CHAPTER 3

Technology and Innovation

Will a rapid wave of human-like AI put us all out of work? Will the recent growth in low-wage work in the service economy be hobbled by algorithms and dexterous robotics? Will robots soon be packing our boxes and caring for the elderly?

We don’t know precisely. The future will contain a mix of technologies and a mix of approaches across firms large and small. We do know that new technologies will evolve within a nation of empowered high-skill work, increasing inequality, eroded worker voice, and racial disparities. Just as policies shape trade and labor institutions, they also shape technology. They shape the rate and manner in which firms develop and adopt technologies, as do organizational cultures, economic incentives, and management practices.

Anxieties about “robots” also express broader cultural unease.[58] Even before COVID-19, middle- and working-class Americans, especially those without post-secondary education or specialized skills, had ample cause for worry, given the unrelenting march toward increasingly precarious forms of labor. The U.S. has a poor record of tending to the needs of workers and communities left behind by technological change. The reasons for these economic transformations remain opaque to the public, making it tempting to focus on iconic “robot” machines that conform to familiar narratives as embodiments of broader, subtler changes.

One reason the 2018 wave of concern about technology and work seemed so salient is that AI threatens to displace work requiring judgment and expertise in the way earlier waves of automation and computerization displaced repetitive physical and cognitive work. Several reports point to highly specialized office work — including, for example, insurance adjusters, paralegals, and accountants — as categories subject to automation and worker displacement. The Task Force brief by Thomas W. Malone, Task Force member Daniela Rus, and Robert Laubacher reviews this situation and considers what may lie ahead.

We also know that the future is not etched into machines and algorithms by laws of mathematics or physics: Myriad moments in the process of technological change enable, indeed require, human choices to shape the outcome. Engineers encode social relationships and preferred futures into the machines they build. And economic incentives, R&D programs, and organizational choices are at least as powerful as engineering visions in shaping the evolution of new technologies. Autonomous vehicle technology, for example, drew on decades of federal support from DARPA and other agencies, legacies that still inflect the technology. Similarly witness the seismic shift to the use of telepresence tools by companies, schools, and governments during the COVID-19 pandemic as a public health crisis inflects development and adoption. Decisions made by R&D program managers, directors in boardrooms, planners in offices, and managers on shop floors also determine how jobs evolve as new tools emerge and become widely available.

This chapter synthesizes research from the Task Force that explores the status of key technologies and assesses their implications for jobs: AI in business processes in insurance and healthcare, autonomous vehicles, robotics in manufacturing and distribution, and additive manufacturing. Some of these technologies, such as autonomous vehicles, are far from widespread use so it remains speculative to forecast how jobs will be reshaped, other than to forecast general timelines and gradual transformation in a decade or more. In other cases, we have a clearer sense, because forms of the technology are already being adopted, such as the robots that now increasingly roam through warehouses. Others are harder to visualize because they involve the use of software to read documents and claims, scan medical prescriptions, or follow transactions to flag potential fraud. All draw on long periods of federally supported basic research to cultivate their genesis and infancy, and to train their practitioners for industry.

Three key themes emerge from this research. First, AI and robotic applications take time to develop and deploy, especially into safety- and production-critical applications. While they are coming, they are not as close as some would fear, offering some glimpses of potential futures and time for preparation. Flexibility in dynamic environments remains a key human attribute still largely out of reach for machines. This gradualism offers an opportunity to consider how to deploy new technologies for the greatest social and economic benefit. That said, if these technologies deploy into an economy run according to our existing inadequate labor institutions, they can easily make current trends worse: technological change where benefits narrowly accrue to employers and the most highly educated workers, leaving rank-and-file workers with little benefit.

Second, technologies offer mixes of job replacement and augmentation, and those mixes are shaped by a variety of factors. In one case below, legal auditors find that AI helps them in their work, freeing their time for other tasks, simultaneously requiring a firm to hire more auditors, and improving efficiency. In other cases, warehouse workers are augmented by mobile robots, focusing the human jobs into dexterous tasks that robots cannot do today.

Finally, organizations have a great deal of influence over how technologies are adopted and deployed, and hence policies that affect organizations can shape technology. Integration and adaptation are costly and time-consuming tasks in the deployment of any technology to support a particular business. Innovations in these phases of the technology curve can be technical, such as easier programming and standardized interfaces, or organizational, such as engaging frontline workers in the deployment of technology. In both cases, they crucially link technological change to higher productivity and a labor market that can provide opportunity, mobility, and a measure of economic security to the majority of workers.

> The ability to adapt to entirely novel situations remains an enormous challenge for AI and robotics, a key reason for companies' continued reliance on human workers for a variety of tasks.

3.1 AI Today, and the General Intelligence of Work

Most of the AI deployed today, while novel and impressive, still falls under a category of what Task Force member, AI pioneer, and Director of MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) Daniela Rus calls "specialized AI." That is, these systems can solve a limited number of specific problems. They look at vast amounts of data, extract patterns, and make predictions to guide future actions. "Narrow AI solutions exist for a wide range of specific problems," write Rus and MIT Sloan School Professor Thomas Malone, "and can do a lot to improve efficiency and productivity within the work world."[59] The systems we will explore below in insurance and healthcare all belong to this class of narrow AI, though they vary in different classes of machine learning, computer vision, natural language processing, or others. Moreover, by their reliance on largely human-generated data, they excel at producing behaviors that mimic human data on well-known tasks (potentially including human biases). The ability to adapt to entirely novel situations is still an enormous challenge for AI and robotics, a key reason for companies' continued reliance on human workers for a variety of tasks.

From a work perspective, these technologies tend to be task oriented, that is they execute limited sets of tasks, more than the full set of activities comprising an occupation. Still, all occupations have some exposure. For example, reading X-ray images is a key part of radiologists' jobs, but one of dozens of tasks they perform. The AI in this case can allow the doctor to spend more time on other tasks, such as conducting physical examinations or developing customized treatment plans.

Artificial general intelligence (AGI), the idea of a truly artificial human-like brain, remains a topic of deep research interest but a goal that experts agree is far in the future. A current point of debate around AGI highlights its relevance for work. MIT professor emeritus, robotics pioneer, and Task Force Research Advisory Board member Professor Rodney Brooks, argues that the traditional "Turing test" for artificial intelligence should be updated. The old standard was a computer behind a wall, with which a human could hold a textual conversation and find indistinguishable from another person. This goal was achieved long ago with simple chatbots which few argue represent AGI.

In a world of robotics, as the digital world increasingly mixes with the physical world, Brooks argues for a new standard for artificial general intelligence: the ability to do complex work tasks that require other types of interactions with the world. One example would be the work of a home health aide. These tasks include physical aid of a fragile human, observations of their behavior, and communications with family and doctors. Brooks's idea, whether embodied in this particular job, that of a warehouse worker, or other kinds of work, captures the sense that today's intelligence challenges are problems of physical dexterity, social interaction, and judgment as much as they are of symbolic processing. As we shall see below, these dimensions remain out of reach for current AI, which has significant implications for work. Pushing Brooks's idea further, the future of AI is the future of work.

> "It's not about the technology," but rather about the ability of the firm to crystalize its problems in a way that they are solvable by even today's technology. "We lack the maturity [as an industry] in coming up with what's possible."

3.2 The Robots You Don't See: AI in Insurance

To explore the current state and future potential of AI in service occupations, MIT researchers did deep dives in insurance and healthcare. They found firms experimenting with new software and AI technologies to redesign workflows, revise task allocation, and improve job design, for both higher- and lower-educated workers, with the aim of boosting productivity. The pace of adoption appears uneven across industries as well as firm sizes. In the insurance industry as well as healthcare, automation is occurring at the task level more so than at the job level, and we are still in the early days of implementation.

