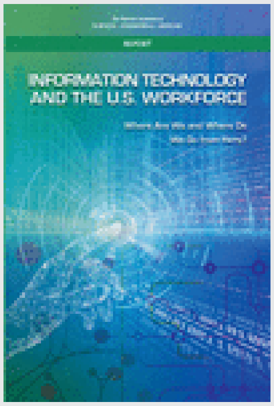

Information Technology and the U.S. Workforce: Where Are We and Where Do We Go from Here?

DETAILS

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INFORMATION TECHNOLOGY AND THE U.S. WORKFORCE

Where Are We and Where Do We Go from Here?

Committee on Information Technology, Automation, and the U.S. Workforce

Computer Science and Telecommunications Board

Division on Engineering and Physical Sciences

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Elsa M. Garmire, NAE, Dartmouth College, and David C. Mowery, University of California, Berkeley, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Preface

The Committee on Information Technology, Automation, and the U.S. Workforce was convened by the National Academies of Sciences, Engineering, and Medicine[1] to examine current and possible future impacts of emerging information and communication technologies on the workforce. The charge to the committee was framed broadly: assess many dimensions of the evolving relationship between technology and work and set forth a research agenda (see Box P.1).

The 13-member committee first met in Washington, D.C., in June 2015 to discuss trends in technology and the workforce in the context of the disciplinary expertise spanned by the committee within the fields of economics, computer science, and social science.

The committee subsequently conducted an information-gathering workshop October 22-23, 2016, in Washington, D.C., with speakers from the private sector, academia, and the government. Panel discussions were organized around the following themes: Current and Emerging Technological Capabilities; Information Technology and Automation in the Workplace; New Modalities of Work; Education, Workforce Development, and Equal Opportunity; and Data Sources and Needs.[2] The workshop was open to the public and included robust discussion from the audience.

Befitting the subject matter of the committee, much of the work was

[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council (NRC) are used in a historical context to refer to activities before July 1.

[2] See Appendix B for the workshop agenda and panelist biographies.

BOX P.1
The Project Statement of Task

A National Research Council study will consider the possible impacts of automation and other applications of information technology on the U.S. workforce. An ad hoc committee will consider current knowledge and open questions about the drivers of increased automation; the types and scale of jobs that might be affected; the societal implications of these changes; the timeframe for impact; and implications for education, training, and workforce development. Through testimony, discussions convened by the committee, a literature review, and committee deliberations, the committee will examine currently available sources of information, consider how different disciplines could contribute knowledge, explore where additional data would help, and frame research questions aimed at better understanding the phenomenon. The committee's report will set forth a research agenda and describe types and sources of data and analysis that would enhance understanding of the workforce impacts of IT and automation and inform future policy making.

done by members in geographically dispersed locations, coordinated electronically via a variety of digital media. The committee held numerous teleconferences to discuss this study, including current knowledge, new ideas, and research challenges. These discussions, individual committee member expertise, input and perspectives from workshop participants, and a review of current literature directly informed this report. We note that the scope and implications of the topics addressed are broad and deep. While we identify many trends, challenges, and open questions, this activity did not aim to make concrete policy recommendations (this was outside of the committee's charge), but rather to surface the key areas for attention and propose ways of improving society's understanding of them. We also note that the topics addressed have global range, significance, and interconnection; while international issues are raised occasionally, in keeping with its charge, the committee's focus was on the United States.

The resulting report is an exploration of the current state, trends, and possible futures of technology and work. It considers the issue from economic, organizational, individual worker, and societal levels, along with the capabilities of certain technologies that are likely to drive significant change. We identify key issues and questions for policy makers and suggest new research pathways and new data-collection efforts that we believe will lead to improved capabilities for detecting and anticipating future impacts of information technology on the workforce, as well as provide an informed basis for debates on which public policies will best adapt to them.

ACKNOWLEDGMENTS

We acknowledge the National Science Foundation for sponsoring this activity and thank Kevin Crowston for his enthusiasm for this project. We also thank the members of the study committee and staff for their contributions and commitment; their expertise and hard work made this report possible. In particular, Emily Grumbling went well beyond the call of duty in supporting and coordinating the work of the committee members and co-chairs. In addition, we thank all of the workshop speakers and participants for providing illuminating perspectives. Their insights helped the committee to identify key challenges, opportunities, and pathways for understanding the societal implications of emerging technologies and changing models and opportunities for work.

Erik Brynjolfsson and Tom M. Mitchell, *Co-Chairs*
Committee on Information Technology,
Automation, and the U.S. Workforce

Contents

Summary

Recent years have yielded significant advances in computing and communication technologies, with profound impacts on society. Technology is transforming the way we work, play, and interact with others. From these technological capabilities, new industries, organizational forms, and business models are emerging.

Technological advances can create enormous economic and other benefits, but can also lead to significant changes for workers. IT and automation can change the way work is conducted, by augmenting or replacing workers in specific tasks. This can shift the demand for some types of human labor, eliminating some jobs and creating new ones.

Advances in fields such as artificial intelligence and robotics are making it increasingly possible for machines to perform not only physical but also cognitive tasks currently performed by humans. These developments have led to widespread interest in the future of work.

This report explores the interactions between technological, economic, and societal trends and identifies possible near-term developments for work. It emphasizes the need to understand and track these trends and develop strategies to inform, prepare for, and respond to changes in the labor market. It offers evaluations of what is known, notes open questions to be addressed, and identifies promising research pathways moving forward.

THE CHANGING TECHNOLOGY LANDSCAPE

Information technologies have already transformed society, and more changes are inevitable. Computing power and network speed have grown dramatically. Access to the Internet has grown in the United States and worldwide. Organizations are increasingly moving their core business processes—such as accounting, sales, and material resource planning—online. Videoconferencing is increasingly used throughout organizations to enable the geographical distribution of project work via meetings that integrate computer presentations, face-to-face exchanges, and data sharing. Peer-to-peer networks have emerged to connect resource holders with resource seekers, leading to companies such as eBay, Uber, and Airbnb, and new online reputation systems facilitate feedback reporting for both providers and customers. Related IT tools have also been steadily augmenting traditional tools for education and training, leading to the emergence of the phenomenon of massive open online courses (MOOCs) and other educational innovations.

At the same time, computers have become increasingly competent at both physical and cognitive tasks that have previously been done primarily by humans, such as speech recognition, identifying faces and other objects in images, interpreting text, analyzing medical data, driving cars, and many other tasks. Much of this progress is due to advances in artificial intelligence (AI)—software-based systems that aim to mimic aspects of human intelligence. Over the past decade, a number of highly visible AI systems have emerged in a range of fields, from mobile devices to cars with autopilot functions. AI has defeated human champions at games such as chess and Go, and AI systems have been developed that are capable of answering a growing range of factual questions and serving as intelligent software agents. Automated software-based agents, such as chatbots that answer simple queries and hold conversations with humans and bots that conduct activities like automated financial trading, are also emerging.

Recent advances in AI have been driven largely by advances in machine learning—algorithms that improve through experience, often by identifying patterns from historical data that may be extrapolated to future purposes. For example, such techniques have been used to predict patient responses to medical treatment based on historical medical records and to process human (or "*natural*") language in useful ways. A particular set of algorithms, called deep neural networks, have been a driver of recent advances in areas such as computer vision, speech recognition, and text analysis. The increasing generation of online data is expected to further fuel the development of these machine learning systems. Advances in robotics have led to increased factory automation and to initial demonstrations of autonomous vehicles on land, sea, and air. Technologies for service and companion robots are in their infancy.

Humans are still more effective than computers at many tasks, especially those that require creative reasoning, nonroutine dexterity, and interpersonal empathy. New models of human engagement have focused on how best to combine the strengths of humans and computers to complete a given task, referred to variously as complementary computing, mixed-initiative interaction, or collective intelligence. The field of human-centered automation focuses on enhancing situational awareness of human operators, developing common operating pictures across multiple users, and building predictive models of human behavior in different contexts.

On balance, the rapid pace of technological advances is likely to continue in frontier areas, where investments in research and development are increasing. Computer performance continues to improve via advances in hardware parallelism, hardware specialization, and enhanced programming languages. Beyond speedup, a broad range of progress has been seen in important technologies such as the mobile Internet, the Internet of Things, cloud computing and storage, AI, robotics, virtual and augmented reality, and machine learning. Research continues in more speculative potential breakthrough areas like bionics. Significant progress in any one of these technologies would likely have profound effects on the workforce.

Opportunities for digitizing and automating tasks are far from exhausted. In particular, the workforce will be increasingly affected as more and more cognitive tasks become fully or partly automatable—from language processing to problem solving and pattern matching—and as advances in robotics yield enhanced physical dexterity, mobility, and sensory perception in machines. These trends will almost surely change the demand for the workers performing these tasks and the nature of the organizations in which they work.

Robotic automation will continue to advance, in assembly lines and other workplaces and in areas that have not yet been touched significantly by robotic technologies. Over the next decade, self-driving vehicles, already in limited trial or commercial use (e.g., from Google/Waymo, Tesla, nuTonomy, Uber, and many others), will mature and become more widespread, with potentially significant impacts on employment in the transportation sector, ultimately reducing the need for human taxi drivers and long-haul truckers. Computer competence in perceptual tasks, including speech recognition and computer vision, will also advance, likely leading to superhuman competencies for listening and image processing by computer. This could affect jobs involving pattern recognition, including those of pathologists, radiologists, and security workers.

Automatic translation between languages by computers, already in use, though imperfect, will probably improve to the point of routine use of real-time translating telephones and earpieces. The ability of computers to interpret and extract information from unstructured text will continue to advance, with potentially significant effects on automating knowledge-worker jobs, such as paralegal research.

EFFECTS OF INFORMATION TECHNOLOGY ON PRODUCTIVITY AND INEQUALITY

Because computerization changes the cost structures of processes, goods, and services, the increasing adoption of IT is transforming the economics of many industries and functions. Productivity growth, the predominant contributor to increases in standards of living, rose rapidly from the late 1990s to the early 2000s, in part reflecting advances in IT. However, productivity growth has slowed during the past 10 years, according to official data from U.S. statistical agencies. Some of this slowdown is accounted for by less rapid improvements in the IT-producing and the IT-using sectors of the economy.[1] However, these statistics are difficult to interpret, partly due to output and input price deflators that cannot fully account for changes in quality as well as the proliferation of free digital goods and services. There is evidence that the diffusion and successful adoption of IT advances is time- and resource-intensive, producing a lag, possibly measured in years or even decades, between technological advances and resulting productivity growth.[2] Emerging evidence suggests that this diffusion is increasingly uneven, leading to bigger productivity gaps between frontier firms and those in the middle of the distribution.[3]

Income and wealth inequality has increased over the past 20 years in the United States, with median family income stagnating while incomes rose significantly for the top 1 percent; significant disparities also exist among the other 99 percent, largely correlated to a rising premium of education. The share of wealth owned by the bottom 80 percent has fallen

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[1] J.G. Fernald, 2015, Productivity and potential output before, during, and after the Great Recession, *NBER Macroeconomics Annual 2014*, doi: 10.3386/w20248.

[2] See, for example, P.A. David, 1990, The dynamo and the computer: An historical perspective on the modern productivity paradox, *American Economic Review* 80.2:355-361; and E. Brynjolfsson and L.M. Hitt, 2003, Computing productivity: Firm-level evidence, *Review of Economics and Statistics* 85.4:793-808.

[3] D. Andrews, C. Criscuolo, and P.N. Gal, 2015, "Frontier Firms, Technology Diffusion and Public Policy: Micro Evidence from OECD Countries, OECD Publishing, http://www.oecd.org/eco/growth/Frontier-Firms-Technology-Diffusion-and-Public-Policy-Micro-Evidence-from-OECD-Countries.pdf.

from 18.7 percent in 1983 to 11.1 percent in 2010.[4] The mix of jobs in the economy continues to change, as many routine information-processing tasks are being automated in whole or in part, even as the numbers of low-wage service jobs and high-skill professional jobs have grown. There is also evidence that, since 2000, social skills have been increasingly valued in the labor market.[5]

It has been predicted that the future effects of IT on the workforce are likely to be larger than those we have already seen, especially as AI-based and robotics systems improve.[6] However, it is not known whether new technologies will automate and replace workers in existing tasks more rapidly than the economy as a whole (driven by various factors, including automation) creates new demands for labor. The net effect is difficult to predict; it is easier to anticipate how new technologies will automate existing tasks than it is to imagine tasks that do not yet exist and how new technologies may stimulate greater consumer demand. Furthermore, the future of employment is not only a question of the availability of tasks to be performed, but how they are organized and compensated. In addition, digital goods have the potential to diffuse rapidly because they are infinitely replicable via shared digital platforms. However, implementation and customization of software can take a surprisingly long time, as can necessary changes to complementary skills, organizations, and institutions. Future innovations could have more immediate impact if organizations become more able to incorporate them quickly. These are matters of business strategy, social organization, economic policies and programs, and political choices and are not simply driven by technology alone.

CHANGES IN THE NATURE OF WORK AND ITS ORGANIZATION

Business organization is also in the midst of a transformation. Not only is the traditional employment model changing, but nontraditional models are increasingly facilitated by technology. For traditional firms, despite a burst of new start-up companies in many areas, statistics suggest

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[4] For this and other statistics on wealth inequality, see E.N. Wolff, 2012, *The Asset Price Meltdown and the Wealth of the Middle Class*, New York University, New York; A.B. Atkinson, T. Piketty, and E. Saez, 2011, Top incomes in the long run of history, *Journal of Economic Literature* 49.1:3-71; and T. Piketty, 2014, *Capital in the Twenty-First Century*, Harvard University, Cambridge, Mass.

[5] See, for example, D.J. Deming, 2015, "The Growing Importance of Social Skills in the Labor Market," National Bureau of Economic Research, doi: 10.3386/w21473.

[6] M. Chui, J. Manyika, and M. Miremadi, 2016, "Where Machines Could Replace Humans—And Where They Can't (Yet)," *McKinsey Quarterly*, http://www.mckinsey.com/business-functions/business-technology/our-insights/Where-machines-could-replace-humans-and-where-they-cant-yet; E. Brynjolfsson and A. McAfee, 2014, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, WW Norton & Company.

there are fewer new, growing companies in the United States today than in the past, and this category now employs a smaller share of the workforce. Data from recent decades also show a drop in the pace of job and worker dynamism and reallocation[7]—especially since 2000. At the same time, nontraditional types of employment—other than the 40-hour-per-week job at a single company offering health and retirement benefits—appear to be increasing. While nontraditional work as independent contractors and temporary agency employees has been growing for decades, IT advances now make it easier to access such employment opportunities, and in some cases to perform work remotely over the Internet. This has given rise to new companies based on technology-mediated "on-demand" or "gig" employment at both the low-skill (e.g., TaskRabbit) and high-skill (e.g., Upwork) ends of the spectrum. For now, the technology-enabled examples of on-demand work are a small fraction of overall employment: recent research suggests that less than 1 percent of the U.S. workforce currently uses online platforms for temporary or gig work.[8]

IT is playing a growing role in many organizations, including greater electronic record keeping, communications, and automation of work flows, although most organizations and markets are far from fully digital. Organizations are now relying increasingly on virtual teams of workers, teams whose members primarily interact via digital technologies across diverse geographies. Increased availability of digital data has facilitated a tripling in the use of "data-driven decision making" between 2005 and 2010.[9] Privacy, security, and data ownership have become increasing concerns as more and more information, including personal data, has been digitized and networked. The number of nonemployer businesses (businesses with no workers or only independent contractors) appears to be growing.

Data on many of these trends are elusive, reflecting both the rapidly changing nature of society and the economy and gaps in national and private data collection and statistical infrastructure. While improvements in and diffusion of IT have had profound effects on many aspects of the workforce, the future effects of these advances on the workforce and the broader economy are difficult to predict. This partly reflects our inadequate understanding of the complex interactions among technologies themselves combined with the skills, organizations, institutions, policies, and human preferences in society.

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[7] Measured either by total job creation plus job destruction, or by total hires plus separations, or by geographic mobility of workers.

[8] L.F. Katz and A.B. Krueger, 2016, "The Rise and Nature of Alternative Work Arrangements in the United States, 1995-2015."

[9] E. Brynjolfsson and K. McElheren, 2016, The rapid adoption of data-driven decision making, *American Economic Review* 106(5):133-139.

Education remains a key influence on worker income. Wage disparities between non-college-educated workers, college-educated workers, and workers with graduate degrees, which grew rapidly in the 1980s and 1990s, have leveled off but remain high in this century. There are also disparities in job stability and benefits between these groups.

New uses of IT in teaching, including online courses,[10] are increasingly available and hold the potential to expand access to education. New companies are specializing in just-in-time training targeted to specific companies and employment opportunities,[11] but the ultimate impact of these tools remains to be seen.

DATA AND METHODS FOR EVALUATING TECHNOLOGY AND WORKFORCE TRENDS

Traditionally, data such as employment numbers and salaries collected by federal statistical agencies have been invaluable for understanding the status of the workforce and the economy at large, and for tracking technology-related measures such as productivity.[12] These surveys are often time- and resource-intensive to complete and must be updated periodically.

At the same time, the ubiquity of digital transactions is producing increasing amounts of born-digital data of potential use for tracking and understanding technology-related workforce trends. Traditional survey data are increasingly being augmented by or integrated with administrative data (collected in the course of routine transactions), resulting in new statistical products and integration of firm-level information with information at the individual worker level. There is also great potential to use online data about worker profiles and job listings to understand worker skills, demand for employees, occupational skills requirements, and related information. New ways to integrate various data sources while also protecting privacy and confidential business information could reveal valuable information about the changing workforce.

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[10] Examples are edX and Coursera, which are both websites that offers free online courses and classes from the world's best universities.

[11] An example is Udacity, a for-profit education organization, which offers nanodegrees and credentials in areas such as web development and data analysis (among others). Udacity was born from a Stanford University experiment where Sebastian Thurn and Peter Norvig offered their "Introduction to Artificial Intelligence" course for free online. See Udacity, 2016, "About Us," *Udacity*, https://www.udacity.com/us, accessed May 2016.

[12] Such sources include data from the Current Establishment Survey, the Quarterly Census of Employment and Wages, the Current Population Survey, the Decennial Census, the American Community Survey, the Job Openings and Labor Turnover Survey, and the Business Employment Dynamics and Business Dynamic Statistics data.

While quantitative information, including analytical methods using very large data sets, can be useful for understanding the labor market and other workforce trends, qualitative and microdata and methods help to elucidate the correct research questions and to understand causality. Such methods, including case studies, participant observation, ethnographic interviewing, life histories, and the textual analysis of data are important for informing macro-level research.

Finally, there is significant interest in predicting which jobs are most likely to be automated (and to what extent), especially due to advances in AI, machine learning, and robotics. Several recent studies have aimed to quantify probabilities of automation by comparing specific technology capabilities to the skills required for tasks associated with specific jobs. While results suggest that automation of a large number of jobs will become increasingly technically feasible, component tasks are more easily automated than entire occupations. Research also suggests that lower-wage jobs may be more susceptible to partial or full automation.

Moving forward, policy makers and the research community would be well served by data collection designed to support longitudinal tracking and analysis of workforce trends and the role of advances in IT.

FINDINGS

Six general findings emerge from this study.

1. Advances in IT are far from over, and some of the biggest improvements in areas like AI are likely still to come. Improvements are expected in some areas and entirely new capabilities may emerge in others.

2. These advances in technology will result in automation of some jobs, augmentation of workers' abilities to perform others, and the creation of still others. The ultimate effects of information technology are determined not just by technical capabilities, but also by how the technology is used and how individuals, organizations, and policy makers prepare for or respond to associated shifts in the economic or social landscape.

3. The recent increase in income inequality in the United States is due to multiple forces, including advances in IT and its diffusion, globalization, and economic policy.

4. IT is enabling new work relationships, including a new form of on-demand employment. Although current digital platforms for on-demand work directly involve less than 1 percent of the workforce, they display significant growth potential.

5. As IT continues to complement or substitute for many work tasks, workers will require skills that increasingly emphasize creativity, adapt-

ability, and interpersonal skills over routine information processing and manual tasks. The education system will need to adapt to prepare individuals for the changing labor market. At the same time, recent IT advances offer new and potentially more widely accessible ways to access education.

6. Policy makers and researchers would benefit significantly from a better understanding of evolving IT options and their implications for the workforce. In particular, (1) sustained, integrated, multidisciplinary research and (2) improved, ongoing tracking of workforce and technology developments would be of great value for informing public policies, organizational choices, and education and training strategies.

A RESEARCH AGENDA

Federal agencies or other organizations that sponsor research or collect data relevant to technology and the workforce should establish a sustained, multidisciplinary research program in order to address the many important yet unanswered questions about how technology is changing, might change, or could help to shape the nature of work and the U.S. national economy. This will help to expand a knowledge base that will ultimately help a variety of stakeholders address productivity growth, job creation, and the transformation of work, and feed directly into the National Science Foundation's new interest in research on work at the human-technology frontier.[13] The program should

1. Target the understanding of how technology choices can affect the workforce to improve the design of policies and technologies that will benefit workers, the economy, and society at large;
2. Emphasize feedback between micro- and macro-level research methods and among the social sciences, economics, computer and information sciences, and engineering; and
3. Establish and facilitate the use of new data sources, tools, methods, and infrastructure to support such research while protecting privacy, including increased use of data sources developed in the private sector.

Such a research program should span a range of themes, such as those described below.

[13] National Science Foundation, 2016, "10 Big Ideas for Future NSF Investments," https://www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf, accessed December 2016.

Theme 1: Evaluating and Tracking Progress in IT

Research to develop new ways of evaluating and tracking progress in IT would help decision makers understand impacts of technology on the workforce and inform strategies to help prepare for imminent changes.

Such research could focus on the following objectives:

- Develop, refine, and test improved strategies for classifying technological capabilities in terms of the human skills and tasks they can or could replace.
- Identify key indicators that could signal the extent of the impact of developments in a given technological field.
- Develop new mechanisms to track and forecast technological and economic changes of particular relevance to the future of the workforce.
- Develop indexes, analogous to the Consumer Price Index, to assess (1) the current state of technologies, (2) the degree of diffusion of technologies into firms and organizations, and (3) the technological capabilities and diffusion of AI and robotics, in particular.

Theme 2: Technology Adoption and Impact Within Organizations

IT can have a significant impact on the type and nature of tasks performed by workers, depending on the specific content of the task. New research could be pursued to elucidate ways in which different industries use technology to organize their operations, allocate tasks, and perform specific functions. Such work could be conducted at both the micro- and macro-level scales to provide a firm- and industry-level window into the impacts of technology on employees in a given industry or at a given organizational level.

Theme 3: Impacts of Policy Choices

Research on impacts of public policy choices could identify policies, resources, and practices that would mitigate technological unemployment, approaches to easing transitions for workers forced to change occupational fields due to technological change, and opportunities for actively guiding the future impacts of technology development and deployment before they occur.

Theme 4: Working with Emerging Technologies

As emerging technologies diffuse into different industries, individuals must learn how to interact with these technologies to successfully complete tasks, which can affect the nature of decision making, teamwork, and organization. Some teams use technology as a means for connecting or convening, or in place of some aspect of human intelligence. The rise of data-driven decision making[14] and new forms of collective intelligence reflect the ways that technology and humans can work together to act more intelligently than they could separately. Research is needed to understand technology-augmented organizations, teams, and individuals and the conditions under which they are most effective.

Theme 5: Societal Acceptance of Automation Technologies

The mere existence of a technology does not guarantee that it will be deployed. Economic costs and benefits influence decisions to deploy technologies, as do many other factors. In some contexts, people (either workers or customers) may prefer to interact with a human over a machine (or vice versa). This may reflect the existence of important, yet largely invisible and unremunerated, human skills that can easily be missed in existing skill categories and national statistics. Consumer behaviors and worker preferences and bargaining power will drive markets; understanding the behavioral economics of automation will be important for understanding its adoption patterns. Additional human factors and the social, philosophical, and psychological dynamics of automation could be explored.

Theme 6: Changing Labor and Skill Demands and Implications for Education and Training

Changes in technology use affect the roles of workers and contribute to changing labor and skills demands. This creates challenges for individuals planning their career strategies and for employers, educational institutions, and policy makers. Research tracking and mapping the changing labor and skills demands in specific industries and occupational fields over time, along with regional variations and associated policy implications, could provide insights into such trends. This research could evaluate the extent of IT diffusion into different occupational fields. Researchers could develop and test hypotheses about how these technologies change the work functions, tasks, skills requirements, and demand for these fields. The economic insecurity felt by many workers under-

[14] See, for example, E. Brynjolfsson and K. McElheran, 2016, Digitization and innovation: The rapid adoption of data-driven decision-making, *American Economic Review* 106.5:133-139.

scores the importance of understanding the interplay of technology with jobs, wages, and opportunity.[15]

Furthermore, the new workplace requires a workforce trained for expertise in areas that will drive the future economy and with the flexibility to adapt to rapid change. Because education will significantly determine the success of the United States in responding to the changing workplace, a better understanding of effective strategies is critical. While the United States has a poor track record of predicting future workforce skills demands, some insight can be gained from how skill demands are currently changing. Additional insights might be gleaned by a partnership between computer scientists, labor economists, and education researchers to assess the kinds of technology capabilities that are likely to emerge and diffuse in coming years, as well as opportunities for providing retraining and continuing education to workers.

Research in this area should aim to assess (1) educational and training needs based upon an understanding of evolving skills demands driven by technological change; (2) ways in which technology can be best used to prepare, train, and retrain the future workforce; and (3) the nature of technologies that can automate work (substituting for labor and existing human capital), augment it (complementing labor or requiring new skills), or transform it entirely (creating new goods, services, processes, and types of skill demand). Key research topics include educational needs, education delivery strategies, education access and incentives, technologies that can replace or complement worker skills, and broader educational policies.

Theme 7: The On-Demand Economy and Emerging Ways of Organizing Work

The emergence of the on-demand economy, in particular for ride-sharing services and crowdsourced work marketplaces, has generated great interest. However, there is little information about the extent of its impact on the economy and workforce. Research on the ability of authoritative economic and labor statistics to capture—and more comprehensive and persistent strategies for measuring—this impact are needed. In addition, research on the rights, protections, and autonomies of workers and how on-demand jobs fit into workers' lives and careers is needed to

[15] There is a strong likelihood that already disadvantaged groups will bear the brunt of the costs of automation. In addition, there is some evidence that a rise in disability rolls may, in part, reflect the role of automation in reducing the employment prospects for some groups. See D.H. Autor and M.G. Duggan, 2007, Distinguishing income from substitution effects in disability insurance, *American Economic Review* 97.2:119-124.

inform policies in this domain. In particular, this work could target the potential for technology-mediated on-demand jobs to provide or augment employment for unemployed or low-income workers.

Technology advances have helped shift the physical and geographical boundaries of work over time, with significant impacts on worker experience and job availability and access. Research in this area could elucidate the current and potential roles of technology in shifting where and how work is conducted, including changes in access to employment in geographically remote or isolated locations.

Theme 8: New Data Sources, Methods, and Infrastructures

All of the preceding themes would benefit from new data sources, methods, and infrastructures to enable the collection, aggregation, and distribution of a diverse range of data. The committee sees opportunities in the following areas:

- *Updating and augmenting authoritative data sources* to include survey questions and methods that directly probe technology-related aspects of employment and organizations.
- *Developing new data sources and methods* by creating new partnerships to provide researchers access to private-sector data, including new strategies for collecting and using born-digital data from multiple public and private sources and developing appropriate machine-learning and data-mining approaches to analyze this data. Research could also be conducted on providing alternate, more frequently updatable, and potentially even automated methods of obtaining information typically generated through cost-, labor-, and time-intensive survey methods.
- *Combining micro- and macro-level data and methods*, via establishment of research infrastructures and collaborations, to enable a comprehensive strategy for understanding the drivers of emerging trends and for testing hypotheses via both quantitative and qualitative approaches.
- *Establishing new infrastructure and partnerships for aggregation, sharing, and collaboration* to enable sharing among researchers of the large amounts of relevant digital data discussed above. Such efforts may be frustrated by existing and potentially outdated government regulations that constrain the ability of government to share certain data sets with researchers. While regulations to protect privacy of individuals are well justified, they may not reflect current approaches for protecting privacy while making data available for analysis. In any case, there is a general and persisting need for research on the technical means for protecting the privacy of individuals' data, far beyond the specific research discussed in this report.

CONCLUSION

Progress in computing and information technologies has been rapid in recent years, and the pace of change is expected to continue or even accelerate in the foreseeable future. These technologies create opportunities for new products, services, organizational processes, and business models, and potential for automating existing tasks—both cognitive and physical—and even whole occupations. At the same time, new job opportunities are expected to emerge as increasingly capable combinations of humans and machines attack problems that previously have been intractable.

Advances in IT and automation will present opportunities to boost America's overall income and wealth, improve health care, shorten the workweek, provide more job flexibility, enhance educational opportunities, develop new goods and services, and increase product safety and reliability. These same advances could also lead to growing inequality and decreased job stability, increasing demands on workers to change jobs, or major changes in business organization. More broadly, these technologies have important implications, both intended and unintended, in areas from education and social relationships to privacy, security, and even democracy.

The ultimate effects of these technologies are not predetermined. Rather, like all tools, computing and information technologies can be used in different ways. The outcomes for the workforce and society at large depend in part on the choices we make about how to use these technologies. New data and research advances will be critical for informing these choices.

1

Introduction

BACKGROUND AND IMPETUS FOR THIS STUDY

Recent years have yielded significant advances in computing and communication technologies, with profound impacts on society. Technology is transforming the way we work, play, and interact with others. People are connected as never before; with the Internet now accessible through mobile devices, tools such as e-mail and video chat have become commonplace, and numerous social media platforms enable us to share and curate pieces of our identity with others. When we begin to type messages, computers can often complete our words. We no longer need to remember phone numbers, appointments, names, or directions.

From these technological capabilities, vast new industries and business models are emerging. Personal health devices, computers that respond to our voices, ride-sharing services, and robot-controlled warehouses are becoming commonplace. Online shopping services allow us to find what we want, comparison shop, and purchase instantly. With the flick of a finger, we can order takeout, call a cab, or open a news article tailored specifically to our interests. Some automobiles can even park themselves. These new capabilities offer convenience and novelty, making some things easier and changing how we interface with the world. Today's changing technological capabilities prompt an examination of what it means to exist in this new, digital world. Some point to how technologies improve our quality of life. Others wonder if they change what it means to be human. What role should technology play? What do we want the future to look like, and how do we get there? Who gets to choose, and how does this change us as a society? Such questions are deeply entwined with our values—our hopes and fears about what we will achieve as a society, for ourselves, and for our children.

Throughout the course of history, humankind has developed technologies that have transformed society and our way of life, with significant impacts on the workforce. Advances ranging from the steam engine to electricity to the personal computer have created efficiencies, enhanced productivity, and improved overall standards of living. These changes have contributed to the displacement of workers, sometimes with a delayed recovery of employment numbers. They have also resulted in new worker skills requirements and the emergence of new types of jobs and leisure activities.

The impact of technology on work is of particular importance. First and foremost, work provides income and economic stability. Jobs enable parents to feed, house, and educate their children. At their best, jobs also employ and cultivate our skills and strengths, provide community, and enable us to contribute to society. Jobs can shape individuals' identities and help provide a sense of meaning or purpose.

According to the World Economic Forum's 2016 *Future of Jobs* report, many industry leaders believe that we are on the cusp of a fourth industrial revolution, one driven predominantly by advances in computing and information technologies. The technologies perceived as top trends (and corresponding time frames of impact) among surveyed industry leaders are summarized in Table 1.1.[1]

Computing, communication, and information technologies are widely seen as the general-purpose technology of the current era. In recent years, advances in these areas have raised significant interest and debate. With the establishment of the Internet and the exponential increases in computing power, networking speed, and generation of digital data over the past few decades, our lives and work have already changed significantly at many levels. Information technology has improved worker performance in many jobs. For example, radiologists now use computer software to flag anomalous locations in X-rays and other medical images. Automated cytopathology has helped pathologists by enabling fast-paced screening for precancerous or cancerous cells. Technology has also enabled automation of other jobs, such as highway toll collection, and created entirely new jobs, such as website development. It has even given rise to entirely new modes

[1] World Economic Forum, 2016, *The Future of Jobs: Employment Skills and Workforce Strategy for the Fourth Industrial Revolution*, http://www3.weforum.org/docs/WEF_Future_of_Jobs.pdf.

TABLE 1.1 Top Perceived Technological Drivers of Change (as reported by industry leaders polled for the 2016 Future of Jobs Report from the World Economic Forum)

Driver of Change	Respondents Rating This as a Top Driver (%)	Time Frame of Impact
Mobile Internet and cloud technology	34	2016-2017
Advances in computing power and big data	26	2015-2017
New energy supplies and technologies	22	2015-2017
The Internet of things	14	2015-2017
Crowdsourcing, the sharing economy, and peer-to-peer platforms	12	Impact felt already
Advanced robotics and autonomous transport	9	2018-2020
Artificial intelligence and machine learning	7	2018-2020
Advanced manufacturing and 3D printing	6	2015-2017
Advanced materials, biotechnology, and genomics	6	2018-2020

SOURCE World Economic Forum, 2016, *The Future of Jobs: Employment Skills and Workforce Strategy for the Fourth Industrial Revolution*, http://www3.weforum.org/docs/WEF_Future_of_Jobs.pdf.

of work, including through the on-demand economy, in which workers are matched by computer to work as it becomes available.

Advances in technology have always shifted the nature of work. Industrialization in the 19th and 20th centuries produced major shifts, from farming and rural life to non-farm jobs in cities. Two major disruptions include the first and second industrial revolutions, with the introduction of the steam engine and broader factory automation, and the introduction of basic computing technologies represents a third paradigm shift. All were costly changes from which we have recovered. However, a debate has emerged as to whether the current pace of advances—and the types of technology that are emerging—may cause more rapid, broad, or deep changes than ever before.

The question of whether technological advances could lead to large-scale worker displacement or unemployment as a result of new forms of automation has become increasingly visible in the media in recent years, driven in part by advances in fields such as AI and robotics that are making it increasingly possible for machines to complete nonroutine physical and cognitive tasks currently performed by humans.

A 2015 survey conducted by the Pew Research Center found that 65 percent of respondents (a sampling of American adults) expected that robots and computers would "definitely" or "probably" do much of the work currently performed by humans by the year 2065. Of this same group, 80 percent expressed the expectation that their own jobs will "definitely" or "probably" still exist at that time.[2]

While many opinions and educated predictions have been offered, the ultimate limits of what can be automated and the rate at which automating technologies will displace existing work functions are not known. Along with the public, researchers are becoming increasingly interested in examining work at the human-technology frontier and the rate and extent to which the nature of work may change; nonetheless, there is much that is not known.

FRAMING THE ISSUES

Work has a central role in supporting stability and productivity in today's society. The nation will benefit from an enhanced understanding of the current state of the workforce and how it is changing—or how it may change—with the further development and adoption of new technologies.

This study aims to address these questions by examining current knowledge, identifying gaps in research and data, and highlighting key issues that will be critical to monitor and anticipate as technology continues to advance. An informed policy debate will require answers to factual questions, including the following, which the committee begins to address in this report.

1. *Technology impact.* What are the most current capabilities of information and automating technologies, what changes are likely, and what are the mechanisms by which technology deployment and diffusion impact U.S. jobs, the economy, and equality in opportunity for workers? What is the best way to monitor and track this impact? What are the costs of failures of technologies upon which businesses have come to rely?
2. *Job creation and elimination.* What is the number and the distribution of jobs that are being eliminated as a result of automation, versus jobs that are being created by new affordances of technology?
3. *Inequality and fairness.* How might new technologies, and the mechanisms for converting them into new products and new wealth, impact

[2] A. Smith, 2016, "Public Predictions for the Future of Workforce Automation," *Pew Research Center,* http://www.pewInternet.org/2016/03/10/public-predictions-for-the-future-of-workforce-automation/.

the fairness of work conditions, the growing skew in income and wealth distributions, and job opportunities across society, especially given that technology-intensive companies often require fewer employees?

4. *Worker experience.* How might the nature of jobs and work functions change in different occupational fields, and how might this impact worker satisfaction, including workers' senses of making a real contribution and their sense that they are being fairly compensated for their work?

5. *Educational needs.* What new kinds of primary, secondary, vocational, university, and continuing education strategies will enable workers to acquire the skills needed in the changing employment environment?

6. *Educational tools.* How can technology, including its use to provide education over the Internet, improve access to and quality of education and workforce preparation for all?

7. *New forms of employment.* What new modes of employment are enabled by technology?

8. *Business dynamism.* How might anticipated technological advances impact the ability of businesses to sprout and grow?

9. *Policy.* How might labor standards and economic policies contribute to or mitigate the negative impacts of technology on the workforce?

A deep and current understanding of these dimensions will require sustained efforts to monitor and unravel how technology is advancing and how it is affecting employment opportunities, employers, income and wealth distribution, education, worker experiences, and related areas.

The discussions that follow in this report explore current technology, business, economic, and policy trends and their interactions; identify potential near-term developments; and emphasize the need to understand and track these trends and develop strategies for adapting to future developments and possible disruptions to the status quo. Rather than aiming to predict the future, this report offers evaluations of what is known, open questions to be addressed, and productive pathways forward.

The committee defines three key terms as follows:

- *Information technology (IT)* is "the technology involving the development, maintenance, and use of computer systems, software, and networks for the processing and distribution of data."[3] In the following discussions, the committee will use this term broadly to connote all computing hardware, software, platforms, and interfaces that enable the storage, transmission, processing, or analysis of data in the digital form, regardless of

[3] Meriam-Webster Dictionary, 2014, "Technology," http://www.merriam-webster.com/dictionary/information%20technology.

degree of maturity. This includes computers, mobile devices, the Internet, telecommunication devices, robotic systems, software, and algorithms.

- *Automation* is defined as "the technique, method, or system of operating or controlling a process by highly automatic means, as by electronic devices, reducing human intervention to a minimum."[4] Throughout this report, the committee uses this term to denote the use of IT to perform any physical or intellectual task or process that would otherwise be done manually, by or under the direct control of a human.
- *Digitization* refers to the process of moving data or operations onto computers and/or online.

ORGANIZATION OF THIS REPORT

The report is organized as follows:

- Chapter 2 describes the major technological trends and emerging capabilities since the turn of the 21st century as well as examples of how they have been applied in business and daily life, likely near-term advances, and their implications for different types of work.
- Chapter 3 reviews the current state of U.S. productivity growth, employment, and income distributions. The current and emerging role of technology is considered for each, building on the discussions from Chapter 2.
- Chapter 4 examines recent changes and emerging trends in the nature of work and how it is organized. It begins by exploring the on-demand economy, contingent labor, and business dynamism, followed by a discussion of the worker experience, including demographics, organizational structures, worker protections, the role of work in our lives, and the importance of education.
- Chapter 5 reviews important and emerging types and sources of data used by researchers and policy makers to track and analyze workforce trends and examine the role of technology, emphasizing the utility and challenges of working with each.
- Chapter 6 identifies important, high-level findings to guide future thinking, proposes a set of key research themes and strategies, and highlights potential mechanisms through which the results of targeted, multidisciplinary, and sustained research can help to inform policy makers.
- Chapter 7 offers final reflections and conclusions.

[4] Dictionary.com, 2016, "Automation," Dictionary.com, http://www.dictionary.com/browse/automation?s=t, accessed April 29, 2016.

2

The Technological Landscape

In order to examine the ways in which IT is changing work, the committee first considers the current and emerging states of technological capabilities and their applications.

Changes to the technological landscape arise from two quite different forces. The first is *technology creation*: the combination of fundamental capabilities enabled by advances in foundational science and engineering research to yield a new functionality. The second force is *technology diffusion:* the adoption of these technologies in new products and services and their emergence in new markets over time.[1,2]

For example, consider the invention of tools such as the Internet, the mobile phone, home wireless networks, computer algorithms that recognize faces, or self-driving vehicles. Although technology for high-speed Internet connectivity has been available for decades, the diffusion of high-speed Internet connectivity to all corners of the Earth is still under way, as are its impacts on the workforce. Similarly, although technology for detecting faces in images has been available since at least the 1990s, it is only over the past 5 years that this technology has been deployed widely in cameras that now automatically detect and adjust camera focus for faces. Technology for self-driving vehicles is at an even earlier stage today, but large research and development (R&D) investments in this area

[1] E.H. Rogers, 1995, *Diffusion of Innovations*, 4th ed., The Free Press, New York.

[2] M. Cain and R. Mittman, 2002, *Diffusion of Innovation in Health Care*, California Healthcare Foundation, Oakland, Calif.

suggest it will mature and diffuse over the coming years, with potentially major impacts on the workforce. The rate of diffusion of technology is itself influenced by many forces, including technology maturity, cost, demand, competitive pressures, societal acceptance and norms, government policies and regulations, safety requirements, resistance by entrenched interests, and the inventiveness of entrepreneurs in creating and marketing products. Given that the diffusion of technology from its birth to widespread adoption can take many years, one can often project changes to the technological landscape by anticipating the continued development and diffusion of technologies that already exist in research laboratories or in leading-edge firms and products.[3] In this sense, the research prototypes and early products of today anticipate technologies that may become widespread tomorrow.

This section characterizes recent trends in technological capabilities and technology adoption and identifies possible changes to the technological landscape over the coming years, with an eye to technologies most relevant to the workforce.

THE DIGITIZATION OF EVERYTHING

Perhaps the most obvious ongoing technology trend is the widespread use of computers, digital and online data, and the communication infrastructure of the Internet. The practice of moving services and data onto computers and online is generally referred to as "digitization." This trend, already decades old, has affected nearly all aspects of our lives, and there are still significant opportunities for more widespread adoption. Individuals routinely see the impact of this digital infrastructure, for example, in automated teller machines (ATMs), online retail services such as Amazon, personalized advertising that is informed by mining traces of our personal digital lives, navigation services available in cars and on smartphones, and free video Internet calls. Business enterprises and their internal operations have been revolutionized by new computer systems that capture, organize, optimize, and partly automate business processes. Health care is also changing due to incorporation of computing technologies, although more slowly than expected; despite sluggish penetration, computing systems are expected to have strong potential for enhancing

[3] W.J. Abernathy and J.M. Utterback, 1986, Patterns of Industrial Innovation, Product Design and Technological Innovation, (UK / Philadelphia: Open University Press: Milton Keynes), 257-264.

the efficiency and quality of health-care delivery.[4] See Box 2.1 for a deeper look at the use of computing technologies in health care.

Dissemination of news and opinions worldwide has also been transformed, with today's IT and communications infrastructure superseding much of the 20th-century system of print newspapers and hard-copy mail. Online publications, e-mail, text messages, Twitter, and websites are targeted to many specialized interests, resulting in nearly instantaneous dissemination of news and opinions and a world where more people than ever before have a platform for their opinions (see Box 2.2). However, access to the necessary resources, such as high-speed Internet, is not equal among all populations. For example, a 2015 issue brief from the President's Council of Economic Advisers highlights this "digital divide," noting that 2013 rates of household Internet access correlate with education level of the head of household and that members of underrepresented minority groups have lower access rates. Geography also plays a significant role in determining access.[5]

Education has also been impacted by digitization, with increasing access to online courses, including video lectures; experts who can answer specific questions through online discussion boards such as Quora.com; and early technologies for customizing courses to individual students based on the digital trace of their performance to date—not to mention the trove of digital knowledge to be explored by learners.

This digitization of nearly every aspect of our lives has important impacts on the workforce. It has changed the nature of individual jobs, decreasing the need for some, empowering others, and creating yet others. It has created opportunities to work more productively at home using video conferencing and online business processes and has led to greater expectations that workers will be available evenings and weekends. It has changed how we find jobs, as many job seekers now use online sites, such as Monster.com or Indeed.com, to find jobs. Freelancers now use online services such as Upwork.com or HourlyNerd.com to locate short-term jobs.

Today, most jobs involve some interaction with IT systems, driving a general need for the workforce at large to be informed about or trained on these systems—and to possess general fluency with IT. This also means

[4] B. Chaudhry, J. Wang, S. Wu, M. Maglione, W. Mojica, E. Roth, S.C. Morton, and P.G. Shekelle, 2006, Systematic review: Impact of health information technology on quality, efficiency, and costs of medical care, Annals Internal Medicine 144:742-752; D. Blumenthal and J.P. Glaser, 2007, Information technology comes to medicine, New England Journal of Medicine 356:2527-2534.

[5] The White House, 2015, "Mapping the Digital Divide," Council of Economic Advisers Issue Brief, July, https://www.whitehouse.gov/sites/default/files/wh_digital_divide_issue_brief.pdf.

BOX 2.1
Digitization of Health Care

Institutional, regulatory, and ethical considerations are often important factors in the diffusion of technologies. This is especially important in the health-care industry. While technologists recognized the potentially transformative impact of digital technologies and artificial intelligence (AI) in this domain, practical effects have taken a long time to materialize. Progress in leveraging computing infrastructure for improving health care has been slower than expected, due to costs, complexities with implementations in a large complex organization, and human factors challenges around human-machine collaboration.[1] A 2009 study found that, while many hospitals leveraged several aspects of computing technologies in health care, basic electronic health record (EHR) systems were only used in a fraction of U.S. hospitals, with greater penetrations in larger teaching hospitals in urban settings. Larger numbers of hospitals had implemented computerized provider-order entry systems.[2] Computing technologies offer the promise of efficient capture, retrieval, and transmission of patients' health and clinical encounter data, efficient work flows via electronic order entry, and improvements in medical care with the delivery of new kinds of clinical decision support for health-care workers. Decision-support opportunities include methods that leverage captured data to predict outcomes (such as the risk of readmission, hospital-associated infection, or onset of sepsis)[3] and that guide alerting and therapy, and that can help to minimize large numbers of preventable errors[4] by employing promising computational methods designed to complement human decision-making.[5] The opportunities for new efficiencies and gains in quality of care have been demonstrated by several deployments, including the successful implementation of electronic records systems by the U.S. Veterans' Hospital Administration, where EHRs have been linked to dramatic improvements in the quality of clinical care.[6]

Other directions in health care include harnessing advances in image analysis to assist pathologists and radiologists in interpreting histological patterns and radiological images, respectively. In other areas, new approaches to sensing and inference show promise for delivering new kinds of useful auxiliary data for detecting illness and promoting health and wellness. Efforts include new types of population-scale screening efforts for identifying illness from behavioral data[7]

that people on the job can encounter and are more influenced by the problems of IT. Because of the centrality of IT, workers and businesses can develop a dependency on systems working "seamlessly" to get core work done.

collected from new kinds of wearable devices that collect and transmit real-time activity data, such as the Fitbit and Apple Watch.

[1] A. Miller, B. Moon, S. Anders, R. Walden, S. Brown, and D. Montella, 2015, Integrating computerized clinical decision support systems into clinical work: A meta-synthesis of qualitative research, *International Journal of Medical Informatics* 84(12):1009-1018, doi: 10.1016/j.ijmedinf.2015.09.005.

