirical literature over the following decades. Most relevant to the discussion in our paper, a number of studies have shown that the surge in US productivity growth in the mid-1990s can in large part be ascribed to the Information and Communications Technology advances of the previous decade, see for example Kevin Stiroh, "Information Technology and the US Productivity Revival: What Do the Industry Data Say?" Staff Report, Federal Reserve Bank of New York, nr. 116, January 2001; and Barry Bosworth and Jack Triplett, "Productivity Measurement Issues in Services Industries: "Baumol's Disease" Has Been Cured", Federal Reserve Bank of New York Economic Policy Review, September 2003; and Barry Bosworth and Jack Triplett, "Services Productivity in the United States", in "Hard-to-measure goods and services: Essays in Honor of Zvi Griliches", University of Chicago Press, 2007.

will be in high demand; so too will managers who understand both their industry and the associated analytics and can reorganize the business to take full advantage of new technologies. As the physical and digital world become more closely intertwined, more new jobs will require us to be equally adept at hardware and software.



Crowdsourcing and open-source collaboration

As the physical and digital world become more closely intertwined, more new jobs will require us to be equally adept at hardware and software.

A defining characteristic of the innovations shaping the future of work is their ability to leverage a larger set of potential resources, with a variable geometry of connections that shift and adapt depending on the problem at hand. Machines can communicate instantly with each other and with us, tapping the support of another machine or the intervention of a technician as soon as needed. Plants can leverage a wider set of suppliers through an online platform, or product designers can quickly channel the feedback of a large customer base into design changes. The same principle applies to human talent.

We have discussed in our previous work[20] how some of the applications of the Industrial Internet are aimed exactly at providing each worker with real-time access to the knowledge and expertise of all her colleagues. We can see this as tapping the "global brain" of a single company. But a much greater value can be gained by tapping the true, unqualified global brain—the collective intelligence of human beings across the globe integrated by digital communication networks. It is the human version of High-Performance Computing.

Open-source platforms and crowdsourcing are two of the most powerful ways to unleash the creativity and entrepreneurship of the distributed global talent pool. They bring to every person, with enough curiosity and access to the internet, the chance to apply her skills and expertise to new problems, including in completely different fields and disciplines. They make it easier for start-ups to raise capital and to attract talent.

Companies are beginning to understand this, and are resorting more frequently and extensively to crowdsourcing and open-source competitions and collaborations. We have mentioned in Section 2 some of GE's initial experiences in this area, and we believe this trend will grow. Accessing a greater pool of talent can leverage not only the ability and experience of a larger number of domain experts, but also the fresh perspectives of brilliant individuals from different disciplines who can approach a specific problem from unconventional angles.

New platforms and companies aimed at facilitating access to the global brain have already emerged, such as GrabCAD for

[20] Marco Annunziata and Peter C. Evans, "The Industrial Internet @ Work", GE White Paper, October 2013.

engineers and Computer Aided Design, and Kaggle for data scientists. Scaling up communities like these will require both experimentation and organizational adaption. Innovating firms need to find the best combination of ongoing, sustained proprietary efforts and open collaboration. Issues of intellectual property will have to be adequately addressed, and new compensation schemes might need to be developed. But the economic incentive is simply too compelling for this process not to move forward.

The global brain is poised to become vastly bigger and more powerful in the coming decades. Faster economic growth in large emerging markets and dramatic reductions in the cost of computing power, together with the rapid spread of mobile telephone networks, are giving millions more people access to the Internet—even if just installed as an ATM-style "hole in the wall" or via a smartphone.

Economic progress is also increasing access to clean water, food and better health care. Precious hours that were previously absorbed attending to basic survival needs can, instead, be invested—at least in part—in both tapping and contributing to the global stock of knowledge. Tens of hundreds of millions more people can learn, think and tackle problems on a globally interconnected network that can make their contribution accessible anywhere in the world.

This process will redefine the relationship between employers and employees, bringing greater flexibility to both. Employers gain access to a larger pool of talent, which can vary depending on the task at hand. Workers gain greater entrepreneurial control over their skills and talents. More people will choose to work freelance, as consultants, or will be changing jobs more frequently. Fast job turnover is common in the high-tech industry. It is the way that talented workers learn, grow and advance more quickly in a fast-paced environment. As industry becomes faster, it will experience the same.

Conclusions

The global brain—the collective intelligence of human beings across the globe integrated by digital communication networks.

The Future of Work is being shaped by a profound transformation, driven by the meshing of the digital and the physical world, the emergence of new design and production techniques, and a seismic shift in the role that human beings play in the production process. Most of these changes have been underway for some time, but they are now gaining speed and scale in a way that will rapidly change the face of industry as we know it.

The Industrial Internet is leveraging the power of big data to create a new generation of brilliant machines that are predictive, reactive and able to communicate seamlessly with each other and with us. Advanced manufacturing techniques like 3D printing are not only yielding new products, but allowing a faster feedback loop between design, prototyping, production and customer experience. They are triggering a data-driven reorganization of the supply and distribution networks that tie the individual factory into its ecosystem of customers, distributors and suppliers.

All this will result in the ability for the entire production process to adjust in real time, automatically, to unexpected circumstances, guaranteeing "zero unplanned downtime" at the production system level. These changes in turn will allow a faster move towards distributed manufacturing, including through greater reliance on micro-factories.

Technological progress will push a growing share of the workforce toward creativity and entrepreneurship, where humans have a clear comparative advantage over machines. The global brain—the collective intelligence of human beings across the globe integrated by digital communication networks—will grow bigger and more powerful as tens of millions more people gain access to education and to the Internet, becoming able to both tap the global stock of knowledge and contribute to it.

This transformation will take time to unleash its full potential. It will require us to invest in new technologies and adapt organizations and managerial practices. We will need a robust cyber security approach to protect sensitive information and intellectual property and safeguard critical infrastructure from cyber-attacks. The education system will have to evolve to ensure that students are equipped with the right skills for this fast-changing economy. Continuous education and retraining can cushion the impact of inevitable transitional disruptions in the labor market.

The Future of Work will require time and investment, but it will reboot productivity growth and economic activity. In subsequent papers, we will explore in greater detail the dynamics and implications of this revolutionary transformation. But it will reshuffle the competitive landscape for both companies and countries, and it will fundamentally change—for the better—the way we work and the way we live.