Task Force executive director Dr. Elisabeth Reynolds led a team of researchers to look closely at a major insurance company's efforts to adopt automated systems.[60] The insurance industry has a long history of leading in information technologies. This company had already experimented with robotic process automation (RPA), which is software that automates rules-based actions performed on a computer, often as an overlay to legacy software systems. The company concluded that RPA hadn't delivered the expected results: Most workers accomplish heterogeneous tasks, and the software is insufficiently flexible to automate all of them. Even people ostensibly doing the same job had different methods or routines for accomplishing them.

So the company reassessed its approach, looking for ways to automate certain functions. These included installing chatbots to handle the simplest questions to their internal help desk and customer service centers, while then training the workers to engage with customers at more meaningful levels.

Overall, automation raised the productivity of the current workforce while reducing the number of workers needed to accomplish the job (though the dynamic may evolve if automation allows the firm to reduce prices or offer better products). Another challenge the company found was to ensure that such automation of tasks didn't lock them into old routines and legacy technologies, which could hobble future efforts at innovation.

The dominant force for this firm was digitalization, advanced applications of information technology, and cloud computing, not necessarily AI-type algorithms. "Our business is technology," one company leader said. "There isn't a separation now." The firm adopted the new management techniques of agile methods and agile software developed over 20 years by the software industry. Agile methods include small, highly cooperative teams that rapidly execute multiple design iterations (as opposed to larger teams that follow more linear workflows). As a consequence, the firm moved from heavy reliance on two software vendors (IBM and Microsoft) to dozens of smaller, cloud-based platforms. These changes in software development and use have had the deepest impacts on how the firm does business.

By contrast, AI applications have not yet lived up to their promise. Deployment of machine learning (ML) based chatbots for customer service and RPA to increase efficiencies in back-office work represent some of the earliest applications of automation technologies. While the latter is not fundamentally new (the initial development was started after the 1990s), its scope and reach into different sectors and companies that have sizable traditional back-office operations have made it a building block of firms' AI strategies. “Consulting firms did a huge disservice to firms like ours by telling them they could save billions with these new AI functions,” one company leader said. “We’ve used some of this, but it hasn’t been dramatically impactful.” The company’s processes were simply not sufficiently homogeneous or standardized to be amenable to today’s AI.

“We’re at the infancy of what AI and ML can bring to the insurance industry,” another leader observed. “We’re tinkering…just scratching the surface of how AI and ML are capable of disrupting the industry.” Moreover, the challenges are business and organizational. “It’s not about the technology,” but rather about the ability of the firm to crystalize its problems in a way that they are solvable by even today’s technology. “We lack the maturity [as an industry] in coming up with what’s possible.”

Consider one example where the firm successfully implemented an AI-based system: creating efficiency in evaluating legal bills. As an insurance company, this firm hires thousands of law firms over a broad area of states and jurisdictions, and the company must audit the legal bills to be sure the charges comply with the company’s policies. It buys more than a billion dollars’ worth of legal services annually and employs a couple of dozen auditors — college-educated attorneys and financial specialists who read through the bills to verify the claims.

Applying AI to this problem required convening three separate groups of experts: data scientists who understood the electronic billing formats, coders who wrote algorithms, and auditors who initially resisted the idea. It took months of learning, coordination, and development to build ML models to calibrate algorithms to detect anomalies in bills. After a few cycles of trial, including presentation to and support from the CEO, the model achieved 85% accuracy. When the models were applied to the end of the auditing process, the results persuaded the auditors that the algorithms could pick up anomalies that the humans had missed. Soon the system was yielding millions of dollars in annual savings, freeing the auditors to move on to more complex work. This AI system has had a substantial impact, though it proceeded like a traditional IT project, requiring the right mix of experts, innovative teamwork, executive support, and upfront investment before showing benefits.

Reynolds and her team found that AI-based software systems did not result in laying off entire teams of people, but they did slow down hiring in relevant departments, as in the earlier example. While both layoffs and hiring slowdowns ultimately mean fewer employees in the affected departments, they have qualitatively different effects on workers.

This company still relies on the traditional role of the insurance agent. Here, AI and RPA have largely been complementary. Insurance, like other retail products, is now sold through an omni-channel approach: direct to consumer (online), direct response center (online plus human on the phone or just the latter), and in-person. This situation is likely to change as the next generation of customers becomes more comfortable engaging the company without human assistance.

Ten years ago, the firm expected to see in-person agent jobs fade away and more direct-to-consumer activity. But despite pick-up in the latter, the number of in-person agents has held relatively steady. Customers still want human interactions before they purchase insurance. While used by only a fraction of customers, self-service options let agents spend more time selling insurance to those who want in-person interactions, increasing their sales and commissions and allowing for more customized insurance packages. At the same time, new digital technologies like e-signatures are making certain tasks more efficient by obviating the need for stacks of documents to be signed. Machine learning algorithms provide more insight into existing or potential customers through the collection, aggregation, and analysis of third-party data. This data enables predictions that a customer might be calling about an upcoming bill; they can suggest calling the family to offer to add a new driver to the auto policy because their child has just turned 16. While agents have had to become more technologically savvy with the use of apps and tablets, the new training required is modest and acquired on the job.

3.3 Invisible Robots in Healthcare

Heavy investment in new tools and technologies in healthcare is yielding rapid change. The Task Force's John Van Reenen and the MIT Sloan School of Management's Joseph Doyle, working with PhD candidate Ari Bronsoler, took a close look at how this technology, including electronic medical records, has impacted the sector.[61]

Healthcare is a potential bright spot for workers in low- and middle-pay jobs. Healthcare employment is growing rapidly, which appears likely to continue as the population ages and new treatments emerge. It is also a sector that offers good jobs, with reasonable wage and non-wage benefits, at least for those working directly for healthcare systems. By contrast, home healthcare workers are poorly paid with few benefits.[62]

The sector is also considered to be recession-proof; though, ironically, the COVID-19 crisis caused a steep fall in healthcare employment as people chose to avoid elective medical procedures and doctors' offices during the pandemic.[63]

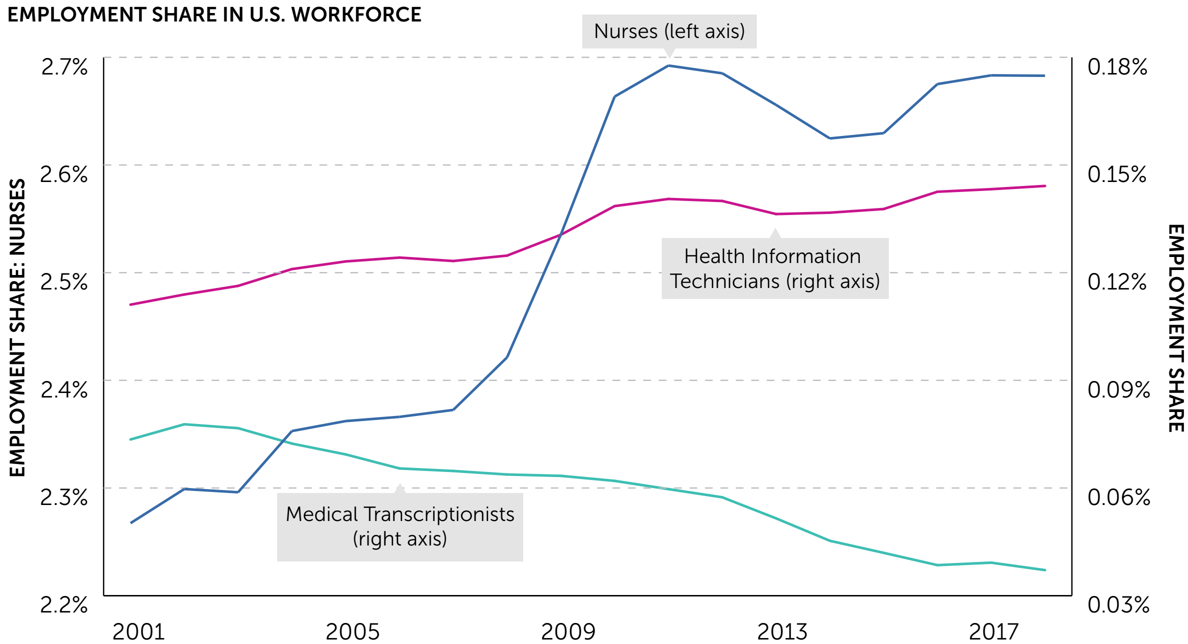
Bronsoler, Doyle, and Van Reenen conclude that the rise of new technologies in healthcare has the potential to slow the growth of new jobs, but not to reduce the overall number of jobs. At the same time, new technology is clearly impacting the mix of workers you might see in a hospital. Workers who specialize in the use of computer applications outpaced nurses in both employment and wage growth in recent years (see Figure 15).