[2] A.K. Jha, C.M. DesRoches, E.G. Campbell, K. Donelan, S.R. Rao, T.G. Ferris, A. Shields, S. Rosenbaum, and D. Blumenthal, 2009, Use of electronic health records in U.S. hospitals, *New England Journal of Medicine* 360:1628-1638, doi: 10.1056/NEJMsa0900592.

[3] A.K. Jha, C.M. DesRoches, E.G. Campbell, K. Donelan, S.R. Rao, T.G. Ferris, A. Shields, S. Rosenbaum, and D. Blumenthal, 2009, Use of electronic health records in U.S. hospitals, *New England Journal of Medicine* 360:1628-1638, doi: 10.1056/NEJMsa0900592; J. Wiens, J. Guttag, and E. Horvitz, 2016, Patient risk stratification with time-varying parameters: A multitask learning approach, *Journal of Machine Learning Research* 17(209):1-23; K.E. Henry, D.N. Hager, P.J. Pronovost, and S. Saria, 2015, A targeted real-time early warning score (TREWScore) for septic shock, *Science Translational Medicine* 7(299), doi: 10.1126/scitranslmed.aab3719; M. Bayati, M. Braverman, M. Gillam, K.M. Mack, G. Ruiz, M.S. Smith, and E. Horvitz, 2014, Data-driven decisions for reducing readmissions for heart failure: General methodology and case study, *PLoS ONE* 9(10):e109264; E. Horvitz, 2010, "From Data to Predictions and Decisions: Enabling Evidence-Based Healthcare," paper presented in Data Analytic Series at Computing Community Consortium, Computing Research Association (CRA), September 16, 2010.

[4] E. Horvitz, 2010, "From Data to Predictions and Decisions: Enabling Evidence-Based Healthcare," paper presented in Data Analytic Series at Computing Community Consortium, Computing Research Association (CRA), September 16, 2010.

[5] M. Hauskrecht, I. Batala, M. Valkoa, S. Visweswaran, G.F. Cooper, and G. Clermonte, 2013, Outlier detection for patient monitoring and alerting, *Journal of Biomedical Informatics* 46(1):47.

[6] B. Chaudhry, J. Wang, S. Wu, M. Maglione, W. Mojica, E. Roth, S.C. Morton, and P.G. Shekelle, 2006, Systematic review: Impact of health information technology on quality, efficiency, and costs of medical care, *Annals Internal Medicine* 144:742-752; D. Blumenthal and J.P. Glaser, 2007, Information technology comes to medicine, *New England Journal of Medicine* 356:2527-2534.

[7] J. Paparrizos, R.W. White, and E. Horvitz, 2016, Screening for pancreatic adenocarcinoma using signals from web search logs: Feasibility study and results, *Journal of Oncology Practice* 12(8):737-744, doi: 10.1200/JOP.2015.010504.

Computing Power and Networking

The increasing use of digital technologies has been enabled by foundational advances in computing power and networked connectivity. Over the last five decades there has been tremendous progress in computing capacity, in line with the famous Moore's Law, which predicts that available computer power will double every 18 months. While this prediction has held remarkably well since 1965, the ability to increase power

BOX 2.2
A Snapshot of Internet Traffic

In March of 2016, typical use of the Internet included

- 7,206 tweets per second
- 722 Instagram photos per second
- 1,117 Tumblr posts per second
- 2,124 Skype calls per second
- 34,952 gigabits of traffic per second
- 54,240 Google searches per second
- 122,590 YouTube videos viewed every second
- 2,489,751 e-mails sent every second

SOURCE: Estimates obtained from "In 1 second, each and every second there are…," *Internet Live Stats*, http://www.Internetlivestats.com/one-second/#tweets-band, accessed March 30, 2016.

by further miniaturizing components of electronic devices will ultimately hit a fundamental limit imposed by the optical limits on the resolution of photolithography, and ultimately by the sizes of atoms. Nonetheless, there has been major progress in the use of new parallel architectures—rather than reduction in component size—to grow computing power, enabling growth to continue to keep pace with Moore's Law. For example, graphical processing units, or GPUs, have enabled a new family of massively parallel architectures that have gained significant popularity for machine-learning and big data applications, as discussed in the section "Advancing Technological Capabilities" below. Given current trends, shown in Figure 2.1, computing power and networking capabilities are expected to continue to advance at least over the coming decade.[6] Research laboratories continue to pursue new approaches, such as quantum computing, which have not yet been proven practical, but which hold the potential for significant future improvements in computing power for some tasks. In addition to advances in computer processing hardware, access to computer networks has extended to a large portion of the population. By 2015, more than 84 percent of the U.S. adult

[6] M. Galloy, 2013, "GPU vs. CPU performance data," *MichaelGalloy.com*, http://michaelgalloy.com/2013/06/11/cpu-vs-gpu-performance.html.

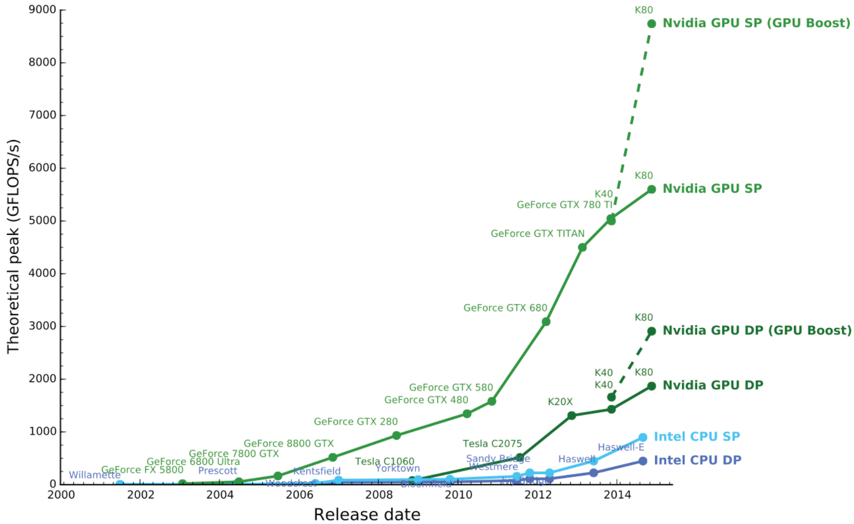

FIGURE 2.1 Illustration of approximate peak computing capacity of commercial processor lines since 2000. Vertical axis indicates the estimated theoretical peak performance of each processor model indicated in gigaflops (billions of floating point operations) per second. SOURCE: M. Galloy, 2013, "GPU vs. CPU Performance Data," *MichaelGalloy.com*, http://michaelgalloy.com/2013/06/11/cpu-vs-gpu-performance.html. Courtesy of Michael Galloy.

population had access to the Internet.[7] Internet bandwidth has grown by approximately 50 percent every year over the last two decades.[8] Wireless connectivity has become faster and more pervasive through 3G and 4G—or third- and fourth-generation—wireless protocols, while wired network speeds have improved. By 2014, a typical Internet speed was 100 megabits per second for end users; Google has introduced gigabit per second access to metropolitan areas across the United States, with companies such as AT&T and Comcast beginning to provide similar service levels. One user's documented evolution of Internet bandwidth since 1983 is illustrated in Figure 2.2.

The Global Positioning System (GPS), an accurate satellite-based method for identifying geographic coordinates, has been an important

[7] A. Perrin and M. Duggan, 2015, "Americans' Internet Access: 2000-2015: As Internet Use Nears Saturation for Some Groups, a Look at Patterns of Adoption," Pew Research Center, http://www.pewInternet.org/2015/06/26/americans-Internet-access-2000-2015/.

[8] J. Nielsen, 1998, "Nielsen's Law of Internet Bandwidth," Nielsen Norman Group, last modified 2014, https://www.nngroup.com/articles/law-of-bandwidth/.

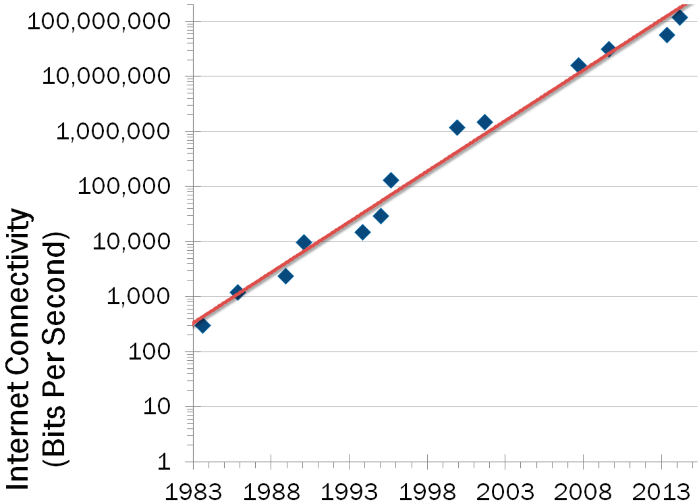

FIGURE 2.2 Internet bandwidth over time. Internet connection speeds in bits per second, as recorded and reported by Jakob Nielson, 1983-2014. SOURCE: "Nielsen's Law of Internet Bandwidth," by Jakob Nielsen (April 5, 1998), last modified 2014, https://www.nngroup.com/articles/law-of-bandwidth/.

enabler of mobile computing applications. GPS dates to the 1970s, when it was developed for use by the U.S. military with an intentionally degraded version made available to consumers, a distinction known as "selective availability."[9,10] In 2000, this intentional degradation was turned off, enabling accurate consumer-level GPS positioning to approximately 10-15 meters; its accuracy has since improved. This capability is now at the heart of mobile computing applications such as location-aware Internet search, real-time traffic directions, and "find my friends" social networking tools. Another benefit of GPS technology is the direct transmission of highly accurate timing signals to computing systems, allowing more effective and cost-efficient synchronization of network activities and work processes.

[9] Federal Aviation Administration, "Satellite Navigation—GPS—Policy—Selective Availability," last modified November 13, 2014, https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/gps/policy/availability/.

[10] W. Reynish, 2000, "The Real Reason Selective Availability was Turned Off," *Aviation Today Magazine Online*, http://www.aviationtoday.com/av/issue/feature/The-Real-Reason-Selective-Availability-Was-Turned-Off_12739.html#.VrOZmDYrLMU.

Enterprise Software

American corporations have spent billions of dollars on digitizing their major processes and operations, investing in a variety of large-scale systems, such as enterprise resource planning, supply chain management, customer relationship management and human resource management, and EHRs. These systems can cost tens or hundreds of millions of dollars to implement and are often deployed over a period of several years. The biggest costs are in process redesign, often led by consulting firms. In addition, employee training and user documentation, manuals, and support documentation must be updated and maintained. As a result, many work processes have been significantly redesigned, or "reengineered," as some authors have called it,[11] boosting productivity and, in many cases, reducing labor requirements.

Few jobs have been untouched by the need to interact with IT systems, which also means that more and more of the workforce at large needs to be informed or trained on IT systems. In most cases, the costs of business process redesign and employee training, including on-the-job learning, vastly exceed the direct costs of IT hardware and software. These costs have been described as investments in organizational capital and human capital since they are expected to yield benefits over many years. Thus, they add to the intangible asset base of companies and the nation, even if they are often unaccounted for on balance sheets.[12]

Mobile and Remote Systems

The broad impact of mobile-based IT on the workforce is due to both hardware and software system evolutions. The history of enterprise-capable mobile hardware technologies dates to the early 1990s, with the advent of systems such as the IBM Simon and the Palm Pilot. In addition to the computing power of the mobile device itself, its utility as a component of an enterprise workplace environment has expanded with wireless network bandwidth capabilities. Such capabilities have expanded from 12.2 kilobytes per second (Global System for Mobile Communications standard) for the first compatible mobile devices in 1993, through five orders of magnitude growth to the long-term evolution, or LTE, standard of 128 megabytes per second in 2013.[13]

[11] M.M. Hammer and J. Champy, 2006, *Reengineering the Corporation: Manifesto for Business Revolution*, HarperCollins, New York.

[12] L. Hitt, S. Yang, and E. Brynjolfsson, 2002, Intangible assets: Computers and organizational capital, *Brookings Papers on Economic Activity* 1:137-199.

[13] L. Tang, W.-T. Tsai, and J. Dong, 2013, "Enterprise Mobile Service Architecture: Challenges and Approaches," *ServiceTech Magazine*, Volume 79 (December), http://www.servicetechmag.com/I79/1213-3.

Combined with the availability of mobile hardware capabilities, enterprise-based mobile communications have enabled the widespread distribution of data, tasks, and workers across a wide range of organizational settings. Since the invention of e-mail in 1980, organizational growth of electronic communications has enabled increased levels of distribution of work and information exchange.[14] "Enterprise e-mail" can be seen as celebrating its 25th anniversary in 2016-2017, dating to the release of Lotus Notes in 1991 and the Microsoft Exchange Client in 1993. The number of e-mail accounts worldwide grew nearly 16-fold, from 25 million to 400 million, between 1996 and 1999. By 2013, business e-mail accounts had exceeded 900 million; although this only represented 24 percent of e-mail accounts, e-mail traffic to business accounts represented a majority of e-mail traffic. Further, a majority of organizational communications were conducted via e-mail.[15] Internet-based infrastructure in the workplace has led to a shift in telephony use, creating large-scale implementation of Internet-based voice-over Internet protocol, or VoIP, as well as digital voice messaging. However, there are limited data regarding the effects of VoIP versus older telephony systems on organizational productivity.

Another result of the shift to Internet-based IT systems has been the growth of videoconferencing as a productivity tool.[16] Videoconferencing has enabled the geographical distribution of project work via meetings that may integrate computer presentations, face-to-face exchanges, and data sharing. The use of these forms of data and information exchange in organizations are affected by combinations of context, task urgency, and bandwidth; although studies of these aspects of organizational data sharing date to the 1990s, the capability of high-speed Internet infrastructure has led to a majority of survey respondents reporting daily or weekly videoconferencing.[17,18] Mobile computing, increased Internet bandwidth and infrastructure support, and cloud-based data storage can also support the growing role of flexible "hoteling" or "touchdown" spaces, which

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[14] Visually, 2011, "The History of EMAIL and Growth of EMAIL Accounts," http://visual.ly/history-growth-email.

[15] S. Radicati, 2013, *Email Statistics Report, 2013-2017*, The Radicati Group, http://www.radicati.com/wp/wp-content/uploads/2013/04/Email-Statistics-Report-2013-2017-Executive-Summary.pdf.

[16] J. Kruger, 2013, "New Research Finds Use of Videoconferencing Growing As an Enterprise Productivity Tool," *IMCCA* (blog), http://www.imcca.org/news/new-research-finds-use-of-videoconferencing-growing-as-an-enterprise-productivity-tool.

[17] B.S. Caldwell, S. Uang, and L.H. Taha, 1995, Appropriateness of communications media use in organizations: Situation requirements and media characteristics, *Behaviour and Information Technology* 14(4):199-207.

[18] J. Kruger, 2013, "New Research Finds Use of Videoconferencing Growing As an Enterprise Productivity Tool," *IMCCA* (blog), http://www.imcca.org/news/new-research-finds-use-of-videoconferencing-growing-as-an-enterprise-productivity-tool.

limit the number of fixed offices necessary for a workforce of a given size. This reduction changes the real estate footprint associated with the size of an organization.[19] These effects of enterprise software, IT infrastructure, and mobile computing devices substantially affect the traditional mappings of organization size to workplace organizational elements such as location, work hours, and distribution of members of work teams.

Educational Tools and Platforms

Traditional models of higher education and training have been steadily augmented by technology for years, from the introduction of overhead projectors to current video streaming and real-time remote-meeting technologies such as Google Hangouts or Skype. IT tools such as Webex, BlueJeans, GotoMeeting, Piazza, and Blackboard can be used by college faculty to record and distribute course content, often with asynchronous file exchange and chat features, to remotely located students.

With the general availability of high-speed networks to people's homes, universities can now stream lectures to students across the world, and students can communicate with instructors and each other via the network. This new mode of online education with many students is called a massive open online course (MOOC). In a typical MOOC, class video lectures are prerecorded and often include associated exercises that are carried out by students in isolation or in very small groups. Tests may be given over the Internet, and in many cases evaluations of tests and exercises are carried out through peer evaluation, which also provides students with a broader perspective. The ability to teach without the use of a physical classroom allows for enrollment of much larger classes, with some MOOC classes having as many as 80,000 students enrolled. Although student completion rates can often be as low as 10 percent, that means 8,000 motivated students may still complete a class. Companies such as Coursera and Udacity, along with many universities, are now experimenting with a wide range of variations on this MOOC model, including methods for tuning individual course delivery for students by automatically tracking their course progress (and with different models for tracking meritorious performance and issuing certification). While these innovative educational tools have stimulated much excitement, it is also important to understand exactly who is participating and benefitting from online courses. Although estimates are difficult to confirm, many of the participants in Coursera and edX courses are those who already have

[19] K. Lazar, and S. Long, 2014, "Downtown Office Market Starts to See Effects of Evolving Workspace Needs," Shepard Schwartz & Harris LLP, http://www.ssh-cpa.com/newsroom-insights-chicago-office-market-hoteling.html.

college degrees, and who may be participating for supplementary "ad hoc" or "just-in-time" learning activities. Studies suggest that students enroll in MOOCs for different reasons, with different engagement levels, and with varying capabilities for success. The MOOC environment is challenging for learners who are not already self-directed.[20] In addition, access to the necessary resources, such as high-speed Internet, is not equal among all populations. For example, a 2015 issue brief from the President's Council of Economic Advisers highlights this "digital divide," noting that 2013 rates of household Internet access correlate with education level of the head of household, and that members of underrepresented minority groups have lower access rates. Geography also plays a significant role in determining access.[21]

At the same time, there are limits to what can be learned through remote online tools, such as for fields relying on intensive apprenticeship with significant hands-on and embodied competency. The important informal dimensions of learning through mentorship, observation, and participation may require different mechanisms. In addition to creating opportunities for learning, this technology may also change the nature of work for teachers and others in education-related professions. While the jury is still out on the final impact of these online methods for education and which types of students they will most benefit, there is no question that they provide new access mechanisms to lifelong education, just-in-time training to workers seeking to qualify for new jobs, and educational materials to many who would not otherwise have access to them.

Peer-to-Peer Exchanges and Matching and Reputation Systems

Advances in IT have led to new online peer-to-peer exchange networks through which resource holders or distributors can easily connect with resource seekers: eBay and Airbnb are examples of companies that have capitalized on these new platforms. One requirement for success for any given application of these peer-to-peer resource-exchange systems is the development of trust between the parties, who are often unknown to one another in advance. Although technology for matching providers to seekers, and for establishing sufficient trust to support the transaction,

[20] Department for Business, Innovation, and Skills, 2013, "The Maturing of the MOOC," BIS Research Paper #130, https://core.ac.uk/download/pdf/18491288.pdf; D. Fisher, 2012, "Warming up to MOOC's," Chronicle of Higher Education, http://chronicle.com/blogs/profhacker/warming-up-to-moocs/44022; A. Kirshner, 2012, A Pioneer in online education tries a MOOC, *Chronicle of Higher Education* 59(6):21-22.

[21] The White House, 2015, "Mapping the Digital Divide," Council of Economic Advisers Issue Brief, July, https://www.whitehouse.gov/sites/default/files/wh_digital_divide_issue_brief.pdf.

has led to success for companies such as those listed above, this technology remains at an early stage.

Reputation systems, which enable providers and seekers to voluntarily rate one another after a transaction, are widely used to establish the trustworthiness of participants. However, these reputation systems rely on voluntary investment of time and energy to provide ratings and may therefore be gamed or simply skewed toward participants with strong views and available time to participate, providing potentially inaccurate or at least unrepresentative data.

When used in the evaluation of individual workers, such reputation systems can impact workers' future salary potential and their ability to retain jobs. Similar reputation systems are also used in more traditional companies to obtain feedback on employees who interface with customers (e.g., customer calls are often greeted with the question "Do you agree to take a brief survey after you have completed your call?"). Given that the use of online peer-to-peer networks has grown very visibly over the past 10 years and that this trend is still in its early stages, it can be expected to continue to diffuse into new applications. Its eventual spread may be determined in part by improvements in the technology for establishing accurate reputations.

The Internet of Things

The Internet of Things is a term introduced to capture the growing accessibility of many diverse devices to the Internet. As Wikipedia defines it, "the Internet of things is the network of physical objects—devices, vehicles, buildings and other items—embedded with electronics, sensors, and network connectivity that enables these objects to collect and exchange data."[22] Already, many devices, from thermostats to home alarms, communicate via the Internet and provide phone apps to interact with them (e.g., to adjust temperature before the user arrives home). But many more devices, from transit buses to refrigerators, already make use of computer processors and are beginning to have Internet connectivity. In addition, radiofrequency identification technology provides a low-cost method to identify and track any physical item without use of battery power and has been widely used, for example, to track items during shipping. The significance of the Internet of Things is that it will further accelerate the trend toward digitization of everything, making it possible for the Internet to serve as a communication tool for capturing, sharing, and acting on even more digital information. While the full impact of this trend is not

[22] Wikipedia, "Internet of things," last update July 23, 2016, https://en.wikipedia.org/wiki/Internet_of_things.

yet certain, experiments are already under way in cities such as Songdo, South Korea, and Santander, Spain, to explore the potential for city-wide connectivity of devices to improve aspects of city life, from the logistics of finding a parking space to improvement of air quality.

The Cloud

One important trend in the use of networking and computing is the growth of companies and services that offer disk storage and computing as a service over the Internet. For example, companies like Dropbox and Box offer the ability to store data in the cloud (i.e., on their servers via the Internet). Other companies such as Amazon and Google offer cloud-computing platforms in which users can rent time on very large computing clusters, accessible over the Internet, instead of purchasing their own hardware to run computationally intensive jobs. Beyond providing cloud access to raw storage and computing power, these and other IT companies, such as Microsoft, IBM, and Salesforce, now provide entire services over the Internet (software as a service). For example, Salesforce offers a cloud-based customer relationship management service used by many companies.

Cloud-based solutions have the advantage that the user can pay for only what they need—only as much storage or computational effort as they need—without investing in their own computing infrastructure. Cloud-based services similarly provide a convenient way to outsource certain tasks; they can be disseminated nearly instantly across the entire Internet, with no need to physically transport equipment or people. In addition, data sharing and other forms of collaboration become easier via the cloud (e.g., Google Docs provides a cloud-based document editor in which multiple users can simultaneously edit a document and view changes being made by all parties in real time), augmenting workers' capabilities.

ADVANCING TECHNOLOGICAL CAPABILITIES

The paradigm shift to digitization enabled by development of the Internet and advances in computational power, networking speed, and data capture and storage has been transforming society for decades. New and compelling uses of these technologies, enabled by enhanced connectivity and computing power, continue to emerge.

Today, many concerned with the impact of technology on the workforce have turned their attention to the progress of technologies that perform functions commonly thought of as "human"—and thus present new opportunities for automating work functions traditionally carried out by people, which could have the effect of eliminating jobs or changing the skills requirements and tasks associated with certain jobs. Many of these areas are still in the research and development phases. In the section below, the committee discusses the progress of these technologies.

Artificial Intelligence

Artificial intelligence, or AI, refers to principles and applications of computer algorithms that attempt to mimic various aspects of human intelligence. Although the term was coined in the 1950s, it took decades of research before aspects of AI research reached the point of significant commercial impact.

By the mid-1990s, practical, commercial AI-based systems for automating or assisting in a variety of human decision-making tasks had been developed and were being used in fraud detection and in the configuration of computer systems.[23,24] While early AI systems were typically constructed manually—that is, with programmers writing computer-interpretable rules to define a computer-based decision process—there has been a shift toward AI systems based on machine learning methods—that is, algorithms that infer their own decision-making rules from training data—by harnessing large data sets. For example, fraud-detection strategies are now developed automatically by machine learning algorithms that analyze millions of historical credit card transactions.

The increasing use of machine learning, along with other innovations, has produced significant progress in a variety of AI subfields, including computer vision, speech recognition, robot control, automated translation between languages, and automated decision-making.[25] These advances in AI component technologies have in turn produced a number of highly visible AI systems over the past decade, including the following:

- *Intelligent agents* such as Apple's Siri, Google Now, Microsoft's Cortana, and Amazon's Echo. These AI systems combine speech recognition, background knowledge about the user, mixed-initiative interaction with users, and a variety of specific apps to perform useful tasks. These systems demonstrate the ability to combine spoken natural-language interaction with a range of intelligent services and electronic commerce.

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[23] S. Zoldi, 2016, "Four Analytic Breakthroughs That Are Driving Smarter Decisions," *Fico Blog*, May 26, http://www.fico.com/en/blogs/analytics-optimization/four-analytic-breakthroughs-that-are-driving-smarter-decisions/.

[24] J. McDermott, 1980, "R1: An Expert in the Computer Systems Domain," Carnegie Mellon University, https://www.aaai.org/Papers/AAAI/1980/AAAI80-076.pdf.

[25] S. Russell and Peter Norvig, 2010, *Artificial Intelligence: A Modern Approach (3rd Edition)*, Prentice Hall, Upper Saddle River, N.J.

- *Self-driving vehicles.* Multiple universities and companies have now demonstrated self-driving vehicles. For example, in 2015 the automotive company Tesla released software that allows its customers to put their automobile into self-driving mode on public highways, and Uber has recently begun testing self-driving cars on the streets of Pittsburgh.[26] This demonstrates that computer perception and control—in particular, computer vision and self-steering—have reached an important threshold of practical reliability.
- *AI and robotic systems that sense and act within the physical world*. An example is Nest's intelligent thermostat, which learns to customize individual buildings to their occupants' routines.
- *AI systems capable of answering many factual questions.* IBM's Watson system defeated the world *Jeopardy!* champion in 2011,[27] and Wolfram|Alpha[28] provides a similar broad-scope resource for answering diverse factual questions. Note that *Jeopardy!* requires the contestant to answer unforeseen questions about a very diverse set of unforeseen topics. Watson's win over humans in *Jeopardy!* demonstrates that computers can achieve human-level competence at answering diverse factual questions, while using huge volumes of unstructured text as underlying sources of knowledge.
- *AI game-playing systems that defeat humans at chess, backgammon, and Go.* In recent years, AI systems for game playing have defeated the top human players in each of these games. Most recently, in 2016, Google's AlphaGo system defeated the world champion Go player in a best-of-five match by a score of four to one. These achievements demonstrate the capability of machine learning to automatically discover complex problem-solving strategies by training on millions of games in which the computer plays against different variants of itself (see Figure 2.3). However, it is important to realize this strategy-learning approach is applicable only to problems where near-perfect simulations are feasible. For example, games can be simulated perfectly, but the effect of a bicycle hitting a rock cannot be.

These visible AI advances illustrate the growing competence of AI technology. The committee examines related technologies in the following sections.

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[26] Reuters, 2016, "Uber Debuts Self-Driving Cars in Pittsburgh," Fortune, September 14, http://fortune.com/2016/09/14/uber-self-driving-cars-pittsburgh/.

[27] D.A. Ferrucci, 2012, "Introduction to 'This is Watson,'" *IBM Journal of Research and Development* 56(3.4):1:1-1:15.

[28] Wolfram|Alpha is a computational knowledge engine that was developed by Wolfram Research. See Wolfram|Alpha, 2016, "About Wolfram|Alpha," Wolfram|Alpha, https://www.wolframalpha.com/about.html, accessed May 27, 2016.

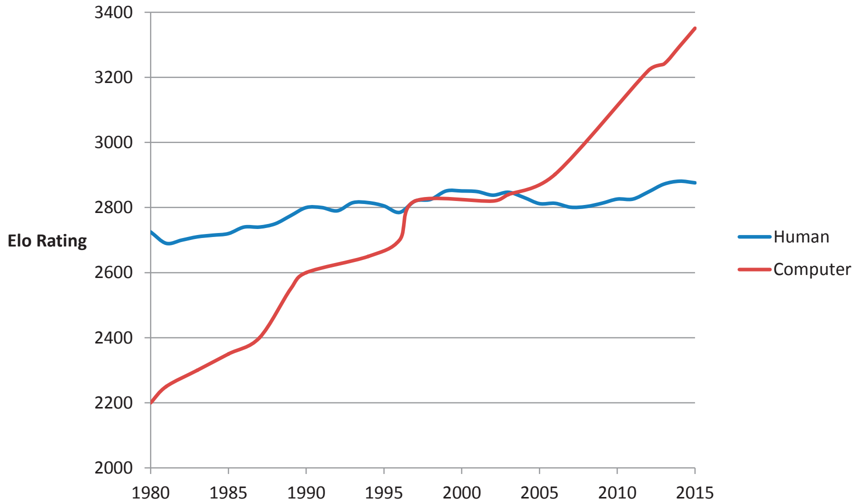


FIGURE 2.3 Elo scores—a measure of competency in competitive games—showing the chess-playing competency of humans and machines, measured over time. SOURCE: Courtesy of Murray Campbell.

Machine Learning and Big Data

One of the most important drivers of AI advances over the past two decades has been machine learning: computer algorithms that automatically improve their competence through "experience." This experience is often in the form of historical data, which the machine-learning algorithm analyzes in order to detect patterns or regularities that can be extrapolated to future cases. For example, given experience in the form of a historical database of medical records, machine-learning algorithms are now able to predict which future patients are likely to respond to which treatments. Given experience in the form of speech signals from a specific individual, machine-learning algorithms now automatically improve their ability to understand the accent of that particular individual. Given experience observing which movies a user watches online, machine-learning algorithms now automatically improve their ability to recommend additional movies of interest. In many cases, including the above examples, the abstracted machine-learning problem is to learn some classification function from training data consisting of input-output pairs for that function. For example, a classification mapping each patient to a recommended treatment may be generated from automated analysis of historical data describing a patient and their successful treatment.

A set of machine learning algorithms called deep neural networks has had a major impact in recent years. These are complex networks of threshold elements trained to fit the training data. These algorithms are able to discover useful abstract representations of complex data. Over recent decades, deep learning has helped to advance the state of the art in computer vision, speech recognition, and other areas, especially in tasks that involve complex perceptual or sensor data.[29] For example, Xu et al. have trained a deep network to generate text captions for photographic images. While this and other deep network algorithms are still limited, their ability to train on millions of examples to generate models with billions of learned parameters has led to major improvements across many applications, such as robotics, information extraction from text documents, and prediction of customer behavior. Over the coming decade, these and other machine learning algorithms are likely to advance further, and new applications of existing algorithms remain to be explored.

While algorithm development is one driver of progress in machine learning, another major driver is the growth of online data that fuel machine-learning systems. Companies now capture growing volumes of data about their customers to learn to better serve and market to them. Companies have also moved an increasing fraction of their routine work flows online, thereby capturing new data that might be used to learn decision-making rules to partially automate these routine work flows. New sensors are appearing in many contexts, from cameras mounted on streetlights to pulse-sensing watches worn by individuals. Building on technological advances in wireless sensor networks and the Internet of Things, much of these data are now available in real time across the network, making it possible to generate intelligent systems that are embedded in critical infrastructure systems. A few such examples include (1) urban mobility, with companies such as Waze providing real-time route advice, and Lyft and Uber using the Internet to match passengers to drivers; (2) smart homes and accommodation systems, with companies like Nest providing home automation and Airbnb providing significant competition to the traditional hotel and short-term rental market; (3) automated agriculture, in which weather, water, and soil data are used to automatically control farming practices; (4) the electric power grid, in which consumer behavior can be learned in real time, making it possible to accurately schedule heterogeneous distributed energy resources, such as solar and wind; and (5) assistive devices, such as robotic wheelchairs

[29] Y. LeCun, Y. Bengio, and G. Hinton, 2015, Deep learning, *Nature Magazine* 521:436-444, doi:10.1038/nature14539.

and new reality and robotic platforms like the PR2 Robot for Research and Innovation,[30] to support design and development of a wide range of personal assistive tasks.

Over the coming decade, the impact of machine learning, big data capture and analysis, and data science is likely to grow as the diversity and volume of online data sets continues to grow, new types of sensors are designed to acquire new types of data, more companies learn how to collect and use online data to optimize profits, and the supply shortage of technical experts in this area is ameliorated by the growing number of college students studying this subject.

At the same time, there are several constraints on the rate and types of progress that can be expected. For example, although the volume of online data will almost certainly grow, *access to data* will likely limit their potential uses. Data access will be bounded by personal privacy concerns, by the willingness of companies that own much of this data to share it, and by government regulations, such as those under the Health Insurance Portability and Accountability Act of 1996, which govern access to medical data. In addition, while some data are in the form of highly structured databases, many are in the form of unstructured video, audio, and text that are much less interpretable by computers, despite recent progress. Other technical issues must also be addressed, such as incompatibilities in data schema across different databases, differences in the temporal and spatial grain size of data, and differences in data distributions sampled by different databases. Growing research in machine learning and data science is actively addressing these issues, but many of these technical issues remain unsolved.

Robotics

Robotics is a field at the intersection of mechanical engineering, electrical engineering, and computer science that "deals with the design, construction, operation, and use of robots, as well as computer systems for their control, sensory feedback, and information processing."[31] In general, a robot is a mechanical machine that uses sensors to gather information about the world it operates in and a computer program to guide its actions. The academic discipline of robotics centers on the study, development, and deployment of electromechanical systems that sense and interact in the physical world, guided by a computer program or

[30] Willow Garage, 2008, "Overview: PR2," last modified 2015, https://www.willowgarage.com/pages/pr2/overview.

[31] Wikipedia, The Free Encyclopedia, "Robotics," last modified March 8, 2017, https://en.wikipedia.org/wiki/Robotics.

simpler electronics. The concept of robotics can be broadened to include embedded sensing and actuation systems, referred to broadly as "cyber-physical systems."

Real-world application of robots dates back to 1961, when George Devol's and Joseph Engelberger's Unimate system was deployed at General Motors for handling of die-cast metal.[32] Use of robots in the automation of physical tasks provides benefits such as quality, repeatability, and power and can enable the removal of humans from dangerous tasks. In their early days, robots were used predominantly in automotive manufacturing. The initial introduction of robots in the automotive industry helped to ensure consistent quality over time and a reduction in defects.

Since then, the field has seen tremendous technical progress. The early robot systems had high mechanical precision but were not programmable. They used a fixed sequence of actions to perform a task. By 1974, the first microprocessor-controlled robot was introduced. Today's robot utilizes different types of sensors, and some of them are directly programmed from human demonstration.

The International Organization for Standardization defines a robot as an "actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks."[33] The standard also distinguishes between industrial and service robots.

This formal definition allows consistent capture of sales and inventory statistics across sectors, regions, and nations. An annual report issued by the International Federation of Robotics[34] captures the sales and inventory of both industrial and service robotics in most countries and includes a break-down across use-cases.

The industrial robotics market today has annual sales in excess of $10 billion each year, or more than $30 billion including installation costs and sale of accessories. Annual sales of industrial robots had grown to 230,000 robots by 2014, with close to 25 percent of sales originating in China. Five countries (China, the United States, Japan, Republic of Korea, and Germany) are responsible for 70 percent of global sales. In the United States, close to 32,000 robots were sold during 2014; see Figure 2.4 for worldwide industry trends over time.[35]

As of 2014, the top use of robots remained as automotive manufacturing, which accounts for 42 percent of all applications, with electron-

[32] S.Y. Nof, 1999, *Handbook of Industrial Robotics*, Volume 1, Wiley & Sons, Hoboken, N.J., doi:10.1002/9780470172506.

[33] ISO Standard 8373.

[34] International Federation of Robotics, 2015, "Industrial Robot Statistics: World Robotics 2015 Industrial Robots," http://www.ifr.org/industrial-robots/statistics/.

[35] Ibid.

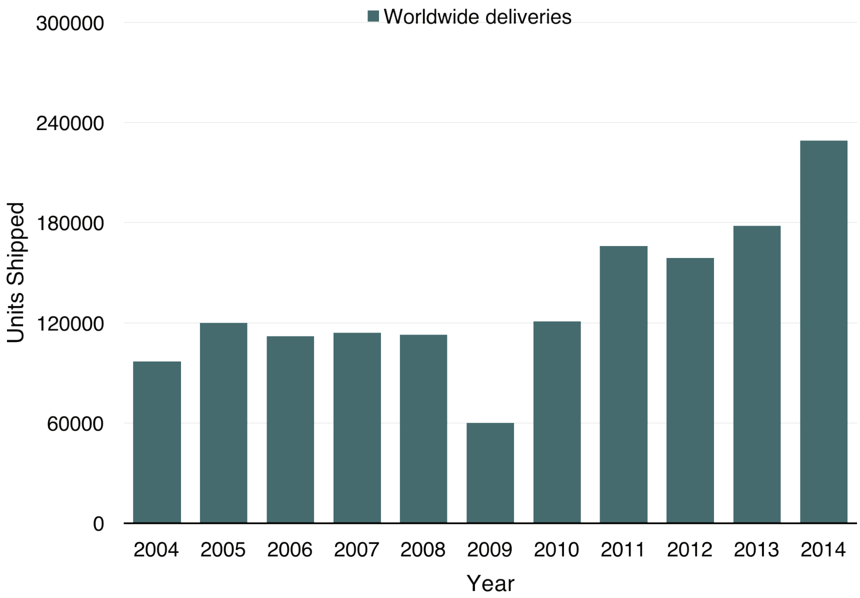


FIGURE 2.4 Worldwide shipping of robots over time. SOURCE: Data from International Federation of Robotics, 2015. "Industrial Robot Statistics: World Robotics 2015 Industrial Robots," last modified 2015, http://www.ifr.org/industrial-robots/statistics/.

ics assembly and metal work accounting for 21 percent and 10 percent, respectively.[36] Figure 2.5 illustrates the distribution of application areas for robotics in 2015.

The number of robots shipped in the United States had a compound annual growth rate of 11 percent between 2009 and 2015.[37] Recently there has been a stronger move toward the use of robot technology to enable increased flexibility and customization of products. For example, automobile manufacturer Audi now has the ability to produce 10^{31} different car model options, customizable to consumer preference for features such as color, wooden panels, audio systems, navigation systems, safety options, and more. At the same time, the lifetime of some products is getting shorter. For example, cell phone models typically have a lifetime of 12 months or less. This requires a manufacturing line to be available for production of multiple product types to allow for capitalization of infra-

[36] Ibid.
[37] Ibid.

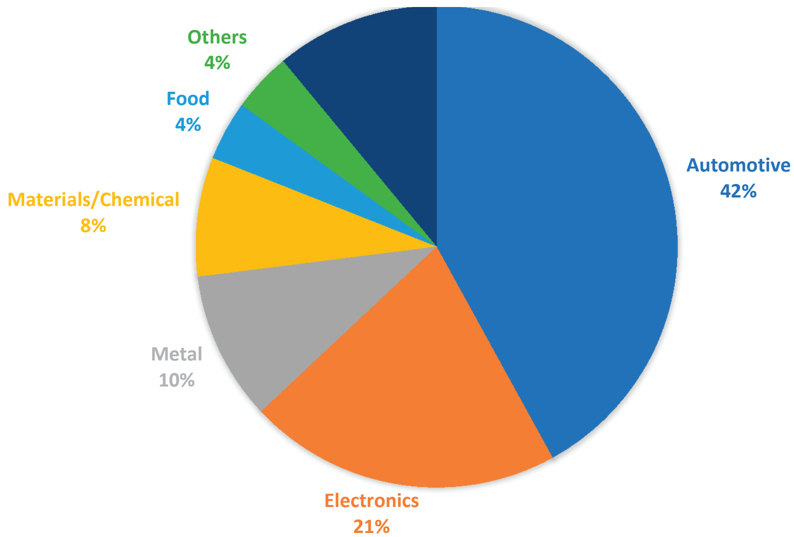


FIGURE 2.5 Robot application areas in 2015. SOURCE: Data from International Federation of Robotics, 2014. "Industrial Robot Statistics: World Robotics 2015 Industrial Robots," last modified 2014, http://www.ifr.org/industrial-robots/statistics/.

structure, again resulting in a requirement for flexibility and reprogrammability in robotic assembly.

A service robot is a robot that "performs useful tasks for humans or equipment, excluding industrial automation applications."[38] The service robotics market is divided into professional and consumer applications. The professional applications include cleaning, material handling, surveillance, rehabilitation, surgery, logistics, and construction as well as defense applications. The market is still small (24,207 units with sales of $3.77 billion in 2014) compared to the industrial robotics market, but it is seeing significant annual growth, with current growth rates on par with those of industrial robots. The biggest market in this segment is robots used in minimally invasive surgery. The service robotics market is expected to see major growth significantly beyond the industrial market, since it includes subsectors such as driverless cars, unmanned aerial vehicles (sometimes referred to as drones), and entertainment robots. Recent industry predictions indicate that first-generation driverless cars will be available by 2020, and by 2030 such cars are likely to be a service. More than 3 million unmanned aerial vehicles have already been sold, and their growth is pre-

[38] ISO Standard 8373.

dicted to be exponential.[39] In February 2017, engineers in Dubai reported a success test flight of a single passenger drone air taxi, with plans to make it available to customers later in 2017.[40]

The consumer market for robots includes household robots and entertainment and leisure robots. This includes domestic service robots, automated wheelchairs, personal mobility assistance robots, and pet-exercising robots. Autonomous pool-cleaning, rain-gutter-cleaning, and carpet-cleaning robots[41] are sold commercially. Hospital robots that deliver supplies are also emerging.[42] While approximately 4.7 million service robots were sold in 2014 for personal and domestic use, this accounted for sales of only $2.2 billion due to lower costs per unit.

In addition to the already fielded applications of robotics, university and corporate research is under way in nearly all aspects of component technologies. Research on computer vision, sound perception, and other modalities for perception; reinforcement-learning algorithms to give robots the ability to improve through experience; and natural-language interaction with robots are active areas discussed in the following sections. There is also research to explore styles of interaction between robots and people, such as work on building robots from more pliable materials to avoid accidental harm to people; research on styles of conversation between robots and people to produce effective communication; human instruction of robots; and robots' explanation of their actions.

Computer Perception: Vision and Speech

Over the last 15 years, tremendous progress has been made in computer perception, especially in the areas of computer vision and speech recognition.[43] Computer vision is widely used today in a range of applications, including fingerprint recognition at safety barriers, high-speed processing of handwritten addresses on letters by the U.S. Postal Service, reading of checks deposited at ATMs or via cell phone cameras, and recognition of individual faces in personal online photo albums. Even 10 years ago, recognition of hundreds of different objects in images was impossible, whereas now systems can classify images of 1,000 different

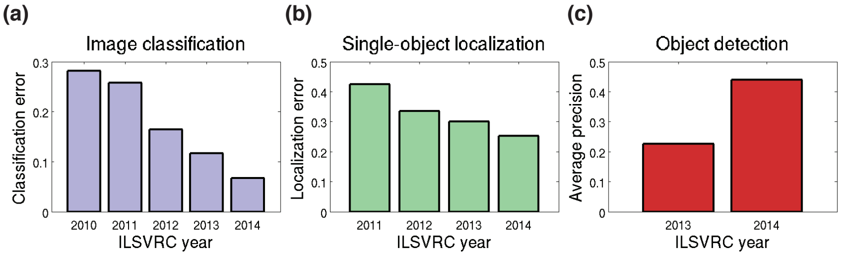
[39] International Federation of Robotics, 2015, "Industrial Robot Statistics."

[40] T. Flanigan, 2017, "Forget Taxis; Dubai Wants to Fly You Around in Passenger Drones," February 16, http://mashable.com/2017/02/16/taxi-dubai-passenger-drones/#HpoK4G4xPmqO.

[41] iRobot Corporation, 2016, "Roomba 98: The Power to Change the Way You Clean," http://www.irobot.com/For-the-Home/Vacuum-Cleaning/Roomba.aspx, accessed March 31, 2016.

[42] Aethon, Inc., 2016, "TUG Robots—Healthcare Benefits," http://www.aethon.com/tug/tughealthcare/, accessed March 31, 2016.

[43] X. Huang, J. Baker and R. Reddy, 2014, A historical perspective of speech recognition, *Communications of the ACM* 57(1):94-103, doi:10.1145/2500887.



Performance of winning entries in the ILSVRC2010-2014 competitions in each of the three tasks. There is a steady reduction of error every year in object classification and single-object localization tasks, and a 1.9x improvement in mean average precision in object detection. There are two considerations in making these comparisons. (1) The object categories used in ISLVRC changed between years 2010 and 2011, and between 2011 and 2012. However, the large scale of the data (1000 object categories, 1.2 million training images) has remained the same, making it possible to compare results. Image classification and single-object localization entries shown here use only provided training data. (2) The size of the object detection training data has increased significantly between years 2013 and 2014.

FIGURE 2.6 Panel (a) shows the dropping error rate in automated image classification, year by year, for the ImageNet Large Scale Visual Recognition Challenge. SOURCE: O. Russakovsky, J. Deng, H. Su, J. Krause, S. Satheesh, S. Ma, X. Huang, et al., "ImageNet Large Scale Visual Recognition Challenge," *International Journal of Computer Vision*, last modified January 30, 2015, http://arxiv.org/pdf/1409.0575v3.pdf, with permission of Springer.

objects with 62 percent average precision.[44] In merely the interval from 2010 to 2014, the error rate in image classification for one major test set of images, the ImageNet set, was reduced from 28 percent to under 8 percent (see Figure 2.6).[45] At the end of 2015, multiple image recognition systems reported reaching human level performance of approximately 4 percent error rates on the ImageNet challenge, widely used to evaluate image classification.[46] Much of this recent improvement has been driven

[44] O. Russakovsky, J. Deng, H. Su, J. Krause, S. Satheesh, S. Ma, Z. Huang, A. Karpathy, A. Khosla, M. Bernstein, A.C. Berg, and L. Fei-Fei., 2015, "ImageNet Large Scale Visual Recognition Challenge," January 30, http://arxiv.org/pdf/1409.0575v3.pdf.

[45] Ibid.

[46] See, for example, R.C. Johnson, 2015, "Microsoft, Google Beat Humans at Image Recognition" EE Times, February 18, http://www.eetimes.com/document.asp?doc_id=1325712; K. He, X. Zhang, S. Ren, and J. Sun, 2015, Delving deep into rectifiers: Surpassing human-level performance on ImageNet classification, pp. 1026-1034 in Proceedings of the IEEE International Conference on Computer Vision, https://arxiv.org/pdf/1502.01852.pdf; and R. Eckel, 2015, "Microsoft Researchers' Algorithm Sets ImageNet Challenge Milestone," Microsoft Research Blog, February 10, https://www.microsoft.com/en-us/research/blog/microsoft-researchers-algorithm-sets-imagenet-challenge-milestone/.

by applying deep network machine learning algorithms to larger training sets of images. Computer vision algorithms are now also capable of tracking people, cars, and other objects in video streams as well as analyzing static images.

Much of the progress in computer vision has been independent of its use in robotics. Recently, vision technology has started to see applications in robotics, in particular for design of "smart" (driverless) cars and for the sorting of goods by supply-chain companies such as Amazon.