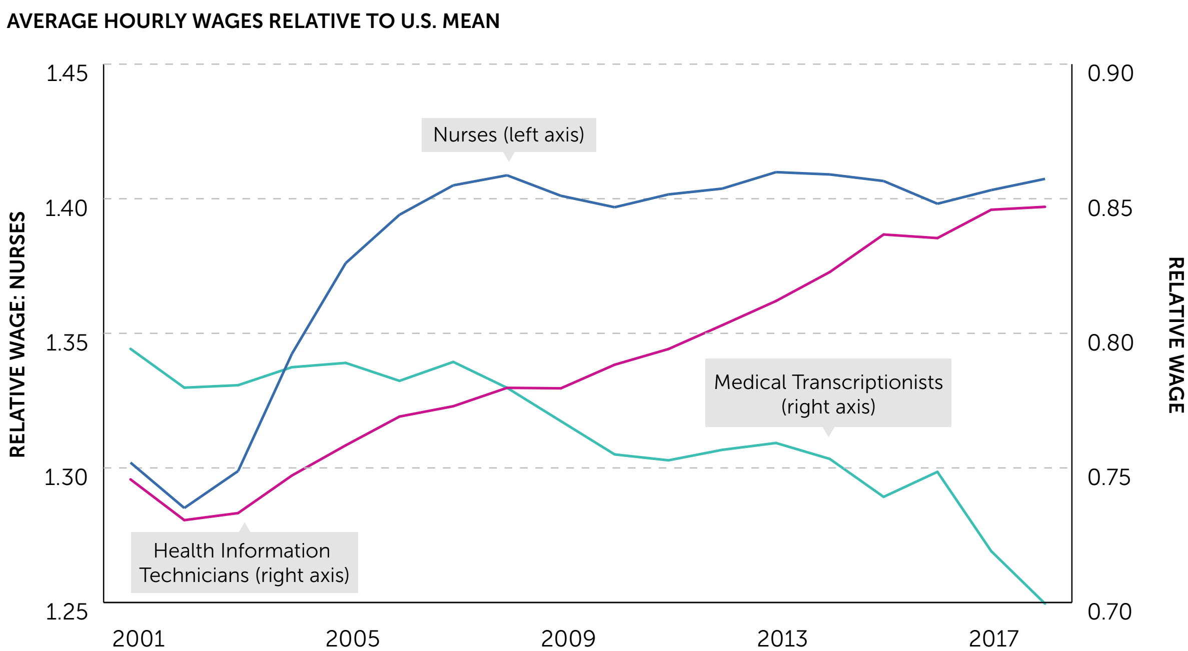
Still, for all of the new healthcare technology and investment in IT, the sector has, surprisingly, shown relatively little productivity growth. Lessons from other industries suggest that the management of new technologies is an important driver of productivity gains.[64] This poses particular challenges for an industry renowned for being highly fragmented, with clinical workers used to a high degree of autonomy when it comes to making choices about patients. "Despite the presence of so much technology in healthcare," one senior healthcare technology leader interviewed during the course of this research acknowledged, "it's hard to bring it together and use it to its full effect."

New Electronic Health Record (EHR) technology such as EPIC is the most significant IT investment in healthcare in decades, with $30 billion dedicated to its implementation since 2010. The rapid adoption of EHR was spurred by the 2009 Health Information Technology for Economic and Clinical Health (HITECH) Act, part of the Affordable Care Act, which aims to increase the use of electronic health records. EHRs serve as a platform for decision support, combining patient-level data with best practices and clinical guidelines, as well as data analytics that can lead to larger long-term gains in quality and efficiency. Yet, for all the benefits and potential it brings to improving healthcare productivity, limitations remain, including a lack of robust competition in the EHR market, which can slow adoption and innovation. "EPIC was designed for the healthcare of the past and built on the healthcare of the past," said one senior healthcare IT expert, "not for the healthcare at the digital frontier."

As in other industries, new technologies in healthcare tend to complement the work of highly educated and highly specialized workers, and to substitute for workers with less specialized expertise. On the clinical side, artificial intelligence and machine learning technologies are driving significant change through the use of medical imaging to read X-rays, natural language processing (NLP) to read clinical documentation, and data science to process massive amounts of data to generate inferences and predictions on patient diagnoses. These technologies tend to provide greater insights for clinicians as well as increased efficiency. New scanning technologies for nurses, for example, where nurses scan every piece of information about a patient's details, including medications, rather than manually typing in information, lead to improved safety and efficiency. Likewise, new communications technologies, such as secure messaging rather than pager technology, allow nurses to reach other team members (doctors, residents, other nurses) in a timely

Figure 15. Employment and Earnings of Nurses, Medical Transcriptionists, and Health Information Technicians, 2001–2018





Notes: Upper panel reports the employment of nurses, medical transcriptionists, and healthcare information technicians as a share of the total U.S. workforce. Lower panel reports the average hourly wages of nurses, medical transcriptionists, and healthcare information technicians relative to the mean hourly wage in the U.S. economy. Figures are based on Occupational Employment Statistics data provided by the U.S. Bureau of Labor Statistics. https://www.bls.gov/oes/tables.htm.

manner about treatment protocols and ensure consistency, accuracy, and timeliness of treatment. In both of these cases, the technology is complementing a subset of tasks while replacing others. Amidst these many technological changes, the wages of nurses as compared to average U.S. workers have remained relatively constant over the past 15 years (while rising for health IT workers — see Figure 15).

New technologies hold the potential for large cost savings in healthcare. In a well-known RAND study, Hillestad et al. estimated that adoption of digital technologies could save between $142 billion and $371 billion over a 15-year period.[65] So far, the actual results of the impact of the HITECH Act have been disappointing. A subsequent RAND study by Kellerman found that the predicted savings had not materialized due, in part, to a lack of information sharing across providers and a lack of acceptance by the workforce in an environment where incentives run counter to the goal of reducing healthcare costs.[66]

When it comes to the impact of new technologies on cost savings, the much greater focus for healthcare systems is in non-clinical work. This includes back-office and clerical work such as finance, administration, compliance, billing, health information, and supply chain management. In interviews at a large healthcare system, senior technology leaders outlined their goal to reduce their labor dependency with automation. One senior executive estimated that 50%–60% of human resource work could be replaced by RPA. The challenge, however, is a familiar one — how to align processes such that they can be easily automated. There is little uniformity on how tasks are performed: "There are 13 different ways of doing things because there are 13 different departments," the executive confirmed. "The challenge is the ability to change the culture within an organization to do things in a particular way."

In the case of one large healthcare system, RPA has been introduced to replace multiple tasks, from the classic scanning of medical records to verifying clinicians' licenses and rapidly communicating details about drug recalls across a hospital. However, one senior leader emphasized that automation has not led to one-for-one replacement of a worker: "No worker has been fully replaced by automation." In most cases, the tasks that have been automated represent a modest subset of the tasks in which the worker is engaged. Typically, workers have been redeployed or have found different jobs within the system, in part because the healthcare system as a whole has been growing in recent years. As suggested earlier, the primary impact on jobs has been the elimination of open positions (retirements have also played a role in the transition), which in the long run implies a decline in employment in those positions.