Computer vision on video and live imagery is also making progress, with advances in identifying objects and recognizing intentions in videos,[47] and for employing machine vision for perceptual tasks for robotics applications in the open world, such as in autonomous and semi-autonomous driving.[48]

Similar progress has been made in the area of speech perception, which is now widely used in phone-based customer service systems and to input commands to mobile phones and other devices. Again, as recently as the turn of the 21st century, it was impossible to achieve speech recognition accuracies sufficient to support such applications (see Figures 2.7-2.8 for an illustration of historical progress in automated speech recognition). As in the case of computer vision, much of the recent progress in speech-to-text systems has been due to the use of deep network machine learning algorithms. Microsoft reported in October 2016 they had reached a 5.9 percent word recognition error rate, equal to humans on the switchboard transcription task.[49]

Natural Language Processing

Natural language processing refers to computer-based analysis of natural language (language written and spoken by humans) in useful ways. Common applications include search engines, spam filters that examine e-mail to determine whether it is spam, systems that automatically extract mentions of people, places, organizations, and events from news articles,

[47] J. Liu, J. Luo, and M. Shah, 2009, "Recognizing realistic actions from videos 'in the wild,'" *IEEE Computer Vision and Pattern Recognition*, doi: 10.1109/CVPR.2009.5206744; R. Poppe, 2010, A survey on vision-based human action recognition, *Image and Vision Computing* 28(6):976-990.

[48] E. Ohn-Bar and M.M. Trivedi, 2016, Are all objects equal? Deep spatio-temporal importance prediction in driving videos, *Pattern Recognition*, in press, http://www.sciencedirect.com/science/article/pii/S0031320316302424.

[49] A. Linn, 2016, "Historic Achievement: Microsoft Researchers Reach Human Parity in Conversational Speech Recognition," October 18, https://blogs.microsoft.com/next/2016/10/18/historic-achievement-microsoft-researchers-reach-human-parity-conversational-speech-recognition/#sm.000vjpv5z169ewp105s11ee1nrzuq.

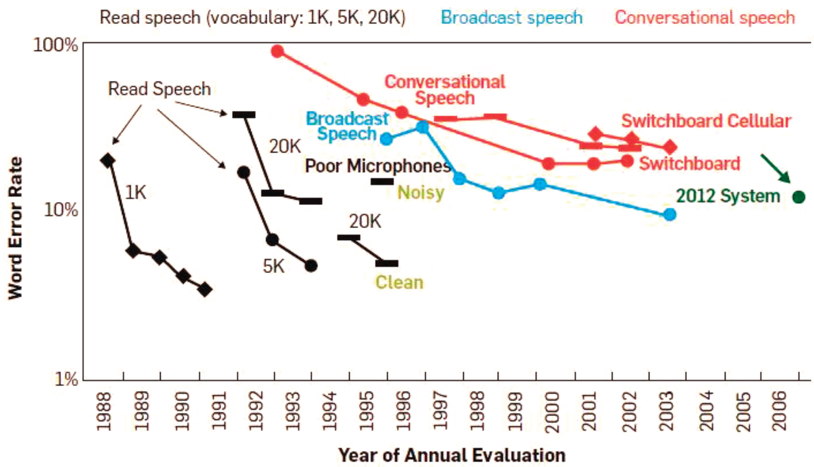


FIGURE 2.7 Historical progress on reducing the word error rate in speech recognition systems for different kinds of speech recognition tasks. Recent competency for the "difficult switchboard" task (human conversation in the wild) is marked with the green dot. SOURCE: X. Huang, J. Baker, and R. Reddy, 2014, A historical perspective of speech recognition, *Communications of the ACM* 57(1):94-103, doi:10.1145/2500887. © 2014, Association of Computing Machinery, Inc. Reprinted with permission.

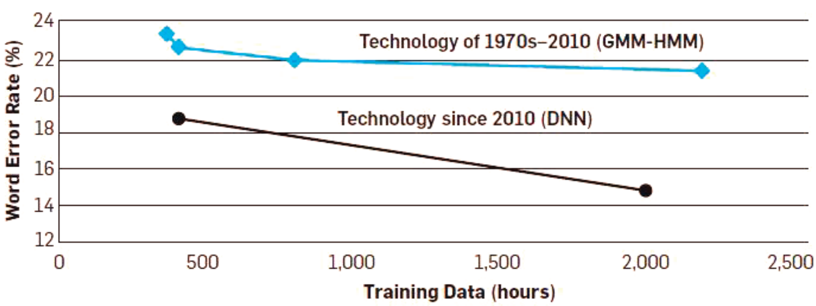


FIGURE 2.8 Recognition word error rate versus the amount of training hours, demonstrating the sensitivity of competency of speech recognition to increasing amounts of data. SOURCE: X. Huang, J. Baker, and R. Reddy, 2014, A historical perspective of speech recognition, *Communications of the ACM* 57(1):94-103, doi:10.1145/2500887. © Association of Computing Machinery, Inc. Reprinted with permission.

systems for automatic translation of text from one language to another, and question-answering systems that respond to questions posed in natural language. Recent years have seen strong progress in the ability to extract structured factual information from unstructured text, although computer methods that understand the full meaning of text are far from realized. Here again, progress has been driven largely by machine learning applied to large text data sets. Due to intense competition in the area of search engines and related problems, corporate investments in research and development are large in this area, suggesting rapid progress in the future. As this technology improves, research assistants and paralegals may rely increasingly on support from computers.

One widely regarded example of intelligent text processing is the IBM Watson family of applications, whose methods were originally designed to participate in *Jeopardy!*. Watson systems operate by interpreting natural language questions, then performing inference on a huge collection of text and other types of data to identify candidate answers and rank them to produce a final answer. This technology has many other potential uses, and IBM is now applying it to medical applications using large collections of medical text. Given that the rate of publication of new medical results outpaces the ability of doctors to read journal articles, decision support systems such as Watson have potentially game-changing consequences for augmenting human capabilities in fields that require knowledge-based decision-making.

Complementary Computing

While computers have remarkable speed and processing capabilities, humans still outperform computers in certain tasks and contexts. New models of human engagement have focused on how best to leverage the strengths of humans and computers for optimal completion of a given task. Such thinking is apparent in emerging modalities of work, including distributed or crowdsourced labor. Methods for supporting and optimizing complementary engagements of people and machines enable a mix of computer and machine initiatives or contributions for addressing tasks and solving problems. Such work includes developing context- and problem-specific models of machine and human competencies, methods for recognizing the state of a solution and the efforts of machines and people, and means for coordinating the contributions of people and machines.[50]

Recent research efforts in this area have focused on applying machine learning methods to enable systems to learn how to best combine the

[50] E. Horvitz, 2007, "Reflections on Challenges and Promises of Mixed-Initiative Interaction," *AAAI Magazine* 28, Special Issue on Mixed-Initiative Assistants.

intellect and physical abilities of people and machines.[51,52] While these approaches are still largely deployed in research prototypes, they illustrate a model where systems leverage the complementary skills of people and machines to complete cognitive and physical tasks. This suggests that new types of work may arise with roles that rely on uniquely human skills.

Complementary computing and mixed-initiative solutions also extend to collaborations between robotic systems and people in the physical world. For example, efforts have been under way to develop collaborative robotic systems in surgery to allow robotic surgical systems to work hand in hand with human surgeons. Promising prototypes and research to date have considered technologies to recognize and understand the actions and intentions of human surgeons and coordinate activities between robotic and human surgeons.[53,54,55]

Directions in research and development on complementary computing systems show how the talents of machine competencies can be joined with the intellect and physical prowess of people and highlight the likelihood that technical advances will bring to the fore new roles and types of work for people in joint human-machine problem solving—where people bring critical, uniquely human contributions into the mix of initiatives. However, the types and nature of contributions and new potential roles for rewarding work for people remain unclear.

Human-Centered Automation

Many automated tasks require machines to interface with humans. For example, some online retailers have highly automated warehouses that use robots to bring items for a retail order from their storage shelves

[51] E. Kamar, S. Hacker, and E. Horvitz, 2007, "Combining Human and Machine Intelligence in Large-scale Crowdsourcing," International Conference on Autonomous Agents and Multiagent Systems, June 4-8, 2012, Valencia, Spain; E. Horvitz and T. Paek, 2007, Complementary computing: Policies for transferring callers from dialog systems to human receptionists, *User Modeling and User Adapted Interaction* 17(1):159-182, doi: 10.1007/s11257-006-9026-1.

[52] D. Shahaf and E. Horvitz, 2010, "Generalized Task Markets for Human and Machine Computation," Association for the Advancement of Artificial Intelligence, http://research.microsoft.com/en-us/um/people/horvitz/generalized_task_markets_Shahaf_Horvitz_2010.pdf.

[53] C.E. Reiley, H.C. Lin, B. Varadarajan, B. Vagvolgyi, S. Khudanpur, D.D. Yuh, and G.D. Hager, 2008, Automatic recognition of surgical motions using statistical modeling for capturing variability, *Studies in Health Technology and Informatics* 132: 396-401.

[54] A. Shademan, R.S. Decker, J.D. Opfermann, S. Leonard, A. Krieger, and P.C.W. Kim, 2016, Supervised autonomous robotic soft tissue surgery, *Science Translational Medicine* 8(337):337ra64, doi: 10.1126/scitranslmed.aad9398.

[55] N. Padoy and G.D. Hager, 2011, "Human-Machine Collaborative Surgery Using Learned Models," in *2011 IEEE International Conference on Robotics and Automation (ICRA)*, doi:10.1109/ICRA.2011.5980250.

to a human worker, who then packs and loads them onto a truck. This interface between machine and human workers requires, for example, that the rate of goods provided by the robot to the human matches the varying rate at which humans can process the workload, and that the robot provide a "failsoft"[56] mechanism for the human to take control in the event that it makes an error. In recent years, advances have been made in designing systems that couple humans with automation: techniques have been developed to enhance situational awareness and to build predictive models of human behavior in different contexts.[57,58] Nevertheless, significant work remains to be done in the development of core scientific and engineering principles for designing such human-in-the-loop systems.

FUTURE TECHNOLOGY TRENDS

Overall, the committee expects the rapid pace of IT advances to continue or accelerate due to (1) continuing advances in AI algorithms and in underlying computational hardware that allows continuing scale-up at reduced cost; (2) continuing growth in the diversity and volume of online data, which, coupled with machine-learning software, is driving many AI advances; and (3) increasing investments by industry in research and development in AI and other parts of IT. Although it is impossible to predict future capabilities perfectly, certain ongoing technology trends make the following workforce-relevant developments likely over the coming decade.

- *Mobile robots*. Over the next decade, it is anticipated that self-driving vehicles, which have been demonstrated and are already in limited commercial use (e.g., the Tesla self-driving mode), will mature and become more widespread, with possibly significant impacts, such as decreased demand for drivers, on employment in the transportation sector. Analogous developments in and deployment of self-flying aerial vehicles is anticipated, if government regulations allow.
- *Assembly-line automation*. Further technical progress in automating assembly lines is expected, including diffusion into lower-volume manufacturing as flexibility and reprogrammability improve. Progress

[56] A "failsoft" is a mode that a particular piece of software enters in the event of disruption that enables retention of some (though generally degraded) level of service, to avoid otherwise substantive failure.

[57] M.R. Endsley, 2000, "Theoretical underpinnings of situation awareness: A critical review," pp. 3-28 in *Situation Awareness Analysis and Measurement* (M. R. Endsley and D.J. Garland, eds.), LEA, Mahwah.

[58] T.G. Dietterich and E.J. Horvitz, 2015, Rise of concerns about AI: Reflections and directions, *Communications of the ACM* 58(10):38-40, doi:10.1145/2770869.

in robotics toward manipulation of soft and inconsistent materials could lead to increased automation in the manufacture of apparel, leather goods, and commodity furniture, which could devalue the labor endowments of some of the poorer countries in the world and potentially lead to some (minimal) reshoring of these industries. Beyond robotic automation, 3D printing (also known as additive manufacturing) is also likely to progress and impact specialized, low-volume manufacturing. Automated assembly, coupled with automated transportation systems, is expected to have serious impacts on manufacturing (partly reshoring), but also the full supply chain, from mine to customer. This could result in decreased demand for workers and the shifting of work tasks in this sector.

- *Computer perception of speech, video, and other sensory data*. It is likely that computer competence in perceptual tasks, including speech recognition, computer vision, and interpretation of nonspeech sounds, will advance, potentially leading to significantly improved abilities in several areas, such as listening and image processing. This could augment or replace human functions for a wide range of jobs, such as security guard and policing jobs. It could also lead to a generation of new products, such as intelligent light bulbs that "see" and "hear" what is occurring in their field of view and use this capability to offer assistance.
- *Automatic translation between languages by computers*. Automatic translation is already in use, although it is imperfect (e.g., Skype now offers an automatic translation service for its calls). This technology might advance over the coming decade to the point of providing widespread, high-reliability, real-time translating telephones.
- *Text reading by computers*. The ability of computers to interpret and extract information from unstructured text documents (e.g., extracting mentions of specific people, companies, and events) has advanced significantly over the past decade, but computer reading skills still fall far short of human competence. This gap is likely to narrow over the coming decade, with potentially significant impacts on automating knowledge-worker jobs such as paralegal researchers and news reporters.
- *Work flow automation*. Businesses, governments, and other organizations are increasingly using computers for conducting routine business, leading to a great deal of online data to train systems to automate or semi-automate routine work flows. New companies such as Claralabs and x.ai now offer an online meeting scheduling service—a service that might initially be performed by remote humans, and that might become increasingly automated by applying machine learning to the large quantities of scheduling training data they acquire over time. Semi-automation of routine work flow may reduce the need for clerical staff, even if it does not automate these jobs fully. Systems such as those developed within IBM's Watson suite have started to generate decision support in the medi-

cal field. This practice is likely to be expanded to a large number of related fields, such as intelligence gathering, equipment maintenance, and business decision support systems.

These areas are likely to advance significantly in the coming years at a level that will impact the workforce.

Additional advances are also possible that, while less likely, would have major impacts on the workforce. For example, if advances are made in technology for privacy-preserving machine *learning methods*, which would use data while guaranteeing preservation of individual privacy, this would dramatically increase the variety of data mining and machine learning applications that reach the market—for example, medical applications that are currently avoided because of privacy concerns. If it becomes possible for computers to learn how to accomplish tasks through instruction from their users, this could have a truly dramatic effect: it would change the number of effective computer programmers from its current short supply to billions of people, enabling each worker to custom instruct their system on how to best assist them. If technology for text analysis reaches the point of human-level reading by computers, the impact would also be dramatic, as computers can scale to read the entire Web and would be better read than any person, by a factor of millions.

The committee also notes the possibility of unanticipated, disruptive changes in the technology landscape—that is, rapid, broad, or deep changes with significant impact on society. First, a major and unanticipated scientific or engineering breakthrough could accelerate the creation or deployment of a new technology, with concomitant disruptions to the workforce, either positive or negative. Of primary concern are disruptions that lead to the displacement or unsettling of workers, industries, or economies that are unprepared to adapt. Examples might include an unexpected breakthrough in AI algorithms that enable the straightforward automation of a type of knowledge work. History provides examples of disruptive inventions, such as the horseless carriage, where the need for physical production resulted in a slow diffusion into society. While today's software innovations can be spread worldwide rapidly by downloading them onto mobile devices, the development, testing, and integration of usable software from fundamental algorithmic advances takes time, as does the integration of new software into businesses. The nature of the corresponding disruption to the workforce would be not only a product of the new technological capability, but also determined by how those in power choose to make use of it, driven largely, by market factors. Second, it is also possible that an existing and ubiquitous technology could undergo a catastrophic failure or collapse—for example, due to emergence of a flaw, collapse of infrastructure as a result of man-made or natural disaster, depletion of the physical resources required to build or run a given technology or product, the sudden imposition of regulatory controls or limitations, or the sudden and widespread loss of trust in a given technology. Such regressive disruptions could remove the affordances of a given technology from the workplace, requiring workers and businesses to get by without the tools to which they are accustomed or necessitating that human workers perform previously automated tasks that they may not have been trained to carry out. Other examples include large-scale disruption to the power grid, depletion of critical materials required for building microchips or other components, or loss of confidence due to a hacking takedown or other security incident with a pivotal software or service.

SUMMARY

Information technology will continue to transform the way we work as well as other aspects of our lives. To summarize,

- The impact of IT is pervasive and has already touched nearly all aspects of our personal and work lives. It has already eliminated and created jobs, but more frequently it has transformed jobs and the way they are performed. IT has transformed business practices as companies have moved routine operations online, where they can be better tracked and partly automated (e.g., supply chain management or customer relationship management). Similarly, it has transformed our personal lives as we have moved our calendars, mail, photographs, and shopping online, again opening up the feasibility of computer support for these core aspects of our lives, including a significant fraction of our social lives. It is beginning to change the nature of education, as video courses become increasingly available over the Internet, and is changing the nature of freelance work, as peer-to-peer networking allows just-in-time matching of customers to resource providers.
- Much of the impact of IT has been driven by *hardware* advances, especially the spread and use of the Internet and inexpensive computing power. Networking has moved from hard-wired to wireless at that same time that the Internet has spread worldwide. The Internet of Things refers to a recent trend in which many physical devices with sensors are increasingly communicating via the Internet, suggesting that we are moving toward a world in which the Internet serves as a worldwide communications network to connect a diverse array of people, institutions, and physical artifacts from buildings to vehicles. This underlying communications network of computing and sensing devices provides the substrate for rapid deployment of new technology. The sensors used in driverless

cars were impractically expensive a decade ago, yet today they are found in some video game consoles. Mobile phones have hastened rapid cost reductions in GPS chips, high-resolution compact cameras, motion sensors, and touch-sensitive and fingerprint-sensing hardware.

- The impact of IT is also largely driven by new *software* advances, especially in AI and machine learning. These software advances have provided reliable speech-recognition systems that are now used routinely on smartphones, image recognition systems capable of recognizing single individuals in photographs, and the first commercial self-driving cars. Machine learning algorithms are now mining the exploding volume of online data to capture regularities that enable them to automate or semi-automate many knowledge-intensive decisions, from deciding which credit card transactions to approve to deciding which X-ray images contain evidence of tumors. As increasing volumes of data and decisions come online, the potential applications of this technology will grow as well. These software advances are enabled and amplified by the hardware advances discussed in the previous paragraph.
- The impact of technology on the workforce follows from both the *invention* of new technologies and the *diffusion* and maturation of existing technologies. For example, although the Internet was invented and deployed decades ago, its impact continues to grow as it diffuses geographically around the globe and as its technology matures (e.g., augmenting early hard-wired Internet connections with wireless Internet connections). In seeking to anticipate future technology trends and their impact on the workforce, it is helpful to consider the likely diffusion and maturation of technologies that already exist in nascent form in research laboratories and forward-leaning companies (e.g., self-driving vehicles, which currently represent only a tiny fraction of vehicles on the road, are likely to diffuse and mature enough to have a significant impact on employment in the transportation sector).

3

Effects of Information Technology on Productivity, Employment, and Incomes

INTRODUCTION

In the next two chapters, the committee turns its focus to the interactions between technology and the economy. An overarching theme emerges: economic and societal changes occasioned by technological developments are shaped, not just by the availability of new technologies and their features, but also by ideologies, power structures, and human aspirations and agendas. Technologies are not exogenous forces that roll over societies like tsunamis with predetermined results. Rather, our skills, organizations, institutions, and values shape how we develop technologies and how we deploy them once created, along with their final impact.[1]

[1] For the impact of available skills and markets on the direction of technological changes, see D. Acemoglu, 1998, Why do new technologies complement skills? Directed technical change and wage inequality, *Quarterly Journal of Economics* 113(4):1055-1090; D. Acemoglu and P. Restrepo, 2016, "The Race Between Machine and Man: Implications of Technology for Growth, Factor Shares and Employment," No. w22252, National Bureau of Economic Research, Cambridge, Mass.; E. Brynjolfsson and A. McAfee, 2014, *The Second Machine Age: Work Progress, and Prosperity in a Time of Brilliant Technologies*, W.W. Norton, New York.

For the importance of complementarities in organizations, see E. Brynjolfsson and P. Milgrom, 2013, "Complementarity in organizations" in *The Handbook for Organization Economics* (R. Gibbons and J. Roberts, eds.), Princeton University Press. On how scarcity might spur innovation, see E. Boserup, 1981, *Population and Technological Change: A Study of Long-Term Trends*, University of Chicago Press, Chicago, Ill. For the impact of workplace organizations on technology, see E. Brynjolfsson and L. Hitt, 2000, Beyond computation: Information technology, organizational transformation and business performance, *Journal of Economic Perspectives* 14(4):23-48, and L. Hitt, S. Yang, and E. Brynjolfsson, 2002, Intangible assets:

In this chapter, the committee considers the current state of (1) productivity growth, (2) employment, and (3) income distribution. In each case, the role of technology is considered, recent changes are summarized, and some potential future developments are considered, building on the discussion in Chapter 2 of current and possible future trends in underlying technologies. The committee is keenly aware that making forecasts about social phenomena is perilous. Doing so with respect to the fast-changing and dynamic area of technology is even more challenging. Nevertheless, interpreting societal and economic responses to developments in technology can at least provide a framework for thinking about the future.

TECHNOLOGY AND PRODUCTIVITY

In his seminal research on economic growth, Robert Solow found that most of the increases in human living standards have come not from working more hours, and not from using more capital or other resources, but from improved productivity—that is, increases in the efficiency of production as defined by the ratio of output to input. In turn, productivity growth comes from new technologies and new techniques of production and distribution.[2] In the mid-1990s, the rate of productivity growth increased significantly in the United States, led by the IT-producing sectors as well as IT-using sectors, a change attributed in part to improvements in the nature and use of IT.[3] However, in the past 10 years, U.S. aggregate productivity growth has slowed, according to official statistics from U.S. government agencies. The slowdown preceded the 2008 Great Recession, suggesting that the recession is not the only explanation for

Computers and organizational capital, *Brookings Papers on Economic Activity* 1:137-199. On the influence of vested interests on blocking of technology, see J. Mokyr, 1990, *The Levers of Riches: Technological Creativity and Economic Progress*, Oxford University Press, Oxford, U.K. For the influence on macro institutions on technology, see D. Acemoglu and J.A Robinson, 2012, *Why Nations Fail: Origins of Power, Prosperity and Poverty*, Crown Publishing Group, Chicago, Ill.

[2] R.M. Solow, 1959, A contribution to the theory of economic growth, *Quarterly Journal of Economics* 70(1):65-94, doi: 10.2307/1884513.

[3] See D.W. Jorgenson, M.S. Ho, and K.J. Stiroh, 2002, Projecting productivity growth: Lessons from the U.S. growth resurgence, *Economic Review* Q3:1-13; S.D. Oliner, D.E. Sichel, and K.J. Stiroh, 2007, "Explaining a Productive Decade," Federal Reserve Board, https://www.federalreserve.gov/pubs/feds/2007/200763/200763pap.pdf; E. Brynjolfsson and L. Hitt, 1995, Computers as a factor of production: The role of differences among firms, *Economics of Innovation and New Technology* 3:183-199; and L. Hitt, S. Yang, and E. Brynjolfsson, 2002, Intangible assets: Computers and organizational capital, *Brookings Papers on Economic Activity* 1:137-199; K.J. Stiroh, 2002, "Reassessing the Impact of IT in the Production Function: A Meta-Analysis," Federal Reserve Bank of New York, http://www.nber.org/criw/papers/stiroh.pdf.

this trend, and has been largely accounted for by slowdowns in the IT-producing and IT-using sectors.[4]

In some ways, this slowdown in productivity growth is counter to the narrative of increasing advances and adoption of IT. The remainder of this section discusses open issues and questions as well as possible pathways for resolving them.

One hypothesis is that there is an increasing measurement problem in the official statistics on productivity. This has been a longstanding research challenge, recognized at least since Solow[5] and Griliches.[6] Griliches noted that the economy has been shifting increasingly to sectors where output and output quality are difficult to measure, such as government, health, and finance. Unlike counting bushels of wheat or tons of steel, outputs for medical treatment or bank loans are less standardized.[7] Measurement is also very challenging in sectors with rapid technological changes, such as the computer and software industries themselves. Output and productivity measurement require measuring output and input price deflators that reflect changes in quality, which is an enormous challenge. How does one compare a smartphone today with a mainframe from 20 years ago, let alone new apps that have no predecessors? Great progress was made in the 1990s and 2000s on improving price deflators for the hardware parts of IT,[8] but the software side has been more challenging. Recent evidence suggests that adoption of cloud computing and other changes are even making it more difficult to assess quality changes for hardware.[9]

A related, but more fundamental, issue is that productivity is neither a measure of technological progress nor welfare. Productivity is based on gross domestic product (GDP), which is in turn a measure of production or output. However, technological progress can increase welfare without increasing output. For instance, if Wikipedia replaces a paper encyclopedia or a free GPS mapping app replaces a stand-alone GPS device, then consumers can be better off even if output is stagnant or declining.[10]

[4] J.G. Fernald, 2014, Productivity and potential output before, during, and after the Great Recession, *NBER Macroeconomics Annual 2014*, Volume 29, doi: 10.3386/w20248.

[5] R.M. Solow, 1987, “We’d Better Watch Out,” *New York Times* book review, July 12, p. 36.

[6] Z. Griliches, 1994, Productivity, R&D, and the data constraint, *American Economic Review* 84(1):1-23.

[7] Ibid.

[8] See Bureau of Economic Analysis, 2000, “National Income and Wealth Division, Investment Branch” and “Computer Prices in the National Accounts,” April.

[9] D.M. Byrne, S.D. Oliner, and D.E. Sichel, 2015, “How Fast are Semiconductor Prices Falling?,” NBER Working Papers 21074, National Bureau of Economic Research, April, doi: 10.3386/w21074.

[10] E. Brynjolfsson, A. McAfee, and M. Spence, 2014,”New World Order: Labor, Capital, and Ideas in the Power Law Economy,” *Foreign Affairs*, https://www.foreignaffairs.com/articles/united-states/2014-06-04/new-world-order; E. Brynjolfsson and J.H. Oh, 2012, “The

Under this view, gains would show up in broader measures of economic well-being but not in GDP (and in turn not in official productivity statistics). While these measurement issues remain an active area of study, the most recent research suggests that at most only a small fraction of the productivity slowdown can be attributed to measurement problems.[11]

Another hypothesis is that the reported slowdown in productivity growth in the IT-producing and IT-using sectors is temporary. Brynjolfsson and Hitt found evidence that the productivity benefits of large enterprise systems took up to 7 years to be fully realized, as significant organizational and process changes were typically required to make full use of accompanying software and hardware investments.[12] The diffusion and adoption of technologies is time- and resource-intensive and requires much experimentation, with failures and variable time lags along the way. Building on work by Paul David, Syverson discussed the slowdown in productivity growth in the historical context of electrification of the production process at the end of the 19th century.[13] He argues that the impact of electrification on productivity came in two distinct waves. The first wave arrived quickly and reflected the adoption of electrification within the existing organization of production. The second wave, delayed by a few decades, reflected new ways of organizing production around this new technology. Achieving the full productivity benefits and impacts of new technology can take decades and may require complementary "co-inventions" of new business practices, infrastructure, and so on, which can dramatically influence the size and distribution of gains from technology and the nature of its societal effects. Similarly, while the first power looms allowed weavers to produce 2.5 times as much cloth per hour, further improvements in the following 80 years in knowledge and skills increased output per hour 80-fold.[14] For IT, the value of intan-

Attention Economy: Measuring the Value of Free Digital Services on the Internet," in *Proceedings of the International Conference on Information Systems*, December.

[11] D.M. Byrne, J.G. Fernald, and M.B. Reinsdorf, 2016, Does the United States have a productivity slowdown or a measurement problem?, *Brookings Papers on Economic Activity* (forthcoming); C. Syverson, 2016, "Challenges to Mismeasurement Explanations for the U.S. Productivity Slowdown," mimeo.

[12] See E. Brynjolfsson and L.M. Hitt, 2003, Computing productivity: Firm-level evidence, *Review of Economics and Statistics* 85.4: 93-808. See also T.F. Bresnahan, E. Brynjolfsson, and L. Hitt, 2002, IT, workplace organization and the demand for skilled labor: A firm-level analysis, *Quarterly Journal of Economics* 117(1): 339-376, doi: 10.1162/003355302753399526.

[13] C. Syverson, 2013, "Will history repeat itself? Comments on 'Is the Information Technology Revolution Over?' *International Productivity Monitor* 25:20-36. See also P.A. David, 1990, The dynamo and the computer: An historical perspective on the modern productivity paradox, *American Economic Review* 80(2):355-61.

[14] J. Bessen, 2015, *Learning By Doing: The Real Connection Between Innovation, Wages and Wealth*, Yale University Press, New Haven, Conn.

gible complements of computer hardware, including changes in business processes and human capital, can have a value 10 times greater than the direct costs of computer hardware, but they also are costly and time-consuming to invent and implement.[15]

In a related manner, there is evidence that adopting new technologies requires organizational changes and restructuring of business practices that take time.[16] For instance, it is easy to imagine significant benefits, eventually, from the widespread digitization of patient data, yet many physicians complain that the adoption process for electronic medical records is slow and cumbersome, with current costs exceeding current benefits.

This perspective may help reconcile the observation of the apparently rapid changes in technology outlined in Chapter 2 with the current sluggish growth in productivity. Yet there are more pessimistic views about the prospects for productivity and economic growth. Some have suggested that recent (post-2000) innovations in information and other advanced technology simply do not have the same high payoff as innovations in earlier periods. The argument is that earlier innovations were in the form of general purpose technologies that had wide application to many industries.[17] Alternatively, some have argued that we are in a period of secular stagnation due to weak aggregate demand.[18] The suggestion is that persistently weak aggregate demand is acting as an overall drag on economic growth.

Firm-level evidence for the United States and the Organisation for Economic Co-operation and Development shows a widening gap between the most and least productive firms within industries in the post-2000 period.[19] Such widening productivity dispersion may reflect increased

[15] E. Brynjolfsson and L.M. Hitt, 2000, Beyond computation: Information technology, organizational transformation and business performance, *Journal of Economic Perspectives* 14(4):23-48; E. Brynjolfsson and L.M. Hitt, 2003, Computing productivity: Firm-level evidence, *Review of Economics and Statistics* 85(4):793-808.

[16] L. Hitt, S. Yang, and E. Brynjolfsson, 2002, Intangible assets: Computers and organizational capital, *Brookings Papers on Economic Activity* 1:137-199.

[17] R. Gordon, 2016, *The Rise and Fall of American Growth: The U.S. Standard of Living Since the Civil War*, Princeton University Press, Princeton, N.J.

[18] L. Summers, 2016, "The Age of Secular Stagnation," *Foreign Affairs*, https://www.foreignaffairs.com/articles/united-states/2016-02-15/age-secular-stagnation.

[19] D. Andrews, C. Crisculo, and P.N. Gal, 2016, "The global productivity slowdown, technology divergence, and public policy: A firm level perspective," Brookings, https://www.brookings.edu/research/the-global-productivity-slowdown-technology-divergence/, and R.A. Decker, J. Haltiwanger, R.S. Jarmin, and J. Miranda, 2016, "Declining Business Dynamism: Implications for Productivity?," Hutchins Center Working Papers presented at Brookings Conference on Slow Growth in Productivity: Causes, Consequences, and Policies, September 2016.

frictions or distortions in the economy (e.g., dampened competition) slowing down the diffusion process or the pace of business dynamism that is critical for moving resources to the more productive firms. The latter has been shown to be an important part of the process of productivity growth, and is discussed further in Chapter 4. From this perspective, the hypothesis is that while the changes in technology outlined in Chapter 2 are indeed occurring, they are slow to show up in economic growth due to slowing diffusion or business dynamism.

All of these hypotheses are active areas of research. The discussion of future research directions in Chapter 6 emphasizes the significance of exploring such critically important questions. It is useful to note that future productivity growth cannot be predicted simply by extrapolating past trends because there is little serial correlation in growth rates from one decade to the next. Instead, future trends will depend on the invention and deployment of new and improved technologies and on the co-inventions by the workforce, organizations, and institutions needed to effectively use them.

TECHNOLOGY AND EMPLOYMENT

Employment in Recent Years

In the past few years, U.S. employment growth has been fairly robust, with accompanying drops in unemployment. For instance, by early 2016, the unemployment rate fell below 5 percent. However, much of this employment growth can be interpreted as a recovery from the Great Recession, which has been slow despite the fact that it officially ended in 2009. Furthermore, jobs lost in the recession are very different from those that appeared during the recovery.[20] While many opportunities continue to be created in fields that do not require a bachelor's degree, the fastest-growing occupational categories all require a bachelor's degree or better, and occupations that require a bachelor's degree are growing at twice the rate of those that do not.[21,22]

There have also been substantial shifts in employment in various occupational categories. For instance, the employment rate in clerical and

[20] A.P. Carnevale, T. Jayasundera, and A. Gulish, 2015, "Good Jobs Are Back: College Graduates Are First in Line," Georgetown University: Center on Education and the Workforce, https://cew.georgetown.edu/wp-content/uploads/Good-Jobs_Full_Final.pdf.

[21] Ibid.

[22] A.P. Carnevale, N. Smith, and J. Strohl, 2010, "Help Wanted, Projections of Jobs and Education Requirements Through 2018," Georgetown University: Center on Education and the Workforce, https://cew.georgetown.edu/wp-content/uploads/2014/12/HelpWanted.ExecutiveSummary.pdf.

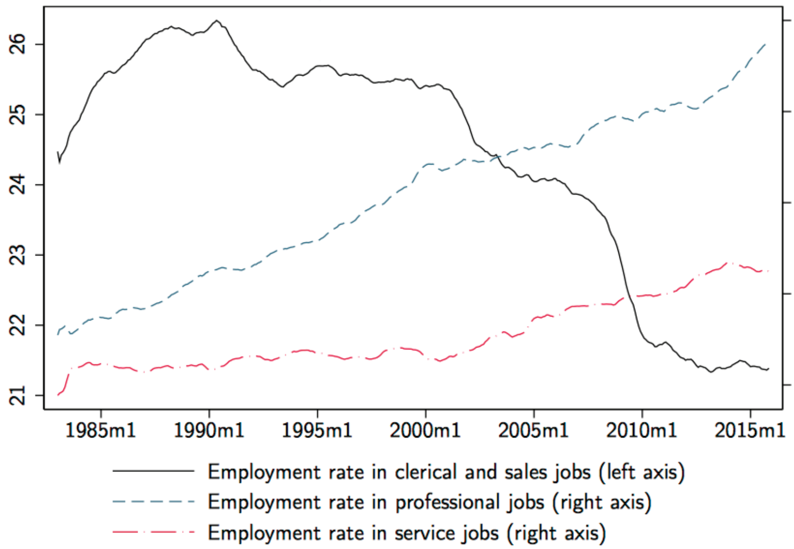


FIGURE 3.1 U.S. employment rates for different occupational categories. SOURCE: P. Restrepo, 2015, "Skill Mismatch and Structural Unemployment," Massachusetts Institute of Technology, http://pascual.scripts.mit.edu/research/01/PR_jmp.pdf. Courtesy of Pascual Restrepo.

sales jobs has fallen sharply, while employment in professional jobs has grown, as shown in Figure 3.1.[23]

Despite the low unemployment rate, the overall U.S. employment rate (the employment-to-population ratio) remains near a 20-year low. The overall U.S. employment rate exhibited an upward trend through 2000, mostly driven by an increased participation of women in the workforce. It began to decline in the post-2000 period, with a sharp drop during the 2008 Great Recession, from which it has recovered slightly. Some of this trend can be accounted for by the aging of the population. However, declines in the employment rate are especially large for young and less educated individuals. Employment rates of prime age (25-54 year-old) males are still low (84 percent in 2014, near the 50-year low of 81 percent in 2010, as compared to a high of 95 percent in 1967, according to the

[23] P. Restrepo, 2015, "Skill Mismatch and Structural Unemployment," Massachusetts Institute of Technology, http://pascual.scripts.mit.edu/research/01/PR_jmp.pdf.

annual averages from the Bureau of Labor Statistics).[24] This highlights that the overall decline cannot be accounted for simply by the aging of the U.S. population.[25,26] While both globalization and technology are seen as important factors, many economists view automation as the single most important factor. For instance, Larry Katz, an expert on labor studies and editor of the *Quarterly Journal of Economics* has said, "Over the long haul, clearly automation's been much more important—it's not even close."[27]

Among young and less educated workers, the declines have also been especially sharp for certain race/ethnicity groups (especially non-Hispanic blacks). In addition, almost a third of all the unemployed in 2014 were classified as "long term unemployed" (i.e., out of the job market for more than 27 weeks), and many eventually become "discouraged workers," people that drop out of the market for employment entirely.[28] Such patterns are of particular concern in the context of this report, since it is these most vulnerable groups that may be left behind by ongoing changes in technology.

Future Prospects for Technology and Employment

Predictions that new technologies will make workers largely or almost entirely redundant are as old as technological change itself. Although the story might be apocryphal, the famous Roman historian Pliny the Elder recounts how the Roman Emperor Tiberius killed an inventor who had supposedly invented unbreakable glass for fear of what this would do to the glassmaking trade. Queen Elizabeth I similarly refused to grant William Lee a patent for his mechanical knitting machine, arguing, "Consider thou what the invention could do to my poor subjects."[29]

It is not only emperors and queens who have feared the implications of new technologies for employment. More famously, British textile workers

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[24] Organization for Economic Co-operation and Development, "Employment Rate: Aged 25-54: Males for the United States," retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/LREM25MAUSA156S, March 15, 2017.

[25] S.J. Davis and J. Haltiwanger, 2014, "Labor Market Fluidity and Economic Performance," University of Chicago and NBER, and University of Maryland and NBER, http://faculty.chicagobooth.edu/steven.davis/pdf/LaborFluidityandEconomicPerformance26November2014.pdf.

[26] S.A. Donovan, "2015, An Overview of the Employment-Population Ratio," Congressional Research Service, May 27, https://www.fas.org/sgp/crs/misc/R44055.pdf.

[27] As quoted in Claire Cain Miller, "The Long Term Job-Killer Is Not China: It's Automation," *The New York Times*, December 21, 2016, https://www.nytimes.com/2016/12/21/upshot/the-long-term-jobs-killer-is-not-china-its-automation.html.

[28] K. Kosanovich and E. Theodossiou Sherman, 2015, "Trends In Long-term Unemployment," Bureau of Labor Statistics, http://digitalcommons.ilr.cornell.edu/key_workplace/1399/.

[29] M. Finley, 1973, *The Ancient Economy*, University of California Press, Berkeley, Calif.; D. Acemoglu and J. Robinson, 2011, *Why Nations Fail*, Crown, New York.

in the early 19th century, known as Luddites, fearing that the new automation coming with power looms, stocking frames, and spinning frames were threatening to replace their expert positions with low-wage laborers, destroyed machines and burned the house of John Kay, the inventor of the "flying shuttle." In an attempt to halt destructive acts, the British Parliament enacted a law making "machine breaking" a capital offense.[30]

More recently, the economist John Maynard Keynes predicted that the introduction of new technologies would create considerable wealth but would also generate widespread technological unemployment as machines replaced humans. In 1930, he predicted that the work week would fall to 15 hours and that the "economic problem" of providing for basic needs would be solved.[31] Economic historian Robert Heilbroner similarly predicted in 1965: "As machines continue to invade society, duplicating greater and greater numbers of social tasks, it is human labor itself—at least, as we now think of `labor'—that is gradually rendered redundant."[32] Nobel Prize winner Wassily Leontief saw an analogy between human labor and horses of the early 20th century, and in 1952 predicted that humans will follow horses in becoming redundant: "Labor will become less and less important. . . . More and more workers will be replaced by machines. I do not see that new industries can employ everybody who wants a job."[33,34]

However, predictions of widespread, technologically induced unemployment have not come to pass, at least so far.[35] Technological changes over the last 200 years (and presumably many of those that came before) stimulated demand, created new markets, and fueled wage growth with few adverse consequences for aggregate employment. To be sure, technologies did and will continue to decimate particular occupations. As the Luddites feared, artisans lost their jobs in spinning and then weaving as new technologies automated tasks they had previously performed.

[30] K.E. Lommerud, F. Meland, and O.R. Straume, Globalisation and union opposition to technological change, *Journal of International Economics* 68(1):1-23, 2006.

[31] J.M. Keynes, 1933, "Economic Possibilities for Our Grandchildren (1930)," pp. 358-373 in *Essays in Persuasion*, W.W. Norton & Company, New York.

[32] R.L. Heilbroner, 1965, Men and machines in perspective, *National Affairs*, Fall, pp. 27-36.

[33] W. Leontief, 1952, Machines and man, *Scientific American* 87(3):150-160. For a more recent perspective on this questions, see E. Brynjolfsson and A. McAfee, 2015, "Will Humans Go the Way of Horses?," *Foreign Affairs* (July/August), pp. 8-14.

[34] Acemoglu and Restropo, 2016, "The Race Between Machine and Man."

[35] We do note, however, that the length of the workweek has dropped significantly since the 1800s, when a workweek of longer than 70 hours was not uncommon. For more discussion of this point, see Economic History Association, "Hours of Work in U.S. History," EH.net, https://eh.net/encyclopedia/hours-of-work-in-u-s-history/, and R.J. Gordon, 2016, *The Rise and Fall of American Growth: The US Standard of Living Since the Civil War*, Princeton University Press, Princeton, N.J.

Similarly, the replacement of horses by automobiles eliminated the need for blacksmiths. But as these jobs disappeared, new ones sprang up to operate, manage, and service the new technologies. For instance, in the late 1800s, the replacement of the stagecoach by the railroad went hand in hand with the creation of new work for managers, engineers, machinists, repairmen, and conductors. Simultaneously, there was a boom in a range of new service occupations, from teaching to entertainment to sales.[36]

Nonetheless, simultaneous automation of a broader range of tasks could create unemployment or perhaps reduce aggregate levels of employment for an extended period of time. As noted in the previous section, over the past 20 years, the share of people working—the employment-to-population ratio—has declined. While there are many factors at work, it is possible that technological substitution for certain types of labor is part of the explanation. As compensation falls for tasks that can increasingly be done by machines, some people may choose to work less or not at all, finding other alternatives, including increased leisure or family time, applying for disability benefits, or investing in education, to become relatively more attractive. Over the longer term, there may be a continuation of the long-term decline in the share of hours worked as society as a whole becomes wealthier and leisure becomes relatively more attractive.

What happens depends, in part, on whether new technologies automate and replace workers in existing tasks more rapidly than they create new demands for labor. Which will be the case is difficult to answer, because it is easier to see how new technologies coming down the line will automate existing tasks than it is to imagine tasks that do not yet exist and how new technologies may stimulate greater consumer demand. Further, the future of employment is not only a question of the availability or necessity of tasks to be performed, but how they are organized, compensated, and more generally valued by society. These are matters of business strategy, social organization, and political choices and not simply driven by technologies themselves.

Consider self-driving cars. In principle, driving and delivery occupations could be automated with the use of such technologies over the next several decades. Visions of a future with fully automated vehicles have captured many people's imagination. However, there are numerous social and cultural as well as technological roadblocks to such an outcome. These include such factors as consumer trust; the fact that there will be a long period of mixed-use road use, with both autonomous driving and manual driving cars sharing the roads; and the infrastructure require-

[36] Acemoglu and Restrepo also provide evidence that there is a large contribution of new occupations to employment growth in the last three decades: Acemoglu and Restrepo, 2016, "The Race Between Machine and Man."

ments needed to expand usage and performance of self-driving cars. It is possible that ongoing development of these technologies, including infrastructure, will create more jobs than are lost in the wake of self-driving vehicles, but it is likely that the skills required for such jobs will be quite different from those currently possessed by today's truckers and taxi drivers. The new jobs are likely to rely more heavily on analytic, cognitive, and technical skills. Indeed, even in the near term, as self-driving technologies are being developed, the occupation of trucking[37] is likely to be transformed. For example, additional IT-based capabilities for driver simulation training can help improve the skill sets of more drivers than would be possible otherwise. In the longer term, increased automation will reduce the need for additional drivers and ultimately reduce overall demand for truck drivers. "Platooning," where a single lead vehicle driven by a driver is followed by a string of other self-driving vehicles, is already emerging as a viable technology for highway driving and can affect employment numbers. As transportation costs drop due to partial automation, it is possible that lower per-unit costs will lead to increased demand (e.g., for more delivery services), resulting in a partially counteracting force in the opposite direction toward increased demand for drivers. Self-driving cars also offer a good illustration of the variable and mixed impact of technology on employment, as well as the long and often uneven march of technology development, which complicates the ability to make accurate long-term projections.

In addition to eliminating some jobs while creating others, technological developments can create new occupations without reducing employment in older occupations. New medical imaging technologies are a case in point. Prior to the development of computer-controlled imaging modalities such as ultrasound, computed tomography scanners, and magnetic resonance imaging, most technicians who worked in radiology departments operated standard X-ray machines and fluoroscopes. The jobs associated with these technologies were not significantly altered by the arrival of digital imaging. Instead, new technicians' occupations arose: the sonographer, the computed tomography technologist, and the MRI technologist as well as the technicians' occupations who service such machines. Thus, in the case of medical imaging, the overall number

[37] Truck driving remains a significant source of employment and middle-class jobs in the United States. In fact, according to a recent analysis by NPR, in 2014, "truck, delivery, and tractor drivers" were the most common occupational category in 29 states, see Q. Bui, 2015, "Map: The Most Common Job in Every State," NPR, http://www.npr.org/sections/money/2015/02/05/382664837/map-the-most-common-job-in-every-state. See also T. Reddy, 2007, "Fleets Eye Safety Gains to Cut Insurance Costs," *Transport Topics*, http://www.ttnews.com/articles/printopt.aspx?storyid=17563, for figures on truck driver hiring and claims of inability to fill positions.

of occupations, and hence people employed as technicians, expanded. Furthermore, with the march of technology, both in terms of advances in imaging and with developments at the intersection of imaging and other areas of biomedical engineering, radiologists began to specialize in particular imaging modalities and in whole new radiology subdisciplines such as "interventional radiology," extending the range of opportunities for careers within radiology and increasing the need for radiologists.[38]

Nonetheless, technologies can also have an impact on how tasks are allocated and how job categories and tasks associated with particular organizational forms and structures are designed. For instance, they can shift the allocation of tasks across occupations such that some occupations contract as the work they once performed is shifted onto members of other occupations.[39] An instructive example is the advent of word processing technologies and online databases in the context of a typical academic department in the university. As recently as the 1980s, administrative assistants answered phones, interacted with students, kept paper records of accounts, filed documents, and typed letters, memos, and manuscripts for faculty (who often wrote first drafts by hand). Today, administrative assistants continue to answer phones and interact with students, but few type documents for faculty. Professors now use a computer to create and revise their own documents. Some faculty also enter their own data on travel expenses and other activities directly into databases, tasks previously performed by administrative assistants. These and other changes removed certain tasks from administrative assistants and transferred them to faculty, which can be viewed as an instance of "disintermediation."[40] Because of the increased efficiency of producing and storing documents and because faculty have assumed the task of producing documents, universities now employ fewer administrative assistants, and some of those who remain have acquired new skills and tasks, such as the maintenance

[38] S.R Barley, 1986, Technology as an occasion for structuring: Evidence From observations of CT scanners and the social order of radiology departments, *Administrative Science Quarterly* 31:78-108; S.R Barley, 1990, The alignment of technology and structure through roles and networks, *Administrative Science Quarterly* 35:61-103.

[39] J. Bessen, 2015, "How Computer Automation Affects Occupations: Technology, Jobs and Skills," Law and Economics Working Paper No. 15-49, Boston University School of Law, Boston, Mass.

[40] Disintermediation refers to the elimination tasks or people in a supply chain or work flow because the tasks are now done by someone positioned earlier in the work flow (R. Benjamin and R. Wigand, 1995, Electronic markets and virtual value chains on the information superhighway, *Sloan Management Review* 36:62-67; A.M. Chircu and R.J. Kauffman, 1999, Strategies for Internet middlemen in the intermediation/disintermediation/reintermediation cycle, *Electronic Markets* 9(1-2):109-117; U. Schultze and W.J. Orlikowski, 2004, A practice perspective on technology-mediated network relations: The use of Internet-based self-serve technologies, *Information Systems Research* 5(1):87-106.

of websites. As noted in Chapter 2, jobs involving physical labor will be increasingly affected by advances in robotics, although there is debate about the timeline.[41]

The committee notes that the effects of technologies on employment can be shaped by interests and social dynamics beyond merely the technological dimension. For example, computer-mediated communications, especially those facilitated by the Web, such as e-mail, computer teleconferencing, and the ability to easily and almost instantaneously transfer documents of all kinds across space (and hence time zones), were initially thought of as simply more efficient ways to communicate. But because these technologies did not require co-location, companies began using such technologies to both outsource and offshore a variety of tasks and even jobs, ranging from clerical to engineering work. There is nothing about computer-mediated communication technologies that preordained such developments. Instead, they are the result of choices (strategic or otherwise) by decision makers in organizations about how the technologies would be deployed and what they would be used to achieve, along with market forces encouraging the adoption of cost-efficient processes. Choices regarding the development of technologies can also be influenced by the same interests and social dynamics. For example, it has been suggested that the decision to develop technologies that automate rather than augment the human role in the machine tool industry was driven by the combined interests of the U.S. Air Force and the Massachusetts Institute of Technology servomechanisms laboratory.[42]

Human Skills Versus Automation

Consideration of whether technology can replace human workers has prompted discussion about the subtle complexity of human skills. A recent paper[43] by economist David Autor invoked the philosopher Michael Polanyi: "We can know more than we can tell. . . . The skill of a driver cannot be replaced by a thorough schooling in the theory of the motorcar; the knowledge I have of my own body differs altogether from

[41] Bill Gates predicted in 2016 that for "pure labor substitution for jobs that are largely physical and visual manipulation—driving, security guard, warehouse work, waiter, maid, that threshold—I don't think you'd get much disagreement that over the next 15 years the robotic equivalents in terms of cost, in terms of reliability, will become a substitute to those activities" (E. Klein, 2016, "Bill Gates: The Energy Breakthrough That Will 'Save Our Planet' Is Less Than 15 Years Away," *Vox*, last updated February, http://www.vox.com/2016/2/24/11100702/bill-gates-energy).

[42] D.F. Noble, 1984, *Forces of Production*, Transaction Publishers Piscataway, N.J.

[43] D. Autor, 2014, "Polanyi's Paradox and the Shape of Employment Growth," Working Paper 20485, National Bureau of Economic Research, Cambridge, Mass.

the knowledge of its physiology."[44] This phenomenon, that tacit knowledge often is greater than explicit cognition, is referred to as Polanyi's Paradox. Currently, computational systems are far from being able to use creativity, intuition, persuasion, and imaginative problem solving, or to coordinate and lead teams. Autor and others have argued that many highly valued and important human capabilities may never be automated.[45] As technology becomes more sophisticated and encapsulated, managing human interfaces may become the dominant component of more and more jobs; there is already evidence that social skills are in increasing demand and valued in the labor market.[46] For instance, while drivers for a ride-sharing service do not need to be experts on the internal combustion engine or smartphone to do their jobs, they do need reasonably good interpersonal skills to be successful in this era of online ratings. Educational programs, even those in vocational disciplines like business and engineering, may need to add interpersonal and creative skills to their mix of hard analytical skills.

The resistance to automating multiple dimensions of human intellect and of the "presence" and leadership of people suggests that there will likely be enduring market value for traits and factors that are uniquely human, as only humans will be able to perform certain types of work for the foreseeable future, if not forever. To what extent are these human attributes, including creativity, empathy, interpersonal skills, leadership, mentoring, and physical presence currently valued in the U.S. labor force, and how will these uniquely human capabilities be valued in the U.S. labor force in the future? A number of these uniquely human attributes include cognitive and "noncognitive" skills. On the other hand, recent improvements in machine learning have enabled significant technical advances in, for example, the field of self-driving cars, suggesting that even Polanyi's archetypal example of driving a motorcar is not immune to automation. The rapidly growing attendance at research conferences on artificial intelligence (AI), like the annual Neural Information Processing Systems and Association for the Advancement of Artificial Intelligence conferences, demonstrates that an increasing number of researchers are attempting to address these challenges, and most of them now focus on approaches that enable machines to learn how to do tasks, from recognizing and labeling objects to understanding speech, improving dexterity and mobility, and mastering increasingly complex games and puzzles.

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[44] M. Polanyi and A. Sen, 2009, *The Tacit Dimension*, University of Chicago Press, Chicago, Ill.

[45] D.H. Autor, 2015, Why are there still so many jobs? The history and future of workplace automation, *Journal of Economic Perspectives* 29(3):3-30.

[46] D.J. Deming, 2015, "The Growing Importance of Social Skills in the Labor Market," *National Bureau of Economic Research*, doi: 10.3386/w21473.

INEQUALITY AND DISTRIBUTION OF INCOME AND WEALTH

Income and Wealth Distribution in Recent Years

It is generally understood that, by increasing productivity, IT will tend to increase overall income—although without a guarantee that these gains will be evenly distributed. Furthermore, while it is common to focus on average levels of income and income growth, the distribution of those gains can also have an effect on well-being. This is true not only because absolute levels directly affect the quality of life of particular groups, but also because broad perceptions of unfairness can have a negative psychological impact, and inequality can contribute to sociopolitical tensions.

Since the mid-1970s, the United States has experienced significant growth in inequality in both income and wealth. This is the subject of a large amount of literature and has been documented in great detail by Acemoglu, Autor, Katz, Piketty, Saez, and many others.[47] One aspect of this is the growing dispersion between productivity growth and median worker compensation, as most of the income growth went to the top of the income distribution. Over the past several decades, IT and automation have been a significant driver of this increase in inequality, although there are also other forces at work.

Much popular attention has been focused on the rising share of income of the top 1 percent of each of these distributions. While this increase has been substantial, with the share of income accruing to the top 1 percent of households increasing from about 10 percent to over 20 percent between 1980 and 2012, there have also been increases in earnings inequality within the other 99 percent, accounted for largely by the increasing skills premium associated with a 4-year college degree. For example, the absolute median earnings gap between those with a high school and a college degree approximately doubled from 1980 to 2012, as the real wages of college graduates rose and those of less educated workers fell through about 2000.[48]

A related phenomenon is the falling share of GDP paid to labor relative to owners of capital (illustrated in Figure 3.5).[49] This trend affects not only income, but also wealth (to which an individual's income contributes

[47] For reviews, see, for example, D.H. Autor, L.F. Katz, and M.S. Kearney, 2008, Trends in US wage inequality: Revising the revisionists, *Review of Economics and Statistics* 90.2:300-323; T. Piketty, 2014, *Capital in the Twenty-First Century*, Harvard University, Cambridge, Mass.; and T. Piketty and E. Saez, 2013, Top incomes and the Great Recession: Recent evolutions and policy implications, *IMF Economic Review* 51 (3):456-478, doi: 10.1057/imfer.2013.14.

[48] D.H. Autor, 2014, Skills, education, and the rise of earnings inequality among the 'other 99 percent,' *Science* 344(6186):843-851.

[49] L. Karabarbounis and B. Neiman, 2013, The global decline of the labor share, *Quarterly Journal of Economics* 128(1):61-103, doi: 10.3386/w19136.

over time). It suggests that trends in income are increasingly favoring those who have already accrued wealth. This decline in the labor share of GDP, if sustained, will affect the distribution of wealth as well as that of income, expanding the share of total income flowing to wealth holders.[50]

Many factors are likely at work in this landscape of inequality; technological change, social biases, increased globalization and trade, the decline in labor union density and power,[51] declines in the real minimum wage, changing norms regarding executive compensation, growing economic deregulation, changes in tax rates, and growing oligopoly—or in some cases, simple monopoly[52]—are among the hypothesized causes of increased inequality of income and wealth over the past 40 years.[53] However, for the purposes of this study, the committee focuses on the role of technology in income and wealth distributions.

As with employment, the case that technological advances have contributed to wage inequality is strong. For most of the 20th century, real median incomes—incomes of people at the 50th percentile—grew at least as fast as overall real GDP per person, suggesting that the benefits of improved technological progress were widely shared. But since the late 1970s, productivity and GDP per person have continued to grow, while median incomes have stagnated (illustrated in Figure 3.2), reflecting growing income inequality over a period of significant technological change.

There is a debate in the research literature, and indeed, among committee members, about how much of the increase in inequality should be attributed to technology. There are three prominent narratives implicating technological change as a force toward greater inequality over the last several decades. First, many new technologies have replaced labor-intensive, routine, and physical tasks and expanded demand for labor in jobs that require social skills, numeracy, abstract thinking, and flexibility.[54] This shift is often said to be responsible for higher returns to a college education and the widening income gap between skilled and less

[50] For this and other statistics on wealth inequality, see E.N. Wolff, 2012, *The Asset Price Meltdown and the Wealth of the Middle Class*, New York University, New York; A.B. Atkinson, T. Piketty, and E Saez, 2011, Top incomes in the long run of history, *Journal of Economic Literature* 49.1:3-71; and T. Piketty, 2014, *Capital in the Twenty-First Century*, Harvard University, Cambridge, Mass.

[51] See, for example, B. Western and J. Rosenfeld, 2011, Unions, norms, and the rise in US wage inequality, *American Sociological Review* 76(4):513-537, doi: 10.1177/0003122411414817.

[52] J. Furman and P. Orszag, 2015, "A firm level perspective on the role of rents in the rise of inequality," White House, https://www.whitehouse.gov/sites/default/files/page/files/20151016_firm_level_perspective_on_role_of_rents_in_inequality.pdf.

[53] See T. Piketty, *Capital in the Twenty-First Century*, Harvard University, Cambridge, Mass, p. 70.

[54] See, for example, D.J. Deming, 2015, "The Growing Importance of Social Skills in the Labor Market," National Bureau of Economic Research, doi: 10.3386/w21473.

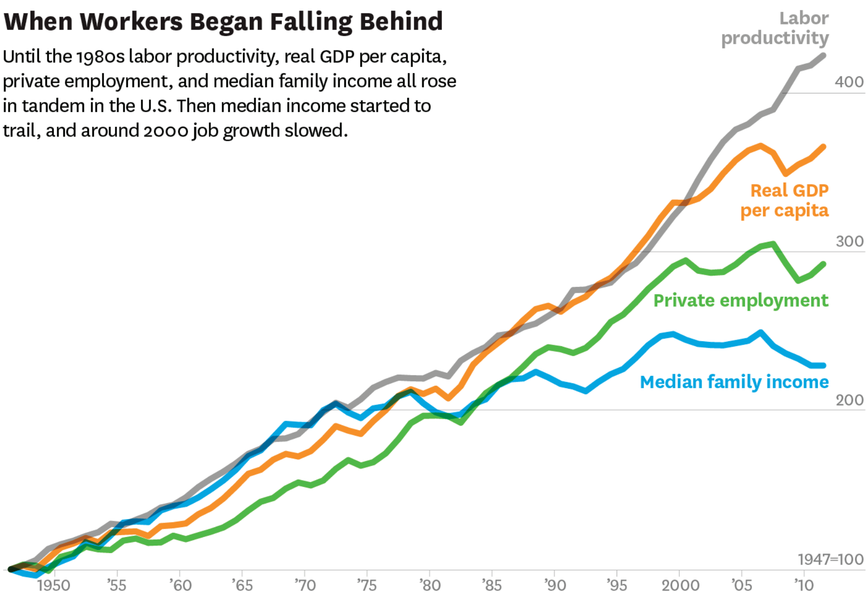

FIGURE 3.2 The decoupling of productivity from GDP per person, employment, and median income. SOURCE: E. Brynjolfsson, and A. McAfee, "Why the Middle Class is Shrinking," *Harvard Business Review,* November 5, 2015, https://hbr.org/video/4598665579001/why-the-middle-class-is-shrinking, accessed April 2016. Data from the Federal Reserve Bank of St. Louis.

skilled workers. Second, as labor-intensive tasks are automated, the share of income going to capital relative to labor can increase, which may also help to explain the falling share of labor in overall GDP (as illustrated in Figure 3.5) both in the United States and abroad. Third, improvements in communication technologies have contributed to what has been termed the "superstar phenomenon" whereby the most successful performers in any occupation can now command a larger share of the global market. This in part reflects their improved ability to sell to not only customers in local markets, but also with greater ease to those in regional, national, and even global markets as improved communications technologies reduce the costs of reaching a broader audience.[55] Geography and consumer ignorance have become less important as barriers to entry, making it

[55] D. Coyle, 1997, "Rich man, poor man, superstar," *Independent*, http://www.independent.co.uk/news/business/rich-man-poor-man-superstar-1271342.html; S. Rosen, The economics of superstars, *The American Economic Review* 71(5):845-858, 1981.

easier for sellers with a superior product to gain a dominant market share.[56] This phenomenon is also sometimes said to explain the growing proportion of the national income garnered by the top 1 percent of the wage distribution.[57]

Changes in IT also seem to be playing a role in the changing demand for skills and the earnings inequality for the other 99 percent. Technology can be a complement for highly skilled workers, as well as a substitute for low- or medium-skill workers. This is often called the skill-biased technological change hypothesis.[58,59,60] When new technologies have different skill requirements than older ones, they tend to favor the hiring of workers possessing these skills. Unless supply changes sufficiently, this will shift wages in favor of the more skilled group.[61] In recent decades, the impact of IT has been uneven across the skill distribution.[62] Since the 1970s, males with graduate or college education have seen their wages grow, while those with a high school education or less have seen falling wages[63] (see Figure 3.3). It has been suggested that this divergence is exacerbated by an increasing reliance on technology in the workplace, as the skills required to work with these technologies are more readily

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[56] E. Brynjolfsson, Y.J. Hu, and M.S. Rahman, Competing in the age of omnichannel retailing, *MIT Sloan Management Review* 54(4):23, 2013.

[57] See, for example, E. Brynjolfsson and A. McAfee, 2014, *The Second Machine Age*, W.W. Norton & Company, New York.

[58] D. Card and J.E. DiNardo, 2002, Skill-biased change and rising wage inequality: Some problems and puzzles, *Journal of Labor Economics* 20:4, doi: 10.3386/w8769.

[59] D.H. Autor, L.F. Katz, and M.S. Kearney, 2008, Trends in U.S. wage inequality: Revising the revisionists, *Review of Economics and Statistics* 90(2):300-323.

[60] C. Goldin and L.F. Katz, 2007, "The Race between Education and Technology: The Evolution of U.S. Educational Wage Differentials, 1890 to 2005," National Bureau of Economics, doi: 10.3386/w12984.

[61] This perspective is different than the common claim that new technologies *always* create inequality. In fact, many new technologies of the 19th century automated previously skilled occupations and expanded unskilled assembly work which paid lower wages than the prior forms of work. For instance, the Luddites may have been misguided in their tactics of smashing mechanical spinning and weaving machines, but they were right that the way these machines were used was bad news for them: relatively highly paid textile workers were gradually replaced by machines and less well paid machine tenders. In general, if there is a mismatch between the skills of the workforce and the skill requirements of new technologies, changes in the structure of pay will tend to follow.

[62] World Economic Forum, Global Agenda Council on Employment, 2014, "Matching Skills and Labour Market Needs: Building Social Partnerships for Better Skills and Better Jobs," http://www3.weforum.org/docs/GAC/2014/WEF_GAC_Employment_MatchingSkillsLabourMarket_Report_2014.pdf.

[63] D.H. Autor, L.F. Katz, and M.S. Kearney, 2008, Trends in U.S. wage inequality: Revising the revisionists, *Review of Economics and Statistics* 90(2):300-323; D.H. Autor, 2014, Skills, education, and the rise of earnings inequality among the 'other 99 percent,' *Science* 344(6186):843-851.

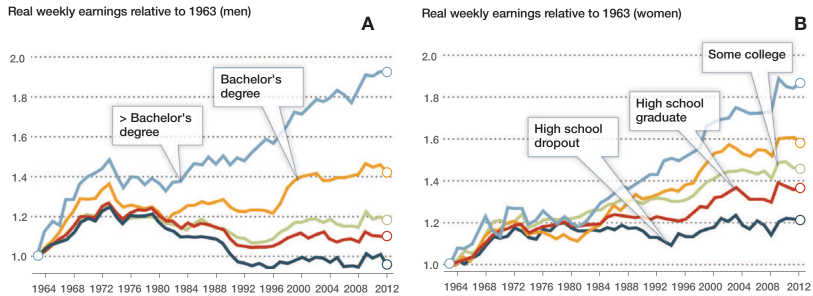

FIGURE 3.3 Changes in wage levels of full-time U.S. workers by sex and education, 1963-2012. SOURCE: D. H. Autor, 2014, Skills, education, and the rise of earnings inequality among the "other 99 percent," *Science* 344 (6186):843-851, http://science.sciencemag.org/content/sci/344/6186/843.full.pdf. Reprinted with permission from AAAS.

acquired through higher education.[64] Related to this challenge, the skills gap continues to widen such that more than half of employers report that they have had difficulty finding qualified job applicants to fill certain jobs, which they believe to be in part due to education gaps.[65,66]

In the 1980s and 1990s, these changes in technology—along with complementary factors such as globalization, deregulation, and deunionization—have likely contributed to the reduction in demand for middle-level skills, and this has been reflected in both the quantity of jobs and in wages for middle-skill workers (see Figure 3.4).

In particular, workers doing routine tasks (such as production tasks in manufacturing or clerical tasks) have seen their demand decline due to multiple factors, including changing technology. This is reflected in a decline in manufacturing employment even as output has grown to an all-time high. Globalization has further eroded the demand for such skills in advanced economies like the United States. In contrast, there have been expanding job opportunities in both high-skill, high-wage occupations like professional, technical, and managerial occupations and low-skill,

[64] R. Valletta, 2015, "Higher Education, Wages, and Polarization," Federal Reserve Bank of San Francisco, http://www.frbsf.org/economic-research/publications/economic-letter/2015/january/wages-education-college-labor-earnings-income/.

[65] CareerBuilder, "The Shocking Truth about the Skills Gap," 2014, http://www.careerbuildercommunications.com/pdf/skills-gap-2014.pdf, accessed August 16, 2016.

[66] A recent survey by Manpower group found this to be a global trend, with 38% of surveyed employers reporting a talent shortage in 2015, a 7-year high; see Manpower Group, 2015, *2015 Talent Shortage Survey*, http://www.manpowergroup.com/wps/wcm/connect/db23c560-08b6-485f-9bf6-f5f38a43c76a/2015_Talent_Shortage_Survey_US-lo_res.pdf?MOD=AJPERES.

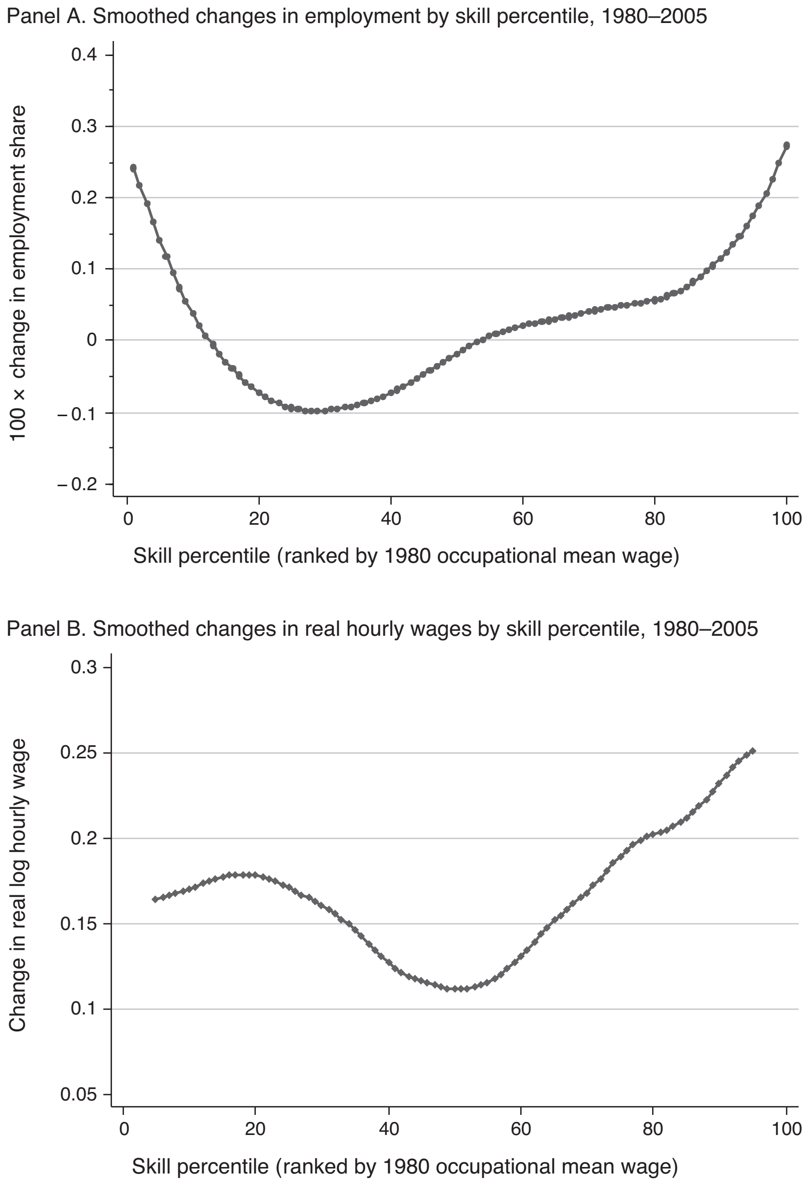

FIGURE 3.4 In panels A and B, workers in the middle of the skill distribution have had lower employment growth and wages growth than workers at the top and bottom. SOURCE: (A) D.H. Autor and D. Dorn, 2013, The growth of low-skill service jobs and polarization of the US labor market, *American Economic Review* 103(5):1553-1597. Courtesy of David Autor, David Dorn, and the American Economic Association.

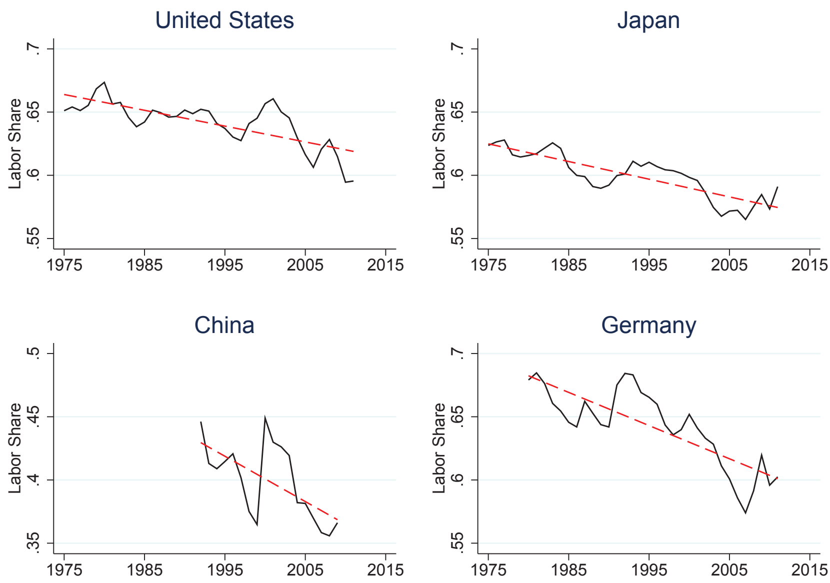

FIGURE 3.5 Declining labor share of income for the largest economies in the world, with linear trend lines. SOURCE: L. Karabarbounis and B. Neiman, 2014, The global decline of the labor share, *Quarterly Journal of Economics* 129(1):61-103, by permission of Oxford University Press.

low-wage occupations such as food service, personal care, and protective service occupations.[67,68]

But changes in skill demand are far from the only factors at work. In addition, technology may be helping to drive a decline in the labor force participation rate and a broader shift in the labor-capital relationship, as advanced technology is embodied in capital equipment that replaces many workers.[69,70] This shift has happened not only in the United States but in many nations around the world. Figure 3.5 illustrates the global decline of the labor share of income.

The reductions in real compensation for labor include the decline of

[67] D. Acemoglu, 2009, Changes in unemployment and wage inequality: An alternative theory and some evidence, *American Economic Review* 89(5):1259-1278.

[68] D. Acemoglu, 2001, Good jobs versus bad jobs, *Journal of Labor Economics* 19(1):1-21.

[69] B. Neiman and L. Karabarbounis, 2013, The global decline of the labor share, *Quarterly Journal of Economics* 129(1):61-103.

[70] E. Brynjolfsson and A. McAfee, 2014, *The Second Machine Age: Work, Progress, and Prosperity In a Time of Brilliant Technologies*, W.W. Norton & Company, New York.

defined-benefit pensions and cuts in employer-provided health insurance.[71] In addition to technological change, the shift in the labor-capital ratio likely reflects increased monopoly power and rents by firms in many industries and the growing share of residential housing in the capital stock.[72,73]

Another factor that is important in this context is that advances in IT often involve significant supply-side economies of scale: the cost of making the first copy of a new enterprise system, video game, or mobile app is often significant, but the cost of making an additional copy is very low. Thus companies whose software has more users will tend to have lower average costs per user. Likewise, there are often demand-side economies of scale as well, which are more commonly called "network effects." Network effects occur when users get more benefits from a product or platform when it is adopted by more users.[74,75] For instance, the value of Facebook or LinkedIn is greater if other people, especially friends, family, or colleagues, also use the same application. Similar logic holds for many business-to-business platforms and, to some extent, even productivity software like word processors, spreadsheets, and presentation software, because they are compatible between users and enable file sharing and collaboration.

Economies of scale on the supply side, the demand side, or both tend to a greater prevalence of "winner take all" outcomes where the leading firm in a particular platform does exceptionally well. Even if the gains are shared across all the workers within the winning firms, this still leads to concentration of the gains to a relatively small share of workers.[76]

That said, gains have not been evenly distributed, with the top employees in firms seeing the biggest gains on average.[77] Founders and

[71] J.A. Cobb, 2015, Risky business: The decline of defined benefit pensions and firms' shifting of risk, *Organization Science* 26(5):1332-1350.

[72] J. Furman and P. Orszag, 2015, "A Firm-Level Perspective on the Role of Rents in the Rise of Inequality," https://www.whitehouse.gov/sites/default/files/page/files/20151016_firm_level_perspective_on_role_of_rents_in_inequality.pdf.

[73] M. Rognlie, 2015, "Deciphering the fall and rise in the net capital share," *Brookings Paper on Economic Activity*, March 19-20, http://www.brookings.edu/~/media/projects/bpea/spring-2015/2015a_rognlie.pdf.

[74] J. Farrell and G. Saloner, 1987, Competition, compatibility and standards: The economics of horses, penguins, and lemmings, in *Product Standardization and Competitive Strategy* (L. Gabel, ed.), North Holland.

[75] G.G. Parker, M.W. Van Alstyne, and S.P. Choudar, 2016, *Platform Revolution: How Networked Markets Are Transforming the Economy—And How to Make Them Work For You*, W.W. Norton & Company, New York.

[76] J. Song, D.J. Price, F. Guvenen, N. Bloom, and T. von Wachter, 2015, "Firming Up Inequality," National Bureau of Economics Research, http://www.nber.org/papers/w21199.

[77] Ibid.

owners of the most successful IT firms and entrepreneurs who have introduced new products, business models, and platforms are among the biggest winners. This is consistent with the rise of the "innovator class," which suggests that neither labor nor capital owners will necessarily benefit the most from technological advances. Instead, the rapid proliferation of digital technology may enable a third class—people who can create and distribute new products, services, and business models—to prosper immensely.[78] In addition, there is evidence that pay for top executives, like CEOs, has grown fastest in industries that use IT the most intensively, which is consistent with them being able to gather more detailed information and relay their decisions more effectively across more people and assets. This can amplify their power, importance, and relative pay.[79]

While the gender wage gap has narrowed since the 1980s, it is important to note that significant wage gaps by both race and gender persist in the United States. According to a recent analysis by the Pew Research Center,[80] 2015 median hourly earnings for women were just 83 percent of white men's, and black workers' only 75 percent of white men's. Much but not all of these gaps have been explained by varying education and experience, or the fact that different groups participate at different rates in different industries and occupational fields. Even when controlling for education, white men out-earned all groups except for Asian men; white and Asian women out-earned Hispanic and black men and women. How these disparities will shift in the future as a result of technological change is an open question; gender and occupational fields are discussed further in Chapter 4.

Future Prospects for Income Distribution

An important variable for understanding and shaping future developments is the way education and vocational training institutions might ameliorate the mismatch between new technologies and existing skills. The early 20th century was also a period of rapid technological change in the U.S. economy. However, existing evidence suggests that wage inequality declined during this era, in part because the U.S. education system substantially increased the availability of workers with primary and

[78] E. Brynjolfsson, A. McAfee, and M.I. Spence, 2014, "New World Order: Labor, Capital, and Ideas in the Power Law Economy," *Foreign Affairs*, https://www.foreignaffairs.com/articles/united-states/2014-06-04/new-world-order.

[79] E. Brynjolfsson, H. Kim and G. Saint-Jacques, 2015, CEO pay and information technology, in *Firms and the Distribution of Income: The Roles of Productivity and Luck*, National Bureau of Economic Research, Cambridge, Mass.

[80] E. Patten, 2016, "Racial, Gender Wage Gaps Persist in US Despite Some Progress," Pew Research Center. http://www. pewresearch. org/fact-tank/2016/07/01/racial-gender-wage-gaps-persist-in-us-despite-someprogress.

secondary schooling. That does not mean that simply investing more in the same sorts of education is the best way to reduce inequality, however. More out-of-the-box thinking may be necessary for prescribing what the educational system needs to deliver. The existing evidence so far suggests that greater numeracy skills and ability to think abstractly might help. A cocktail of other skills are also likely to be affected, including cognitive, physical, interpersonal, networking, and problem-solving skills. But an emphasis on any fixed set of skills might be too backward-looking. As technology continues to evolve, the future workforce will also likely need to evolve. This suggests that flexibility will likely continue to be a valued skill—one that may be particularly underprovided by the current schooling system—in particular, to enable lifelong learning and adaptability to a changing labor market.

This discussion suggests that for society to make the best use of new technologies without increasing income inequality, adjustments are necessary. Although the heaviest burden of adjustment is likely to fall on the skills, competencies, and flexibility of workers, the perspective that technology is not a force of nature and can be shaped and adapted by societal decisions suggests that technology can have positive societal impacts if it is designed with certain values in mind. Can society continue to harvest the benefits of new technologies while at the same time modifying their implementation so that they create more work for those at the margins of society, make better use of existing workers, and yield deeper satisfaction for workers?

The history of numerically controlled, or programmed, machine tools is instructive on this point. In the early days of numerical control, the task of writing programs for machine tools was allocated to programmers, not machinists. The programs were encoded on paper tapes or punch cards and fed to the machine tools. Machinists simply monitored the tools. This led some to argue that machinists would be deskilled because management desired to separate cognition from execution. But with the rapid improvements in the microchip, computers became small enough to embed in the machine tools, and machinists now had access to the computers and the programs. They began to learn to alter and eventually revise the code that controlled their tools. In short, programming became part of the machinist's task.[81] More recent technologies like the Baxter and Sawyer robots from Rethink Robotics take this a step further, enabling line workers to "program" the machines simply by physically guiding them through the steps, rather than by writing computer code.[82]

It bears repeating that this discussion of technology and inequality

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[81] D.F. Noble, 1984, *Forces of Production*, Transaction Publishers.

[82] Rethinkrobotics, "Products & Software," http://www.rethinkrobotics.com/products-software/, accessed May 2016.

should not be read to imply that all aspects of inequality and its recent increase in much of the Western world can simply be attributed to technological change: one must also consider the role played by the demise of unions, concessions on wages and job structures, the offshoring of work to places with lower wage rates, tax policy, and the increasing contribution played by financial investments in the accumulation of wealth. Indeed, increasing inequality in the United States has a political dimension, a phenomenon that is, of course, not new. Politically powerful individuals and groups have long deployed their power in order to increase their economic rents. This is seen today in the form of some business groups campaigning for special treatment of their line of business or for the continuation of tax loopholes. Nevertheless, there is a technological element to such rent-seeking, and to inequality as well. Some of the most spectacular salaries on Wall Street are paid by hedge funds that deploy more and more sophisticated computers and algorithms to execute trades or arbitrage information, before their competitors, in a matter of milliseconds. This is just one facet of the potential use of technology in ways that do not necessarily advance social welfare, but create large benefits for those who deploy and control it.

In sum, new technologies can participate in eliminating occupations, creating new occupations, shifting the distribution of tasks among occupations, and altering the geographical division of labor.[83] The dynamics of employment and wage inequality are driven by forces that are not exclusively or even primarily technological in nature: institutional patterns, legal structures, tax structures, and managerial ideologies that emphasize the accumulation of wealth also play a role. Most importantly, these forces interact with technology, and vice versa, to shape ultimate outcomes. Consequently, the ways that any particular technology, or a range of new and rapidly changing technologies, will affect employment and income are not predetermined, but rather a function of choices.

SUMMARY

The committee ends by again cautioning the reader against believing that all the effects of a technology on employment and inequality are inherent in the nature of the technology itself. How technologies affect work and employment hinge not only on the constraints and affordances

[83] There are some interesting parallels to the effects of import competition. For instance, Autor, Dorn, and Hanson (2013) found that rising Chinese imports caused higher unemployment, lower labor force participation and reduced wages in the local markets that had manufacturing plants with competing products (D.H. Autor, D. Dorn, and G.H. Hanson, 2013, The China syndrome: Local labor market effects of import competition in the United States, *American Economic Review* 103.6:2121-2168).

of the technology, but also on complex interactions among technologies, organizations, skills, institutions, markets, culture, and public policies. Nevertheless, on the basis of previous research, the committee believes several generalizations are possible.

1. Productivity is the key driver of increased living standards. In turn, innovation, diffusion, or adoption of technology is the key driver of improvements in productivity. The most important technology of this era is IT. However, the existence of technology alone is not enough to enhance productivity. Effective use of technology typically requires a shift toward complementary skills profiles in the workforce and adaptation of business processes, organization of work, and institutional processes. These changes can be costly and take decades to play out.

2. While productivity is still growing, it does not appear to be growing as rapidly as it did in the late 1990s and early 2000s. This may reflect a combination of factors, including mismeasurement of some of the benefits, reduced dynamism, the inherent lags often associated with the implementation of new technologies, or secular stagnation.

3. Technology has transformed employment by automating some tasks and creating the need for new ones, a trend that is likely to continue. As a result, some entire occupations may become obsolete, and new occupations will come into being. Employment will shift from one occupation to another, while some occupations will simply experience changes in their required skill sets. While the share of people working has declined over the past 20 years, shifts within and across occupations will likely be much more economically significant than changes in the overall level of employment.

4. New computerized technologies do appear to have contributed to increased income inequality and are likely to continue to do so as long as they replace skills and tasks historically associated with low-wage or middle-wage occupations. The jobs that remain tend to require more abstract, cognitive skills, or they provide personal services that are not currently economically valued. These differences will tend to be mainly reflected in wages and incomes, although they may also show up to some extent in hours worked and overall employment as well.

4

Changes in the Nature of Work and Its Organization

INTRODUCTION

Technological change affects more than productivity, employment, and income inequality. It also creates opportunities for changes in the nature of work itself. Numerous ethnographic studies have shown how a variety of new technologies have altered the way work is performed, the roles that workers play in a firm's division of labor, and the way these changing roles alter the structure of organizations.[1] In this chapter, the analysis of technology and society continues, with a focus on (1) changing forms of work, including occupations and contingent jobs; (2) dynamism and flexibility in the workforce; (3) demographics and job satisfaction; (4) the organizations and other institutions in which we work; (5) changes in the role of work in people's lives; and (6) education and job training.

As the nature of the work environment continues to change, new trends have emerged at the individual, team, and organizational levels. The workforce is now more demographically diverse than ever, and

[1] A. Aneesh, 2006, *Virtual Migration: The Programming of Globalization*, Duke University Press, Raleigh, N.C.; M. Baba, 1999, Dangerous liaisons: Trust, distrust, and information technology in American work organization, *Human Organization* 58(3):331-333; N. Natalia and E. Vaast, 2008, Innovating or doing as told? Status differences and overlapping boundaries in offshore collaboration, *MIS Quarterly* 32:307-332; S.R. Barley, 1990, The alignment of technology and structure through roles and networks, *Administrative Science Quarterly* 35:61-103; D.E. Bailey, P.M. Leonardi, and S.R. Barley, 2012, The lure of the virtual, *Organization Science* 23:1485-1504; S.R. Barley, 2015, Why the Internet makes buying a car less loathsome: How technologies change role relations, *Academy of Management Discoveries* 1:5-35.

older workers represent a significant subset of the working population.[2] Increased technology and the growing complexity of tasks have given rise to more virtual and interdisciplinary teams.[3,4] Furthermore, interest in multinational organizations has grown as many companies seek to increase their overseas assignments.[5] If society is receptive to these changes and also able to adapt quickly to new technology, it can lead to benefits for both employees and organizations. However, history suggests that these trends can lead to hurdles and unexpected negative consequences, such as decreased job satisfaction, poor work/life balance, and neglect of personal and long-term career development.[6,7] A brief summary of the most prominent trends within today's workforce is discussed below.

THE ON-DEMAND ECONOMY

The rapid rise of firms like Uber, along with an increased recognition that IT permits individuals to connect and coordinate in unprecedented ways, have prompted great interest in the on-demand economy.

In the official aggregate statistics from U.S. statistical agencies, there is mixed evidence on the current role and extent of the on-demand economy. However, this may largely reflect a lack of clear measures of the relevant types of work.

U.S. statistical agency data, when controlled for cyclical variation, suggest that part-time work, multiple job holders, and short-duration jobs have not been rising. However, the number of companies with zero employees, which the U.S. Census calls "nonemployers,"[8] has risen substantially over the last 10 years, from about 18.7 million in 2003 to 23 mil-

[2] Bureau of Labor Statistics, 2014, "Labor Force Statistics from the Current Population Survey: Labor Force Characteristics 2014," last modified March 10, 2016, http://www.bls.gov/cps/lfcharacteristics.htm#emp.

[3] N.J. Cooke, E. Salas, J.A. Cannon-Bowers, and R. Stout, 2000, Measuring team knowledge, *Human Factors* 42:151-173.

[4] L. Gratton and T.J. Erickson, 2007, "Eight Ways to Build Collaborative Teams," *Harvard Business Review,* November, pp. 101-109.

[5] R. Maurer, 2013, "International Assignments Expected to Increase in 2013," Society for Human Resource Management, https://www.shrm.org/hrdisciplines/global/articles/pages/international-assignments-increase-2013.aspx; B. Frith, 2015, "Companies expect to increase international assignments," *HR Magazine,* http://www.hrmagazine.co.uk/article-details/companies-expect-to-increase-international-assignments.

[6] J. Wajcman, 2014, *Pressed for Time: The Acceleration of Life in Digital Capitalism*, University of Chicago Press, Chicago, Ill.

[7] P.F. Drucker, 2002, *Managing in the Next Society*, Truman Talley Books, New York.

[8] Specifically, nonemployers are businesses that report revenue from business activity but do not have employees, and the newly self-employed may be showing up in this category.

lion in 2013;[9] this category includes employees earning income as independent contractors (via Internal Revenue Service 1099-MISC forms). It has been hypothesized that many 1099 workers consider themselves as employees and report themselves as such in surveys, such as the Current Population Survey, yielding underreporting in certain categories.

Recent independent research found that the overall share of workers in alternative arrangements[10] increased from 10 percent to about 16 percent between 2005 and 2015. Of these, less than 0.5 percent of the workforce (about 600,000 people) worked with online services, with Uber being by far the most common.[11] However, the online sector, including a range of on-demand services, appears to be growing very rapidly and could account for millions of workers within a few years.[12]

The Internet-enabled on-demand economy is new, and the extent of its potential impact is as yet unknown. One challenge for monitoring this trend will be ensuring that the official statistics and other data available to the research and policy communities are adequate to capture the changing trends in the coming years.

One hypothesis is that individuals will increasingly provide their labor services in some form of independent contractor relationship with firms; independent contractors can now offer their services efficiently to a much bigger customer base. Alternatively, part of the on-demand or "gig" economy may be a new version of a personal service economy where personal services like transportation and delivery of food and other services are accessible through widely available technology on smartphones and other similar devices. For workers in the personal services component of the gig economy, such jobs may fit into a worker's career in a variety of ways. They can be stopgap or secondary jobs, or, in some cases, their flexibility permits individuals to participate in the labor market to a greater extent than they would otherwise. However, note that Uber, the largest gig economy employer to date, has invested heavily in automation technologies and is already testing self-driving vehicles that could one day greatly reduce or even eliminate its need for human drivers.[13]

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[9] U.S. Census Bureau, 2015, "Nation Gains more than 4 Million Nonemployer Businesses Over the Last Decade, Census Bureau Reports," *U.S. Census Bureau Newsroom* (blog), May 27, http://www.census.gov/newsroom/press-releases/2015/cb15-96.html.

[10] These include independent contractors, workers at temporary help firms, on-call workers, and workers provided by contract firms.

[11] L.F. Katz and A. Krueger, 2016 forthcoming, "The Rise of Non-Standard Work Arrangements and the Gig Economy?"

[12] Remarks by Jonathan Hall (Uber Chief Economist) and by Larry Katz (Professor at Harvard) at the On-Demand Economy Workshop and Conference, MIT Initiative on the Digital Economy, Cambridge, Mass., March 14, 2016.

[13] Reuters, 2016, "Uber Debuts Self-Driving Cars in Pittsburgh," *Fortune*, http://fortune.com/2016/09/14/uber-self-driving-cars-pittsburgh/.

ORGANIZATION AND DISTRIBUTION OF WORK TASKS

Some production activities have historically taken the form of bringing groups of individuals together for specific projects, as in the construction and entertainment industries. The rise of IT-based work platforms that support new definitions and distributions of work tasks in new ways provides another illustration of the variable potential for application and use of technologies. Such platforms employ Internet-based communications and smartphone applications to make work available, and then assign that work to individuals or groups based on bid, proposal, or contest mechanisms. Crowdsourcing, open-call, and open innovation platforms can be used to redefine the nature of tasks themselves and to change how that work is organized and distributed both within and across organizational bounds.

Crowdsourcing platforms, for instance, work on the basis of tasks being decomposed into smaller units, even to the level of microtasks. These are then made available through open-call or auction mechanisms to people beyond strictly defined work teams or organizational bounds, including, but not necessarily beyond, a given firm. In addition, crowdsourcing mechanisms can be—and are—used within firms to open up the performance of work tasks broadly to their existing employees.[14]

Contest-based work solicitation systems, in contrast, operate by seeking solutions to often large-scale, complex challenges, but they too reach out to people beyond the boundaries of traditionally assigned job roles. And, although contest-based systems such as Innocentive support the outsourcing of work, such outsourcing is not necessarily inherent to this technological form. Like crowdsourcing, contests can be run internally at a firm among already salaried employees.

Even in the case of internal uses of crowdsourcing and contests, designing how work will be performed, managing both the processes and labor of production, and ensuring quality affects the work people do and how they do it. Managers may no longer have the same level of authority in managing where and how employees' time is invested. Workers may find that their ability to control their own performance is more tightly circumscribed, or the opposite—they may be responsible for providing a particular output but be free to select how to arrive at that outcome. Collaborations and work relationships can be both forged and weakened by these mechanisms.[15]

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[14] M. Cefkin, O. Anya, and R. Moore, 2014, "A Perfect Storm? Reimagining Work in the Era of the End of the Job," pp. 3-19 in *2014 Ethnographic Praxis in Industry Conference Proceedings*.

[15] Ibid.

In general, IT can lower the costs of transactions and searches, which leads to more market-based interactions and temporary contracting.[16] These developments suggest that the overall demand for work may not necessarily be threatened by technology, but rather that the shape of that work, and whether the tasks remain bundled into traditional "jobs," is subject to change.[17] This is especially evident in the rise of contingent labor.

CONTINGENT LABOR

"Contingent work" is a general term referring to nonstandard work arrangements, including temporary or contract work. Although contingent work is not new (firms such as Kelly Services and Manpower, for example, have been in the business of providing temporary clerical and industrial workers for many years), it has grown and attracted renewed attention recently with the online, open-call work platforms described above.[18]

Typically, contingent workers are not employees of the firms or people who profit from their services (although there are some exceptions). Contingent workers may be independent contractors or employees of staffing agencies that act as the worker's employer of record for tax purposes.[19] According to a recent report of the Government Accountability Office (GAO), approximately 7.9 percent of U.S. workers in 2010 were agency temps or on-call workers. A broader definition of contingent work, including part-time, self-employment, and other nontraditional work arrangements, would place the estimate at more than one-third of the 2010 workforce.[20]

Many workers prefer the flexibility, diverse income sources, and ability to control their work schedule and activities that are associated with employment via independent contracting, but this is not the universal

[16] T.W. Malone, J. Yates, and R.I. Benjamin, 1987, Electronic markets and electronic hierarchies, *Communications of the ACM* 30(6):484-497.

[17] Z. Ton, 2014, *The Good Jobs Strategy: How the Smartest Companies Invest in Employees to Lower Costs and Boost Profits*, Houghton Mifflin Harcourt.

[18] M.C. White, 2014, "For Many Americans, 'Temp' Work Becomes Permanent Way of Life," http://www.nbcnews.com/feature/in-plain-sight/many-americans-temp-work-becomes-permanent-way-life-n81071.

[19] Some companies provide contingent workers as part of the payroll/tax service (so called professional employer organizations or PEO's) but temporary staffing companies like Manpower have the full employer responsibility, including managing HR aspects of the employee.