Not all transitions have been painless, however. Employees with non-transferable skills, such as those engaged in medical transcription, have been hit hard as their relative employment and wages have fallen steadily since the early 2000s. According to HR leaders, workers in these positions have been challenging to redeploy within the organization, and many have been let go since the introduction of EHRs. Some recent studies conclude that every position in healthcare based on paperwork will eventually become obsolete, although there may be much work remaining in the non-paperwork versions of those activities.[67]

The introduction of healthcare IT tends to be associated with an increase in costs, as Bronsoler, Doyle, and Van Reenen discuss, but it has had a positive impact on patient outcomes. One can anticipate with reasonable (but far from complete) confidence that the former will tend to decrease while the latter will continue to grow. Healthcare IT will likely be adopted at an increasing rate. The impact on the workforce, as with other industries, appears likely to be a steady increase in the need for technical skills, whether working on the frontlines or in the back office.

3.4 A Driverless Future?

Few sectors better illustrate the promises and fears of robotics than autonomous cars and trucks. Autonomous vehicles (AVs) are essentially high-speed industrial robots on wheels, powered by cutting-edge technologies of perception, machine learning, decision-making, intelligence ethics, regulation, and user interfaces. Their cultural and symbolic resonance has brought AVs into the forefront of excited press coverage about new technology, and have sparked large investments of capital, making a potentially "driverless" future a focal point for hopes and fears of a new era of automation.

The ability to transport goods and people across the landscape under computer control embodies a dream of 21st technology, and also the potential for massive social change and displacement. In a driverless future, accidents and fatalities could drop significantly. The time that people waste stuck in traffic could be recovered for work or leisure. Urban landscapes might change, requiring less parking and improving safety and efficiency for all. New models for the distribution of goods and services promise a world where people and objects move effortlessly through the physical world, much as bits move effortlessly through the internet.

As recently as a decade ago, it was common to dismiss the notion of driverless cars coming to roads in any form for many decades. Federally supported university research in robotics and autonomy had evolved for two generations and had just begun to yield advances in military robotics. Yet today, virtually every car maker in the world, plus many startups, have engaged to redefine mobility. The implications for job disruption are massive. Auto manufacturing itself accounts for just over 5% of all private sector jobs, according to one estimate. Millions more work as drivers and in the web of companies that service and maintain these vehicles.

Task Force members John J. Leonard and David A. Mindell, with graduate student Erik L. Stayton, have both participated in the development of these technologies and studied their implications. Their research suggests that the grand visions of automation in mobility will not be fully realized in the space of a few years.[68] The variability and complexity of real-world driving conditions require the ability to adapt to unexpected situations that current technologies have not yet mastered. The recent tragedies and scandals surrounding the death of 346 people in two Boeing 737 MAX crashes stemming from flawed software, as well as accidents involving self-driving car testing programs on public roads, have increased public and regulatory scrutiny, adding caution about how quickly these technologies will be widely dispersed. The software in driverless cars remains more complex and less deterministic than that in airliners; we still lack technology and techniques to certify it as safe. Some even argue that solving for generalized autonomous driving is tantamount to solving for artificial general intelligence.

Analysis of the best available data suggests that the reshaping of mobility around autonomy will take more than a decade and will proceed in phases, beginning with systems limited to specific geographies. More automated systems will eventually spread as technological barriers are overcome, but current fears about a rapid elimination of driving jobs are overstated.

Autonomous vehicles, whether cars, trucks, or buses, combine the industrial heritage of Detroit and the millennial optimism and disruption of Silicon Valley, as well as a DARPA-inspired military vision of unmanned weapons. Truck drivers, bus drivers, taxi drivers, auto mechanics, and insurance adjusters are but a few of the workers expected to be displaced or complemented. This transformation will come in conjunction with a shift toward full electric technology, which would also eliminate some jobs while creating others.[69] Electric cars require fewer parts than conventional cars, for instance, and the shift to electric vehicles will reduce work supplying motors, transmissions, fuel injection systems, pollution control systems, etc. This change too will create new demands, such as for large-scale battery production (that said, the power-hungry sensors and computing of AVs will at least partially also offset the efficiency gains of electric cars). AVs may well emerge as part of an evolving mobility ecosystem, as a variety of forces including connected cars, new mobility business models, and innovations in urban transit converge to reshape how we move people and goods from place to place.

Transportation Jobs in a Driverless World

The narrative on autonomous vehicles (AV) suggests the replacement of human drivers by artificial intelligence-based software systems, itself created by a few PhD computer scientists in a lab. This is, however, a simplistic reading of the technological transition currently underway as MIT researchers discovered through their work in Detroit. It is true that AV development organizations tend to have a higher share of workers with advanced degrees compared to the traditional auto industry. Even so, implementation of automated vehicle systems requires efforts at all levels, from automation supervision by safety drivers to remote managing and dispatching to customer service and maintenance roles on the ground.

Take for instance a current job description for "site supervisor" at a major AV developer. The job responsibilities entail overseeing a team of safety drivers focused in particular on customer satisfaction and reporting feedback on mechanical and vehicle-related issues. The job offers a middle-range salary with benefits, does not require a two- or four-year degree, but requires at least one year of leadership experience and communication skills. Similarly, despite the highly sophisticated machine learning and computer vision algorithms, AV systems rely on technicians routinely calibrating and cleaning various sensors both on the vehicle and in the built environment. The job description for "field autonomy technician" to maintain AV systems provides a middle-range salary, does not require a four-year degree, and generally only requires background knowledge of vehicle repair and electronics. Some responsibilities are necessary for implementation — including inventorying and budgeting repair parts and hands-on physical work — but not engineering.

The scaling up of AV systems, when it happens, will create many more such jobs, and others to ensure safety and reliability. An AV future will require explicit strategies to enable workers displaced from traditional driving roles to transition to secure employment.

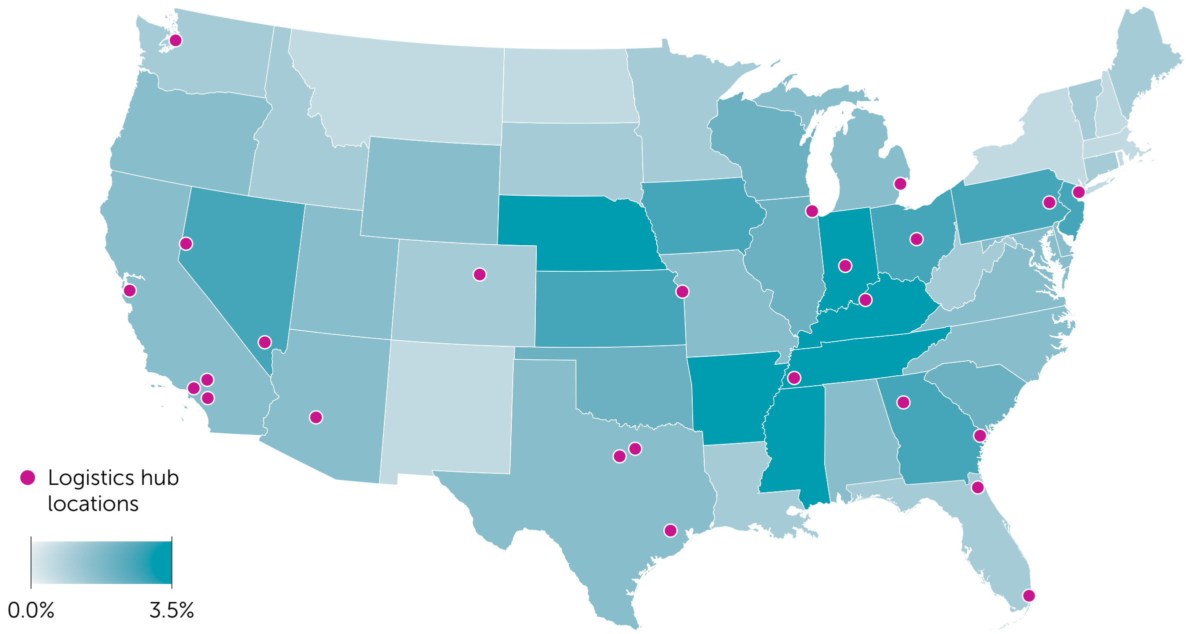
As with other new technologies, introducing new modalities into a region's evolving mobility ecosystem will just perpetuate existing inequalities as they relate to access and opportunity if institutions that support workers don't evolve as well.[70]