[20] C.A. Jeszeck, 2015, "Letter to The Honorable Patty Murray and the Honorable Kirsten Gillibrand: Contingent Workforce: Size, Characteristics, Earnings, and Benefits," Government Accountability Office, http://www.gao.gov/assets/670/669766.pdf.

experience. Some contingent work is also "precarious," which the committee defines as "uncertain, unpredictable, and risky from the point of view of the worker"[21]—for example, due to part-time or short-term employment, intermittent or unpredictable work hours, poor wages, or insecure jobs. The GAO found that "core" contingent workers (primarily agency temps and on-call workers) in the United States were "more likely to be younger, Hispanic, have no high school degree, and have low family income."[22] Over the last decade, for a significant share of the workforce, precarious positions associated with nontraditional employment models have become a permanent way of life. In fact, some argue that a new social class has risen from this trend, "the precariat," made up of individuals facing insecurity, poverty, and a work life with no significance.[23] In addition to gaining attention from the popular press, the rise of precarious work has led to a research stream investigating the consequences of temporary work. For example, in a review of studies on precarious employment conducted between 1984 and 2001, Quinlan, Mayhew, and Bohle found a negative relationship between precarious employment and occupational health and safety, concluding that it leads to a stressful and disorganized work environment.[24]

Contingent work relationships come in a variety of forms, involving various types of employment relationships and various types of worker benefits. Scholarship is at an early stage when it comes to analyzing the scope of contingent work and the implications of each type for employment structures, employment relations, and the welfare of workers. The use of IT-based platforms to access contingent work adds a new dimension to this category of employment.

For instance, there remains a vibrant business in providing temporary workers who fill in for sick or vacationing full-time workers or who are assigned to jobs for short periods of time to augment a firm's full-time labor force when the firm finds itself understaffed yet unable to hire full-time employees. This contrasts with the highly skilled contractors and freelancers studied by Barley and Kunda and by Osnowitz, who work for longer periods of more than 6 to 18 months on projects inside a firm, often

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[21] A.L. Kalleberg, Precarious work, insecure workers: Employment relations in transition, *American Sociological Review* 74(1):1-22, 2009.

[22] Jeszeck, 2015.

[23] G. Standing, 2014, *The Precariat: The New Dangerous Class*, Bloomsbury Academic, London.

[24] M. Quinlan, C. Mayhew, and P. Bohle, 2001, The global expansion of precarious employment, work disorganization, and consequences for occupational health: a review of recent research, *International Journal of Health Services* 31(2):335-414.

alongside full-time employees.[25,26] Such contractors are typically compensated more per hour than full-time employees, after accounting for benefits. By hiring such individuals, firms relieve themselves of the costs of paying employment taxes, providing health insurance, contributing to pension funds, or investing in training. A technology-enabled platform, Upwork, provides highly skilled workers similar to high-tech contractors, except that the contractors are often located outside the United States and are subject to different labor laws and employment systems.

Other contingent workers use technology platforms to identify short-term and often unskilled personal service jobs for individuals who seek a service provider though websites or apps—for example, Uber drivers, those who perform odd jobs through TaskRabbit, or those delivering meals through GrubHub. These gigs may pay relatively little and are subject to unforeseen developments that may reduce their rate of pay. To make a living, gig workers require a steady stream of gigs.

Despite their diversity and the great variation in the duration of their projects, contingent workers often share a number of characteristics that place them outside the traditional system of employment relations in the United States, which assumes a long-term relationship with a single, stable employer. Many contingent workers receive no health-care benefits from their employers, receive no employer contributions to retirement funds, and are responsible for their own training and development as well as paying employment taxes.[27] Staffing agencies may also extract a significant portion of revenue paid by clients for the contingent worker's labor. Downtime between jobs is to be expected, although how well workers can manage or circumvent downtime depends on the type of contingent worker. Some contingent workers have a great deal of control over when they work, while others have very little control. Certain types of contingent work resemble the system of contract employment used in manufacturing during the late 19th century.[28]

Ensuring that the expansion of contingent work provides new opportunities for workers to control their work life, rather than leaving them

[25] S.R. Barley and G. Kunda, 2004, *Gurus, Hired Guns and Warm Bodies: Itinerant Experts in a Knowledge Economy*, Princeton University Press, Princeton, N.J.

[26] D. Osnowitz, 2010, *Freelancing Expertise: Contract Professionals in the New Economy*, Cornell University Press, New York.

[27] S.R. Barley and G. Kunda, 2004, *Gurus, Hired Guns and Warm Bodies: Itinerant Experts in a Knowledge Economy*, Princeton University Press, Princeton, N.J.

[28] On the role of outsourcing, contracting, and the putting out system in American factory production see D. Nelson, 1975, *Origins of the New Factory System in the United States: 1880-1920*, University of Wisconsin Press, Madison, Wisc.; J. Christiansen and P. Philips, 1991, The transition from outwork to factory production in the boot and shoe industry, 1930-1880, in *Masters to Managers: Historical and Comparative Perspectives on American Employers* (S.M. Jacoby, ed.), Columbia University Press, New York.

disadvantaged, will require changes to the organization of work and the institutions in which it is embedded. One example may be to stimulate the formation of organizations or occupational associations, similar to the Freelancers Union, that provide contingent workers with avenues for acquiring portable health insurance and retirement savings programs. Regulations could also be shaped to better enable contingent workers who have been traditionally categorized as independent contractors to access benefits and protections through their employer, ensuring protection of their rights under U.S. employment law. There is already mounting political pressure to both use existing regulations and introduce new ones to prevent the rise of contingent work in certain areas (such as the taxicab market). Much of this pressure might be motivated by narrow-interest politics (e.g., protecting rents for certain workers or business owners), which is certainly no substitute for a holistic rethinking of regulations, given the extent of contingent work today.

There are limited data on the nature and extent of contingent work in the U.S. workforce and how IT is affecting its role in the labor market. A clear and longitudinally valid system for characterizing contingent jobs could help to clarify the economic and social effects of different forms of contingent work and how they are changing. It is worth noting that 2005 was the last year that the Bureau of Labor Statistics collected data on the contingent workforce, although plans for another survey are under way and an independent, standalone version of a similar survey was conducted through the RAND Corporation, as contracted by economists Alan Krueger and Larry Katz.[29] Data collection is discussed in more detail in Chapter 6.

DYNAMISM AND FLEXIBILITY OF THE U.S. WORKFORCE

A hallmark of the U.S. economy has long been its high business dynamism (its pace of business formation, expansion, contraction, and exit) and labor market fluidity (its pace of the flows of workers between jobs and firms). Dynamism and fluidity are inherently linked because much of the flow of workers across jobs stems from business expansion, contraction, entry, and exit. However, “churning” of workers (fluidity in excess of that due to business dynamism) has increased as workers (especially young workers) engage in job hopping (frequent transitions

[29] L.F. Katz and A.B. Krueger, 2016, “The Rise and Nature of Alternative Work Arrangements in the United States 1995-2015,” Princeton University and NBER, https://krueger.princeton.edu/sites/default/files/akrueger/files/katz_krueger_cws_-_march_29_20165.pdf.

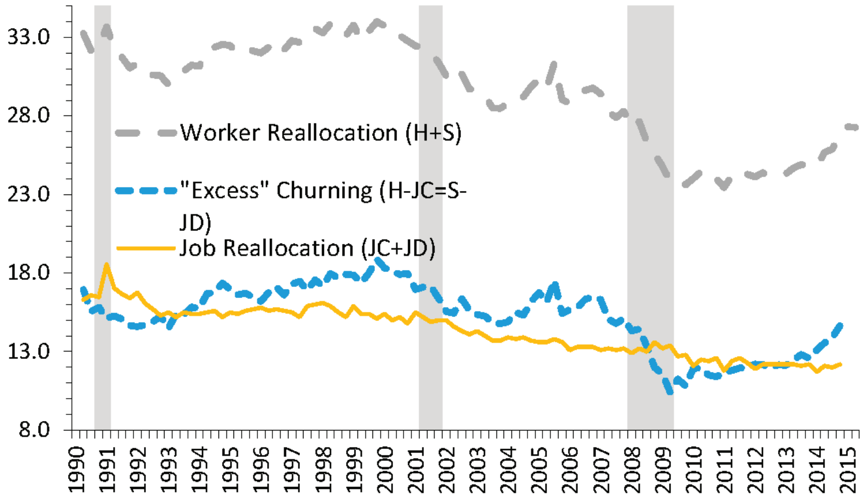

FIGURE 4.1 Quarterly job and worker reallocation rates for the U.S. private non-farm sector. NOTE: Sources Business Employment Dynamics and JOLTS (tabulations by Davis and Haltiwanger (2014)). H, hires; S, separations; JC=job creation; JD, job destruction. All statistics are percentages of employment. Scope is employer firms (firms with one or more paid employees) in U.S. private, non-farm sector. SOURCE: After S. J. Davis and J. Haltiwanger, 2014, *Labor Market Fluidity and Economic Performance*, No. w20479, National Bureau of Economic Research, Cambridge, Mass.

between jobs) to develop their careers and find the best match for their skills and interests.

Historically, the United States has exhibited strong indicators of dynamism, such as a high pace of job and worker reallocation, job hopping, and geographic mobility. This dynamism has enabled the United States to reallocate resources from less productive to more productive businesses with less time and resource costs than other countries (e.g., without high rates or long durations of unemployment). In the last several decades—and especially since 2000—there has been a decline in several indicators of business dynamism and labor market fluidity. As illustrated in Figure 4.1, the pace of job reallocation (the sum of jobs created and destroyed) has declined, and the pace of worker reallocation (the sum of hires and separations) has declined. This is linked to declines in related measures of labor market fluidity. The pace of job hopping, as measured by the fraction of workers switching directly from one job to another, often called job-to-job flows, has also declined.[30] Job-to-job flows have historically been critical for helping young workers build their human capital and their careers. Workers moving directly from job to job in the United States have largely reflected workers moving up the job ladder, defined in terms of firm wages or productivity. Geographic mobility has also declined, although the U.S. labor market is still generally more flexible than those of other developed countries and thus perhaps better positioned to adapt to technological change.[31,32]

There are also fewer new companies in the United States. New companies accounted for about 13 percent of all firms in the late 1980s, but only 8 percent in 2007.[33] This has direct implications for the adoption and diffusion of new technologies. Since the year 2000, there has been a similar decline in the number of high-growth start-ups and the amount of employment in these firms, as indicated in Figure 4.2.[34]

There are many open questions about this phenomenon, and it is difficult to draw inferences about these changes. There is no doubt, however, that the decline in dynamism and start-ups are connected to the decline in labor market fluidity. Young firms exhibit an especially high pace of job reallocation, with some firms rapidly expanding while others contract and exit. This implies a high pace of hires and separations at such firms. The implication is that a decline in start-ups translates into a decline in labor market fluidity. Moreover, dynamism and flexibility have arguably facilitated the ability of the United States to adapt to past periods of rapid technological change. Davis and Haltiwanger provide evidence that the decline in labor market fluidity has had an adverse effect on labor force participation, especially among the young and less educated. These are the most vulnerable groups that may be left behind by technology.[35]

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[30] S.J. Davis and J. Haltiwanger, 2014, "Labor Market Fluidity and Economic Performance," No. w20479, National Bureau of Economic Research. See also Figure 3-19, "Economic Report of the President," Council of the Economic Advisers, February 2015, https://www.whitehouse.gov/sites/default/files/docs/cea_2015_erp_complete.pdf.

[31] *The Economist*, 2014, "America's Famously Flexible Labour Market Is Becoming Less So," August 28, http://www.economist.com/news/finance-and-economics/21614159-americas-famously-flexible-labour-market-becoming-less-so-fluid-dynamics.

[32] R.J. Gordon, 2003, "Exploding Productivity Growth: Context, Causes, and Implications," Brookings Papers on Economic Activity, No. 2, Brookings Institution, Washington, D.C.

[33] R.A. Decker, J. Haltiwanger, R.S. Jarmin, and J. Miranda, 2015, "Where Has All the Skewness Gone? The Decline in High-Growth (Young) Firms in the U.S," NBER Working Paper No. 21776, last revised January 8, 2016, http://www.nber.org/papers/w21776.

[34] Ibid.

[35] S.J. Davis and J. Haltiwanger, 2014, "Labor Market Fluidity and Economic Performance," University of Chicago and NBER, and University of Maryland and NBER, http://faculty.chicagobooth.edu/steven.davis/pdf/LaborFluidityandEconomicPerformance26November2014.pdf.

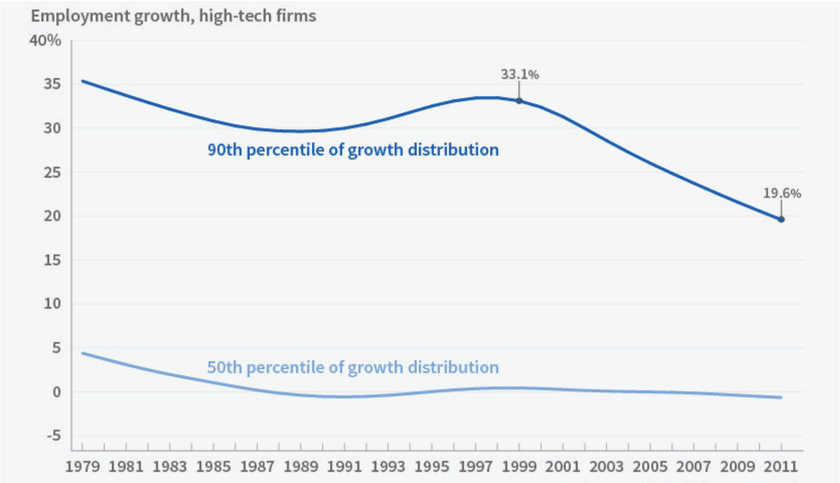

FIGURE 4.2 High-tech firm employment growth, 1979-2011. NOTE: Data shown as Hendrick-Prescott trends. SOURCE: J. Fitzgerald, 2016, "The Number of High-Growth, Job-Creating Young Firms Is Declining," http://www.nber.org/digest/feb16/w21776.html. Author's calculations using Compusat and Longitudinal Business Database data.

These findings seem inconsistent with an increase in contingent workers engaged in short-duration gig jobs. As noted above, there is currently not much evidence that gig economy jobs are quantitatively significant in the overall U.S. economy.[36] However, the statistics reported in this section reflect employers with at least one paid employee (and the employers themselves), which excludes many gig workers who are more likely to be independent contractors.

Changes in the Prevalence of Start-up Companies

Underlying part of this decline is a decline in dynamism in the pace of start-ups and high-growth young firms. Before 2000, this phenomenon was concentrated in certain sectors, such as retail trade, where there has been a shift in the business model toward large national chains (see Figure 4.3 for the fraction of employment over time attributed to jobs at young firms in specific sectors). Evidence suggests that such companies

[36] Katz and Krueger, 2016, "The Rise and Nature of Alternative Work Arrangements in the United States 1995-2015."

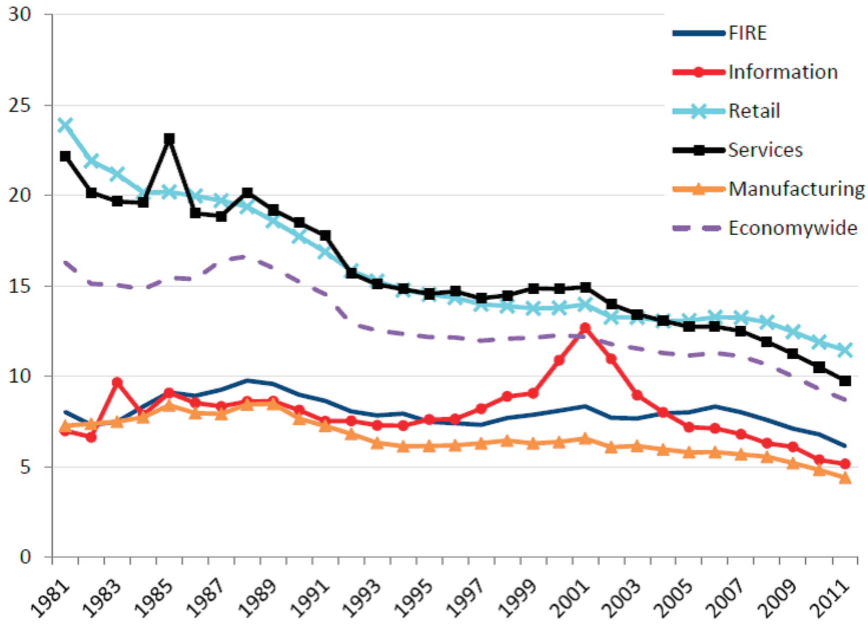

FIGURE 4.3 Share of employment accounted for by young firms (less than 5 years old) for selected industries. Tabulations from Longitudinal Business Database. NOTE: FIRE, finance, insurance, and real estate. SOURCE: Reprinted from R.A. Decker, J. Haltiwanger, R.S. Jarmin, and J. Miranda, 2016, Where has all the skewness gone? The decline in high-growth (young) firms in the United States, *European Economic Review* 86:4-23, copyright 2016, with permission from Elsevier.

are both more productive and stable than the small, single-unit establishment firms that have been displaced. This highlights the fact that a high pace of start-ups and business dynamism is not an economic objective in and of itself. Instead, the optimal pace of start-ups and reallocation should balance productivity and economic growth benefits with the costs of this reallocation. The latter can be high for certain firms and individuals who experience the most change. As argued above, in retail trade this change in the business model has arguably had some positive effects where the decline in startups and dynamism is associated with improved productivity in this sector. Evidence suggests that this change has been facilitated by IT, which has enabled large multinational retail firms to develop efficient distribution networks and supply chains globally. Of potentially greater concern is the decline in high-tech start-ups and in young business activity in the United States since 2000,[37] as illustrated in Figure 4.3. Prior to 2000, high-growth firms in high tech (those with an employment-weighted growth rate in the 90th percentile) had annual net employment growth rates more than 30 percent higher than the median firms; these firms were predominantly young. Since 2000, high-growth firms declined, and the 90-50 differential dropped to less than 20 percent. This is the same period in which there has been a decline in the growth of productivity in the high-tech sectors.[38,39]

These trends, especially in the high-tech sector, raise a variety of questions. One interpretation is that changes in IT and automation have favored larger organizations. Network externalities imply common adoption of software and hardware platforms. Consistent with this, it may be that as the information and technology revolution has matured, the objective of start-ups developing new innovations has changed from internal high growth to being acquired by dominant firms in their industry. These patterns do not imply that high-growth start-ups in high tech are no longer playing an important role. It is evident that there are rapid increases in start-ups in the sharing economy; however, the business model of such start-ups is to grow via partnerships rather than by increasing numbers of paid employees. It is also possible that high-tech companies with potential for high growth are increasingly basing their production activities worldwide and thus not increasing their domestic employment. Overall, the organizational structure and incentives of start-ups may underlie these changes, which are also driven by changes in IT.

CHANGING WORKER DEMOGRAPHICS AND JOB SATISFACTION

While considering the role of information technologies in the changing nature of work, it is important to keep concurrent social changes in mind. The demographics of the U.S. population are undergoing a major shift: it has been projected that there will be no ethnic or racial majority in the United States by 2050. The demographics of today’s employees are also changing. Women make up nearly half of the labor force today and,

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[37] High Tech is defined using the approach of Daniel E. Hecker (see D.E. Hecker, 2005, High-technology employment: NAICS-based update, *Monthly Labor Review*, July, pp. 57-72). It is based on the most STEM intensive 4-digit NAICS industries. It includes all of the sectors normally considered part of the ICT industries (in the information, service and manufacturing industries).

[38] J.G. Fernald, 2015, Productivity and potential output before, during, and after the Great Recession, in *NBER Macroeconomics Annual 2014*, *Volume 29*, University of Chicago Press, Chicago, Ill.

[39] Decker et al., 2015, “Where Has All The Skewness Gone?”

as of June 2012, 36 percent of workers were not Caucasian. The millennial generation, which recently surpassed the baby boomers as the largest generation,[40] is also the most racially and ethnically diverse. As more millennials enter the workforce and older individuals retire, the racial and ethnic diversity of the workforce is expected to continue to increase.[41,42]

Even as the diversity of the workforce is increasing, significant inequalities exist. Social, economic, racial, and political backgrounds are highly correlated with academic achievement, economic opportunity, income, and social mobility. For example, the wealth gap between racial and ethnic groups has widened since the Great Recession; the Pew Research Center estimated that the 2014 median net worth of white households was 13 times that of African American households (up from a factor of 10 in 2007, and a factor of 6 from 1998-2001) and 10 times that of Hispanic households (up slightly from a factor of 8 in 2007).[43]

While an increasing number of African Americans and Hispanics have been attending postsecondary institutions, and representation of these groups at top-ranked colleges has grown slightly since the 1990s, significant disparities remain. Of the net new enrollments from 1995 to 2009, the majority (more than 80 percent) of white students went to selective colleges, while the majority (more than 70 percent) of African American and Hispanic students attended open-admissions 2- and 4-year colleges.[44,45,46]

In the long term, disparities in opportunity and achievement, and racial and ethnic isolation by school selectivity, will keep some workers at a disadvantage in meeting current and changing workforce requirements. In response, some organizations are increasing investments in

[40] R. Fry, 2016, "Millennials overtake Baby Boomers as America's largest generation," Pew Research Center, http://www.pewresearch.org/fact-tank/2016/04/25/millennials-overtake-baby-boomers/.

[41] C. Burns, K. Barton, and S. Kerby, 2012, "State of Diversity in Today's Workforce: As Our Nation Becomes More Diverse So Too Does Our Workforce," Center for American Progress, https://cdn.americanprogress.org/wp-content/uploads/issues/2012/07/pdf/diversity_brief.pdf.

[42] A. Mitchell, 2013, "The Rise of the Millennial Workforce," *Wired*, http://www.wired.com/insights/2013/08/the-rise-of-the-millennial-workforce/.

[43] R. Kochhar and R. Fry, 2014,"Wealth Inequality Has Widened Along Racial, Ethnic Lines Since End of Great Recession," Pew Research Center, http://www.pewresearch.org/fact-tank/2014/12/12/racial-wealth-gaps-great-recession/.

[44] Georgetown University Center on Education and the Workforce, Analysis of Current Population Survey, March Supplement, 1980.

[45] Georgetown University Center on Education and the Workforce, Projection of Labor Force Makeup by Race/Ethnicity, 2014.

[46] A.P. Carnevale and J. Strohl, 2013, "Separate and Unequal: How Higher Education Reinforces the Intergenerational Reproduction of White Racial Privilege," Georgetown University Center on Education and the Workforce, Washington, D.C.

diversity training programs, described as "a distinct set of programs aimed at facilitating positive inter-group interactions, reducing prejudice and discrimination and enhancing the skills, knowledge and motivation of people."[47,48]

The stagnation of median wages (discussed in Chapter 3) and the contingent nature of parts of the current workforce may be correlated with the continued decline in reported employee job satisfaction. According to one study, job satisfaction was at 61.1 percent in 1983, and this number has steadily decreased over time.[49] A recent Conference Board report[50] indicated that a majority of Americans (52.3 percent) are not satisfied with their job, and satisfaction across almost all job domains has decreased since 2011. The decreases were most pronounced in the areas of job security, health coverage, and sick leave policies. In spite of increased hiring, only 46.6 percent of employees indicated feeling satisfied with their job security (which is down from 48.5 percent before the Great Recession). Another potential source of decreased job satisfaction may be that employers are offering fewer benefits.[51] Indeed, 63 percent of workers identified this as very important to their job satisfaction.[52]

ORGANIZATIONS AND INSTITUTIONS

IT not only affects the nature of work and the labor market, but it also reshapes organizations by changing internal and geographical divisions of labor. Adoption of IT alone has not been sufficient to guarantee gains in productivity; new technologies must be accompanied by changes in the organizational structure of firms, including human resource practices.[53,54]

In addition, as technologies refashion aspects of organizations, they

[47] K. Bezrukova, K.A. Jehn, and C.S. Spell, 2012, Reviewing diversity training: Where we have been and where we should go, *Academy of Management Learning and Education* 11(2):207-227.

[48] H. Alhejji, T. Garavan, R. Carbery, F. O'Brien, and D. McGuire, 2015, Diversity training programme outcomes: A systematic review, *Human Resource Development Quarterly* 27(1):95-149.

[49] L. Weber, 2014, "U.S. Workers Can't Get No (Job) Satisfaction," *Wall Street Journal* blog, June 18, http://blogs.wsj.com/atwork/2014/06/18/u-s-workers-cant-get-no-job-satisfaction/.

[50] C. Mitchell, R.L. Ray, and B. van Ark, 2014, "CEO Challenge 2014," *The Conference Board*, https://www.conference-board.org/retrievefile.cfm?filename=TCB_R-1537-14-RR1.pdf&type=subsite.

[51] L. Weber, 2014, "U.S. Workers Can't Get No (Job) Satisfaction," *Wall Street Journal* blog, June 18, http://blogs.wsj.com/atwork/2014/06/18/u-s-workers-cant-get-no-job-satisfaction/.

[52] Society for Human Resource Management, 2015.

[53] E. Brynjolfsson and L.M. Hitt, Beyond computation: Information technology, organizational transformation and business performance, *Journal of Economic Perspectives* 14(4):24-48.

[54] N. Bloom, B. Eifert, A. Mahajan, D. McKenzie, and J. Roberts, 2013, Does management matter? Evidence from India, *Quarterly Journal of Economics* 128(1):1-51.

may also occasion new organizational forms and arrangements. Because policies and macro-institutional frameworks are becoming increasingly inadequate for this bewildering array of changes, new macro-institutional responses may be necessary. Each of these topics is addressed in turn.

Vertical Integration, Disintegration, and Geographical Proximity

Many companies took advantage of the range of technological opportunities of the late 1800s to create vertically integrated firms, an organizational form that combined many stages of the production process.[55] When the transaction and communication costs of vertically integrating different stages of production appeared prohibitive, a firm and its suppliers developed close long-term relationships, often aided by geographic proximity. The auto industry, surrounded by its various suppliers within the Detroit area, is a prime example of this structure. Over time, integrated functional organizations developed a distinct system of employment relations, distinguished by long job tenure, internal promotion structures, and an acceptance of trade and industrial unions as the main vehicle for worker voice and protection.[56] This system of organizing began to change significantly in the late 1970s. Although the major recession of that decade played a role in the system's demise, technological change also enabled companies to move away from this structure. Gradual but transformative improvements in computer and communication technology reduced the need for geographic proximity with suppliers. They also enabled a finer division of labor, parts of which could be easily outsourced. Computerized communication and information technologies allowed firms to offshore many stages of production to parts of the world where they could be performed more cheaply (often because labor was cheaper).

Products such as the iPod, although designed in the United States, are produced by combining more than 450 parts, produced in Japan, South Korea, and Taiwan, that are assembled in China.[57] A global division of labor enabled Apple to take advantage of expertise in making specific components distributed around the world (such as hard drives manufac-

[55] O.E. Williamson, 1975, *Markets and Hierarchies*, Free Press, New York; A. Chandler, 1977, *The Visible Hand: The Managerial Revolution in American Business*, Harvard University Press, Cambridge, Mass.

[56] M. Piore and C. Sabel,1984, *The Second Industrial Divide*, Basic Books, New York; T.A. Kochan, H.C. Katz, and R. B. McKersie, 1986, *The Transformation of American Industrial Relations*, Cornell University Press, Ithaca, N.Y.

[57] K.L. Kraemer, G. Linden, J. Dedrick, 2011, "Capturing Value in Global Networks: Apple's iPad and iPhone," University of California, Irvine, http://pcic.merage.uci.edu/papers/2011/value_ipad_iphone.pdf; H. Varian, 2007, "An iPod Has Global Value. Ask the (Many) Countries That Make It," *New York Times*, June 28, Section 3C.

tured by Toshiba in Japan) and of the cheaper cost of assembly in China than in the United States. Even for products that are produced domestically, geographical proximity plays less of a role than it did in the 19th and 20th centuries. As a result of these changes, organizational theories have begun to speak of network forms of organizing as an alternative to markets and hierarchies.[58]

Distributed and Interdisciplinary Teaming and Networks

Geographically distributed teams, whose members not only span a firm's domestic locations but often include members or collaborators from other countries and continents, have increased.[59] Historically, collaboration and communication among team members has required co-presence in time and space. IT can enable teamwork in the absence of co-presence and has enabled the rise of distributed teams. On the one hand, distributed teaming enables firms to take advantage of pockets of expertise regardless of where they exist and to have someone available to work on a project literally 24 hours a day. Such teams are composed of members that primarily, and in some cases only, interact via technological means.[60,61,62] Such teams are generally designed to allow for optimal team composition without the burden of travel expenses and allow workers to work more efficiently and hone skills by working on a larger variety of complex tasks; it also enables a seamless transition from one project to another.

However, the rise of distributed teams has created numerous organizational challenges, ranging from communication breakdowns and problems in the production process to cultural misunderstandings, incongruent work ethics, and the inability of team members to identify accurately

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[58] W.W. Powell, 1990, Neither market nor hierarchy: Network forms of organization, pp. 295-335 in *Research in Organizational Behavior* (B.M. Staw and L.L. Cummings, eds.), JAI Press, Greenwich, Conn.

[59] J.P. MacDuffie, 2007, 12 HRM and distributed work: Managing people across distances, *Academy of Management Annals* 1(1):549-615.

[60] W.F. Cascio, 1998, The future world of work: Implications for human resource costing and accounting, *Journal of Human Resource Costing and Accounting* 3(2):9-19.

[61] *Business Week*, 1997, "Power gizmos to power business," November 24, http://www.bloomberg.com/news/articles/1997-11-23/power-gizmos-to-power-business.

[62] S.M. Fiore, E. Salas, H.M. Cuevas, and C.A. Bowers, 2003, Distributed coordination space: Toward a theory of distributed team process and performance, *Theoretical Issues in Ergonomics Science* 4(3-4): 340-364.

who is on their team.[63,64,65] It may be necessary for organizations to create effective norms to help mitigate challenges associated with virtual tools (e.g., reduced understanding as a consequence of being unable to perceive the nonverbal cues and gestures afforded via face-to-face communication).

Similarly, the use of interdisciplinary teams (IDTs) has also gained popularity, namely in the area of health, but its usage is beginning to take root in corporate and science, technology, engineering, and mathematics (STEM) fields as well.[66] IDTs are comprised of experts within a given field that collaborate and coordinate with each other to complete complex tasks.[67] According to the American Geriatrics Society, IDTs allow medical professionals to address a patient's overall needs, which can remain unmet in a noncollaborative setting.[68] Each team member brings unique strengths to the team as a consequence of possessing different expertise. Such teams are able to collectively provide more to patients.

However, as the prevalence of IDTs grows, organizations will have to increasingly contend with the challenges such teams face; it has been suggested that employees from different disciplines may differ in regard to training, professional values, understanding of team roles, communication skills, vocabulary, and approaches to problem solving.[69] As a consequence of these differences, team members from different disciplines may ultimately lack common understanding. These problems can negatively affect team performance. For example, teamwork failures in interdisciplinary health-care teams have been linked to reduced quality of patient care. Conversely, enhanced teamwork in such teams has been

[63] D.E. Bailey, P.M. Leonardi, and S.R. Barley, 2012, The lure of the virtual, *Organization Science* 23:1485-1504; P.J. Hinds and S. Kiesler, 2002, *Distributed Work*, MIT Press, Cambridge, Mass.; M. Mortensen and P. Hinds, 2001, Conflict and shared identity in geographically distributed teams, *International Journal of Conflict Management* 12(3):212-238; C.D. Cramton and P.J. Hinds, 2005, Subgroup dynamics in internationally distributed teams: Ethnocentrism or cross-national learning, *Research in Organizational Behavior* 26:231-263.

[64] C.D. Cramton, 2001, The mutual knowledge problem and its consequences in geographically dispersed teams, *Organization Science* 12(3):346-371.

[65] P. Kanawattanachai and Y. Yoo, 2007, The impact of knowledge coordination on virtual team performance over time, *MIS Quarterly* 31(4):783-808.

[66] T.A. Slocum, R. Detrich, S.M. Wilczynski, T.D. Spencer, T. Lewis, and K. Wolfe, 2014, The evidence-based practice of applied behavior analysis, *The Behavior Analyst* 37(1):41-56.

[67] S.A. Nancarrow, A. Booth, S. Ariss, T. Smith, P. Enderby, and A. Roots, 2013, Ten principles of good interdisciplinary team work, *Human Resource Health* 11(19), doi: 10.1186/1478-4491-11-19.

[68] C.A. Orchard, V. Curran, and S. Kabene, 2005, Creating a culture for interdisciplinary collaborative professional practices, *Medical Education Online* 10(11), http://www.med-ed-online.net/index.php/meo/article/viewFile/4387/4569.

[69] P. Hall, 2005, Interprofessional teamwork: Professional cultures as barriers, *Journal of Interprofessional Care* 19(Supplement 1):188-196.

linked to increased patient care and patient safety.[70,71] Evidence suggests that team training is one method to improve effectiveness in interdisciplinary teams, allowing team members to work effectively despite differing in many respects.[72] Thus, if the trend of using IDTs continues, organizations may need to increasingly invest in training to ensure effective team performance.

Changing Employment Relationships

In addition to the changes described above, advances in IT have also helped unravel the foundation of traditional employment relationships.

Beginning with Henry Ford's car factories, during the 20th century many firms made a concerted effort to pay relatively high wages to their employees as a way of creating relationships of mutual loyalty. In particular, Henry Ford was worried about high rates of absenteeism. High wages would reduce turnover, motivate workers to work harder, and create goodwill between employers and employees.[73] Recent advances in the ability of firms to monitor their employees effectively through computer technologies and to outsource activities that can be performed more cheaply elsewhere may have reduced the need to pay attractive wages, thus reducing the cost of labor for certain types of firms and, hence, reducing the "quasi-rents" that workers enjoy from the employment relationship. The role of computerization in reducing wages has, of course, been amplified by attempts to dismantle or avoid unions[74] and by Wall Street's willingness to reward firms for finding ways to turn labor into a variable

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[70] E. J. Dunn, P. D. Mills, J. Neily, M. D. Crittenden, A. L. Carmack, and J. P. Bagian, 2007, Medical team training: Applying crew resource management in the Veterans Health Administration, *Joint Commission Journal on Quality and Patient Safety* 33(6):317-325.

[71] T. Manser, 2009, Teamwork and patient safety in dynamic domains of healthcare: A review of the literature, *Acta Anaesthesiologica Scandinavica* 53(2):143-151.

[72] Ibid.

[73] C. Shapiro and J.E. Stiglitz, 1984, Equilibrium unemployment as a worker discipline device, *American Economic Review* 74(3):433-444; G.A. Akerlof, 1984, Gift exchange and efficiency-wage theory: Four views, *American Economic Review* 74(2):79-83; T.F. Bewley, 1995, A depressed labor market as explained by participants, *American Economic Review* 85(2):250-254.

[74] T.A. Kochan, H.C. Katz, and R.B. McKersie, 1986, *The Transformation of American Industrial Relations*, Basic Books, New York; P. Osterman, T.A. Kochan, R.M. Locke, and M.J. Piore, 2001, *Working in America: Blueprint for the New Labor Market*, MIT Press, Cambridge, Mass.; A.L. Kalleberg, B.F. Reskin, and K. Hudson, 2000, Bad jobs in America: Standard and nonstandard employment relations and job quality in the United States, *American Sociological Review* 65(2):256-279.

cost, to some degree by breaching implicit, long-term agreements with workers.[75]

Furthermore, while there is much attention to the effects of IT on start-ups and on large, but relatively new, technology companies, traditional companies are also in the midst of a transformation. Walmart has been a leader in adopting supply-chain management systems, radiofrequency identification tags, and other technologies that enable it to manage its operations more efficiently, better understand customer demand, reduce costs, and substantially increase productivity. Many of its biggest successes came in the 1980s and 1990s,[76] but it is still an important force in retailing and the economy more broadly. Walmart employs far more people than Amazon, Apple, Facebook, Google, and Microsoft combined. This suggests that a large part of the impact of IT on workers is occurring through traditional firms. As noted by Zeynep Ton, there is wide variation in pay and working conditions in industries such as retail, hospitality, health care, and other big users of labor.[77] Understanding how IT is being used as part of a business strategy in firms that are providing stable jobs would be helpful in identifying private and public policy options for improving workforce conditions.

Consequences of Transformations of Traditional Organizations

The transformation of traditional organizations may have numerous and far-reaching social consequences. Three are highlighted.

First, if organizations are now providing less secure and shorter-term employment, workers may not have the financial means to withstand more lengthy spells of unemployment or underemployment. For workers to flourish in more fluid labor markets, basic skills will probably be even more important than they are today. New education policies may be needed that not only strengthen existing educational institutions (so that high schools become much better at providing basic skills as well as vocational skills) but also promote new ways of encouraging people to acquire general, portable skills. Although making college more affordable

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[75] S.R. Barley and G. Kunda, 2004, *Gurus, Hired Guns and Warm Bodies: Itinerant Experts in a Knowledge Economy*, Princeton University Press, Princeton, N.J.

[76] For instance, a report by McKinsey Global institute estimated at that as much as a quarter of the productivity revival in the late 1990s could be directly or indirectly attributed to Walmart's effects on the retailing sector and its supply chain. See, for example, B. Lewis, A. Augerau, M. Cho, B. Johnson, B. Neiman, G. Olazabal, M. Sandler, et al., 2001, "US Productivity Growth, 1995-2000," McKinsey Global Institute, http://www.mckinsey.com/global-themes/americas/us-productivity-growth-1995-2000.

[77] Z. Ton, 2014, *The Good Jobs Strategy: How the Smartest Companies Invest in Employees to Lower Costs and Boost Profits*, Houghton Mifflin Harcourt, Boston, Mass.

to more people is a reasonable first step, it is also worth reconsidering the type of skills that young people require aside from purely technical skills, which may have a short shelf life. Simply recommending that more young people attend college may not be sufficient.[78]

Second, as traditional employment relationships decrease, it is unclear how workers will secure the benefits, security, and voice that organizations provided during the mid-20th century. The result of the New Deal was a series of laws that tied permanent employment to having good health-care benefits and pension funds. As long-term employment becomes less common, new ways of providing for health care and pensions for all workers need to be considered that transcend their relationships with particular employers. For example, one option would be to institute portable pension plans administered by membership organizations dedicated to the well-being of their members.

Unions, as already noted, played an important role in the era of bureaucratically organized firms. They not only negotiated higher wages but also better working conditions, which then spread to other industries either through pattern bargaining or because firms wished to avoid being unionized. Unions also provided workers with voice. An oft-used framework for thinking about workplace relations emphasizes the balance between exit, voice, and loyalty.[79] Workers use their voice to communicate their knowledge and demands when they have high attachment to their organization; alternatively, they may use their exit option when opportunities for voice are not available. This framework, although conceptually powerful, has become less applicable today: more workers choose to or are forced to exit despite their willingness to stay. To the degree that exit becomes more attractive than voice, organizations lose the communication channels that traditional unions were able to provide. This may imply the need for new organizational pathways for ensuring that workers continue to have a voice, both about their working conditions as well as broader societal issues.

In industries where unionization is in significant decline, the best a union can do is negotiate a better deal for their remaining members, often at the expense of other workers. New organizational pathways for workers to have an effective voice in the face of increasingly fluid work conditions are becoming even more important.

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[78] See D. Acemoglu and D. Autor, 2011, Skills, tasks, and technologies: Implications for employment and earnings, pp. 1043-1171 in *Handbook of Labor Economics, Volume 4b*, Elsevier B.V., Amsterdam, The Netherlands; and P. Beaudry, D.A. Green, and B.M. Sand, 2014, "The Great Reversal in the Demand for Skill and Cognitive Tasks," National Bureau of Economic Research, doi: 10.3386/w18901.

[79] A.O. Hirschman, 1970, *Exit, Voice, and Loyalty*, Harvard University Press, Cambridge, Mass.

Guaranteeing a voice to workers in a more flexible and uncertain economy may require entirely new organizational forms. There are two alternatives of note that have been used in other countries. The first is the German-style work council, which is as focused on communication and coordination as it is on negotiation. Although these councils have flourished in the context of traditional organizations, a more flexible version could play a role in the age of more fluid organizations. The second is the Scandinavian-style industry or occupational union, which represents workers across establishments, thereby enhancing resilience in the face of very high mobility across firms. Once again, the traditional form of these trade unions is probably inadequate for the modern organization (because the industry or occupation may not be the right level of aggregation), but it may provide a stepping stone for a more appropriately tailored pathway of communication for the modern age.

Third, more attention could be given to the "macro-institutions" that determine national or state-level frameworks and policies. The need to rethink these macro-institutions stems from two distinct but related considerations. First, many of the organizational issues that require fundamental modification cannot be done in a decentralized fashion. Making health insurance and pension benefits more portable within the economy is not something that individual firms can achieve. Nor can local communities independently provide a modern social safety net; this requires appropriate tax and redistribution policies from state and federal governments. One such policy that has been considered in the United States in the past (and is currently being tested and studied in the Netherlands) is a minimum guaranteed income for all; this has been discussed as a potential safety net against technological or other widespread unemployment.[80] Even with new organizational forms for worker representation, it would likely be necessary for the federal government to be involved by, for example, rewriting labor laws to enable such a transformation.

The potential for many new technological developments to lead to inequality, at least in the medium run, and the potential of some of these technologies, through automation, to reduce employment opportunities for major segments of the population, make the need for responsive national policies more important than ever, in the committee's judgment. At the same time, many feel that today's political institutions are less responsive and less accountable to the welfare of the whole. Part of this may be unrelated to technology and may result from a change in the distribution of power between different segments of society (or it may be

[80] In particular, the experiment is studying the impact of an annual income equivalent to roughly US$13,000 (T.B. Hamilton, 2016, "The Netherlands' upcoming money-for-nothing experiment," *The Atlantic*, June 21).

driven by ideological factors that have made major political parties in the United States less responsive). However, even these developments may be a result of technological change. Some technological transformations may have increased the political voice and power of some segments of society over others. Some writers contend, for example, that Wall Street's rise to political power is partially rooted in technological capabilities that allow traders and hedge fund managers to accumulate wealth at a faster rate than other groups.[81]

No matter what its causes, the debate over increasing the responsiveness and accountability of the political process is an important part of the broader debate about how to reshape organizations and institutions to be more congruent with social needs, including vibrant dialogue on how to make better use of new technologies. Some of this has already taken place in other countries, for example, by enabling greater voter participation and direct input into politics and creating greater transparency.

THE ROLE OF WORK IN OUR LIVES

Work occupies a great deal of people's time and attention and has played a central role in shaping a sense of worth and identity. More importantly, in the context of this report, technological developments have at least indirectly shaped how people experience the place of work in their lives. For example, prior to the development of the clock and eventually electrical lighting, work time and personal time were largely synchronized to daily and seasonal cycles. Following the spread of these technologies, work hours became partially decoupled from nature's cycles. Stints of work grew increasingly longer until, after decades of union agitation, Congress eventually passed the Fair Labor Standards Act of 1938, which limited the standard work week to a maximum of 40 hours and mandated premium pay for additional hours.[82] The 8-hour day, coupled with the routine and repetitive nature of many jobs (such as typing, data entry, and operating machine tools on assembly lines), contributed to the separation of work and leisure typical of many workers of the 1940s through the 1970s. After working an 8-hour shift, workers returned to their homes exhausted and fatigued, but the evenings were theirs to use

[81] N. Fligstein, 1993, *The Transformation of Corporate Control*, Harvard University Press, Cambridge, Mass.; M. Lewis, 2014, *Flash Boys*, Norton, New York.

[82] J. Grossman, "Fair Labor Standards Act of 1938: Maximum Struggle for a Minimum Wage," United States Department of Labor, https://www.dol.gov/oasam/programs/history/flsa1938.htm#1.

as they wished, and weekends became times for leisure and for dreaming of vacations and retirement.[83]

Computerized information and communication technologies are similarly affecting workers' lives on at least four fronts: (1) the gradual erasure of the boundaries between work and other aspects of their lives, particularly the family; (2) the use of computer systems to monitor workers' performance, with potential intrusion on the workers' privacy; (3) the potential to displace the physical workplace as a primary locus of social identity and sociality; and (4) shifts in the labor market that could help confound gender stereotypes.

Because of IT (including e-mail, teleconferencing systems, and the use of the Web as a work tool), it is now much easier for work to spill over into workers' family life in any field that employs them. Although these developments are often heralded as a form of freedom that can allow individuals to work from anywhere at any time, thereby maximizing a worker's temporal freedom and flexibility, there is considerable evidence that such flexibility has come at the cost of blurring the boundaries between work and other aspects of life. Over the last several decades, researchers have accumulated a large body of research on work-family balance, and most of the evidence points toward a single conclusion: work has begun to infiltrate times and places it previously did not (and vice versa), potentially leading to an increase in work-family conflict.[84] Although the rise of dual-career families has contributed strongly to these developments, the use of IT is also strongly implicated.[85] When workers are linked on distributed teams, the ability to hold meetings and send

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[83] For excellent account of the role of work and leisure among blue collar factory workers of the 1940s and 1950s, see C.R. Walker and W.H. Guest, 1952, *The Man on the Assembly Line*, Harvard University Press, Cambridge, Mass.

[84] J.B. Schor, 1993, *The Overworked American: The Unexpected Decline of Leisure*, Basic Books, New York; J.A. Jacobs and K. Gerson, 2004, *The Time Divide: Work, Family and Gender Inequality*, Harvard University Press, Cambridge, Mass.; P. Moen, 2003, *It's About Time: Couples and Careers*, ILR Press, Ithaca, N.Y.; L. Alvarez, 2005, "Got 2 Extra Hours for Your E-Mail?," *New York Times*, November 10, http://www.nytimes.com/2005/11/10/fashion/got-2-extra-hours-for-your-email.html?_r=0; W.C. Murray and A. Rostis, 2007, Who's running the machine? A theoretical exploration of work, stress and burnout of technologically tethered workers, *Journal of Individual Employment Rights* 12:349-263.

[85] J.A. Jacobs and K. Gerson, 2004, *The Time Divide: Work, Family and Gender Inequality*, Harvard University Press, Cambridge, Mass.; L.A. Dabbish and R.E. Kraut, 2006, "Email Overload at Work: An Analysis of Factors Associated With Email Strain," pp. 431-440 in *Proceedings of the ACM Conference on Computer Supported Cooperative Work*, ACM Press, New York; N. Chesley, 2005, Blurring boundaries? Linking technology use, spillover, individual distress, and family satisfaction, *Journal of Marriage and Family* 67:1237-1248; K. Renaud, J. Ramsay, and M. Hair, 2006, 'You've got e-mail!' . . . . Shall I deal with it now? Electronic mail from the recipient's perspective, *International Journal of Human-Computer Interaction* 21(3):313-332.

work-related e-mails across time zones extends people's work into the mornings before they go to the office and into the evenings after they come home.[86] The ability to engage in work-related communications during lunches, dinners, and even social events leads people to feel obligated to do so and infuses settings that were previously primarily social with work-related content.[87] At the same time, technology provides increased opportunities for leisure activities at work, from mobile games and online shopping to social media and personal communications. There is evidence that the blurring of work and other aspects of life are especially common among people in managerial, professional, and technical occupations.[88] Given the strength of the research on this phenomenon and the evolving functionality of smartphones, there is no reason to believe this phenomenon will disappear. In short, information and communication technologies appear to be eliminating the boundary between work and the other arenas of life that were forged by the combination of technologies, institutions, and social understandings that marked the mid-20th century.

Over the last several decades, employers have increasingly used information technologies to monitor the productivity and diligence of white-collar workers, even as the shift from physical to mental tasks reduced the direct visibility of many types of work. The use of data collected by computers and information technologies enables employers to impose and enforce productivity objectives and to reward and punish workers who do or do not achieve those objectives. Although this kind of monitoring is widespread in call centers, for example, where workers are expected to handle a set number of calls per unit time and to spend a set number of minutes per call, monitoring also extends to workers of all types, including professionals.[89] Computerized monitoring extends and intensifies the kind of performance monitoring analogous to the time and motion studies typically conducted by industrial engineers in factory set-

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[86] S.R Barley, D.M. Meyerson, and S. Grodal, 2011, Email as a source and symbol of stress, *Organization Science* 22:262-285.

[87] M. Mazmanian, J. Yates, and W.J. Orlikowski, 2006, "Ubiquitous Email: Individual Experiences and Organizational Consequences of Blackberry Use," in *Proceedings of the 65th Annual Meeting of the Academy of Management*, Academy of Management, Atlanta, Ga.

[88] S. Schieman and P. Glavin, 2008, Trouble at the border?: Gender, flexibility at work, and the work-home interface, *Social Problems* 55(4):590-611; S. Schieman and P. Glavin, 2011, Education and work-family conflict: Explanations, contingencies and mental health consequences, *Social Forces* 89(4):1341-1362.

[89] R. Batt and L. Moynihan, 2002, The viability of alternative call center production models, *Human Resource Management Journal* 12(4):14-34; R. Batt, V. Doellgast, and H. Kwon, 2006, Service management and employment systems in U.S. and Indian call centers, in *Brookings Trade Forum 2005: Offshoring White-collar Work—The Issues and Implications* (S. Collins and L. Brainard, eds.), Brookings Institution, Washington, D.C.

tings to white-collar and professional work. Monitoring has been poorly received in the past by blue-collar employees; some attempts to put such monitoring systems into place led to strikes, for instance the 1911 strike at the Watertown Arsenal in response to Frederick Taylor's attempt to introduce time and motion studies.[90] It is not clear that contemporary workers are any more willing to accept computerized monitoring, assuming that they are aware it is happening, but they are less likely to possess forums for collective action.

For many, the workplace acts as a site for social engagement, both positive and negative, and serves as a key interface between people's working and personal lives. Indeed, out of social interactions at the workplace and the work that people actually perform, they construct significant components of their identities and self-worth. Communication technologies shape many aspects of when, where, and how social interactions occur and the tenor of their experience. If work becomes less centered on a specific geographic locality, this will fundamentally transform the nature of the social interactions around work. Offshored call-center workers provide an illuminating example. On the one hand, the call center itself may continue to serve as a site of interaction, camaraderie, and competition, while on the other hand, it shifts relations at home when a spouse, sibling, or parent works nights and learns to speak in another accent.[91] In short, the offshoring of work via new communications technology can bring to people in other cultures some of the same work-family dynamics found in the United States and discussed above. Other benefits of virtual working include the potential for greater inclusion of people with disabilities and those with children or elder dependents. But not every organization or person will find that this model works for them.

More generally, however, the rise of distributed and contingent project-based work that can be completed from anywhere, including one's home, while attractive to some workers (especially parents of young children), threatens to undermine the social benefits of being co-present with others in a workplace. Indeed, one of the chief complaints of full-time telecommuters has long been the sense of being isolated and disconnected from one's colleagues and the fear that being away from the workplace will lead to fewer opportunities for visibility and advancement.[92] Despite

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[90] H.G.J. Aitken, 1985, *Scientific Management in Action: Taylorism at Watertown Arsenal, 1908-1915*, Princeton University Press, Princeton, N.J.

[91] A. Aneesh, 2006, *Virtual Migration: The Programming of Globalization*, Duke University Press, Raleigh, N.C.

[92] R.E. Kraut, 1989, Telecommuting: The tradeoffs of home work, *Journal of Communication* 39:19-47; D.E Bailey and N.B. Kurland, 2002, A review of telework research: Findings, new directions, and lessons for the study of modern work, *Journal of Organizational Behavior* 23(4):383-400; L.A. Perlow, 1997, *Finding Time*, ILR Press, Ithaca, N.Y.

a great deal of initial fanfare, telecommuting was for decades actually quite rare because managers discouraged it regardless of company policy and, in part, because only certain occupations performed work that was amenable to long absences from the workplace (for instance, software developers and academics). However, working when and where one prefers may become an option for more people with the increased access to work through digital devices and Internet connections, including open-call work platforms, and more opportunities for just-in-time contracts and other temporary work arrangements. Such arrangements preclude the opportunity for social engagement and the sustained work relationships afforded by spatial and organizational co-location.

Under such circumstances, what role will work play in shaping social identities and sense of self? At the moment, very little is known about this topic. There is a long stream of research on careers that suggests that people will construct careers and identities whether or not they have the support of an organization or a recognized occupation.[93] But what sort of identities, careers, and selves will people construct in the future, for example, if work becomes a series of gigs done for and with people one never actually meets? Conceivably, under such conditions, people will reemphasize connections with nonwork friends and family. They may also construct unique careers by acquiring additional skills and achievements. But, coupled with the previously discussed precariousness of making a living in contingent labor markets, the committee suspects that these changing employment relations will alter the role work has played in how people assess their sense of value and self-worth.

Gender is yet another aspect of the interplay between technology and work. Most new occupations begin without a gender label, until they are filled by employers and gender correlations emerge.[94] To the extent that IT contributes to the creation of new occupations, it provides employment opportunities that are less likely to be associated with gender stereotypes. To the extent that IT and automation may contribute to the displacement of jobs, they are likely to encroach more slowly on many types of care and interactive service work—occupations that have been traditionally populated by women. Indeed, many of the fastest-growing occupations are in labor-intensive service and care occupations, such as child care, nursing, and health technicians. According to the Bureau of Labor Statistics, the health care and social assistance sector is projected to experience the

[93] E.C. Hughes, 1958, *Men and Their Work*, Free Press, Glencoe, Ill.; S.R. Barley, 1989, Careers, identities, and institutions: The legacy of the Chicago School of Sociology, pp. 41-66 in *Handbook of Career Theory* (M.B. Arthur, D.T. Hall, and B.S. Lawrence, eds.), Cambridge University Press, New York.

[94] For historical examples, see R. Milkman, *Gender at Work: The Dynamics of Job Segregation by Sex during World War II*, University of Illinois Press, 1987.

largest number of new jobs creation from 2014 to 2024.[95] If this trend continues, a key question is whether men will also seek employment in such occupations and find it fulfilling. There are very few historical instances of occupations being transformed from female to male occupations (the converse is more common), although males entering traditionally female fields often ride a "glass escalator" to the upper levels of the field.[96] The extent to which gender roles and other work-related aspirations might or might not conflict with the new world of employment that technology is creating, and how such social attitudes might be formed or reformed, is an open question for research. Rethinking attitudes toward these roles could benefit women as well as men, since the persistent gender gap in pay is tightly intertwined with occupational segregation by gender.

EDUCATION AND JOB TRAINING

Technological progress affects the demand for education and training and how education and training are provided.

The common perception that college students are all young adults who enroll in a 4-year college upon completion of high school is no longer correct. For the past 30 years, close to a third of students enrolled in postsecondary institutions have been over the age of 30, and they have pursued various types of professional credentials that include but are no longer limited to bachelor's degrees. These students enroll for many reasons, especially to become more effective or competitive in their current jobs.[97]

In the 21st-century economy, higher levels of educational attainment correlate to higher earnings in a given field. However, earnings can vary greatly from field to field, so skills and field of training are an important currency in job markets.[98] If workers take on a larger variety of jobs over their career, or if skills requirements shift (whether due to technology or other economic factors), they will need to learn a more diverse set of

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[95] The Bureau of Labor Statistics has projected roughly 3.8 million new health care and social assistance jobs between 2014 and 2024, nearly 40% of all new jobs; see Bureau of Labor Statistics, "Table 2, Employment by Major Industry Sector," Economic News Release, last modified December 8, 2015, http://www.bls.gov/news.release/ecopro.t02.htm.

[96] B. Reskin and P. Roos, 1990, *Job Queues, Gender Queues*, Temple University Press, Philadelphia, Pa.; C. Williams, 1995, *Still a Man's World: Men Who Do Women's Work*, University of California Press, Berkeley, Calif.

[97] A.P. Carnevale, N. Smith, M. Melton, and E.W. Price, 2015, *Learning While Earning: The New Normal*, Georgetown University Center on Education and the Workforce, Washington, D.C.

[98] A. Carnevale, S.J. Rose, and B. Cheah, 2011, *The College Payoff: Education, Occupations, Lifetime Earnings*, Georgetown University Center on Education and the Workforce, Washington, D.C.

skills over time. This requires an educational system that provides access to continuing education relevant to the changing nature of work. It also requires a primary and secondary education that prepares students to be flexible learners who are capable of acquiring more diverse skills over time.

At the same time, IT is changing how education is provided—both the nature of coursework, and access to education via the Internet. As described in the section "Educational Tools and Platforms" in Chapter 2, recent years have witnessed a growth in the availability of online classes over the Internet, creating a new mechanism for access to education by students worldwide. Organizations such as Coursera, edX, and Khan Academy offer hundreds of online courses, and companies such as Udacity now team with employers to create and deliver online training in areas that enable employees to move up the career ladder and acquire skills in high demand. The promise of change in online education is enabled by a combination of broad access to the Internet, ease of creating video and recorded lectures and hosting them (e.g., on YouTube), and innovations in combining lecture-style training, online exercises, and crowd-sourced grading. Although this model of online education is still young and its eventual impact unproven, it does offer the promise of a potentially significant increase in access to education. By globalizing the delivery of education, it also holds the potential of giving students access to the best teachers worldwide, although the extent of this access will be limited to the volume of participating students. Despite the increased availability of courses and educational materials over the Internet, there is a large skew in the utility of this content to different types of students and in the educational topics covered. Furthermore, as discussed in Chapter 2, there is evidence that online courses benefit most those students who already have well-developed learning skills and a strong educational background, and may leave students already behind in education even further behind.

It should be noted, however, that a large number of "traditional" universities also provide a wide range of online education programs leading to undergraduate and graduate degrees, and these programs have a separate set of rankings within the *US News and World Report* ranking system.[99] Students enrolled in online degree programs may complete some or all of their courses online, resulting in degrees with identical designations and transcript notations as campus-only students. Not only bachelor's but master's degree programs are taught with this model, which emphasizes students' ability to return to gain additional "lifelong learning" experiences while working full time in a professional setting.

[99] *U.S. News*, 2016, "Best Online Programs—U.S. News & World Report Rankings," http://www.usnews.com/education/online-education, accessed April 2016.

In contrast to MOOC (massive open online course) models such as those promoted by Coursera or edX, some traditional universities have been engaged in distance education for 40 years or more, ranging from radio and television programs[100] to web-based offerings.[101] The advances of IT access and bandwidth have reduced the barriers of delay and cost compared to sending audio or video tapes through the U.S. Postal Service. Even during the 1990s, when this model of videotapes through mail delivery was the dominant form of "distance education," more than 1,200 U.S. higher-education institutions were engaged in distance education, enrolling over 1 million students per year.[102] From this perspective, IT can be seen as enabling and enhancing a traditional form of public higher education, rather than a completely new approach to higher education. The difference in perspectives may be due in part to differences in assumptions about the content (what) and form (for whom) of higher education, and not just its mechanisms for delivery (how).

As for *what* needs to be learned by future employees, the situation is even more complex. Surveys of employers show that they evaluate both elements of domain knowledge (things one knows about) and specific skills (things one knows how to do) when considering employment readiness.[103] In fact, areas of domain knowledge, facility with specific tools and interfaces, and communication skills can even be considered as distinct *dimensions* of expertise, with different foundations as well as varying demands for education and training programs.[104] It is unrealistic to assume that all members of the U.S. populace should be able to interchangeably attend any model[105] of educational institution and receive an

[100] *Wikipedia*, "Sunrise Semester," last modified May 2016, https://en.wikipedia.org/wiki/Sunrise_Semester.

[101] Purdue Engineering, 2016, "Accreditations & Rankings," https://engineering.purdue.edu/ProEd/accreditations-rankings, accessed April 2016; D. Goldberg, 1998, "Learning from a Distance," *The Washington Post*, April 5, https://www.washingtonpost.com/archive/1998/04/05/learning-from-a-distance/124a3b3b-c1c6-46fc-8d50-bcdaaa61cdca/.

[102] D. Goldberg, 1998, "Learning from a Distance."

[103] J. Casner-Lotto, L. Barrington, and M. Wright, 2006, "Are they really ready to work?," *Conference Board*, http://www.p21.org/storage/documents/FINAL_REPORT_PDF09-29-06.pdf.

[104] S.K. Garrett, B.S. Caldwell, E.C. Harris, and M.C. Gonzalez, 2009, Six dimensions of expertise: A more comprehensive definition of cognitive expertise for team coordination, *Theoretical Issues in Ergonomics Science* 10(2):93-105; J. Winterton, F. Delamare-Le Deist, and E. Stringfellow, 2006, "Typology of knowledge, skills and competences: clarification of the concept and prototype," Office for Official Publications of the European Communities, Luxemburg, http://www.cedefop.europa.eu/files/3048_en.pdf.

[105] Higher-education institutions can be separated into four general emphases, based on four distinct historical contexts. The "liberal arts college" model derives from a European tradition, where general knowledge and intellectual refinement, rather than specific job skills development, were the primary goals. By contrast, the "vocational" programs in community

interchangeably robust experience to attain broad knowledge, a vast array of specific job skills, and fluid access to any element of the workforce. As IT continues to impact the evolution of types and numbers of jobs available, as well as the skills required for these positions, educational options must shift as well. It is in the best interest of society to develop a system that enables everyone who wants to work to have employable skills. If this does not happen, societal tensions will mount, and those unable to adapt will be left further behind and dependent upon social safety nets. Studies on the adaptability of workers from different educational and demographic backgrounds could highlight areas where changes to the educational system or new economic or social policies would help.

It is very difficult to predict specific future skills needs for different components of the workforce.[106] There are three areas of capabilities that can be emphasized: (1) general adaptability, as evidenced by critical thinking and flexibility of learning approach;[107] (2) capacity for lifelong learning;[108] and, as mentioned previously, (3) social skills.[109]

For decades, American companies have sent manufacturing work overseas to places with significantly lower wages, such as China, Vietnam, India, and the Philippines. As mentioned previously, IT facilitated this by enabling communication between headquarters and remote locations. This "off shoring" reduced production costs in the manufacturing sector, translating into cheaper prices for U.S. consumers. Since 2009, some

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colleges are more the philosophical heirs of the apprenticeship guilds of pre-industrial Europe, where students focused primarily or exclusively on the activities of particular trades (J.L. Epstein, 1988, "Homework Practices, Achievements, and Behaviors of Elementary School Students," Center for Research on Elementary and Middle Schools, http://files.eric.ed.gov/fulltext/ED301322.pdf). A third, "practical arts" model of public universities grew largely out of the Morrill Act of 1861-62, substantially changing American attitudes towards engineering and agriculture as a more economic- and jobs-based form of education among the land grant universities (J.Y. Simon, 1963, "Politics of Morrill Act," *Agriculture History,* Volume 37, p. 103). (Importantly, a second "land-grant" Act of 1890 led to the development of a set of institutions for the training of African-Americans, creating a majority of what is now known as Historically Black Colleges and Universities, or HBCUs, such as North Carolina A&T, Prairie View A&M, or Tuskegee (Conner et al., 2006). A subset of "liberal arts" and "practical arts" universities have also evolved, primarily since World War II, to create the concept of a fourth type of university: the "research university," where fundamental advancements in knowledge occurs with substantial extramural funding from government, industry, and research enterprise sources.

[106] This was a recurring theme at the committee's information-gathering workshop. See Appendix B for workshop agenda.

[107] D.F. Halpern, 1998, Teaching critical thinking for transfer across domains: Dispositions, skills, structure training, and metacognitive monitoring, *American Psychologist* 53(4):449-455.

[108] R. Blakiston, 2011, Building knowledge, skills, and abilities: Continual learning in the new information landscape, *Journal of Library Administration* 51(7-8):728-743.

[109] D.J. Deming, *The Growing Importance of Social Skills in the Labor Market*, National Bureau of Economic Research, 2015, doi: 10.3386/w21473.

American companies have begun bringing some manufacturing back to the United States in a process known as "reshoring."[110] Multiple factors are understood to contribute to this trend. In part, further improvements in technology have reduced some labor requirements of manufacturers, which in turn reduces the importance of lower labor costs overseas.

At the same time, rising wages overseas, growing risk of reengineering of products by overseas competitors, geopolitical risks, natural disasters, evolution toward customization of products to the preferences of individual consumers (aided by closer proximity to consumers), and growing demand for faster delivery have also increased incentives for companies like GE and Whirlpool to reshore some of their production activities to the United States. Such new efforts have renewed concerns about skills shortages in technical fields that have grown in importance to manufacturers. This has led to renewed efforts to find more efficient ways of training workers for middle-skill jobs. However, as automation of manufacturing processes continues, there may be lower overall demand for manufacturing workers, whether abroad or reshored.[111] The impact of this trend on jobs in the developing world may be substantial; however, this topic is beyond the scope of this report.

A number of discussions regarding an increasing emphasis on certifications and "badges" have attempted to clarify the ability of employers to evaluate "what one knows about" and "what one knows how to do" in rapidly changing organizational contexts and technological environments. There have been calls for more traditional universities to provide more badges and more specific open-access training modules, and even patents for evaluating and calibrating such badges.[112] Unfortunately, such efforts to provide badging are themselves subject to substantial conceptual development and empirical and theoretical research, and in some cases subsequent disconfirmation.[113] Conversely, some specific skills

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[110] According to one report, between 2003 and 2014 the United States has gone from losing 140,000 manufacturing jobs per year to offshoring to gaining 10,000 manufacturing jobs per year due to reshoring and foreign direct investment (Reshoring Initiative, 2014, *Reshoring Initiative Data Report: Reshoring and FDI Boost Manufacturing in 2014*, Kildeer, Ill.).

[111] M.B. Sauter and S. Stebbins, 2016, "Manufacturers Bringing the Most Jobs Back to America," *USA Today*, April 23, http://www.usatoday.com/story/money/business/2016/04/23/24-7-wallst-economy-manufacturers-jobs-outsourcing/83406518/.

[112] T.V. Kurien, D.F. Brinkman, V. Balasubramaniam, S. Sinha, A.R. Gaglani, and T.S. Nene, "U.S. Patent: 13/925,632—Badge Notification Subscriptions," October 9, 2014; T.V. Kurien, D.F. Brinkman, V. Balasubramaniam, S. Sinha, A.R. Gaglani, and T.S. Nene, "U.S. Patent: 13/925,619—Badge Authentication," October 9, 2014; T.V. Kurien, D.F. Brinkman, V. Balasubramaniam, S. Sinha, A.R. Gaglani, and T.S. Nene, "U.S. Patent: 13/925,630—Badge Local Grouping According to Skills and Training," October 9, 2014.

[113] See, for example, S. Abramovich, C. Schunn, and R.M. Higashi, 2013, "Are Badges Useful in Education? It Depends Upon the Type of Badge and Expertise of Learner," Associa-

badges, such as training in automotive robotics, have been in place for nearly 30 years.[114]

New competency-based education and noncredit education models that empasize mastery rather than accomulation of course hours could also benefit students and workers who return to college for job training. Such approaches are common in vocational or career-based education and training programs, with curriculum often informed directly by local employer needs. They enable direct matching of individuals with employment opportunities, and can be ideal for those whose time is largely already dedicated to work.

Despite innovations in the delivery of education, several rigidities remain, particularly in enrollment and completion disparities in postsecondary institutions linked to race and ethnicity, propoagated from those apparent from K-12. As school attendance in most school districts is based on residence, residential segregation has resulted in de facto segregation of schools. And though college attendance has increased, for African Americans and Hispanics, participation is lower for these students compared to white students, and they have lower completion rates and less favorable post-graduation outcomes largely because they are more likely to attend open-access or less-selective colleges. African Americans and Hispanics who attend a selective college exhibit 50% higher completion rates and earn 21 percent more than those who attend open-access schools.[115] In today's information-based economy that favors skills, this means that many low-income and minority groups lack access to many of the skills and opportunities higher education provides.[116] Regardless of reason, it has been suggested that many community college students are unprepared to move into the realms of advanced liberal arts

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tion for Educational Communications and Technology, http://www.lrdc.pitt.edu/schunn/research/papers/Abramovich-Schunn-Higashi.pdf; R. Elliott, J. Clayton, and J. Iwata, 2014, Exploring the use of micro-credentialing and digital badges in learning environments to encourage motivation to learn and achieve, pp. 703-707 in *Rhetoric and Reality: Critical Perspectives on Educational Technology. Proceedings of the Ascilite Conference* (B. Hegarty, J. McDonald, and S.K. Loke, eds.); R.S. Davies, D.L. Randall, and R.E. West, 2015, Using open badges to certify practicing evaluators, *American Journal of Evaluation* 36(2):151-163; E. Fields, 2015, Making visible new learning: Professional development with open digital badge pathways, *Canadian Journal of Library and Information Practice and Research* 10(1).

[114] H. Shimatake, 1987, Training in robotics at Nissan Motor Company, *Advanced Robotics* 2(4):389-395.

[115] A.P. Carnevale and J. Strohl, 2013, *Separate & Unequal: How Higher Education Reinforces the Intergenerational Reproduction of White Racial Privilege*, Georgetown Public Policy Institute Center on Education and the Workforce, Washington, D.C., https://cew.georgetown.edu/wp-content/uploads/2014/11/SeparateUnequal.FR_.pdf.

[116] Ibid.

or research university environments, either from a technology innovation or advanced communication skills perspective.[117]

It may have once been thought that more advanced educational attainment, as is characteristic of the research university, would make one immune to the IT-based automation affecting others in the workforce. Evidence suggests this is no longer the case. For example, automated image recognition and processing is changing the work of the research astronomer, and robotic techniques for automatic gene sequencing affect the need for graduate assistants in bench research in the life sciences. Thus, prior lessons gained from training shop-floor operators in increasingly automated manufacturing settings[118] could be important across a range of job categories whose associated tasks were previously thought to be uniquely human activities.

Technical change and evolving work models are leading to new demands for a more flexible and lifelong educational system, while at the same time providing the basis for new kinds of broadly accessible online education. Primary, secondary, and postsecondary educational institutions, including the liberal arts, practical arts, and vocational schools and research universities, attempt to offer different types of education. The curricula of all of these may need to be reevaluated and redesigned to better meet the needs of future workers.

The rapid recent growth in online education at both post-secondary (e.g., edX) and primary and secondary levels (e.g., Khan Academy) provide a new kind of educational resource—one where geographic distance need not prevent access, although access to the necessary technology is still not universal. These tools may also facilitate a lifelong learning approach that makes it easier for many people to update their knowledge and skills throughout their careers (though, as noted in Chapter 2, the reach and efficacy of such technology-enabled platforms likely varies with student demographics). For all these types of education providers, a key unknown is exactly what should be taught in order to best prepare individuals for their future career. It is easy to support the idea of education that prepares the workforce for future dynamism in employment opportunities and enables lifelong learning. It is much more difficult to answer the question of what specifically to teach, and how, in order to achieve that educational goal. This is a question deserving of substantial new research and experimentation.

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[117] H. Coates, 2013, Assessing higher education outcomes and performance, in *Tertiary Education Policy in Australia* (S. Marginson, ed.), Centre for the Study of Higher Education, University of Melbourne, Melbourne, Australia.

[118] See, for example, A. Pennathur, A. Mital, V. Rajan, D. Kaber, P. Ray, R. Huston, D. Thompson, et al., 1999, A framework for training workers in contemporary manufacturing environments, *International Journal of Computer Integrated Manufacturing* 12(4):291-310.

SUMMARY

Several important themes emerged from the committee's review of how technology is changing the nature of work and organizations.

1. In the judgment of the committee, contingent work will expand as a result of the continued use and development of computer-based information technologies and business models based on web-based matching algorithms.
2. With the decline of unionization, the prevalence of contingent work, and a more mobile workforce, new institutions that also offer workers a greater voice in their workplace and in the political arena are becoming increasingly important for worker fairness and equality.
3. Because work has become increasingly nontraditional (detached from single employers over the course of a career), enabled in part by technology, employment institutions may need to change in order to provide all workers with access to health care, pension funds, and other elements of the social safety net that have been historically tied to full-time traditional employment.
4. Because of the increasing ability to use IT to reduce the need for co-location, a widening geographical division of labor is likely to continue, and new ways of organizing that preclude regular face-to-face interaction will emerge, at least for those tasks in which direct interaction is not essential.
5. To the degree that IT alters the skill structure on which the division of labor is based, educational systems will need renewed attention. Although encouraging more young people to pursue a college education and acquire the skills needed for service-oriented jobs or for STEM fields makes sense, these efforts will not be sufficient; strategies for strengthening social and other uniquely human skills and enabling flexibility in the face of changing circumstances will likely be important.
6. The exact nature of the changes depends not only on technological advances, but on a complex interplay of skills, organizations, institutions, culture, and policies. There is no guarantee that economic and social changes will be gradual or that they will be beneficial for everyone. Unanticipated breakthroughs not only in technology, but in any of these other factors, or in their interaction, could lead to large-scale disruption of the status quo.

Research on how work fits into and shapes the lives of individuals who are pursuing new forms of employment would help elucidate the range of potential outcomes and the policy and other choices that will create the greatest benefits for society. New data and methods would enable this research. These issues are discussed in more detail in Chapters 5 and 6.

5

Data Sources and Methods

INTRODUCTION

We can be confident that technologies and applications for digitization and automation will continue to advance. However, it is difficult to predict the exact nature of these advances, much less their myriad effects on the U.S. workforce. This underscores the need for careful and timely evaluation and monitoring of trends in technology and the workforce, and for an improved understanding of the relationship between the two. Such analyses will rely heavily on data, and new data sets and analyses may be needed or become available as the landscape continues to change.

Today, a variety of data sets exist that contain important information about technology, workers, employment, and the national economy. In particular, federal statistical agencies have been the predominant source for national-level collection of economic, employment, and demographic data about individuals and businesses. Additional data are increasingly being collected by other means, both in the private sector and by academic researchers. Such data range from "naturally occurring" data, created and saved as a byproduct of digital transactions, to detailed case studies of a work process or environment, obtained by methodical, scientific observation of employees at work. All of these categories of information present both advantages and challenges.

In this chapter, the committee discusses (1) key existing federal data sets and how they inform understanding of the impact of technology on the U.S. labor market and the economy at large; (2) emerging data sources and analytical tools that are increasingly enabled by the Internet and digitization of information; (3) the use of ethnographic and other qualitative data for understanding causality, and (4) strategies for quantifying technological advancement and its ability to automate work functions. The committee then addresses the value of integrating these diverse data sets to better understand the implications of technology in the changing workforce, both from the top down and the bottom up.

DATA FROM FEDERAL STATISTICAL AGENCIES

The U.S. government collects important economic and employment data that have been critical for understanding workforce trends and the changing nature of firms and workplaces.

There are three primary and general federal statistical agencies: the Bureau of the Census, the Bureau of Economic Analysis (BEA), and the Bureau of Labor Statistics (BLS); additional federal statistical agencies are dedicated to particular sectors or activity of specific types, such as the National Center for Health Statistics (NCHS).

The agencies collect data via surveys on both households and businesses, yielding statistics that are made available to the public and aggregated at the national, state, local, and industry levels. Tabulations at these levels are further classified by worker characteristics, such as demographics and education, and firm characteristics, such as firm size and firm age. Individual-level data from household surveys are also released to the public in aggregate to protect privacy and confidentiality. The data collected and statistics produced from these surveys are used to generate key national economic indicators such as gross domestic product (GDP), productivity, employment, unemployment, and inflation.

In addition, federal agencies obtain administrative data as byproducts of various programs and activities, such as household and business tax collection and related filings or other transactions or record keeping. Core administrative data are housed at the Internal Revenue Service and Social Security Administration, both of which have statistical arms that provide important measures of economic activity; much of these data are also provided to the Census Bureau.

The Confidential Information Protection and Statistical Efficiency Act of 2002 (44 U.S.C. § 101) standardized the privacy and confidentiality protections of data collected by the three major federal statistical agencies and enabled limited data sharing. However, this legislation does not permit the business tax data used by the Census Bureau to be shared with BLS and BEA, and thus impedes the integration of these data into a common framework to improve the quality of key indicators, such as the GDP, and enable new discoveries. Furthermore, researchers must query these organizations individually and may encounter data gaps.

In recent years, some repositories of key administrative data have been made available to the research community on a restricted-use basis. For example, the Federal Statistical Research Data Centers, funded jointly by the Census Bureau and the National Science Foundation, allow approved research institutions to access census and NCHS data for statistical use; other agencies, such as BLS, are scheduled to join this system. Studying restricted-use data at the household and business level has already proven essential for improving understanding of changing workforce trends and the changing nature of employer-employee relationships. Further integration of these and other alternative data sources on workers and firms has great promise for enabling future research, as discussed in research theme 8 in Chapter 6. The goals for and benefits of reuse of federal administrative data for statistical purposes are discussed extensively in *Fiscal Year 2016: Analytical Perspectives of the U.S. Government*, a deeper analysis of content in the 2016 budget request.[1]

Changes in technology and automation are both facilitating and generating new challenges for collecting and producing core economic indicators from the U.S. statistical system. IT enables processing and integration of large-scale administrative data with traditional survey data in unprecedented ways. In addition, data can be collected from households and businesses electronically rather than simply through paper forms. However, response rates on surveys by both households and businesses are declining, even when respondents use digital methods. Given these challenges, the statistical agencies are beginning to explore naturally occurring data from the private sector (e.g., transactions or scanner data in the retail trade sector). Fortuitously, the digital data revolution is creating a wealth of such naturally occurring data and providing new opportunities for more timely and comprehensive data for tracking economic activity. The future of economic statistics is likely to involve partnerships between the public and private sector.

For the purposes of this study, while current surveys and administrative data provide a wealth of information for tracking workforce trends and the changing nature of firms and the workplace, this information does not provide much contextual information about the evolving workplace. In the discussion of data sources below, the committee addresses how contextual information could be acquired and integrated into these sources. Sometimes this is through supplemental modules on surveys,

[1] Office of Management and Budget, *Fiscal Year 2016: Analytical Perspectives of the U.S. Government*, 2015, https://www.whitehouse.gov/sites/default/files/omb/budget/fy2016/assets/spec.pdf, Chapters 7 and 16.

and sometimes it is by integrating data from other sources, including the private sector.

The following sections describe key federal databases, the types of data they contain and how they were collected, their curation and access models, and the infrastructure that supports them. The utility of each data set as well as the challenges faced by researchers using the data are discussed.

Current Establishment Survey and the Quarterly Census of Employment and Wages

The Current Establishment Survey (CES), often called the "payroll survey," is the core source of key national, industry, and regional indicators of earnings and employment for the United States. It is a monthly survey of approximately 300,000 establishments tracking earnings, hours, and employment statistics for wage and salary workers, administered by BLS. Survey enrollment is conducted over the phone, with data subsequently collected each month via computer-assisted telephone interviewing or self-reporting via touch-tone phone entry, fax, Web collection, or electronic data interchange.[2] The CES provides a monthly picture of wage and salary earnings and employment dynamics for the U.S. private, nonfarm sector, to supplement the Quarterly Census of Employment and Wages (QCEW), a comprehensive data set (or "universe file") generated from administrative data on all private, nonfarm establishments in the United States. CES data are generally used to evaluate monthly employment and earnings growth rates, rather than absolute levels, and are annually benchmarked (or normalized) to the more comprehensive QCEW.

The CES, the QCEW, and related sources (such as county business patterns) are used to track the changing industrial structure of employment activity in the United States. For example, these data have been used to track the shift away from goods production to services in detail by sector and location.

Current Population Survey, Decennial Censuses, and the American Community Survey

The Current Population Survey (CPS) is the primary household survey used to track the monthly labor market activity of individuals. The survey is conducted in person or by phone by the Census Bureau on behalf of the BLS, reaching approximately 60,000 households every month. The

[2] Bureau of Labor Statistics, 2016, "Current Employment Statistics—CES (National)," http://www.bls.gov/web/empsit/cesfaq.htm, accessed April 2016.

CPS is used to produce key indicators such as the unemployment rate, the employment-to-population ratio, measures of wages, and hours per worker. The CPS covers all forms of work, including workers engaged in wage and salary employment as well as those who are self-employed and those who are unemployed but actively seeking employment, in contrast to the CES, which only covers employees of industries that are covered by unemployment insurance. Results from the CPS are made publicly available online in the form of aggregated statistics and as "public-use microdata" (individual-level responses about which additional information, such as geographic location, has been suppressed for anonymization purposes). These data play a critical role in tracking workforce trends in employment, unemployment levels, the employment-to-population ratio, and working hours and wages; these data are also tracked by demographic information (such as an individual's race or marital status) and job characteristics (such as industry and occupation).

The CPS is one of the primary sources for tracking self-employment activity. As noted in the section "The On-Demand Economy" in Chapter 4, the CPS shows no recent increase in the share of workers having at least some self-employment activity, nor does it show any increase in the share of workers with multiple jobs. Both of these findings raise questions about the quantitative importance of the growth of the on-demand or "gig" economy. However, as noted, there is some question as to whether changing workforce arrangements are appropriately captured via the current interview process (e.g., workers may identify differently than researchers would have classified them). It is also possible that new uses of technology for organizing such work are not creating a new growth sector, but rather centralizing existing informal work patterns. Existing data do not allow for a definitive interpretation.

The Census Bureau conducts an annual supplement to the CPS that it uses for tracking key trends in the U.S. economy. The CPS and other household surveys also include additional, periodic supplements designed to capture changing workforce trends. For example, the CPS has had periodic supplements focused on the contingent workforce, the last of which was conducted in 2005. An updated "Contingent Worker Supplement" is planned to be included in the May 2017 CPS.[3]

Related household-based sources for tracking the evolution of the workforce include the long form of the Decennial Census through 2000 and the more recent American Community Survey (ACS), both collected by the Census Bureau. The much larger samples in the Decennial Census and the ACS permit cross-classifying workforce trends by demographics,

[3] T. Perez, 2016, "Innovation and the Contingent Workforce," U.S. Department of Labor blog, January 25, https://blog.dol.gov/2016/01/25/innovation-and-the-contingent-workforce/.

occupations, industries, and locations in a manner not possible for the CPS due to factors such as CPS sample size and location suppression in its public-use microdata.

Data Sources Tracking Workforce and Employer Dynamics: JOLTS, BED, BDS, and QWI

The CES and CPS are invaluable sources for tracking core indicators of the labor market, but they should primarily be interpreted as providing information about the changing characteristics of workers and firms over time. To understand the changing nature of the labor market, it is also critical to track workforce and employer dynamics and transitions.

Measures of vacancy postings, hires, and separations from the BLS Job Openings and Labor Turnover Survey (JOLTS) enables the tracking of workers engaged in labor market transitions. The JOLTS survey is establishment-based and provides these statistics at the national, regional, and industry level along with statistics by employer characteristics, like employer size.

BLS Business Employment Dynamics (BED) data track establishment expansions and contractions and establishment openings and closings on a quarterly basis, using administrative data about private, nonfarm-sector establishments. Similarly, the Business Dynamic Statistics (BDS) data at Census Bureau tracks job creation and destruction statistics annually using administrative data on U.S. businesses in the private, nonfarm sector. A highlight of the BDS is that it permits the tracking of business formation and business failure at the firm level. Entrepreneurship has historically played a critical role in the innovation, growth, and job creation dynamics of the United States. The BDS has shown that business formation rates have declined in the United States even in the high-tech sector in the post-2000 period. The BED and BDS data are available in the public domain at the national, industry, and local levels and by a variety of firm and establishment characteristics. These data are also available for restricted-use analysis in the Federal Statistical Research Data Centers.

JOLTS, BED, and BDS provide rich information tracking labor market dynamics but are limited in that they are based on establishment- and firm-level information alone. The Longitudinal Employer Household Dynamics (LEHD) project at the Census Bureau has created a longitudinal employer-employee matched data infrastructure for studying labor market dynamics from both the worker and business perspective. Key data products from the LEHD project are the Quarterly Workforce Indicators (QWI), which provide information on labor market transitions, including both worker and firm characteristics. Indicators of job-to-job flows that track workers transiting directly from one job to another, even without first being unemployed, are a novel component of the QWI that has recently been released. As discussed in Chapter 4, job-to-job flows have been a critical way for young workers to build careers and also show how workers impacted by changing technologies have adapted by changing employers. The new job-to-job flow statistics show there has been a decline in the pace of such transitions, posing concerns about workers getting caught up in the changing nature of work.

These household surveys and censuses are increasingly being integrated with administrative data to yield new statistical products. For example, all of these data have been integrated in the LEHD data infrastructure, discussed in the next subsection. Such data integration enables researchers to combine information on firm-level measures of changing technology with what happens to the workers caught up in such changes.

The business-level and person-level data underlying the JOLTS, BED, BDS, and QWI are increasingly being used in restricted-use environments to track workforce trends. Development and access to the longitudinal microdata are critical for capturing the changing nature of work. For example, Abraham et al.[4] use the integration of the person-level CPS and the LEHD-matched employer-employee data to study changing labor market trends. They find, for example, that many individuals in the CPS state that they are working as wage and salary workers, but the administrative data underlying the QWI and other related sources at the Census Bureau show that they are working as independent contractors. It is such discrepancies that may in part underlie the difficulty of identifying the impact of the on-demand economy on the workforce.

As discussed further in the following subsection, the longitudinal business data and longitudinal employer-employee matched data have great promise for tracking the impact of changing technology on workers. Workers who find themselves at firms engaged in changing the nature of the workplace can be tracked over the course of their career. If displaced, the outcomes in terms of employment and earnings can be tracked. Alternatively, the changing nature of the workplace at some firms may lead to new opportunities that can be tracked.

Given the interest in and possible growth of the on-demand economy, the matched employer-employee data need to be supplemented to include workers who are independent contractors. Fortunately, the statistical agencies, as well as Internal Revenue Service and Social Security Administration, have administrative data sources that track such activity already—although for the most part these sources have not yet been integrated into

[4] K.G. Abraham, J. Haltiwanger, K. Sandusky, and J.R. Spletzer, 2013, Exploring differences in employment between household and establishment data, *Journal of Labor Economics* 31(2,part 2):S129-S172.

the LEHD data infrastructure.[5] Integrating alternative types of workforce arrangements should be a high priority for the future.

Tracking Changes in Technology Using U.S. Federal Data Sources

The federal statistical agencies have a wide array of business surveys that provide information on the changing nature of technology and workplace organization at U.S. firms. At the core, the business surveys and economic censuses yield the data that permit constructing indicators of productivity (such as labor productivity or total factor productivity). Productivity measures are commonly used to make inferences about the pace of technological change in the economy. As discussed in Chapter 3, productivity growth in the United States surged during the tech boom in the 1990s through the early 2000s but has slowed since the mid-2000s.

Direct measures of changing technology and innovation stem from survey and administrative sources. The Census Bureau conducts the Business Research and Development and Innovation Survey on behalf of the National Science Foundation. This survey tracks research and development (R&D) activity and innovation activity at the firm-level. It provides invaluable information about the sectors where R&D and innovative activity are concentrated, which is disproportionately in manufacturing. The data have been integrated into the wide range of business survey and administrative data to study the impact of R&D and innovation on productivity and job creation.

Modules and supplements are periodically added to business surveys to track changes in technology. For example, in some sectors and firms, the design of new products is conducted in the United States, but all or much of the actual production is outsourced. As a result, some firms are considered producers of goods even though they conduct little or no production activity. To capture such activity, the Census Bureau has added a series of modules to the U.S. economic censuses since 2002 on the contraction of manufacturing services.[6]

Household surveys conducted by the Census Bureau have been collecting data on computers and Internet use periodically since the 1980s. The CPS has had periodic modules about computer use at the household level through the early 1990s and about both computer and Internet use

[5] See, however, the NBER/CRIW paper by Goetz et al. (2015) that discusses integrating the self-employed including independent contractors into the LEHD data infrastructure (C. Goetz, H. Hyatt, E. McEntarfer, and K. Sandusky, 2015, "The Promise and Potential of Linked Employer-Employee Entrepreneurship Research," NBER Working Paper w21639, doi: 10.3386/w21639).

[6] A.B. Bernard and T.C. Fort, 2015, Factoryless goods producers in the US, *American Economic Review* 105(5):518-523.

from the late 1990s through the present. The ACS has collected data about computers and Internet use annually since 2013. Such household data does not provide much detail about the specific nature of technological innovation, but it is important for quantifying the penetration of the use of IT across the population.

The U.S. Patent and Trademark Office tracks all patents in the United States, including information on the firms and inventors for the patents as well as the nature of the patents. The research community has been using this as an important source for tracking technological change for years, but these data are now increasingly being integrated into the other survey and administrative data discussed above. Research projects with participants from the academic community, the patent office, and the statistical agencies are integrating patent and other related data on innovation to longitudinal business data (i.e., the microdata underlying the BDS) and the longitudinal, matched employer-employee data (i.e., the LEHD data infrastructure).[7] Such data integration permits tracking of the outcomes of innovative activity in unprecedented ways as well as tracking of the careers of innovators. Along with patent citation data, integration with matched employer-employee data enables the study of the networks and clustering activity of innovation in unprecedented ways.

Integration of data tracking changes in technology at the firm level with matched employer-employee data also has the potential to permit study of the impact of changing technology on the workers caught up in such changes. This would allow tracking of employment, earnings, and career paths for those workers who find themselves at firms that are replacing production workers with machines or with globalized production.

Tracking Changing Occupational and Skill Requirements

Changes in the demand for different types of skills are a critical aspect of the changing nature of work. Data on the changing occupational mix and the skill requirements of these occupations are a vital source for tracking these changes. As noted above, household surveys such as the CPS, ACS, and the Decennial Census are useful sources for characterizing the changing occupational mix of the U.S. workforce over time.

The Occupational Employment Statistics survey, administered cooperatively by the Bureau of Labor Statistics and state workforce agencies, collects information about employees at nonfarm establishments. These

[7] D. Acemoglu, U. Akcigit, N. Bloom, and W. Kerr, 2013, "Innovation, Reallocation, and Growth," Massachusetts Institute of Technology Department of Economics, April 12, http://economics.mit.edu/files/8790.

data complement the household-based surveys by providing data on wages by detailed occupation and location as reported by employers. These data are actively used for occupational projections.

In order to classify jobs by their types, functions, conditions, and associated competency requirements, the U.S. Department of Labor's Employment and Training Administration established the Dictionary of Occupational Titles (DOT), in use from 1938 through the late 1990s. The DOT details a taxonomy of occupations and the associated competencies (cognitive and noncognitive) required for success in those occupations. Autor et al. used elements of the DOT data in their discussion of how IT relates to a decline in the demand for routine-intensive occupations.[8]

In 1992, the Employment and Training Administration established the Occupational Information Network (O*NET) online database, which describes the detailed competencies and characteristics of occupations required for success on the job; it ultimately replaced the DOT. Whereas the DOT offered detailed information on more than 10,000 occupations, O*NET consolidated and grouped these occupational titles and now covers about 1,000 occupations. The content model contains information on 33 knowledge bases, 35 skills, and 52 abilities, among other competencies. The profiles are periodically updated based on results from the O*NET Data Collection Program's worker questionnaire, which is sent to a sampling of workers and occupational experts.

While O*NET is quite valuable for understanding current jobs and associated requirements, researchers face some challenges when aiming to use its content to help assess changing skills requirements and the likely impacts of technology on a given occupational field. First, the database is not intended to be longitudinal; O*NET 20.2 (released in February 2016) is not directly compatible with previous versions of O*NET. Both the O*NET questionnaire and associated occupational codes have changed significantly over time in such a way that O*NET classifications are not directly comparable from year to year. Furthermore, the system is updated on a rolling basis, with competency requirements for some fraction of all occupations updated every year. The census occupational coding system was significantly altered between the 1990 and 2000 censuses to account for technological advances in occupational structure and structural changes in the economy overall, representing a further challenge to monitoring changes within a given field.

It has also been noted that the degree of variability in the responses between occupations is lower than expected. For example, one might expect an engineer to use critical thinking skills more intensely or at a

[8] D.H. Autor, F. Levy, and R.J. Murnane, 2003, The skill content of recent technological change: An empirical exploration, *Quarterly Journal of Economics* 118(4):1279-1333.

higher level than, for example, a baker. However, worker survey responses might show similar required levels or intensity of use of critical thinking between these two different occupational categories. The sheer number of competencies identified for each occupation can be overwhelming, with 120 identified skills, knowledge areas, and abilities used as classifiers; consolidating to a more manageable number of factors proves challenging. The classifiers themselves are not necessarily directly linkable to requirements for using technology, making it difficult to assess the diffusion of technology into the corresponding occupational fields.

In addition, the knowledge provided by O*NET about which occupational competencies are required for success in a given occupation is not accompanied by information about how to teach or attain these competencies. There is also little guidance on attainment levels required to meet the demands of the occupation, although the data set does separately identify "job zones," or groups of occupations with similar requirements.

Despite these challenges, this information has been valuable to labor market analysts and workforce participants and has also proven critical for use by the research community to help quantify and address the nature of work. For example, MacCrory et al. have identified and tracked changes in seven orthogonal dimensions of skill in the O*NET data set,[9] and O*NET classifications have been used in several recent studies aiming to examine what current jobs or work functions could potentially be automated, as discussed in the section "Evaluating Job Susceptibility to Automation" below.[10]

WEB-BASED AND PRIVATE-SECTOR DATA

Government statistics are invaluable sources of longitudinal, large-scale, and standardized data. However, such data can be costly and time-consuming to collect, especially from offline surveys. However, the digitization of economic and labor market transactions has created new opportunities for tracking and evaluating workforce trends. In particular, the rise of the Internet, enterprise software systems, mobile devices,

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[9] F. MacCrory, G. Westerman, and E. Brynjolfsson, 2015, "Identifying the Multiple Skills in Skill-Biased Technical Change," Thirty Sixth International Conference on Information Systems, http://aisel.aisnet.org/cgi/viewcontent.cgi?article=1655&context=icis2015.