A rapid emergence of automated vehicles would be highly disruptive for workers since the U.S. has more than 3 million commercial vehicle drivers. These drivers are often people with less education as well as immigrants with language barriers. Leonard, Mindell, and Stayton conclude that a slower adoption timeline will ease the impact on workers, enabling current drivers to retire and younger workers to get trained to fill newly created roles, such as monitoring mobile fleets. Again, realistic adoption timelines provide opportunities for shaping technology, adoption, and policy. A 2018 report by Task Force Research Advisory Board member Susan Helper and colleagues discusses a range of plausible scenarios.[71]

Meanwhile, car and truck makers already make vehicles that augment rather than replace drivers. These products serve as high-powered cruise control and warning systems, and frequently appear on vehicles sold today. At some level, replacement-type driverless cars will be competing with augmentation-type computer-assisted human drivers. In aviation, this competition went on for decades before unmanned aircraft found their niches, while human-piloted aircraft became highly augmented by automation. When they did arrive, unmanned aircraft such as the U.S. Air Force's "Predator" and "Reaper" vehicles required many more people to operate than traditional aircraft, and offered completely novel capabilities such as persistent, 24-hour surveillance.[72]

Based on the current state of knowledge, we estimate a slow shift toward systems that require no driver, even in trucking, one of the easier use cases, with limited use by 2030. Overall shifts in other modes, including passenger cars, are likely to be no faster.

Figure 16. Warehousing, Storage, and Freight Trucking Employment as a Percentage of Total Employment



Source: Authors' calculations.

Even when it's achieved, a future of automated vehicles will not be jobless. New business models, potentially entirely new industrial sectors, will be spurred by the technology. New roles and specialties will appear in expert, technical fields of engineering of automated vehicle systems and vehicle information technologies. Automation supervision or safety-driver roles will be critical for levels of automation that will come before fully automated driving. Remote management, or dispatcher, roles will bring drivers into control rooms and require new skills of interacting with automation. New customer service, field support technicians, and maintenance roles will also appear. Perhaps most important, creative use of the technology will enable new businesses and services that are difficult to imagine today. When passenger cars displaced equestrian travel and the myriad occupations that supported it in the 1920s, the roadside motel and fast-food industries rose up to serve the "motoring public." How will changes in mobility, for example, enable and shape changes in distribution and consumption?

3.5 Warehousing and Distribution

Technologies often have their greatest impact, and create the most jobs, when they enable new business models and transform industries, more than automating tasks previously done by people. The rise of e-commerce, whereby the internet has enabled entirely new ways of shopping and ordering for consumers and for business, epitomizes such a transformation, and especially its impact on the movement and distribution of goods ("logistics").

E-commerce can be seen as a kind of automation of retail shopping, with corresponding employment effects in the retail sector. Whereas a customer used to have to visit a store to select, purchase, and carry home a product, now the consumer can use a web page to enter an order directly into a semi-automated supply chain, with the delivery accomplished by a mix of people and machines.

Major technologies often take four decades from invention to full adoption. The greatest impact of technology on logistics and warehousing is perhaps only part-way through this 40-year cycle, with information technology and networking still transforming the system.

As with mobility, news reports on distribution might lead one to believe that jobs are about to start drying up. Indeed, a Google search for "warehouse automation" produces 73 million hits, many of them promotions for new systems, suggesting a rapidly changing landscape. The landscape is unquestionably rich with exciting new technology and investment.[73]

But Task Force member Frank Levy, working with Wellesley College student Arshia Mehta, found a gradual process of adoption underway. They queried automation suppliers, distribution center managers, and leaders in established companies and startups. One-third of respondents to a recent published survey reported using automated guided vehicles but less than one-fifth reported using automated packaging solutions, collaborative robotics, or automated picking.[74]

Compared to other industries, logistics is geographically dispersed, and present in more rural areas (see Figure 16). We define logistics as a sum of three industries: warehousing and storage, freight trucking, and freight trucking arrangements (i.e., brokers and third-party logistics providers or 3PLs), accounting for just over 3 million jobs (before the COVID-19 pandemic). This amounts to about 2% of jobs in the economy (about one-fourth the fraction in manufacturing).

E-commerce has driven two fundamental changes in logistics. First, the industry has historically been set up for the delivery of goods in bulk sizes to local retailers for sale. E-commerce has changed the endpoint for the bulk of those deliveries from warehouses and distribution centers to individual residences.

Second, e-commerce has radically reduced the size of orders that logistics centers must now handle, right down to individual items. The warehouse industry was traditionally built around the bulk movement of goods. Trucks would line up at rows of doors to disgorge products that would get reshuffled and dispatched again in large quantities to stores, restaurants, or other warehouses for further processing. But with e-commerce, warehouses now are just as likely to handle huge numbers of individual or small-batch items: a single toy ordered by a customer in California, for example, or a half-dozen bottles of hand sanitizer ordered by a doctor's office in Connecticut.

Levy and Mehta argue that if we think of logistics employment as a tug of war between job gains from e-commerce and job losses from automation, job gains are winning decisively at present. Since 2000, the trucking industry added 130,000 jobs (to 1.75 million). The warehousing and storage industries more than doubled to 1.1 million during that same period (about 30% of these are low-wage manual laborers). More of these gains were in rural than in urban areas.

By some measures, productivity has not improved despite this vast expansion. Industry statistics find that productivity rose more than 20% from 2000–2014 but actually declined thereafter, leaving it less productive in 2019 than in 2000. A plausible explanation for this reversal is that the challenge of logistics has increased in the e-commerce era.[75] Today, distribution and fulfillment centers face the problem of unloading, unwrapping, storing, accurately selecting ("picking"), and packing products, from small jewelry to 50-pound bags of pet food and large sports equipment.

Warehouses have been slow to adopt automation; their rapid output increases from 2014–2019 have been achieved by adding labor in less automated facilities. Many of these tasks — in particular, picking and packing individual items ("each picks") — are still performed by people. The simple challenge of removing plastic wrapping from a pallet of goods remains beyond today's commercially available robots.

"In warehousing," Levy and Mehta write, "robotic arms that can identify, grasp, and manipulate streams of diverse items are still in their infancy." Great effort and investment is going into automated gripping systems, but it will take an estimated three to five years to develop the technologies that would endanger the

Data-Enabled Trucking

Thirty years ago, an employee in a truck brokerage connected firms to truckers using a Rolodex, a telephone, personal relationships, and a fax machine. The connection process began when a firm called a broker with the details of a shipping job including what they wanted to pay (subject to negotiation). In making the connection, the size of the broker's Rolodex was key. A large set of contacts meant the broker might be able to offer a trucker a sequence of shipments with little time when the truck was driving empty.

Third-party logistics firms (aka 3PLs) operated in a similar way with one important addition: the need to plan an efficient route in which a trucker delivered shipments from several firms to several different destinations. By the end of the 1980s, 3PLs were using computerized spreadsheets (e.g., Lotus 1-2-3) to help in trial-and-error route design.

Because brokers and 3PLs deal in information, the evolution of digital tools has sharply increased what employees can do and how they do it. For the traditional broker, a connection no longer begins with a phone call from a firm with a shipping job. Instead, many firms now post jobs directly on large, digital job boards. A broker surveys one or more boards to find jobs for which he or she thinks they have a potential driver. Being able to view many jobs at once increases the chances of constructing a trip with limited time spent driving empty.

Some startups are expanding the self-service aspect of the digital job board by encouraging drivers to use proprietary mobile phone applications to access their job board directly. In a few cases, a startup can use machine learning to identify the kinds of jobs a trucker prefers and alert the trucker when such jobs appear. While humans are still needed to deal with problems that might arise — for example, a scheduled shipment that isn't ready to be picked up — these startups are trying to automate broker jobs much as direct purchase of airline tickets has automated travel agent jobs.

At the same time, digitalization allows brokers and 3PLs to automate highly routine tasks that were previously performed by lower-level employees. In some cases where a 3PL has a steady relationship with a firm, it can offer a self-service ordering portal where a firm can specify all aspects of a shipment — the type and shape of containers, the precise location of pick-up and drop-off, the presence of any hazardous materials, and so on. Previously, this information might have been collected in a back-and-forth exchange with a person. Similarly, shipping documents that used to be hand collected from the web (e.g., a signed proof of delivery) are now scraped off the web automatically.

As a result, the employment mix, particularly in 3PLs, has shifted away from hourly personnel to salaried personnel with training in software design, data analysis, and related fields.

numerous jobs in picking and packing.[76] This timeframe, however, does not account for the extended time for broad diffusion, as retrofitting older warehouses and fulfillment centers with state-of-the-art technology is a disruptive and risky investment (some industry leaders we spoke to see the timeline for automated picking pushed out further still). Today, human-like physical dexterity, including its wondrous flexibility, remains out of reach for robotic systems.

As elsewhere, major impacts on labor and efficiency are coming from maturing applications of decades-old information technology. What gains in efficiency there have been in trucking have come from the "arrangements" sector, where digital tools improve processes like brokering, loading, and scheduling. "Significant technology," write Levy and Mehta, "is not always the newest technology."

Similarly, the technologies transforming most warehouses are not robots at all, but information technology, often known as "Warehouse Management Systems." These software systems record and track products from loading dock to loading dock and connect to other systems that track the supply chain.

Many fewer warehouses use robotic systems. A 2019 survey conducted by the Modern Materials Handling Institute confirms that while 80% of survey respondents use warehouse management systems and 86% use barcode scanners, only 26% use even the mature technology of Radio Frequency Identification (RFID) tags. With respect to automated goods movement, 63% use conveyor and sortation systems, but only 22% use automated storage and retrieval systems, and 15% use autonomous mobile robots.

Robotics and automation, especially when combined with IT innovations, are rapidly evolving and taking novel forms. Automated storage and retrieval systems (ASRS) resemble automated warehouses in a box, though they remain expensive and suitable for only the largest, high-throughput applications. In Amazon's Kiva robot system, armies of mobile robots carry shelves of randomly mixed items to human pickers, forming a kind of distributed ASRS. Elsewhere in "Pick to light" systems, computer-controlled lights guide human pickers to select items. Robotic carts (such as those made by 6 River Systems, recently acquired by Shopify) accompany human pickers through aisles and help them rapidly pick orders. Various forms of automated forklifts and tuggers are finding niche applications and will surely grow in robustness and flexibility.

"What I would really like is software that keeps track of every person and every robot on the floor and tells each of them what it should do next," one manager told Levy and Mehta. Such systems exist today. But they are complex and extremely difficult to develop and deploy, especially in a rapidly changing industry that is simply struggling to keep up with demand. They also raise concerns about surveillance. One can imagine an evolution toward a world where an entire fulfillment or distribution center, or even an entire supply chain, becomes a collaborative robotic system comprising people, robots, and infrastructure, all quickly reconfigurable with software. How can such systems develop to value human autonomy and flexibility, without simply treating workers like software-directed automata?

As in manufacturing, higher levels of automation are most viable for large firms. Smaller firms often pursue automation investment incrementally; leased robots are finding some success as a business model because they enable smaller firms to apply robots without capital expense in a rapidly changing industry. The largest warehouse firms gain a potentially large cost advantage because they have the resources to afford the risk and expense required to implement advanced automation.

Outside of the warehouse, the logistics industry stands to benefit from the advancing capabilities of autonomous vehicles described above. As in other AV arenas, the path remains long and the direction uncertain. We described above the AV potential in long-haul trucking. But even if the driverless truck problem were perfectly solved today, the time constant for change would be half a generation. The typical Class 8 truck (over 33,000 pounds) stays on the road an average of 14 years before it is junked (though they might be retired sooner were sufficiently better technology to come along). Automated platooning, with a single human driver leading several follower unmanned vehicles, is likely coming sooner, though the labor impacts are more incremental. As with other types of robots, autonomous trucks are likely to benefit larger, better-capitalized fleets like J.B. Hunt, and corporate fleets like UPS and Walmart.

Much of the employment growth in e-commerce trucking has been in the last few miles of local delivery. Techie publications abound with images of mini delivery robots plying urban streets or delivery drones serving up much-needed medicines to rural areas. The possibilities are indeed compelling and the technologies exciting (potentially more so in the COVID era). Current demonstrations of these delivery robots are often monitored by human operators with back- up radio control. The promise is that these operators, like the safety drivers in autonomous cars and trucks, will be removed at some point in the future, or will supervise large fleets of vehicles. But the complexity of the environment, including navigating curbs, pets, and non-cooperative (i.e., ordinary) pedestrians, suggests that for some time it will be hard to achieve autonomous operation outside of constrained and well-defined areas.

Levy and Mehta conclude that fully autonomous trucks are not likely to displace significant numbers of truck drivers for at least a decade. During that time, warehouses will likely be dominated by low-wage jobs,

> Today's gripping systems are evolving rapidly toward enabling robotic hands to grasp an ever-greater variety of products and parts. The search remains for a general-purpose gripper that could pick any product in any orientation.

some of which are at risk from increasing automation in picking and packing. Automation and robotics will create jobs for technicians, software developers, data scientists, and similarly skilled positions, but they will likely eliminate a larger number of picker and packer jobs in warehousing and driver jobs in trucking. "The occupational structure of freight transportation arrangements [brokers and 3PLs]," they note, "already favors skilled positions, and continued automation of routine clerical tasks will further tilt the balance." As elsewhere, the development of new technologies will favor large firms, and middle- and higher-skill workers.

3.6 Lights Out Factories? Or Lights Dimmed?

The current state of the art in manufacturing parallels that in AVs — promising technologies abound, but the crucial work of making them robust and reliable poses myriad challenges.

As part of the Task Force's research, MIT robotics professor Julie Shah and her students studied the deployment of industrial robots in Germany, one arm of "Industry 4.0" efforts underway across Europe. Industry 4.0, which began as a strategic initiative in Germany in 2011, bills itself as the "fourth industrial revolution." Its goal is to knit together machines and processes in factories so they can be monitored and controlled through advanced digital tools. Shah and her team assessed which technologies have been developed by researchers and adopted by industry, the challenges they faced, the future paths that companies deemed important, and the research challenges that remain for robotics to be widely adopted by industry. They found sizable gaps between technology's potential, even when demonstrated in research settings, and its actual use on shop floors today.[77]

Shah and her team looked at "top-down" approaches to automation — where the tasks are adapted to the technology — and "bottom-up" where workers start with tasks to be done and adapt technology accordingly. Generally, bottom-up approaches appear more successful, as the solutions are closer to the people and the tasks in need of improvement. One company set up Robotic Experience Centers on the factory floor, where engineers, working closely with line workers, could generate new ideas, prototype solutions, and make changes to production lines. Companies preferred "programming the task, and not the robot" — that is, solving a larger job to be done, and empowering people to guide the deployment of robots to raise productivity and address "pain points." As other Task Force studies have shown, worker voice remains an important component of success with today's automation.

Challenges remain in integrating robotics into manufacturing lines. Industrial robots have been at work at large scale for decades, but most remain dangerous to people around them. Innovation in safety systems allows robotic systems to work more closely with people. Collaborative robot arms are one approach to this problem — they carry lighter payloads, run at slower speeds, and have other characteristics that make them acceptable to work outside of cages. Their low cost also offers lower barriers to experimentation and deployment. However, to ensure safety, collaborative robots function at slower speeds and with less mechanical force than caged robots, which reduces their output and range of capabilities.