[10] S.W. Elliott, 2014, Anticipating a Luddite revival, *Issues in Science and Technology* 30(3):27-36; C.B. Frey and M.A. Osborne, 2013, "The Future of Employment: How Susceptible Are Jobs to Computerization," *Oxford Martin School*, September 17, http://www.oxfordmartin.ox.ac.uk/downloads/academic/The_Future_of_Employment.pdf; McKinsey Global Institute, 2015, "Four Fundamentals of Work-place Automation," *McKinsey Quarterly*, http://www.mckinsey.com/business-functions/business-technology/our-insights/four-fundamentals-of-workplace-automation.

and computational and data storage capacity have led to unprecedented amounts of data being "born digital," including some of the administrative data discussed in the Introduction to this chapter. Much as advances in analytical methods have enabled new products, services, and tools for research and business (with implications for the workforce), such methods also present new opportunities for identifying and understanding changes in the labor economy.

For example, consider the rise of "big data" and associated analytics. Digital data are now being created at vastly greater quantities than ever before. They are available more quickly, often in real time, and they are available in many forms and types.[11] Big data are commonly described as differing from traditional data sources due to the volume, velocity, and variety of these data.[12]

The following types of naturally occurring data—that is, data that would exist in digital form whether or not someone sought them—provide key examples of analytical opportunities for researchers.

- *Individual worker profiles.* Online networking platforms, especially professional networking or job-seeking platforms such as LinkedIn or Monster.com, enable individuals to create and maintain personalized profiles and help to match individuals with potential job prospects. Users may input their employment status, current and past employers, job titles, certifications, and skills, as well as their educational background, geographical location, professional interests, relevant experience, and the type of job they are seeking (if applicable). Some of these data are publicly searchable online—for example, if a user chooses to make his or her profile visible to the public. Some of it is kept private or confidential, either to protect the personal information of the individual or to be used exclusively by the platform owner for its own analytics—to generate revenue by selling targeted advertising or to enhance its service or product. Analysis of privately held data can also enable a company to conduct its own research about the labor market to inform future business models, or the data could be made available to outside researchers.
- *Job listings.* Companies seeking to hire may post vacancy announcements on a range of websites, including their own and those of professional societies, local news outlets, employment services, and online professional networking platforms. Again, much of this information is

[11] See also E. Brynjolfsson and A. McAfee, 2012, Big data: The management revolution, *Harvard Business Review* 90(10):60-68.

[12] META Group, 2001, "3D Data Management: Controlling Data Volume, Velocity, and Variety," February 6, https://blogs.gartner.com/doug-laney/files/2012/01/ad949-3D-Data-Management-Controlling-Data-Volume-Velocity-and-Variety.pdf.

publicly accessible and searchable. Advances in big data approaches and computational and storage capacity make it possible to monitor, track, and analyze job openings over time, including key elements such as position title, industry sector, listed skills and educational requirements for a given job title, and how long the posting persists before it is removed. Factors that must be taken into account during aggregation and interpretation of these data include the existence of multiple postings for the same position, delayed updates or removal of advertisements for filled positions, a lack of information about jobs not posted on publicly searchable sites, and other incomplete or inaccurate information. Analysis of these and other data mined from the Web present opportunities for close monitoring and dynamic analysis of the labor market. For example, Burning Glass Technologies analyzes millions of job postings to track skills gaps in real time.[13] Real Time Macroeconomics works similarly, making use of Google Trends and scraping online data from job postings, layoff announcements, and wage reports to develop economic indicators that supplement government data.[14]

Additional information, such as retail or online purchasing trends (tracked via bar-code scanners in brick-and-mortar stores or product numbers in online purchases), search queries (inputs into online search engines), social media content, and related data, may contain useful evidence of technology diffusion, economic change, and employment or business trends.

A wealth of information (including from some of the categories identified above) is held or generated by the private sector, such as corporations with large employment numbers, employment services, and others whose business practices would shed light on how technology is changing the U.S. and global economies and workforce. However, much of this is not publicly available for reasons such as the need to protect individual privacy or proprietary business information.

Overall, Web-based and private-sector data present great potential for enabling new insights into the changing nature of work and workforce trends. For example, in 2009, Hyunyoung Choi and Hal Varian developed a model that predicted initial claims for unemployment benefits using data from Google Trends.[15] They created two variables to account for the frequency of job-related as well as welfare and unemployment search

[13] Burning Glass Technologies, 2016, "About Burning Glass Technologies," http://burning-glass.com/about/, accessed April 2016.

[14] Real Time Macroeconomics, 2016, "Real Time Online Economic Data," http://www.realtimemacroeconomics.com/#real-time-online-economic-data, accessed April 3, 2016.

[15] H. Choi and H. Varian, 2012, Predicting the present with Google Trends, *Economic Record* 88(s1):2-9.

terms. After adding the variables to the standard forecasting model, Choi and Varian found their Google Trends model outperformed other models of the Department of Labor's initial claims data. Wu and Brynjolfsson[16] also used Google Trends to predict housing-price changes. Although they constructed the model to be simpler than the one used by the National Association of Realtors, by using real-time data, they were able to make predictions more accurately than the experts.[17]

Federal statistical agencies have begun to use big data sources in their evaluations. For example, the BLS currently uses "web-scrape characteristics for hedonics" to help calculate the Consumer Price Index (CPI).[18] Meanwhile, the BEA also uses various digital data sources, including QuickBooks, Mint Bills, PayCycle, credit card data, and the Consumer Financial Protection Bureau Consumer Credit Panel as well as "billions of claims from both Medicare and private commercial insurance to determine the spending for over 250 diseases."[19]

A very promising example of analytics using web-based data is the Billion Prices Project (BPP), which includes a daily price index to extend the monthly CPI.[20] The BPP collects and aggregates the prices of approximately 15 million products and calculates a *daily*, not annual, inflation index for 20 countries. It is considered more accurate than the official price indexes of some governments and enables analysis of other trends, such as premiums paid for green products, adjustment of prices to shocks, and price "stickiness."[21] It is important to note that the BPP is not meant to be treated as a substitute for official statistics, but rather as a complement, in part because BPP and the CPI do not always measure the same

[16] L. Wu and E. Brynjolfsson, 2009, The future of prediction: how Google searches foreshadow housing prices and quantities, p. 147 in *ICIS 2009 Proceedings*; L. Wu and E. Brynjolfsson, 2014, "The Future of Prediction: How Google Searches Foreshadow Housing Prices and Sales," paper presented at the meeting Economics of Digitization: An Agenda, June 6-7, 2013, http://conference.nber.org/confer//2013/DIGs13/Wu_Brynjolfsson.pdf.

[17] Ibid.

[18] E. Groshen, Bureau of Labor Statistics, "Government and Big Data: What's Our future?," presentation at American Enterprise Institute for the Federal Statistical System in a Big Data world, March 12, 2015.

[19] D. Johnson, "Commercial Big Data and Official Statistics," Bureau of Economic Analysis—Federal Economic Statistics Advisory Committee presentation in BEA Expert Meeting on Exploiting Commercial Data for Official Economic Statistics on November 19, 2015; B.C. Moyer, "Big Data Landscape, 2015-2020," Bureau of Economic Analysis, presentation at Global Conference on Big Data for Official Statistics, October 20, 2015.

[20] A. Cavallo and R. Rigobon, 2016, The Billion Prices Project: Using online prices for measurement and research, *Journal of Economic Perspectives* 30(2):151-178.

[21] A. Cavallo, 2013, Online and official prices indexes: Measuring Argentina's inflation, *Journal of Monetary Economics* 60(2):152-165; N. DuVergne Smith, 2010, "Billion Prices Project: Introducing Real-Time Economics," *MIT News*, December 1, http://news.mit.edu/2010/billion-prices-project.

prices. (For example, the BPP cannot easily account for services.) Similar complementary models could be developed to identify technology trends and advances, changing employment opportunities or skills demands for different occupational fields, and potential correlations between these trends.

Work is also under way to use social media to track economic trends. In particular, analysis of Twitter fields, conducted jointly by experts in computer science and economics, has been used to track and predict unemployment trends.[22]

Such successes demonstrate the potential for digital and web-based data to yield new insights into current and potential workforce changes. In general, these data could be uniquely useful to researchers and policy makers since they can be collected and searched in real time, at high granularity, and reveal unanticipated trends.

However, there are notable challenges associated with web-based and private-sector data sets. First, valuable data held by the private sector are not generally available to researchers; if they were, steps would likely be needed to protect proprietary business information. Pilot efforts testing the potential of public-private data sharing to yield more complete data sets while reducing costs are underway at BLS, the Census Bureau, and BEA (although details and results of these efforts are not available). Although private sector data sets are clearly of significant value to the companies that collect them, there may well be motivations on both sides to share and aggregate data and to make aggregate statistics available to researchers and the public.[23]

Second, large-scale collection and analysis of nonpublic information, such as credit-card transactions, or even some publicly available data, such as social media information, and much of the administrative data described above could have significant privacy or ethical implications, which will not be explored here. Finally, big data and data-mining-based approaches to uncovering important trends also have the potential to surface spurious correlations, and decisions about how to sort or filter input data prior to analysis may be subjective and yield skewed results. Even if trends and correlations are accurately identified, analytics alone may not

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[22] D. Antenucci, M. Cafarella, M. Levenstein, C. Ré, and M.D. Shapiro, 2014, “Using social media to measure labor market flows,” NBER Working Paper No. 20010, National Bureau of Economic Research, doi: 10.3386/w20010.

[23] Technical and policy issues associated with such partnerships for aggregating diverse data for the enhancement of federal statistics are currently being explored as part of another study of the National Academies of Sciences, Engineering, and Medicine. See the website for the Panel on Improving Federal Statistics for Policy and Social Science Research Using Multiple Data Sources and State-of-the-Art Estimation Methods, at http://sites.nationalacademies.org/DBASSE/CNSTAT/DBASSE_170268.

provide insight into the underlying causes of or meaning behind such trends—even if they also yield accurate predictions.[24] More qualitative or in-depth examination of workforce and technology trends, along with hypothesis-driven research grounded in established scientific theory, will be needed to unravel the bigger picture.

QUALITATIVE METHODS

Macroeconomic and quantitative analytical approaches are invaluable for identifying and understanding overall trends and indicators, but they may not provide a clear picture of what is occurring at the level of individual workers or families. As mentioned in the previous section, these methods may also fail to reveal causality.

For these insights, the committee may turn to microdata and qualitative social science methods. These methods include case studies, participant observation, ethnographic interviewing, life histories, and the analysis of textual data. Of these methods, participant observation and ethnographic interviewing have contributed the most to an understanding of the changing nature of work. Participant observation (or fieldwork) involves long periods of immersion in setting, a subculture, an occupation, or a workplace.[25] Indeed, much of what is known about the social organization of work as it existed in the mid-20th century derives from fieldwork con-

[24] See, for example, D. Boyd and K. Crawford, 2012, Critical questions for big data: Provocations for a cultural, technological, and scholarly phenomenon, *Information, Communication and Society* 15(5):662-679.

[25] There are numerous texts that cover how to do fieldwork and ethnographic interviewing. Some of the most widely used include the following: A.L. Strauss and J. Corbin, 1990, *Basics of Qualitative Research: Grounded Theory Procedures and Techniques*, SAGE Publications, Thousand Oaks, Calif.; J.P. Spradley, 1979, *The Ethnographic Interview*, Holt, Rinehardt and Winston, New York; J. Lofland and L.H. Lofland, 1984, *Analyzing Social Settings: A Guide to Qualitative Observation and Analysis*, Wadsworth, Belmont, Calif.; J. Van Maanen, 1988, *Tales of the Field: On Writing Ethnography*, University of Chicago Press, Chicago, Ill.; M. Agar, 1980, *The Professional Stranger*, Academic Press, New York.

ducted in mines,[26,27] factories,[28,29] offices,[30] construction sites,[31,32] and other work settings.[33,34] In fact, field studies such as these provided the situated, contextual insights that enabled sociologists to elaborate on theories of bureaucratic organizing as well as the grounding for large-scale survey research on the nature of work and work life throughout the remainder of the century. Ethnographic research continues to provide grounded understandings of the changing nature of work in the 21st century. Examples include studies of finite element analysis and other mathematical simulation tools in automobile engineering,[35] the work and careers of financial analysts on Wall Street,[36] the work of technicians in a variety of settings,[37,38] and the work of personal service workers[39] and contract workers.[40,41] These and other ethnographies offer considerable fodder for developing a more macro-oriented understanding of the variety of trends characteristic of changes in the nature of work and the structure of the workforce. Moreover, data from field studies and related methods are likely to raise questions that will fruitfully guide more macro-level research.

When carefully coupled, mixed-methods research can help to address

[26] E.L. Trist and K.W. Bamforth, 1951, Some social psychological consequences of the Longwall method of coal getting, *Human Relations* 4(1):3-38.

[27] A.W. Gouldner, 1954, *Industrial Bureaucracy*, Free Press, New York.

[28] C.R. Walker and W.H. Guest, 1952, *The Man on the Assembly Line*, Harvard University Press, Cambridge, Mass.

[29] F.C. Mann and R.C. Hoffman, 1960, *Automation and the Worker*, Henry Holt and Company, New York.

[30] P.M. Blau, 1955, *The Dynamics of Bureaucracy*, Chicago University Press, Chicago, Ill.

[31] R. Dubin, 1956, Industrial workers' worlds: A study of the 'central life interests' of industrial workers, *Social Problems* 3(3):131-142.

[32] J. Haas, 1977, Learning real feelings: A study of high steel ironworkers' reactions to fear and danger, *Sociology of Work and Occupations* 4(4):147-170.

[33] R.L. Gold, 1964, In the basement: The apartment building janitor, pp. 1-49 in *The Human Shape of Work: Studies in the Sociology of Occupations* (P.L. Berger, ed.), Macmillan, New York.

[34] L. Braude, 1975, *Work and Workers: A Sociological Analysis*, Praeger Publishers, New York.

[35] D.E. Bailey, P.M. Leonardi, and S.R. Barley, 2012, The lure of the virtual, *Organization Science* 23(5):1485-1504.

[36] K. Ho, 2009, *Liquidated: An Ethnography of Wall Street*, Duke University Press, Durham, N.C.

[37] S.R. Barley, 1996, Technicians in the workplace: Ethnographic evidence for bringing work into organization studies, *Administrative Science Quarterly* 41(3):404-441.

[38] S.E. Zabusky and S.R. Barley, 1996, Redefining success: Ethnographic observations on the careers of technicians, in *Broken Ladders* (P. Osterman, ed.), Cambridge University Press, Cambridge, Mass.

[39] A.R. Hochschild, 1983, *The Managed Heart: Commercialization of Human Feeling*, University of California Press, Berkeley, Calif.

[40] S.R. Barley and G. Kunda, 2004, *Gurus, Hired Guns and Warm Bodies: Itinerant Experts in a Knowledge Economy*, Princeton University Press, Princeton, N.J.

[41] V. Smith, 2001, *Crossing the Great Divide: Worker Risk and Opportunity in the New Economy*, Cornell University Press, Ithaca, N.Y.

important questions simultaneously from the bottom up and the top down, leading to more informed interpretations of data, deeper and more complete knowledge, and new, testable hypotheses.

EVALUATING JOB SUSCEPTIBILITY TO AUTOMATION

Until recently, it was generally accepted that routine tasks (whether manual or cognitive) were the most susceptible to automation (as opposed to nonroutine tasks).[42,43,44] It is becoming clear that advances in artificial intelligence (AI), machine learning, and robotics are increasingly making the automation of some nonroutine tasks, such as writing news articles, answering questions, driving, and even navigating uneven terrain, practically feasible, as discussed in Chapter 3.

Recent approaches to analyzing the types of jobs subject to automation have involved matching current technological capabilities with the skills or tasks associated with common occupational fields, in particular, as identified in the O*NET system (see the section "Tracking Changing Occupational and Skill Requirements" above for a discussion of O*NET).[45,46,47] This approach provides a systematic identification of human skills to be compared to or qualified in terms of technical capabilities, although it is limited to some extent due to the challenges of using O*NET classifications for longitudinal tracking, as outlined in the section.

The first such study,[48] from 2013, estimated that approximately 47 percent of U.S. jobs are at high risk (≥70 percent probability) of being automated over the next few decades as a result of advances in AI, machine learning, and mobile robotics. This evaluation considered only the technological capability of completing the associated work tasks, to the exclusion of other economic, organizational, and social considerations. Authors Frey and Osborne used a machine-learning approach, classifying the suscep-

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[42] D.H. Autor, F. Levy, and R.J. Murnane, 2003, The skill content of recent technological change: An empirical exploration, *Quarterly Journal of Economics* 118(4):1279-1333.

[43] M. Goos, A. Manning, and A. Salomons, 2009, Job polarization in Europe, *American Economic Review* 99(2):58-63.

[44] D.H. Autor and D. Dorn, 2013, The growth of low-skill service jobs and the polarization of the US labor market, *American Economic Review* 103(5):1553-1597.

[45] S.W. Elliott, 2014, Anticipating a Luddite revival, *Issues in Science and Technology* 30(3):27-36.

[46] C.B. Frey and M.A. Osborne, 2013, "The Future of Employment: How Susceptible Are Jobs to Computerization," Oxford Martin School, http://www.oxfordmartin.ox.ac.uk/downloads/academic/The_Future_of_Employment.pdf.

[47] McKinsey Global Institute, 2015, *Four Fundamentals of Work-place Automation*, McKinsey Quarterly, http://www.mckinsey.com/business-functions/business-technology/our-insights/four-fundamentals-of-workplace-automation.

[48] Frey and Osborne, 2013, "The Future of Employment."

tibility of 70 specific jobs to automation by eye (assigning a "1" to jobs for which all tasks are automatable by a state-of-the art computer with sufficient availability of big data, and a "0" to those for which at least one task cannot be automated), then used this assessment as the training data for categorizing 703 jobs classified in O*NET on a probability spectrum from 0 to 1.

A related study in progress, preliminarily reported on in 2014,[49] sampled a decade's worth of articles from *AI Magazine* and *IEEE Robotics & Automation Magazine*, identifying specialized research of note in these fields and grouping the reported technical accomplishments into four categories (language, reason, vision, and moving). The capabilities of these top technologies were compared to the "anchoring tasks" provided as benchmarks for the O*NET ability-level rating system in relevant skills categories. This preliminary qualitative analysis suggested that the abilities of these leading-edge IT and robotics systems were analogous to the skill level required to successfully perform approximately 81 percent of current U.S. jobs. While, again, there are many additional factors to consider, including the costs and barriers to further develop these technologies and bring them to market, challenges associated with integrating these components into larger systems, and market demand for and societal acceptance of such automation practices, this evaluation suggests that automation of a vast number of jobs is becoming increasingly technically feasible. A full report of these results is currently in development for *The Oxford Handbook of Skills and Training*.[50]

Another analysis came from the McKinsey Global Institute, whose researchers evaluated which of 2,000 occupational activities characterized by the O*NET system could be automated through some application of current technologies. Their analysis suggested that 5 percent of jobs could currently be automated in their entirety, and that 60 percent of jobs could have at least 30 percent of their associated tasks automated by existing technologies. Overall, they estimate that 45 percent of work activities are currently automatable, although this number would rise to 58 percent if natural-language processing were to reach the median level of human performance. The researchers thus suggest that in the near term it is more appropriate to focus on the automation of specific work tasks than the automation of complete jobs—suggesting the potential for significant change to the structure of work.[51]

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[49] Elliott, 2014, Anticipating a Luddite revival.

[50] Ibid.

[51] McKinsey Global Institute, 2015, *Four Fundamentals of Work-place Automation.*

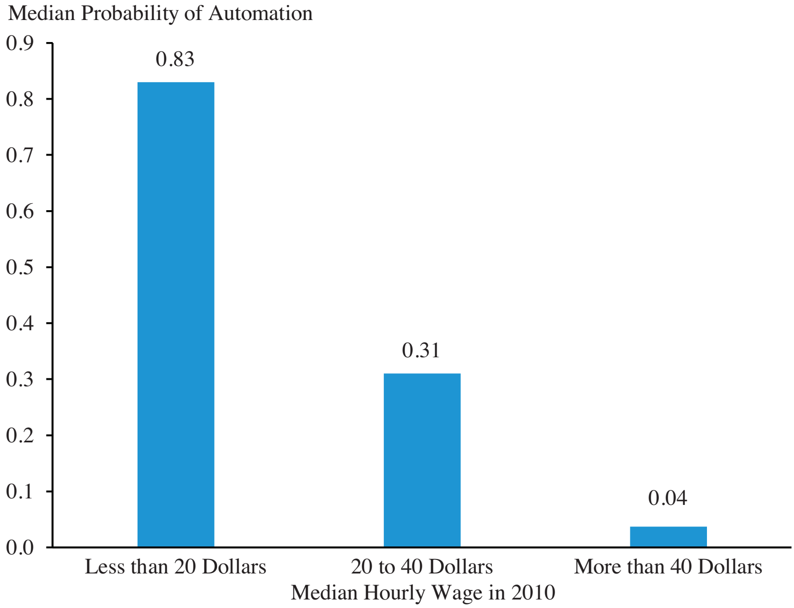

FIGURE 5.1 Median probability of automation by an occupation's median hourly wage. SOURCE: Council of Economic Advisors (CEA), 2016, *Economic Report of the President*, p. 239, https://www.whitehouse.gov/sites/default/files/docs/ERP_2016_Book_Complete%20JA.pdf. Data from Bureau of Labor Statistics; C.B. Frey and M.A. Osborne, "The Future of Employment: How Susceptible Are Jobs to Computerisation?," working paper, Oxford Martin Programme on the Impacts of Future Technology, September 17, 2013, http://www.oxfordmartin.ox.ac.uk/publications/view/1314; CEA calculations.

It is noteworthy that the 2016 Economic Report of the President[52] addressed the question of automation of work. It contains an analysis by the Council of Economic Advisors that makes use of Frey and Osborne's results to assess the probability of automation of jobs according to wage groups. Figure 5.1 shows their results, illustrating the estimate that lower-paying jobs are more likely to be automated.

While such evaluations of susceptibility of work to automation are relatively new and not without limitations, they are provocative and present systematic approaches for addressing the question of what

[52] Council of Economic Advisors, 2016, *Economic Report of the President*, p. 249, https://www.whitehouse.gov/sites/default/files/docs/ERP_2016_Book_Complete%20JA.pdf.

jobs may become fully or partially automated. There is rich potential to expand upon this research, in particular by refining or augmenting these approaches; identifying strategies for testing the accuracy of such predictions; and incorporating other factors, such as societal acceptance of a given technology, that contribute to automation of particular work functions and jobs.

SUMMARY

Data collected by federal statistical agencies have been invaluable for understanding the status of the workforce and the economy at large, such as employment numbers and salaries, and for tracking technology-related values such as productivity. Many of these data sets are authoritative and comprehensive. However, collection and curation of such statistics is resource-intensive, and data sets must be updated periodically, while limited update frequencies can be a challenge for researchers. There is potential for technology to reduce some of these costs, for instance, via automated AI telephone interview systems, large-scale digital surveys, and more effective use of administrative data and the increasing amounts of digital data created for other purposes. In many cases, data are updated annually; other data sets are only updated periodically (e.g., it has been more than 10 years since the last Contingent Worker Supplement to the Current Population Survey). Additional challenges to using these data sets include the redefinition of certain classifiers or categories over time, which can make it challenging to track longitudinal trends, or the irregular updating of subsections of data sets (such as with O*NET); in the committee's judgment, some data set (whether based on O*NET or otherwise) that enables longitudinal analysis of shifting job definitions and skills requirements for occupational fields would be beneficial.

Coupled with advances in tools for data mining and big data analytics, the digitization of myriad business, employment, and economic transactions as well as administrative and other born-digital data presents new opportunities for analyzing changing economic, workforce, technology, and societal trends. Academic researchers and private-sector organizations are already exploring these opportunities. These approaches could potentially augment or complement federal statistics and provide new ways of monitoring emerging workforce and technology trends. However, these approaches require rigorous privacy-protection measures, protection of confidential business information, and cognizance of the potential for intrinsic bias in mined data; such challenges extend broadly to all data-driven research.

While large-scale quantitative data sets are critical for understanding current trends and correlations, they do not always reveal causality and may provide a picture that is somewhat removed from actual human experience. The use of microscale social science methods, such as interview, field work, and other ethnographic approaches, can help researchers bridge these critical gaps by testing conclusions from quantitative data and lead to new hypotheses and study, survey, or experiment design.

There are few methods for quantifying technological progress or foundational advances in science and engineering that can be used for developing indicators of impending changes to the labor economy.

There are a number of areas where useful data may be incomplete or unavailable. For example, there is currently no regular source of information about contingent workers (although another Contingent Work Supplement to the CPS is in the works). Other gaps include information about computer capital broken down at the firm and occupational levels; longitudinal information about skill changes over time by occupational field; information about organizational practices; and data on the diffusion and effectiveness of various educational practices for preparing individuals for work.

Moving forward, the research community would be well served by data collection designed to support longitudinal tracking and analysis of workforce trends and the role of advances in IT.

6

Findings and a Path Forward

GENERAL FINDINGS

From the discussions of the preceding chapters, a number of key findings emerge.

1. Advances in information technology (IT) are far from over, and some of the biggest improvements in areas like artificial intelligence (AI) are likely still to come. Improvements are expected in some areas and entirely new capabilities may emerge in others.

The past decade has yielded significant scientific and technological advances in many areas, including ubiquitous networking and sensing, AI and its subdisciplines of machine learning, computer vision and speech recognition, robotics, the Internet of Things, and other areas.

At the same time, productivity growth has slowed, a fact often read as an indication of decreased technological progress. However, the committee's judgment is that the productivity data are not necessarily inconsistent with a period of significant technical change, because they measure somewhat different concepts and because there are important lags associated with adoption, co-invention, changes in organization, and the updating of skills that are typically required to translate technical change into economic value.

As companies increasingly adopt AI-based technologies to produce new products, their increasing research and development (R&D) investments in these areas are likely to further technical progress over the coming decade. Beyond *invention* of altogether new technologies, we can also expect to see strong influences over the coming decade from *diffusion and maturation* of technologies that already exist today in early forms in research laboratories and leading-edge technology companies (e.g., self-driving cars, conversational AI agents). Both will affect the workforce; it remains to be seen how such advances will impact productivity.

2. These advances in technology will result in automation of some jobs, augmentation of workers' abilities to perform others, and the creation of still others. The ultimate effects of information technology are determined not just by technical capabilities, but also by how the technology is used and how individuals, organizations, and policy makers prepare for or respond to associated shifts in the economic or social landscape.

Technology has been augmenting and replacing human labor in many tasks for hundreds of years, and we can expect this trend to continue. Increasingly, we will see robots used to automate more complex physical tasks in manufacturing, transportation, retailing, and many other industries, and AI to automate knowledge-based tasks.

Because most jobs involve multiple subtasks, and because technology typically targets specific tasks, one common impact of technology is to shift the distribution of tasks the human worker performs in a job (e.g., authors today spend less time proofreading for incorrect spelling, enabling them to spend more time on the content of what they are writing). Technology also makes new tasks and new jobs possible, transforming the nature of work in many, and ultimately most, industries.

While technology may threaten the existence of some jobs via automation, it is also producing new modes of education and training that are more accessible. It has also led to new opportunities for freelance employment via Internet platforms that can match job seekers to jobs in real time and to opportunities to work from home. The net impact of technology, mediated by the decisions of many organizations (businesses, governments, and philanthropic entities) and individuals, is multifaceted. Its full impact is not predetermined, but will depend on the decisions of governments, companies, and individuals about how to use technology and how to prepare for or respond to associated shifts in the economic or social landscape. Technologists, policy makers (such as private-sector managers and public officials), and other leaders have the power to design IT and deploy it for the benefit of society, driven by a broad discussion of what impacts are desirable and a deeper understanding of how design, deployment, and policy decisions can achieve these impacts.

3. The recent increase in income inequality in the United States is due to multiple forces, including advances in IT and its diffusion, globalization, and economic policy.

While technologies enable the automation of some tasks, the demand for labor is not uniformly affected. Changes in demand affect wages and employment, and in turn the underlying mix of skills demanded in the economy. Over the past 20 to 30 years, a large fraction of income disparity has stemmed from changes in demand (due in part to changes in technology) and changes in supply (due to changes in the quality, quantity, and types of education). Employers report shortages of job candidates with needed skills at the same time that salaries for employees with high school degrees have dropped. The wage premium for college degrees remains quite large, even as salaries for bachelor's degree holders have leveled off on average in recent years. Companies that are heavy users of technology and automation often require dramatically fewer workers than the dominant companies of the past century. This reduced need for labor has the effect of further skewing the distribution of income and wealth created by new companies in this category and could limit the ability of reshoring to create new jobs. At the same time, while automation has contributed to inequality, it also is a key driver of productivity and economic growth. This growth can enable more options for easing the implementation of public policies that improve the equity of economic outcomes in the United States. However, such policies cannot be implemented without public and political support.

4. IT is enabling new work relationships, including a new form of on-demand employment. Although current digital platforms for on-demand work directly involve less than 1 percent of the workforce, they display significant growth potential.

Many employers are increasingly viewing their relationship with employees as a short-term commitment rather than a lifelong investment. As Manpower Group CEO Jonas Prising recently put it, "Employers have gone from being builders of talent to consumers of work."[1]

While freelance or on-demand work has long been part of the economy, new IT platforms have changed this aspect of the economy significantly. Internet platforms now match drivers to riders (e.g., Uber, Lyft), producers of goods to buyers (e.g., Etsy, eBay), computer programmers to employers (e.g., Upwork), and high-end consultants to businesses (e.g., HourlyNerd). This "on-demand" or "gig" economy has expanded rapidly, although current government labor statistics make it difficult to track.

[1] Manpower Group, 2016, *Human Age 2.0: Future Forces at Work*, http://www.manpowergroup.com.

Some workers report that they enjoy the flexibility of working only when they wish to, and some workers use these platforms as a secondary form of income. For workers for whom it is their only job, the question of how to obtain health and other standard benefits is important, and some policies are being considered to make it easier for such freelancers to obtain and carry benefits from job to job.

Beyond enabling this on-demand economy, advances such as more widespread access to the Internet have also enabled more full-time employees to work at home part of the time, enabling more full-time employers to offer their employees flexible work hours and work locations.

5. As IT continues to complement or substitute for many work tasks, workers will require skills that increasingly emphasize creativity, adaptability, and interpersonal skills over routine information processing and manual tasks. The education system will need to adapt to prepare individuals for the changing labor market. At the same time, recent IT advances offer new and potentially more widely accessible ways to access education.

While education must change to deliver new content and to teach new skills, the details of exactly what should be taught, and how, are not well understood. There is evidence that "softer" skills have been increasingly valued in the labor market. At the same time, the 20th-century model of degree completion followed by a semipermanent job based on that education is yielding to a model where degree completion is followed by more specialized on-demand education over one's entire career (which may include multiple occupations). The most logical developers of new educational approaches are local, state, and federal governments, as well as researchers and research agencies.

There are significant opportunities for IT to be used to advance educational strategies and delivery. For example, online education companies such as Coursera, EdX, and Udacity have begun to experiment with new modes of Internet-based continuing education. While IT is likely to enable broader access to education, individuals without the opportunity or incentives to access it are at risk of being left even further behind, potentially reinforcing existing racial, ethnic, and socioeconomic disparities in society. While these tools show promise, their efficacy and the extent to which they can be truly democratizing remain to be seen.

6. Policy makers and researchers would benefit significantly from a better understanding of evolving IT options and their implications for the workforce. In particular, (1) sustained, integrated, multidisciplinary research and (2) improved, ongoing tracking of workforce and

technology developments would be of great value for informing public policies, organizational choices, and education and training strategies.

Despite much anecdotal evidence suggesting that big changes are under way, surprisingly little data are available to help determine which anecdotes correspond to significant country-wide or economy-wide trends and understand the nature of these changes and how potential policy choices can influence them.

For example, although there is much anecdotal evidence that the on-demand economy is growing, better data are needed to understand issues such as what is driving it (e.g., how much is due to the business cycle versus improvements in technology or the invention of new business models?); whether it is particularly important or attractive in specific sectors of the economy (e.g., computer programmers versus taxi drivers); and whether it is lowering the barrier for creation of new businesses (e.g., by reducing the need to hire full-time employees in early stages).

New data across all aspects of technology's progress, its diffusion into firms and products, and its impact on the economy, along with tools to analyze these data, could shed important light on the types of public policies that might optimize the benefits of technological advances for the workforce and society. As new data sets emerge, it will be important to design them to accommodate potential future research needs.

Achieving the goal of a more evidence-based understanding of the forces at work depends on overcoming barriers to data access for the research community. A critical step is enabling collaboration between U.S. statistical agencies. Providing these agencies with access to and integration of (1) federal tax information for statistical purposes and (2) additional administrative data from federal and state sources would provide new opportunities for economic research. In March of 2016, the federal government passed a law to establish the Commission on Evidence-Based Policymaking; this group is likely to address some of these challenges and may facilitate enhanced data access for the research community.[2]

The interplay between technology and work is complex and changing, and important public policy issues are already arising. There are many open questions that policy makers may face. For example:

1. How can the United States make use of technology to maximize overall economic growth while maximizing access for everyone to the economic and other benefits afforded by new technologies?

[2] The Evidence-Based Policymaking Commission Act of 2016, Public Law 114-140.

2. What policies, resources, and practices would ease transitions for workers forced to change occupational fields due to technological change?
3. How can we anticipate and actively guide the future impacts of newly developed technologies before they occur?

RESEARCH PATHWAYS

While it is not within this committee's charge to recommend specific policy actions, it is within its purview to advocate for well-informed policy discussions about how IT is affecting the workforce, including job opportunities and workers' quality of life. The committee believes that the foundational knowledge and insights essential to an informed policy debate can best be attained through a strategic research program to better track the changes that are occurring and to understand the mechanisms by which advances in technology influence our economy, workforce, and society. Such a research program will be important for helping stakeholders address productivity growth, job creation, and the transformation of work.

The committee recommends that federal agencies or other organizations that sponsor research or collect data relevant to technology and the workforce establish a sustained, multidisciplinary research program to address the many important questions about how IT is changing or how it might change the nature of work and the U.S. national economy. This program should

1. Target a deeper understanding of how choices about technology use or functionality can affect the workforce in order to inform the design of technologies and policies that will benefit workers, the economy, and society at large;
2. Emphasize integration of micro- and macro-level research methods from disciplines including the social sciences, economics, computer and information sciences, and engineering; and
3. Establish and facilitate the use of new data sources, tools, methods, collaborations, and infrastructures to facilitate such research while protecting privacy with appropriate data-management practices.

The committee envisions this as a highly multidisciplinary, sustained research program that integrates a range of strategies, from bottom-up ethnographic studies to large-scale quantitative approaches, including survey data, administrative data, research-generated data, and privately collected data. This research should take advantage of what can be learned from the experiences of other countries faced with similar trends, to learn from their experiences with different policies regarding education, worker benefits, and so on, as well as learn from historically analogous events, such as the advent of farm and factory automation during the early 20th century. There are myriad opportunities for cross-fertilization across disciplines such as machine learning, data science and statistics, economics, sociology, anthropology, and other social sciences.

In some instances, ethnographic components will be crucial for understanding the right questions to ask and provide insight about how worker experiences may vary. The quantitative components are critical for understanding the breadth of developments and, perhaps more importantly, where within the economy effects are located (which occupations, types of organizations, and geographical regions). It is critical that research on work consider variations between different demographic groups, geographic regions, industries, technologies, and occupations.

Such a research program should span a range of research themes, which the committee describes below. These issues fall under the U.S. National Science Foundation's "Big Ideas" for investigation, "work at the human-technology frontier," announced in 2016.[3]

Theme 1: Evaluating and Tracking Technological Progress

While many researchers or individuals who follow technology trends may have a strong understanding of current technological capabilities, a uniform strategy is currently lacking for tracking new developments across a broad range of technology fields, their capacity for automating or augmenting human work functions, and the degree to which they are diffusing into industry and firms. More rigorous measures and awareness of the state of the art of technology would help to signal the potential for corresponding workforce impacts.

Research to develop new ways of evaluating, tracking, and projecting technological progress would help enhance understanding of the impacts of technology on the workforce, inform strategies to help prepare for likely changes, and reveal what kinds of indicators might point to upcoming disruptions.

Such research should include objectives such as the following:

- Further develop, refine, and test strategies for classifying technological capabilities in terms of the human skills and tasks they can or could replace. Several strategies making use of the O*NET (Occupational Information Network) classifications have been reported, which could

[3] National Science Foundation, 2016, "10 Big Ideas for Future NSF Investments," https://www.nsf.gov/about/congress/reports/nsf_big_ideas.pdf, accessed December 2016.

serve as a starting point. New strategies should also be explored—in particular, to consider not only the tasks that might be automated but also the context and systems within which they are conducted.

- Identify key indicators that could signal the extent of the impact of developments in a given technological field.
- Develop new mechanisms to track and forecast technological and economic changes of particular relevance to the future of the workforce, potentially via the development of metrics that would quantify such changes and their impact.

Key research questions include the following:

- What technological fields are advancing the most rapidly? What new fields are emerging?
- How can we track and predict the types of human tasks that can be automated? Which technologies are having the biggest impacts in industry, and how might we best track their adoption?
- What are key benchmarks that might indicate the imminence of groundbreaking progress with significant economic impact?

Multidisciplinary research, including economists and technologists, should investigate possible input categories, measures, and output scales for a set of useful indexes, such as the following:

1. *Technology progress index*. Analogous to the Consumer Price Index, this index would measure and summarize the *current state* of technology and its impact on the economy and workforce, aggregating quantitative data from diverse sources. For instance, it could track progress in computational hardware (Moore's Law), data storage costs and speeds, communication speed, saturation of high-speed Internet coverage across the United States, progress on specific technologies such as speech recognition and computer vision using standard benchmarks (e.g., the ImageNet benchmark for testing computer-vision algorithms and the COCO benchmark for image captioning), and so on. Such a generalized index could make it easier to understand how technology is advancing, enabling better determination of how and whether rates of technological progress translate into productivity growth.
2. *AI progress index*. The potential for AI to significantly advance automation capabilities make this a field of particular interest to track. An AI progress index could focus specifically on the progress in AI and machine learning. This index would track progress on specific technologies, such as speech recognition and computer vision, robotic dexterity and mobility, autonomous vehicles, medical diagnosis, legal and investment advice,

ability to converse with humans in formats like the Turing Test, proficiency in various games, structured and unstructured problem solving, and other areas of AI, using standard benchmarks (e.g., the ImageNet benchmark for testing computer-vision algorithms). Relatedly, a Turing Olympics or Turing Championship,[4] consisting of a variety of tasks, could be organized, providing both a structured way to track progress and a set of milestones to motivate future work.

3. *Organizational change and technology diffusion index.* This index might look at the gap between the productivity of frontier firms and the median firm, adoption rates of technologies, the rate of start-ups, patenting activity, business dynamism, labor shortages and skills mismatching (e.g., the Beveridge curve), and the time it takes for technologies to go from invention to implementation across industries. Diffusion of AI technologies could be tracked via a market-based approach, perhaps analogously to that used in Robo Global's index.[5] Various measures of performance of current AI systems could also be used to track foundational capabilities in AI.

In addition to the above quantitative indexes, methods for modeling and predicting technological progress at various confidence intervals should then be developed for specific fields. In addition, a forward-looking panel of technical experts could be created to *forecast technological progress* and its impacts, analogous to groups of expert economists who attempt to forecast the economy. These forward-looking subjective forecasts can be combined with data from the above quantitative indexes to form a broad view of the state and future direction of technology and its impacts. While expert forecasts, whether of technology or other topics, generally have a poor record, practices exist that are correlated to useful predictions.[6]

Together, such indicators could provide important knowledge for many decision makers, from individuals considering possible training and job changes, to educational institutions designing their curricula, to the Federal Reserve Board assessing the economy. Furthermore, these methods of quantifying technological advances and their diffusion into

[4] See, for example, the webpage for the "Beyond the Turing Test" workshop at the Twenty-Ninth AAAI Conference on Artificial Intelligence (AAAI-15) on January 25, 2015 at http://www.math.unipd.it/~frossi/BeyondTuring2015/.

[5] Robo Global, 2016, "Robo US Index," http://roboglobal.com/us-index, accessed May 2016.

[6] Such practices are discussed in the context of economic and political predictions in P.E. Tetlock and D. Gardner, 2016, *Superforecasting: The Art and Science of Prediction*, Random House, New York.

industry could provide a basis for testing the various hypothesized explanations for the slowing of productivity growth discussed in Chapter 3.

Theme 2: Technology Adoption and Impact Within Organizations

Technologies can greatly affect the type and nature of tasks conducted by individual workers. Whether they can completely replace a human worker depends on the specific context in which individual tasks are conducted. Understanding the impact of technology on workers within a firm requires an understanding of the organizational systems through which individual tasks combine to meet the company's goals. Research on how different industries use technology to organize their operations, allocate tasks, and perform specific functions, at both the micro- and macro-level scales, should be undertaken to provide a firm- and industry-level window into the impacts of technology on employees in a given industry or at a given organizational level.

Key research questions include the following:

- How are decisions relating to technology and labor made within these organizations? How does this vary across firm/enterprise types and life cycles, and over time?
- Is the increasing importance of online data (e.g., for targeted marketing) creating a less even playing field for new start-ups that lack the legacy data of incumbents?
- Are businesses' production processes being segmented differently? What kinds of changes are emerging, for example, with respect to outsourcing?
- How does the adoption of IT into work processes affect the distribution of work tasks for employees in specific industries?

Theme 3. Impacts of Policy Choices

Important public policy issues are already arising as a result of the changing technological landscape and its impact on the U.S. workforce; the urgency of these issues may increase. Research to inform national and regional policy decisions and strategies to enable innovation and the use of IT to maximize overall economic growth while maximizing access for everyone to jobs, opportunities, and the economic and other benefits afforded by technologies is critical.

This research should aim to understand which policies, resources, and practices would (1) mitigate technological unemployment, (2) ease transitions for workers forced to change occupational fields due to technological change, and (3) provide opportunities for actively guiding the future impacts of technology development and deployment before they occur. In particular, this could include assessment of the efficacy of new social policies—for example, the impact of a guaranteed income or specific proposals for retraining and continuing education initiatives—in the United States. It could also include evaluation of strategies for providing incentives to private companies to share data that will enable better monitoring of the impacts of technology on jobs and workers.

Although this report focuses on the U.S. workforce, many of the same issues regarding the impacts of IT are being faced in other countries, whose circumstances could serve as a pool of diverse case studies to help illustrate the variety of mechanisms by which IT can impact the workforce and how related social and economic policies can mitigate or exacerbate any negative impacts. Similarly, U.S. history includes episodes of automation and technological developments that have had major impacts on the workforce and can demonstrate how related social and economic policies can mitigate or exacerbate any negative impacts. Although today's software-driven changes are different in many ways from the impact of earlier technological advances, there are lessons to learn from both historical and international case studies.

Key research questions include the following:

- What are differences across existing case studies, in their demographics, pool of available jobs, training level of their workforce, exposure to international trade, and other factors that may influence how technological advance leads to augmentation or replacement of workers? How can these different case studies be used to build a more robust model of how technologies can impact the workforce and how policies can influence these impacts?
- What is the inventory of policies attempted across different countries and throughout history regarding continuing education, workforce benefits, social safety nets, and other relevant issues?
- What data exist regarding the impact of past policies adopted in different contexts? What projections might be made regarding the impact of such policies on particular sectors of today's U.S. workforce and economy?
- What are the global interactions that influence how technological advances impact the workforce, given today's highly multinational economy? How do differing labor pools and labor conditions in different countries lead to different types or rates of influence of new technologies on the workforce? Do these differences result in an uneven playing field in the rate of adoption of new technologies?

Theme 4: Working with Emerging Technologies

As emerging technologies are increasingly implemented in different industries, individuals must learn how to interact with and successfully complete tasks with them. One key implication of this shift is a change in the nature of decision making, teamwork, and organization. In some cases, robots are displacing positions that would have previously been assigned to people,[7] and other members of the team must learn to collaborate with nonhuman members and interact with technology in the place of human intelligence. Organizations are also increasingly relying on teams that primarily use virtual tools to collaborate.[8] These are just two examples; there are many current changes occurring that are affecting the way individuals collaborate.

More research is needed examining how these teams may function differently than traditional teams and how this will impact organizations. Research is also necessary to uncover under what conditions these teams are as effective as, or more effective than, traditional teams.

Key research questions include the following:

- How do teams using these technologies function, and how is that different from teams without them?
- What impact do different technologies have on the functioning of teams? For instance, are there discernible differences between those physically augmenting human actions, such as robotic arms, versus those providing data or making decisions?
- How do emerging technologies impact organizational outcomes and, ultimately, high-level organizational trends?
- What conditions affect the effectiveness of teams using emerging technologies? When are they as effective as or more effective than traditional teams?

Theme 5: Societal Acceptance of Automation Technologies

While tasks cannot be automated without mature technologies capable of performing a given function, the mere existence of technological capabilities does not guarantee that a given technology will be deployed. Economic costs and benefits will influence decisions to deploy technolo-

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[7] G. Graetz and G. Michaels, 2015, "Robots at Work," CEP Discussion Papers dp1335, Centre for Economic Performance, LSE, https://ideas.repec.org/p/cep/cepdps/dp1335.html.

[8] T. Minton-Eversole, 2012, "Virtual Teams Used Most by Global Organizations, Survey Says," Society for Human Resource Management, July 19, https://www.shrm.org/resourcesandtools/hr-topics/organizational-and-employee-development/pages/virtualteamsusedmostbyglobalorganizations,surveysays.aspx.

gies, but other factors may also be at play. In some contexts, people (either workers or consumers) may prefer to interact with a human over a machine. This may reflect the existence of important yet largely invisible and unremunerated human skills that can easily be missed in existing skill categories and national statistics but are valued by individuals. Consumer behaviors and worker preferences and bargaining power drive markets; understanding automation's behavioral economics will be important for understanding its adoption patterns. Additional human factors and the social, philosophical, and psychological dynamics of automation should be explored.

Key research questions include the following:

- What factors determine whether or not individuals will accept automated analogues to traditionally human-performed tasks? How does this vary with the type of technology or task?
- Can such behavior or preferences be modeled? To what extent do current behaviors conform to existing economic models? How might this change as technologies become more established?
- Can existing deployments of automation (such as digital assistants, ATMs, or self-service checkout lines) serve as models for understanding new applications of AI, machine learning, or robotics?
- What opinions and perceptions does the public have about automation in various contexts? How are these related to established societal norms, and how might this inform decisions about what to automate and how to design automated systems?

Theme 6: Changing Labor and Skills Demands and Implications for Education and Training

Changes in technology use affect the roles of workers and contribute to changing labor and skills demands. This creates challenges for individuals as they plan and adjust their career strategies, as well as for employers, educational institutions, and policy makers. The economic insecurity felt by many workers underscores the importance of understanding the interplay of technology with jobs, wages, and opportunity, and not simply looking at technology in isolation. Furthermore, there is a good likelihood that already disadvantaged groups will bear the brunt of the costs of automation.[9] Research examining changing labor and skills demands in specific industries and occupational fields over time, along

[9] In addition, there is some evidence that the rise in disability rolls may, in part, reflect a lack of employment prospects for some groups. The extent to which automation of jobs contributes to this is an open question. See D.H. Autor and M.G. Duggan, 2007, Distin-

with regional variations and associated policy implications, would help to provide a basis for understanding and anticipating future trends and for informing education, training, and retraining strategies.