> Rethinking production systems to combine IT with operations technology (OT) and generate vast amounts of real-time data creates challenges that are as much cognitive, social, and organizational as they are technical.

But even as robots are coming down in cost, the human labor of integrating them into existing lines remains expensive. Efforts are underway to ease the transitions with better interfaces and easier programming, though the work remains hampered by a lack of standards and the high levels of human skill required to do the integrations. In fact, the adoption of the industrial "internet of things" (IoT) — low-cost ubiquitous sensor networks — has been slow, mostly due to data and security concerns and unclear value. Digital twins, advanced simulation, and augmented and virtual reality systems all remain promising colors in future automation palettes, but broad adoption requires overcoming similar challenges.

Technological bottlenecks also remain: in vision, perception and sensing, and robustness and reliability. "Deep learning-based approaches," for example, "haven't delivered well on their promise within industrial environments." Such techniques require vast amounts of data, which is hard to come by in factories; they tend to be brittle and difficult to adapt to new situations, and sensitive to their original data sources as well as variations in the environment.

Autonomous guided vehicles (AGVs) have had impact in industry in materials handling (as in warehousing, discussed above). These mobile robots carry everything from small totes to large vehicles around a production environment. Future visions include production lines where the line itself is never fixed and merely consists of products on AGVs carried past various self-organizing workstations — which are themselves made up of AGVs and robotic arms. But this vision has yet to materialize, held back among other things by the inability of AGVs to navigate with the millimeter precision required for production operations.

Better interfaces that enable easier programming push the applications of robotic systems closer to production lines, increasing flexibility and reducing costs. But because robotic systems remain difficult and expensive to program, Shah's team found that they largely remain technological islands on factory floors, not part of integrated digital oceans powered by AI. The researchers concluded that these technologies — even in Germany, where they are deeply rooted — "have yet to permeate the industrial landscape."

Shah also found a bottleneck identified in other Task Force studies: inadequate robotic dexterity. Until recently, robots used traditional forms of two-fingered pincers or single-purpose tools which can pick up objects but risk damaging soft or inconsistent materials. More recently, purpose-built automated grippers directed by machine vision can do remarkably delicate and precise work, for example, picking up glazed donuts on an automated bakery line without cracking the shiny coating. But such a gripper might work only on doughnuts. It can't pick up a clump of asparagus or a car tire.

Today's gripping systems are evolving rapidly toward enabling robotic hands to grasp an ever-greater variety of products and parts. The search remains for a general-purpose gripper that could pick any product in any orientation. Deep learning and other AI techniques have helped here (and they are making an impact in the logistics industry). Still, despite investment and confident predictions, most AI techniques remain too brittle, complex, or slow for manufacturing operations. As noted earlier, some think that the generalized robotic dexterity problem may, like driving, equate to the search for artificial general intelligence. Major players in manufacturing and distribution have told us they believe that this problem is a decade or more away from resolution.

These findings largely resonate with the research of a team of MIT researchers led by Task Force Research Advisory Board member Susan Helper. Helper and colleagues interviewed many U.S.-based large firms, primarily automotive companies and their Tier 1 (major) suppliers. They chose automotive because about 40% of all robots in the United States (and globally) are found in this industry.[78] While firms in this sector are striving to move toward a more data-intensive and analytic form of manufacturing, company production systems remain siloed within firms as well as between firms and their suppliers.

Nevertheless, significant changes are afoot. Firms are experimenting with technologies and production systems that will flexibly adapt, whether they are making traditional vehicles or those that incorporate more electric or autonomous capabilities. Given the uncertainty regarding these markets, firms are emphasizing flexibility. Like Shah's findings in Germany, Helper's team found that workers are still central to firms' production processes. However, firms have different practices in how they use technologies that affect which technologies are substitutes for, or complements to, worker skills, and which may be the subject of organizational tension. In one case, a firm's data scientists developed an algorithm to determine when cooling fans should be replaced; technicians were expected to follow the algorithm and to eschew discretion. In other cases, firms have been adding or deepening problem-solving tasks for their shop floor workers. One company introduced a machine vision system that at first led to a dramatic spike in reported defects. Because of their experience and training in statistical process control, workers were able to quickly point out that many of the defects were false positives. Together with engineers, they determined how to relocate the vision system for better results.

Rethinking production systems to combine IT with operations technology (OT) and generate vast amounts of real-time data creates challenges that are as much cognitive, social, and organizational as they are technical. Decisions about how the data is used, interpreted, and shared all shape how workers fit into the factories of the future and whether jobs are deskilled or upskilled.

3.7 "Surprised to Find Very Few Robots Anywhere": Small and Medium-Sized Firms

Shah's research team focused on robot makers and relatively cutting-edge firms in Germany, while Helper's team focused on large, U.S.-based automotive-related companies that had used robotics in manufacturing for many years. Task Force member Suzanne Berger led a team studying manufacturing in the U.S. with a particular focus on small and mid-sized manufacturing firms. Berger, who led MIT's Production in the Innovation Economy study in 2013, drew on several decades of research in the U.S., China, Japan, and the E.U.

Some U.S. firms are well on the road to using advanced automation, including America's automotive factories and Amazon warehouses. But Berger's researchers found a sharp divide between the automation in some large companies and in smaller mid-sized companies.[79]

The team visited plants owned by 44 U.S. companies, 10 of which were large multinationals and 34 of which were small and medium-sized enterprises (SMEs) in Ohio, Massachusetts, and Arizona. SMEs are companies with fewer than 500 workers; they represent 98% of all manufacturing establishments in the U.S. and employ 43% of the nation's manufacturing workers. More than half of the companies that the team studied had previously participated in the 2013 study, enabling some analysis of change over time.

Productivity growth in manufacturing has been slow over the past decades in comparison with that in other advanced industrial countries. It has been even slower in manufacturing SMEs. If we want to accelerate growth, shift to "greener" production, or raise wages, the work of Berger's team underscores that we need to understand why, when, and how SMEs acquire new technologies and train their workers for new skills. The researchers asked each company about new technology adoption in the past five years, how they found the skills to operate the equipment, and what became of workers who used to do the job in cases where the new technology was so radically different that it required new operators to perform the task.

"We had read the literature predicting a massive wave of robots replacing workers over a 5- to 10-year horizon," the team reported, "so we were surprised to find very few robots anywhere." The largest adopter of robots they found was an Ohio company they had first visited in 2010, which had subsequently been acquired by a Japanese company. It now had more than a hundred robots, while its workforce had more than doubled. In all the other Ohio SMEs they studied, the team found only a single robot purchased in the previous five years. In Massachusetts: one. In Arizona: three.

Equally telling were the reasons that managers at these SMEs gave to explain the robot scarcity. Several said they wished they could purchase robots, but that the typical size of the orders they received rarely justified the purchase. SMEs are mostly high-mix/low-volume producers. Robots are still too inflexible to be switched at a reasonable cost from one task to another. As Shah reported, the price of a robot is only about one-quarter of the total cost. The rest is the cost of programming and integration into a work cell or process.

All of the firms had, however, purchased new equipment or software over the same previous five years, including CNC machines, new welding technology, laser- and water-jet cutters, servo-press metal stamping machines, and sensors. They also purchased computer-aided-design (CAD), data analytics, and even blockchain software. They were capturing data on production processes, though, like managers interviewed in large companies, the SMEs said they did not know what to do with most of the data they collected.

Smaller firms tend to automate incrementally, adding a machine here or there, rather than installing whole new systems that are more expensive to buy and integrate. This approach minimizes disruptions for workers while generally increasing factory productivity.[80]

Often, technology acquisition means modifying existing machines with new hardware and software rather than purchasing new ones. This approach leads to a kind of layering of technology: bringing in new alongside older equipment, some dating back to the 1940s. This may be one reason why acquiring new technology in SMEs has not typically led to layoffs. Older workers without the skills to work on the new equipment continue to work on the older machines while younger workers, who are excited about the newest technologies, may be unwilling to invest time in older equipment. The companies that the researchers visited both in 2013 and in 2019 had increased their number of workers over that time period, and no firms reported layoffs due to new technology.

Even for some of the larger firms interviewed, automation today is as much about quality as it is about reducing the number of workers. A Boston-based plant manager put the goal as not "lights out" but "lights dimmed" — moving away from people manipulating objects on assembly lines toward people on the shop floor analyzing production statistics on screens — though we note that the number of workers in that particular plant has declined by 50% in the past two decades.

New orders and new production demands from customers drive technology acquisition in SMEs. And new technology drives the search for new skills and training. When researchers asked managers what they were looking for in new hires, the most frequent response was "someone who will show up on time and stay." Many managers were deeply skeptical about the value of formal workplace education in community

> Artificial intelligence, machine learning, robotics, and additive manufacturing are indeed poised to transform the economy. But those transformations will be the culmination of thousands of innovations from managers, organizations, and business models.

colleges and other programs for jobs they wish to fill. It's only when advanced technology enters the shop that their search for skills begins. The "perfect hire" would be someone who had previously done the same job, but such a person is rarely available, at least at the wages the manager is willing to pay. So, managers usually turn to younger or more enterprising workers they already employ and ask them if they can figure out how to use the new software or hardware. The workers often turn to online videos. As one worker who learned online how to master a new set of CAD/CAM software in order to work on a new CNC machine said: "Technology takes a step, then workers take a step forward, too. People grow with the software."

For all these reasons, a promising route both to productivity growth and to better jobs starts with aiding the adoption of advanced manufacturing technology in the SMEs. At present, the largest national programs that work with SMEs are the Manufacturing Extension Partnership (MEP), whose major focus has been on improving "lean" manufacturing practices, and the Manufacturing USA institutes, which support and diffuse applied R&D, working primarily with large manufacturing companies. New policy levers can advance technology and skills in SMEs.

Despite the 20th-century rise in uniformity and mass production, manufacturing today remains a highly dynamic environment. Model changes, evolving technology, shifts in supply chains, even upheavals such as Brexit and COVID-19 all mean that 21st-century manufacturing operates within an environment of constant change, even for stable, highly standardized products. A rubber gasket that fits into a chassis one day may not fit the same way the next day when its supplier changes. Robotics and automation still do best when most variables are fixed and operations are highly standardized, while human workers remain key to adapting to changing conditions. New AI and ML-based approaches to robotics, new sensors and actuators, and new software are making these machines more flexible, but it remains early in a long evolution.

3.8 Additive Manufacturing

3D printer technology is advancing rapidly and could be the most disruptive manufacturing technology on the horizon. Using a single machine to craft a complex finished part has the potential to replace vast numbers of production jobs. Aerospace engineers now use 3D printers to make inspection tooling and auto plants, and other manufacturers make prototypes and fixtures on the machines. The machines are spreading, but their use remains limited, and concentrated in large firms with well-funded internal technology budgets.

3D printing has generated a great deal of excitement in the past decade for its potential impacts on manufacturing and supply chains. While not traditionally considered part of robotics, 3D printers can be thought of as desktop robots that mix hardware, materials, and software to create objects in entirely new ways. These machines have found traction as consumer products for "Makers," and have occasioned strong industrial interest as well. The ability to produce prototypes, parts, or even entirely new products at the place and time of use has far-reaching implications. The supply chain could become digital until the point of purchase or deployment. Production can be distributed into digital warehouses that produce parts on demand. Already, companies like Mercedes-Benz use this technology to print spare parts for legacy vehicles.

"Additive manufacturing" (AM) is the more formal, general term for the colloquial "3D printing." Additive distinguishes the approach from "subtractive manufacturing" such as machining, where material is subtracted by a cutting tool from raw stock such as a block of steel. In AM, material is laid down in small increments by a computer-controlled placement head. While familiar consumer desktop 3D printers can do this with colored plastic and small parts, today's AM machines range from the nanoscale to large structural or metal components, in materials ranging from high-precision polymers to aerospace-grade titanium.

The power of AM not only lies in the moment of fabrication itself, but also reaches far upstream into design and downstream into the supply chain. Where subtractive manufacturing must obey rules of cutting tools, AM upends the traditional tradeoffs of cost and complexity, providing designers greater freedom in realizing complex shapes. It also opens the door to AI-enabled "generative design" techniques, where AI designs prototypes that AM builds and engineers test, that can optimize parts for cost, weight, or strength in entirely new ways. Experts expect AM to complement more than replace subtractive manufacturing, and also to have profound effects on how products are designed, manufactured, and brought to market.

"Realizing mass customization at scale," writes Task Force member John Hart, a leading expert in AM, "would be unthinkable were it not for the rapidity of converting digital information into a physical form through the use of AM." Hart studied the spread of AM and concluded that it will eventually allow companies to shift effortlessly to supply changing needs.[81] AM can also open the way for new businesses that couldn't exist without the tool. Align Technology's Invisalign® product, for example, makes custom orthodontic retainers based on scans of an individual patient's mouth.

Configurable production assets, including AM systems, may enable firms to respond quickly in periods of uncertainty to pivot their production activities if needed. During the COVID-19 pandemic, for example, additive manufacturing firms were quick to leverage existing production infrastructure and pre-qualified medical-grade materials for the production of nasopharyngeal swabs. These swabs are vital for virus testing and were in drastically short supply early in the crisis. The project, initiated by faculty at Harvard and MIT, in collaboration with companies Desktop Metal, Formlabs, Carbon, and others, resulted in the production of millions of swabs per week within a few weeks of initiation.

Still, large-scale adoption of AM, and its attendant potential impact on jobs, is slowed by high (though falling) costs and a lack of common standards, which may take years to develop. AM-based systems still do not have the high speed or low cost required for large-scale production that have developed over more than a century in subtractive manufacturing. Material properties of built-up parts can lack the predictability that subtractive techniques already deliver for critical components. Standards for AM design, testing, and materials are lacking. And, ironically in light of our discussion of job loss, the growth of the industry is currently limited by the need for specialized professionals trained in AM techniques. These limitations will all be addressed over time, from innovations in high-rate AM production equipment to new training pipelines.

So, as in other areas, we see the opportunity to apply smart training strategies to ease factory workers into emerging roles. Manufacturers will likely need smaller teams of workers, but those remaining will need specialized training to operate the new machines.

In Hart's study, the owner of one small Ohio plant predicted that he could transition entirely to the new technology in about a decade, and that it would result in many fewer jobs if his production volume stayed constant. But he also believed that he would grow so productive compared to his competitors that his own workforce would likely grow. Whether this means more industry jobs in net, or simply more jobs at this firm but fewer at its competitors, depends on how customer demand responds to improving quality and lower costs.[82]

3.9 Momentous Impacts, Unfolding Gradually

Just as it took years to diffuse the major technological advances of earlier eras — such as interchangeable parts, electrification, and internet connectivity — it will take time to roll out today's advanced technologies throughout the economy. The most profound effects are still playing out from the internet, mobile and cloud computing, and other innovations dating back to the 1990s and earlier. Artificial intelligence, machine learning, robotics, and additive manufacturing are indeed poised to transform the economy. But those transformations will be the culminations of thousands of innovations from managers, organizations, and business models.

It is hopeful and not a skeptical view to empirically chart where today's promising technologies lie along their developmental curves. Those curves, long and uncertain, nonetheless offer glimpses of different futures scattered across the industrial landscape, glimpses that enable us to prepare for what comes next, in as much as we can discern it today.

It is the job of engineers, entrepreneurs, venture capitalists, and journalists to envision their preferred futures, persuade others to join them, and set about making those futures happen. But it is the job of thousands of plant managers, line operators, operations leaders, and others to manufacture products, deliver goods, offer services, and produce the throughput that keeps the economy running. Those responsible for this daily output are inevitably skeptical of new technologies, most of which do not work very well when they're new. Adoption at scale is the product of tens of thousands of small adoption decisions, each time someone with line responsibility sees potential ways to do their job better.