This research should examine existing trends in both authoritative economic statistics and emerging data sources and methods, identify correlations to changes in technological capabilities and diffusion in different fields, and hypothesize and test causal relationships using results from research about organizational practices.

Key research questions include the following:

- What types of worker skills and traits are currently becoming more or less valuable in specific sectors of the labor market?
- Do these changes correlate to the development or deployment of specific technologies that enable, augment, or replace such skills?
- How might measures and projections of technology impact and diffusion enable modeling of changing skills demands and income distributions, and how much might such models be tested?
- How do the uses of specific technologies in specific jobs impact work conditions and worker job satisfaction in the most common occupational fields?
- Under what scenarios might the creation of new jobs outpace the reduction in existing jobs, and vice versa? How is this balance likely to change over time? Which job types are likely to be most affected?
- What kinds of indicators might be useful for identifying disruptions to the types of skills required by workers in a given occupational field? What data-collection strategies would enable the development of such indicators?

The new workplace requires a workforce trained for expertise in areas that will drive the future economy and with the flexibility to adapt to rapid change. The U.S. education system has already begun to evolve in response at the levels of primary, secondary, vocational, college, graduate, and continuing education. However, it is far from clear at this point exactly what children should be taught and how to best prepare displaced workers for the future. It is unclear how to best take advantage of the new opportunities for online or other IT-enabled training, how to construct the most effective online courses, and how to best incentivize students and workers to complete the courses they begin. Because education will largely determine the success of the United States in responding to the changing workplace, a better understanding of effective strategies is criti-

guishing income from substitution effects in disability insurance, *American Economic Review* 97.2:119-124.

cal. Some insight into changing skill needs can be inferred from how skill demands are currently changing; additional insights might be gleaned by a partnership between computer scientists, labor economists, and education researchers to discuss the kinds of technology capabilities that are likely to emerge in coming years.

Research in this area should aim to assess educational and training needs based on understanding of skills demands driven by technological change, and ways in which technology can be best used to prepare and train the future workforce.

Key research topics include the following:

- *Educational needs.* What skills will be most valuable for young students and for employed and unemployed adults seeking better jobs? What are the best practices for teaching these different skills, and what new innovations are possible? What are the current and emerging technological substitutes and complements to these skills?
- *Education delivery.* How can education best be delivered? How can traditional classroom models be augmented by online education, workplace apprenticeships, peer-to-peer education, and other models for optimal success rates? How might new approaches that leverage IT, such as gamification or simulation-based learning, be deployed to improve learning outcomes?
- *Education access and incentives.* How can the benefits from educational opportunities be extended to all segments of society, including students who cannot or will not attend 4-year colleges? What programs are needed to assure that primary and secondary schools have the tools they need to help students?
- *Education policy.* Various countries have policies that provide for worker education. For example, workers in France accrue a credit of 20 hours of paid time for continuing education for each year they work.[10] What would be the expected impact if the United States were to adopt similar policies?

Additional questions include the following:

- What are the factors contributing to gaps in educational attainment, and is the United States on a trajectory to narrow or widen current gaps in educational attainment? Where can learning technologies help to

[10] Y. Lochard and B. Robin, 2009, "France: Collective Bargaining and Continuous Vocational Training," EurWORK, http://www.eurofound.europa.eu/observatories/eurwork/comparative-information/national-contributions/france/france-collective-bargaining-and-continuous-vocational-training, accessed May 2016.

bridge these gaps, especially for women, underrepresented minorities, people with disabilities, and the economically disadvantaged?

- What is the mean time to development for the most valued skills, and how do these relate to job hopping?
- Are certificate and test-based certificate programs serving employment goals? What does the future look like as certificate programs continue to proliferate and compete for attention?
- What is the current state of vocational education opportunities? Are these meeting current needs?
- What changes should be made to what is being taught, how it is being taught, and who is being taught?
- What positive outcomes can online learning effectively offer in both general education and training programs to prepare individuals for the workforce?
- How can online or other IT-assisted learning techniques be best leveraged to assist in retraining or just-in-time learning for individuals undergoing work transitions?

Theme 7: The On-Demand Economy and Emerging Modalities for Organizing Work

The emergence of an on-demand economy, in particular for ride-sharing services and crowdsourced work marketplaces, has created great interest and excitement. However, there is little information about the extent of its impact on the economy and the workforce. Research on the ability of authoritative economic and labor statistics to capture this impact, and more comprehensive and persistent strategies for measuring it, are needed. In addition, social science research to illustrate the rights, protections, and autonomies of workers, and how on-demand jobs fit into workers' lives and careers, is needed to understand the impact and need for policies in this domain. Through this work, the potential for on-demand jobs to effectively provide or augment employment for unemployed or low-income workers, as well as other associated advantages and disadvantages, should be elucidated.

Key research questions include the following:

- To what extent do current measures of business dynamism capture activity in the on-demand economy? How can they be improved?
- To what extent do on-demand workers in this sector lose income and legal protections (the right to unionize, the right to minimum wage, and the right to overtime pay)?
- To what extent do on-demand workers gain or lose control over their schedules and other types of autonomy?

- Where do on-demand jobs fit into the career path of workers? What are the longer-term implications of this type of work for individuals and society?

Physical and geographical boundaries of work have shifted over time, with significant impacts on worker experience and job availability and access. Technology has enabled this to a large extent, and the emergence of new technologies could continue to change this landscape. Research in this area could aim to elucidate the role of technology in shifting where and how work is conducted and lay the groundwork for anticipating future changes and opportunities.

Key research questions include the following:

- How might new technologies continue to change the costs and benefits of telecommuting, globalization, or other aspects of the geography of work? What are the technological and nontechnological drivers of these changes?
- How might developers and organizations design technologies and strategies for technology use that will create more work for those at the margins of society, make better use of existing workers, and yield deeper satisfaction for workers?
- What is the impact of new modalities of organizing work on organizational forms such as corporations, limited-partnerships, freelancing, volunteer organizations, and so on?

Theme 8: New Data Sources, Methods, and Infrastructures

As described at the outset of this chapter, the interplay between technology and work may be studied at various levels, with different lenses provided by a range of academic disciplines. Part of the challenge of developing a holistic understanding of the interplay between technology and work stems from the vastness of these interactions, which is accompanied by gaps in information gathering and a need for deeper interdisciplinary collaboration. How can researchers design comprehensive strategies for understanding the role of a given technology in a given occupational field, both from the top down and the bottom up?

New sources, methods, and infrastructure to enable the collection, aggregation, and distribution of a diverse range of data are needed to support investigation of the preceding themes to understand what technology advances are in fact occurring, along with their impact and the mechanisms by which they affect workers and the economy.[11] Below, the committee discusses data strategies that would advance understanding of the impacts of IT and automation on the U.S. workforce. The committee recognizes that new government data-collection efforts such as those discussed below would most likely require additional resources.

Updating and Augmenting Authoritative Data Sources

As discussed in Chapter 5, much useful quantitative data comes from government sources such as the Bureau of Labor Statistics (BLS) and the U.S. Census Bureau. Updates to existing government survey tools and instruments with methods (e.g., questions, sampling techniques) that better target the impact of new technologies and related work processes and task structures on organizations, workers, and management capabilities would greatly assist researchers. The Current Population Survey (CPS) (of households) and the Current Employment Statistics Survey (of establishments) could potentially benefit from new questions that can help to assess the impact of new technology on workers as well as the size of the on-demand economy. For example, the planned revival of the Contingent Worker supplement to the CPS is an important opportunity to obtain well-defined information about worker participation in the on-demand economy; sustained efforts to collect such information would yield an important longitudinal database. Only these large-scale surveys, conducted at regular intervals, have the capacity to track such phenomena over time.

Development of New Data Sources and Methods

Much data about investment, employment, and sales that could be of great value to researchers aiming to unravel technology's role in workforce and economic trends are currently held by private-sector organizations (discussed in Chapter 4). Opportunities for obtaining useful research data via partnerships with private industry should be pursued.

Furthermore, creative efforts to mine and interpret "born-digital" data from a range of sources could lead to new, real-time monitoring of key employment and economic trends. Applications of contemporary analytical tools based on data mining and machine learning should be pursued. Researchers in this area might pursue the following:

[11] See also the efforts of a panel of the Committee on National Statistics of the National Academies of Sciences, Engineering, and Medicine on Improving Federal Statistics for Policy and Social Science Research Using Multiple Data Sources and State-of-the-Art Estimation Methods at http://sites.nationalacademies.org/DBASSE/CNSTAT/DBASSE_170268.

1. New methods of obtaining, augmenting, or validating the information provided by authoritative sources that may be updated in real time and do not depend on existing cost- or labor-intensive methods; and
2. New types of indicators of technology diffusion, shifts in labor or skills demands, and the connection between the two.

Classifications and Indicators for Job Types and Categories

Researchers face additional challenges with respect to monitoring. Key research questions include the following:

- How might the classification of job types, categories, and characteristics be standardized to enable identification and longitudinal tracking of changes due to technology-related trends?
- To what extent are human attributes—including creativity, empathy, interpersonal skills, leadership, mentoring, and physical presence—currently valued in the U.S. labor force? How might this be tracked in the future?
- How can independent, freelance, and contingent labor be characterized and measured?
- How can the deployment of new worker-engagement models and trends, such as the more general "task markets" that compose the intellectual and physical abilities of machines and people in new, more flexible ways be monitored and understood?[12]

Combination of Micro- and Macro-Level Data and Methods

The importance of targeted qualitative, ethnographic, microscale, and case-study and fieldwork investigations must not be overlooked. As many researchers come to rely on identification of trends—or even predictive models—based on very large and, increasingly, born-digital data sets, the underlying causes or mechanisms behind these trends may not be clear. Qualitative and interview-based approaches—for example, investigation of the specific deployment of a particular technology into the work flow of an organization, how workers are trained on it, and its impact on their job satisfaction—could be used to test conclusions that may be inferred from macroeconomic trends, and likewise provide insights into drivers of trends that may emerge on the horizon at the macroscale. Moreover, data

[12] D. Shahaf and E. Horvitz, 2010, "Generalized Task Markets for Human and Machine Computation," *AAAI 2010*, July.

from field studies and related methods are likely to raise questions that will fruitfully guide more macro-level research.

New Infrastructure and Partnerships for Aggregation, Sharing, and Collaboration

Beyond simply collecting and analyzing relevant data, the development of an infrastructure to enable access to, interoperability of, and new multidisciplinary strategies for using data could be a great benefit for researchers, policy makers, and others. In particular, this infrastructure could enable researchers to access and share the very large amounts of relevant digital data being created, gathered, and shared by private companies and via emerging technologies and platforms (such as the Internet of Things and mobile phones) and integrate it with data collected by governments. Such an infrastructure could provide insights about the labor market with much more detail and at a higher frequency than ever before.

One strategy could be to establish data clearinghouses or data centers, ideally virtual, that permit integration of real-time data from U.S. statistical agencies with that of companies, such as the data centers currently used by firms like Burning Glass, LinkedIn, Google, ADP, and many others, with these combined core data sets tracking changes in innovation, changing skill demands, productivity, and the workforce. Such an approach could enable continuous monitoring of where novel jobs are being created and how skills requirements are changing for specific occupational fields, which could be correlated to trends in technology. This could also be used to facilitate matching between employers and job applicants, or current or potential workers with training or educational pathways.

More generally, many believe that the future of economic statistics lies in the integration of survey, administrative, and commercial data,[13] and the use of federal administrative data was named a priority of the executive branch for fiscal year 2016.[14] Such integration is expected to revolutionize key national indicators and also allow much more timely and granular tracking of economic data by detailed geography, industry, occupational fields, worker characteristics, and other classifiers. Academia can play a critical role as honest brokers between the public and private sectors with respect to these data sets. This would likely require address-

[13] See, for example, efforts of the American Economic Association and the Sloan Foundation to identify sources and procedures for researcher access to Federal Administrative Data at https://www.aeaweb.org/about-aea/committees/economic-statistics/administrative-data.

[14] Office of Management and Budget, 2015, *Fiscal Year 2016: Analytical Perspectives of the U.S. Government*, https://www.whitehouse.gov/sites/default/files/omb/budget/fy2016/assets/spec.pdf, Chapters 7 and 16.

ing organizational barriers to information and data sharing and standardization of information-sharing levels and ranks across organizations. There are also measurement and methodological issues in developing key indicators from the new data infrastructure that will emerge. These could build on the newly created Federal Research Data Centers—which now house data from the Census Bureau, BLS, the National Center for Health Statistics, and the National Center for Education Statistics, with plans to add data from the Internal Revenue Service and the Bureau of Economic Analysis—and could potentially bring private-sector sources into the mix from willing partners. The new national Commission on Evidence-Based Policymaking may reflect efforts in this direction.[15]

Such efforts may be frustrated by existing and potentially outdated government regulations that constrain the ability of government to share certain data sets with researchers. While regulations to protect the privacy of individuals are well justified, they may not reflect current approaches to protecting privacy while making data available for analysis. In any case, there is a general and persisting need for research on strategies for protecting the privacy of individuals' data beyond the context of this particular research agenda.

Finally, creative strategies for integrating qualitative and quantitative data from research pursued through the lenses of social science, technology, and economics could help to build a holistic research community and transform the ability to interpret technology and workforce trends, evaluate their consequences, and inform future policies, with great potential benefit for the nation.

[15] The Evidence-Based Policymaking Commission Act of 2016, Public Law 114-140.

7

Conclusion

Progress in many of the basic computing and information technologies has been rapid in recent years, and the committee does not expect the pace of change to slow down in the foreseeable future. While some technologies are reaching maturity now, many important technologies have enormous future potential. As more of the world's information is digitized and more people and things are networked, the economics of the digital, networked economy will become ever more important. This includes the ability to make copies of goods and services at almost zero cost and deliver them anywhere on the planet almost instantaneously. Furthermore, digitization of products, services, processes, and interactions makes it possible to measure and manage work with far more precision. Data-driven decision making and machine learning provide vast opportunities for improving productivity, efficiency, accuracy, and innovation.

The committee expects important innovations to come in the area of artifical intelligence (AI) and robotics. Several decades ago, humans were unable to converse with machines using ordinary speech; now it is done routinely. Machines are learning to effectively translate from one language to another, a task once seen only in science fiction. We are moving from an era where machines were blind, unable to recognize even simple objects, to an era where they can distinguish faces, read street signs, and understand the content of photographs as well as—or better than—humans. They are being put to work reading X-ray and MRI images, advising doctors on potential drug interactions, helping lawyers sift through documents, and composing simple stories about sports and finance for newspapers. Machines are becoming much better at reasoning and can now defeat the best humans at most games of skill, from checkers and chess to trivia and Go. Machines are learning to drive cars, which could potentially save thousands of lives in the United States and millions worldwide. Bipedal robots are learning to navigate stairs and uneven terrain, while their cheetah-like brethren can outrun even the fastest humans. Many of the technologies with the greatest impact will likely look unlike any human or animal, but will transport shelves of inventory throughout warehouses, assemble basic electronics in factories, fly to disaster zones with medicine, swim beneath the waves to gather data for oceanographers, and haunt computer networks in search of cyberattacks. In fact, many of these exist in some form already, although they are likely to become more widespread and more competent.

While there are undoubtedly important technological breakthroughs to come, it is critical to note that the technologies that exist today and those under active development have important implications for the workforce. They create opportunities for new products, services, organizational processes, and business models as well as opportunities for automating existing tasks, even whole occupations. Many cognitive and physical tasks will be replaced by machines. At the same time, we expect new job opportunities to emerge as increasingly capable combinations of humans and machines attack problems that previously have been intractable.

Advances in IT and automation will present opportunities to boost America's overall income and wealth, improve health care, shorten the work week, develop new goods and services, and increase product safety and reliability.

These same advances could also lead to growing inequality, decreased job stability, increasing demands on workers to change jobs, and changes in business organization. There are also important implications for other aspects of society, both intended and unintended, not the least of which include potentially profound changes in education, privacy, security, social relationships, and even democracy.

The ultimate effects of these technologies are not predetermined. Rather, like all tools, computing and information technologies can be used in many different ways. The outcomes for the workforce and society at large depend on our choices. Technology can be a powerful tool. What do we want for our future society? How do we decide this?

Potential future technological capabilities and innovations are largely unpredictable, and their implications and interactions are complex. Investing in extensive and effective data gathering, a robust infrastructure for analyzing these data, and multidisciplinary research will enable a deeper understanding of emerging changes in technology and the workforce. The results of this research will inform the adoption of policies that will help maximize the resilience and prosperity of the institutions, organizations, and individuals in our society.

Appendixes

A

Statement of Task

A National Research Council study will consider the possible impacts of automation and other applications of IT on the U.S. workforce. An ad hoc committee will consider current knowledge and open questions about the drivers of increased automation; the types and scale of jobs that might be affected; the societal implications of these changes; the time frame for impact; and implications for education, training, and workforce development. Through testimony, discussions convened by the committee, a literature review, and committee deliberations, the committee will examine currently available sources of information, consider how different disciplines could contribute knowledge, explore where additional data would help, and frame research questions aimed at better understanding the phenomenon. The committee's report will set forth a research agenda and describe types and sources of data and analysis that would enhance understanding of the workforce impacts of IT and automation and inform future policy making.

B

Workshop Agenda and Panelist Biographies

WORKSHOP ON IT, AUTOMATION, AND THE U.S. WORKFORCE

National Academy of Sciences
Washington, D.C.
October 22, 2015

8:30 a.m.	**Welcome and Introduction** *Committee Co-Chairs:* Erik Brynjolfsson, Schussel Family Professor, the Sloan School, Massachusetts Institute of Technology Tom M. Mitchell, E. Fredkin University Professor, Carnegie Mellon University
8:45	**Current and Emerging Technological Capabilities** *Moderator:* Eric Horvitz, Technical Fellow and Managing Director, Microsoft Research Gill Pratt, Executive Technical Director, Toyota Peter Lee, Corporate Vice President, Microsoft Research Andrew Ng, Chief Scientist, Baidu Research (remotely)
10:00	Break
10:20	**IT and Automation in the Workplace** *Moderator:* Ruth Milkman, Professor of Sociology, City University of New York Graduate Center Diane Bailey, Associate Professor, University of Texas, Austin David Rolf, International Vice President, Service Employees International Union

	Judy Wajcman, Professor of Sociology, London School of Economics
	Sree Ramaswamy, Senior Fellow, McKinsey Global Institute
11:35	**New Modalities of Work**
	Moderator: Stephen R. Barley, Richard W. Weiland Professor of Management, Stanford University
	Byron Auguste, Managing Director, Opportunity@Work
	Sara Horowitz, Founder and Executive Director, Freelancer's Union
	Stephane Kasriel, CEO, Upwork
	Tess Posner, Managing Director, Samaschool
12:50 p.m.	Working Lunch
2:15	**Education, Workforce Development, and Equal Opportunity**
	Moderator: Barrett Caldwell, Professor of Industrial Engineering, Purdue University
	Heidi Shierholz, Chief Economist, U.S. Department of Labor
	Tom Kalil, Deputy Director for Policy, White House Office of Science and Technology Policy
	David Autor, Associate Department Head, Department of Economics, Massachusetts Institute of Technology
	Yscaira Jimenez, CEO, LaborX
3:30	Break
3:45	**Data Sources and Needs**
	Moderator: John Haltiwanger, Professor of Economics, University of Maryland, College Park
	Erica Groshen, Commissioner, Bureau of Labor Statistics
	Yoav Shoham, Professor (emeritus), Stanford University; Principal Scientist, Google
	Dan Restuccia, Chief Analytics Officer, Burning Glass
5:00	**Discussion of Societal Challenges and Research Pathways**
	Moderated by Committee Co-Chairs
5:30	Adjourn

PANELIST BIOGRAPHIES

BYRON AUGUSTE is the managing director of Opportunity@Work, a civic enterprise based at New America in Washington, D.C., which aims to rewire the U.S. labor market in ways that enable more Americans to achieve upward mobility in the job market and workplace. Prior to co-founding Opportunity@Work, Mr. Auguste served for 2 years in the White House as Deputy Assistant to the President for Economic Policy and Deputy Director of the National Economic Council. Until 2013, Mr. Auguste was a senior partner at McKinsey & Company in Washington, D.C., and Los Angeles, where he was elected principal in 1999 and director in 2005. His professional experience prior to McKinsey was as an economist at LMC International, Oxford University, and the African Development Bank. Mr. Auguste has been active in a number of not-for-profit organizations, serving as board chairman of the Hope Street Group and as a member of the boards of trustees of the William and Flora Hewlett Foundation and Yale University. He is a member of the Council on Foreign Relations and the Pacific Council on International Policy. Mr. Auguste earned a B.A. in economics and political science from Yale University and a M. Phil. and D.Phil. in economics from Oxford University.

DAVID AUTOR is a professor and associate head of the Massachusetts Institute of Technology (MIT) Department of Economics and a faculty research associate at the National Bureau of Economic Research. His research analyzes the labor market impacts of technological change and globalization, earnings inequality, and disability insurance and labor supply. Dr. Autor is an elected fellow of the Econometrics Society, the Society of Labor Economists, and the American Academy of Arts and Sciences. He received a National Science Foundation (NSF) CAREER award, an Alfred P. Sloan Foundation fellowship, the Sherwin Rosen Prize for outstanding contributions in the field of labor economics, and MIT's James A. and Ruth Levitan Award for excellence in teaching. Dr. Autor earned a B.A. in psychology from Tufts University and a Ph.D. in public policy from Harvard's Kennedy School of Government in 1999. Prior to graduate study, he spent 3 years directing computer skills education for economically disadvantaged children and adults in San Francisco and South Africa.

DIANE E. BAILEY is an associate professor in the School of Information at the University of Texas, Austin, where she studies technology and work in information and technical occupations. Her current research interests include engineering product design, remote occupational socialization, big data in health care, and ICT4D (Information and Communications

Technologies for Development). With an expertise in organizational ethnography, Dr. Bailey conducts primarily large-scale empirical studies, often involving multiple occupations, countries, and researchers. She publishes her research in organization studies, engineering, information studies, and communications journals. She is a co-author, with Paul Leonardi, of *Technology Choices, Why Occupations Differ in Their Embrace of New Technology*. Dr. Bailey has won teaching awards at University of Texas, Austin, Stanford University, and the University of Southern California. Her research has won best paper awards, a dissertation award, and an NSF CAREER award. She is founding director of the Information Institute, the professional development resource of the School of Information. She holds a Ph.D. in industrial engineering and operations research from the University of California, Berkeley.

ERICA L. GROSHEN became the 14th Commissioner of Labor Statistics in 2013. Prior to joining the Board on Labor Statistics (BLS), Dr. Groshen was a vice president in the Research and Statistics Group at the Federal Reserve Bank of New York. Her research has focused on labor markets over the business cycle, regional economics, wage rigidity and dispersion, the male-female wage differential, and the role of employers in labor market outcomes. She also served on advisory boards for BLS and the U.S. Census Bureau. Before joining the Federal Reserve Bank of New York in 1994, Dr. Groshen was a visiting assistant professor of economics at Barnard College at Columbia University and an economist at the Federal Reserve Bank of Cleveland. She was a visiting economist at the Bank for International Settlements in Basel, Switzerland (1999-2000). Dr. Groshen earned a Ph.D. in economics from Harvard University and a bachelor's degree in economics and mathematics from the University of Wisconsin, Madison.

SARA HOROWITZ is the Freelances Union's founder and executive director. She has been helping the new workforce build solutions together for nearly two decades. A MacArthur Foundation "Genius" fellow and deputy chair of the Federal Reserve of New York, Ms. Horowitz is a leading voice for the emerging economy. Today, 53 million Americans are independent workers—about one-third of the entire workforce. With a membership of more than 250,000 nationwide, Freelancers Union is building a new form of unionism through creative, cooperative, market-based solutions to today's social challenges.

YSCAIRA JIMENEZ is CEO of LaborX and founder and CEO of Plexx. A Dominican immigrant from the Bronx, Ms. Jimenez is inspired by the poverty issues of people in her community and feels compelled to use education and employment to break the cycle of poverty. She started a tutoring business in high school helping kids in her neighborhood who were struggling in school. She also founded La Pregunta Arts Cafe, an arts cafe in Harlem, and worked for three New York education start-ups (Rocket Learning, Learn-It Systems, and Platform Learning) in business development, operation, and corporate trainer roles, bringing tutoring to more than 10,000 low-income students across the United States. She earned a B.A. in arts, English, and Latin American studies from Columbia University and an M.B.A. in entrepreneurship and innovation from MIT. She speaks Spanish, Portuguese, and conversational Italian.

THOMAS KALIL is the deputy director for policy for the White House Office of Science and Technology Policy and senior advisor for science, technology and innovation for the National Economic Council. From 2001 to 2008, Mr. Kalil was special assistant to the chancellor for science and technology at University of California, Berkeley. He was responsible for developing major new multi-disciplinary research and education initiatives at the intersection of information technology (IT), nanotechnology, microsystems, and biology. He also conceived and launched a program called "Big Ideas @ Berkeley," which provides support for multidisciplinary teams of Berkeley students that are interested in addressing economic and societal challenges such as clean energy, safe drinking water, and poverty alleviation. In 2007 and 2008, Mr. Kalil was the chair of the Global Health Working Group for the Clinton Global Initiative, where he developed new public and private sector initiatives in areas such as maternal and child health, under-nutrition, and vaccines. He was also a senior fellow with the Center for American Progress (CAP), where he co-authored *A National Innovation Agenda*, one of the four pillars of CAP's "Economic Plan for Plan for the Next Administration." He was also a member of the scientific advisory board of Nanomix and has served on three committees of the National Academies of Sciences, Engineering and Medicine, including the Committee to Facilitate Interdisciplinary Research. Previously, Mr. Kalil served as the Deputy Assistant to President Clinton for Technology and Economic Policy and as Deputy Director of the White House National Economic Council (NEC). He was the NEC's point person on a wide range of technology and telecommunications issues, such as the liberalization of Cold War export controls, the allocation of spectrum for new wireless services, and investments in upgrading the U.S. high-tech workforce. He led a number of White House technology initiatives, such as the National Nanotechnology Initiative, the Next Generation Internet, bridging the digital divide, e-learning, increasing funding for long-term information technology research, making IT more accessible to people with disabilities, and addressing the growing imbalance between support for biomedical research and for the physical sciences and engineering. He was also appointed by President Clinton to serve on the G-8 Digital Opportunity Task Force. Prior to joining the White House, Mr. Kalil was a trade specialist at Dewey Ballantine, where he represented the Semiconductor Industry Association on U.S.-Japan trade issues and technology policy. He also served as the principal staffer to Gordon Moore in his capacity as chair of the Semiconductor Industry Association Technology Committee. Mr. Kalil received a B.A. in political science and international economics from the University of Wisconsin, Madison, and completed graduate work at the Fletcher School of Law and Diplomacy. He is the author of articles and op-eds on science and technology policy, the use of prizes as a tool for stimulating innovation, nanotechnology, nuclear strategy, newborn health, vaccines, the impact of mobile communications in developing countries, U.S.-Japan trade negotiations, U.S.-Japan cooperation in science and technology, the National Information Infrastructure, distributed learning, and electronic commerce.

STEPHANE KASRIEL is the CEO of Upwork, driving the company's vision of connecting businesses with talent. In today's competitive job market where most face the challenging war for talent, Mr. Kasriel has mastered how to find, attract, and retain highly skilled talent. At Upwork (formerly Elance-oDesk), he built and led a distributed team of more than 300 engineers located around the world as senior vice president of engineering before ascending to be CEO of the company. His e-book *Hire Fast & Build Things* details how to think bigger and find the best technical talent to power your business—but his expertise goes beyond just engineering. He has applied his knowledge to nearly every industry—from customer service to design to law—experience that earned him his current role leading the company in its quest to reimagine work. Mr. Kasriel holds an M.B.A. from INSEAD, a master's in computer science from Stanford University, and a B.S. from Ecole Polytechnique in France.

PETER LEE, corporate vice president, Microsoft Research, is responsible for Microsoft Research New Experiences and Technologies (MSR NExT), an organization of world-class researchers, engineers, and designers devoted to creating potentially disruptive technologies for Microsoft and the world. While NExT will continue to advance the field of computing research and produce work with significant scholarly impact, its priority is developing technologies that benefit Microsoft and the world more broadly. In this role, Dr. Lee oversees Microsoft Research Asia, Microsoft Research Technologies, FUSE Labs, and Microsoft Research Special Projects, along with several incubation project teams. Prior to joining

Microsoft, he held key positions in both government and academia, most recently at the Defense Advanced Research Projects Agency (DARPA), where he founded and directed a major technology office that supported research in computing and related areas in the social and physical sciences. Prior to DARPA, Dr. Lee served as head of Carnegie Mellon University's nationally top-ranked computer science department. He also served as the university's vice provost for research. Dr. Lee has shown executive-level leadership in world-class research organizations spanning academia, government, and industry. He is a fellow of the Association for Computing Machinery and serves the research community at the national level, including policy contributions to the President's Council of Advisors on Science and Technology and membership on the Computer Science and Telecommunications Board of the National Academies and the Advisory Council of the Computer and Information Science and Engineering Directorate of the National Science Foundation. He was the former chair of the Computing Research Association and has testified before both the U.S. House Science and Technology Committee and the U.S. Senate Commerce Committee. Dr. Lee holds a Ph.D. in computer and communication sciences from the University of Michigan, Ann Arbor, and bachelor's degrees in mathematics and computer sciences, also from the University of Michigan, Ann Arbor.

ANDREW NG is an associate professor of computer science at Stanford University; chief scientist of Baidu; and chairman and co-founder of Coursera. In 2011, he led the development of Stanford University's main MOOC (Massive Open Online Courses) platform and also taught an online machine-learning class to more than 100,000 students, leading to the founding of Coursera. Dr. Ng's goal is to give everyone in the world access to a great education, for free. Today, Coursera partners with some of the top universities in the world to offer high-quality online courses and is the largest MOOC platform in the world. Dr. Ng also works on machine learning with an emphasis on deep learning. He founded and led the "Google Brain" project, which developed massive-scale deep learning algorithms. This resulted in the famous "Google cat" result, in which a massive neural network with 1 billion parameters learned from unlabeled YouTube videos to detect cats. More recently, he has continued to work on deep learning and its applications to computer vision and speech, including such applications as autonomous driving. Dr. Ng received an undergraduate degree in computer science from Carnegie Mellon University, a master's degree from MIT, and a Ph.D. from University of California, Berkeley.

TESS POSNER is the managing director of SamaUSA. Ms. Posner built and launched the first SamaUSA program in 2013. She oversees current programs and SamaUSA departments, funding, and advisory partnerships and leads geographic and programmatic expansion efforts. Prior to Sama, she was assistant director of employment and education at First Place for Youth, where she led their education and employment programs in four bay area counties. Before First Place, she managed education and literacy programs in underserved public schools in New York City. Her passion and expertise lies in creating employment and education programs that focus on empowerment and tangible outcomes for participants. Ms. Posner holds a master's degree in social enterprise administration from the Columbia University School of Social Work.

GILL PRATT joined Toyota in September 2015, after serving for 5 years as a program manager at DARPA. At Toyota, Dr. Pratt is directing new research in the field of collaborative autonomy. At DARPA, he worked in the Defense Sciences and Tactical Technologies offices managing research programs in robotics and neuromorphic systems (computers whose architecture is inspired by the brain). His robotics work included the DARPA Robotics challenge, where teams from around the world competed to develop and test robots for disaster response. The challenge spurred several countries and many commercial companies to increase their investment in the field. Besides conceiving of and running DARPA research programs, Dr. Pratt facilitated the negotiation and signing of a landmark collaboration agreement in disaster robotics between Japan and the United States. From 2000 to 2010, he was a founding professor and associate dean of faculty affairs and research at the Franklin W. Olin College of Engineering. Prior to working at Olin, he was an associate professor of electrical engineering and computer science (EECS) at MIT, where he directed the MIT Leg Laboratory. He earned his Ph.D., S.M., and B.S. degrees in EECS from MIT.

SREE RAMASWAMY is a senior fellow at the McKinsey Global Institute (MGI), McKinsey's business and economics research arm. He leads research on the activities of corporations and their contribution to productivity, growth, and competitiveness. Mr. Ramaswamy also leads MGI's work on the future of global manufacturing and the impact of changes in demand costs, technologies, and policies on various industries. In this capacity, he has worked on issues related to advanced industries, investment and trade, and the trend of next-shoring in manufacturing. Other recent work includes an in-depth look at game-changing opportunities for the U.S. economy—in energy, advanced industries, and infrastructure—and studies on labor and talent challenges in the United States and other advanced economies. Previously as a McKinsey consultant for 3 years, Mr. Ramaswamy worked on topics related to regional and city economic development, public sector efficiency, and business strategy for private-sector clients in aerospace, energy, and high-tech industries. Prior to joining McKinsey, he spent 10 years in the U.S. telecom and aerospace sector. He worked on systems research and design for advanced telecommunication networks and holds three patents in the field. Mr. Ramaswamy also worked on international regulation and policy issues related to satellite communications. He has an M.B.A. from Columbia Business School, where he received a board of overseers fellowship. He also has an M.S. in telecommunications from the University of Pittsburgh and a bachelor's degree in computer engineering from the University of Poona in India.

DAN RESTUCCIA is Burning Glass' chief analytics officer, leading Burning Glass's knowledge architecture and research divisions. Prior to becoming chief analytics officer, he served as Burning Glass' director of applied research. Mr. Restuccia joined Burning Glass following a decade in education reform, driving innovations that improve college and career success for young people. While at Jobs for the Future, a national education reform and advocacy organization, he developed partnerships between high schools and colleges to improve college matriculations and graduation rates for low-income and at risk students. Mr. Restuccia has also served as a middle and high school math teacher. He holds a B.A. in applied mathematics and urban studies from Brown University. His work has been published in numerous education and community development publications.

DAVID ROLF has been called "the most successful union organizer of the last 15 years." He is the architect of the historic fights to win a $15 living wage in SeaTac, Washington, in 2013 and a citywide $15 minimum wage in Seattle in 2014. Mr. Rolf is the president of Service Employees International Union (SEIU) 775, the fastest growing union in the Northwest, representing 44,000 home care and nursing home workers. He serves as an international vice president of the SEIU in Washington, D.C. Mr. Rolf has helped to organize more than 100,000 workers into unions during his career. The *American Prospect* said that "no American unionist has organized as many workers, or won them raises as substantial, as Rolf." Known nationally as an innovative labor leader, Mr. Rolf has founded organizations including the Fair Work Center in Seattle, which enforces labor laws such as the $15 minimum wage, and Working Washington, which supports economic justice activism. In 2014, he founded the California-based Workers Lab, an "accelerator" for new labor initiatives. The Workers Lab invests in projects that will create the next generation's labor movement, building economic power for working people at a large scale while developing self-sufficient organizational revenue models. Mr.

Rolf is also the founder and chair of the SEIU Benefits Group, which provides health benefits to tens of thousands of home care aides in the Northwest and runs the largest long-term care sector workforce development institution in the country.

HEIDI SHIERHOLZ is chief economist to U.S. Secretary of Labor Thomas E. Perez. She held previous positions at the Economic Policy Institute in Washington, D.C., and the University of Toronto in Toronto, Ontario. She has done research in the areas of wage inequality, employment and unemployment policy, long-term unemployment, labor force participation, the minimum wage, young workers, and immigration. She received an M.A. and Ph.D. in economics from the University of Michigan, Ann Arbor, an M.S. in statistics from Iowa State University, and a B.A. in mathematics from Grinnell College.

YOAV SHOHAM is a professor of computer science at Stanford University, where he has been since receiving his Ph.D. in computer science from Yale University in 1987 and after spending an abbreviated postdoctoral position at the Weizmann Institute of Science. He has worked in various areas of artificial intelligence, including temporal reasoning, nonmonotonic logics and theories of commonsense. Dr. Shoham's interest in recent years has been multiagent systems and in particular, the interaction between computer science and game theory. He is a fellow of the American Association of Artificial Intelligence and a charter member of the Game Theory Society. Dr. Shoham is an author of four books, an editor of one, and an author of numerous articles. He is also a founder of several successful e-commerce software companies.

JUDY WAJCMAN is the Anthony Giddens Professor of Sociology at the London School of Economics. She is also a research associate of the Oxford Internet Institute. She was previously a professor of sociology in the Research School of Social Sciences at the Australian National University. She has been president of the Society for the Social Studies of Science and was the 2013 recipient of the William F. Ogburn Career Achievement Award of the Communication, Information Technologies, and Media Sociology section of the American Sociological Association. Her books include the following: *The Politics of Working Life*, *TechnoFeminism*, *Managing Like a Man: Women and Men in Corporate Management*, *Feminism Confronts Technology*, and *The Social Shaping of Technology*. Her work has been translated into French, German, Greek, Korean, Japanese, Portuguese, and Spanish. Her latest book is *Pressed for Time: The Acceleration of Life in Digital Capitalism* (2015).

C

Biographical Sketches of Committee Members and Staff

COMMITTEE

ERIK BRYNJOLFSSON, *Co-Chair*, is the Schussel Family Professor at the Massachusetts Institute of Technology (MIT) Sloan School of Management and the director of the MIT Initiative on the Digital Economy, research associate at the National Bureau of Economic Research (NBER), and chairman of the *MIT Sloan Management Review*. His research examines the effects of information technologies on business strategy, productivity and performance, Internet commerce, pricing models, and intangible assets. At MIT, he teaches courses on the economics of information. Dr. Brynjolfsson was among the first researchers to measure the productivity contributions of information technology (IT) and the complementary role of organizational capital and other intangibles. His research also provided the first quantification of the value of online product variety, often known as the "long tail," and developed pricing and bundling models for information goods. His recent work examines the social networks revealed by digital information flows, such as e-mail traffic, and their relationships to information worker productivity. Dr. Brynjolfsson's research has appeared in leading economics, management, and science journals. It has been recognized with 10 best paper awards and five patents. He is the author or co-editor of several books, including *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*; *Wired for Innovation: How IT is Reshaping the Economy*; and *Understanding the Digital Economy*; and editor of the Social Science Research Network's Information System Network.

He has served on the editorial boards of numerous academic journals as well as *Time* magazine's Board of Economists and the Academic Advisory Council of the Federal Reserve Bank of Boston. He served on the National Academies of Sciences, Engineering, and Medicine committee that produced the 1998 report *Fostering Research on the Economic and Social Impacts of Information Technology*. Dr. Brynjolfsson holds bachelor's and master's degrees from Harvard University in applied mathematics and decision sciences and a Ph.D. from MIT in managerial economics.

TOM M. MITCHELL, *Co-Chair*, is the E. Fredkin University Professor in the School of Computer Science at Carnegie Mellon University (CMU) and chair of the Machine Learning Department at CMU. His research interests are generally in machine learning, artificial intelligence, and cognitive neuroscience. His recent research has focused both on machine learning approaches to extracting structured information from unstructured text and on studying the neural representation of language in the human brain using functional magnetic resonance imaging. Dr. Mitchell is a past president of the American Association of Artificial Intelligence (AAAI), past chair of the American Association for the Advancement of Science (AAAS) Section on Information, Computing, and Communication, and author of the textbook *Machine Learning*. From 1999 to 2000, he served as chief scientist and vice president for WhizBang Labs, a company that employed machine learning to extract information from the Web. Dr. Mitchell has served on the Computer Science and Telecommunication Board of the National Academies and on the committee that produced the report *Information Technology for Counterterrorism: Immediate Actions and Future Possibilities*. He has been a member of the National Academy of Engineering (NAE) since 2010. He is also a fellow of the AAAS and a fellow of the AAAI. Dr. Mitchell received his Ph.D. in electrical engineering with a computer science minor from Stanford University.

DARON ACEMOGLU is the Elizabeth and James Killian Professor of Economics in the Department of Economics at MIT. He is also affiliated with NBER, the Center for Economic Performance, the Center for Economic Policy Research, and Microsoft Research Center. Dr. Acemoglu is a leader in both theoretical and empirical research in political economics, macroeconomics, and growth, focusing especially on human capital and the roles and evolution of institutions. His work covers a wide range of areas within economics, including political economy, economic development and growth, human capital theory, growth theory, innovation, search theory, network economics, and learning. He is a fellow of the Society of Labor Economists, the American Academy of Arts and Sciences, the Econometric Society, the European Economic Association, and a member of the National Academy of Sciences. Dr. Acemoglu received his Ph.D. in economics from the London School of Economics in 1992.

STEPHEN R. BARLEY is the Christian A. Felipe Professor of Technology Management at the College of Engineering at the University of California, Santa Barbara (UCSB). Prior to coming to UCSB, Dr. Barley served for 10 years on the faculty of the School of Industrial and Labor Relations at Cornell University. He then moved to Stanford University where he was the Richard Weiland Professor of Management Science and Engineering, the associate chair of the Department of Management Science and Engineering (2011-2015), and was the co-founder and co-director of the Center for Work, Technology and Organization at Stanford's School of Engineering (1994-2015). He was editor of the *Administrative Science Quarterly* (1993-1997) and the founding editor of the *Stanford Social Innovation Review* (2002-2004). Dr. Barley serves on the editorial boards of the *Academy of Management Discovery*, the *Academy of Management Annals*, the *Research in the Sociology of Organizations* (book series), *Information and Organization*, *Engineering Studies*, and the *Journal of Organizational Ethnography*. He has been the recipient the Academy of Management's New Concept Award and was named Distinguished Scholar by the Academy of Management's Organization and Management Theory Division (2006), Organization Communication and Information Systems Division (2010), and Critical Management Studies Division (2010). He has been a fellow at Center for Advanced Study in the Behavioral Sciences and is a fellow of the Academy of Management. In 2006, the *Academy of Management Journal* named Dr. Barley as the author of the largest number of interesting articles in the field of management studies. He was a member of the board of senior scholars of the National Center for the Educational Quality of the Workforce and co-chaired National Academies' committee on the changing occupational structure in the United States. He holds an AB. in English from the College of William and Mary, an M.Ed. from Ohio State University, and a Ph.D. in organization studies from MIT.

BARRETT S. CALDWELL is a professor in the School of Industrial Engineering and holds a courtesy appointment in the School of Aeronautics and Astronautics at Purdue University. His research applies human factors and industrial engineering principles to team performance in complex task environments. Dr. Caldwell's group is concerned with analysis, design, and improvement of how humans work with, and share knowledge through, information and communication technology systems on Earth and in space. His early research examined the potential social and technological effects of Internet multimedia communications, even before the release of the Mosaic browser in 1993. Dr. Caldwell's discovery of the importance of information delay with increasing bandwidth has been meaningful since the growth of Internet file sharing, which demonstrated that delay remains a concern to ensuring satisfactory quality of service. He is a fellow of the Human Factors and Ergonomics Society. Dr. Caldwell received his Ph.D. in social psychology in 1990 from the University of California, Davis.

MELISSA CEFKIN is a principal scientist and design anthropologist at the Nissan Research Center, Silicon Valley, where she focuses on the development of autonomous vehicles from a social and cultural standpoint. Before joining Nissan, she served as manager of the Discovery Practices group in IBM's Accelerated Discovery Lab. At IBM, she focused on reconfigurations of work and labor related to new ways of conceptualizing, designing, and executing work using open, crowd, and big data-driven practices. Dr. Cefkin previously served as director of user experience and member of the Advanced Research group at Sapient Corporation. She was also a senior research scientist at the Institute for Research on Learning. She is the editor of *Ethnography and the Corporate Encounter: Reflections on Research in and of Corporations* (2009) and served as the president of the board of the Ethnographic Praxis in Industry Conference. Dr. Cefkin is a Fulbright award grantee. She received her Ph.D. in anthropology from Rice University in 1993.

HENRIK I. CHRISTENSEN is the KUKA Chair of Robotics at the College of Computing of the Georgia Institute of Technology. He is also the executive director of the Institute for Robotics and Intelligent Machines. Dr. Christensen does research on systems integration, human-robot interaction, mapping, and robot vision. The research is performed within the Cognitive Robotics Laboratory. He has published more than 300 contributions across artificial intelligence, robotics, and vision. His research has a strong emphasis on "real problems with real solutions." A problem needs a theoretical model, implementation, evaluation, and translation to the real world. He is actively engaged in the setup and coordination of robotics research in the United States (and worldwide). Dr. Christensen received the Engelberger Award in 2011, the highest honor awarded by the robotics industry. He was also awarded the Boeing Supplier of the Year in 2012, with three other colleagues at Georgia Tech. Dr. Christensen is a fellow of AAAS and the Institute of Electrical and Electronic Engineers (IEEE). He received an honorary doctorate in engineering from Aalborg University in 2014. He collaborates with institutions and industries across three continents. His research has been featured in major media such as CNN, *The New York Times*, and BBC. He serves as a consultant to companies and government agencies across the world. Dr. Christensen received his Ph.D. in electrical engineering from Aalborg University in 1990.

JOHN C. HALTIWANGER is a distinguished university professor in the Department of Economics at the University of Maryland, College Park. He is also the first recipient of the Dudley and Louisa Dillard Professorship, in 2013. After serving on the faculty of the University of California, Los Angeles (UCLA) and Johns Hopkins University, Dr. Haltiwanger joined the faculty at University of Maryland in 1987. In the late 1990s, he served as chief economist of the U.S. Census Bureau. He is a research associate of NBER, a senior research fellow at the Center for Economic Studies at the U.S. Census Bureau, and a fellow of the Society of Labor Economics. Dr. Haltiwanger has played a major role in developing and studying U.S. longitudinal firm-level data. Using these data, he has developed new statistical measures and analyzed the determinants of firm-level job creation, job destruction, and economic performance. He has explored the implications of these firm dynamics for aggregate U.S. productivity growth and for the U.S. labor market. The statistical and measurement methods Dr. Haltiwanger has helped develop to measure and study firm dynamics have been increasingly used by many statistical agencies around the world. His own research increasingly uses the data and measures on firm dynamics from a substantial number of advanced, emerging and transition economies. His work with the statistical agencies has been recently recognized in his being awarded the Julius Shiskin Award for economic statistics in 2013 and the Roger Herriott Award for innovation in federal statistics in 2014. He has published more than 100 academic articles and numerous books, including *Job Creation and Destruction* (with Steven Davis and Scott Schuh). Dr. Haltiwanger received his Ph.D. in economics from Johns Hopkins University in 1981.

ERIC HORVITZ is a technical fellow and director at the Microsoft Research Lab at Redmond, Washington. He has pursued principles and applications of machine intelligence, with a focus on the use of probability and decision theory in systems that learn and reason. Dr. Horvitz has made contributions in automated diagnosis and decision support, models of bounded rationality, machine learning, human-computer collaboration, and human computation and crowdsourcing. His research and collaborations have led to fielded systems in health care, transportation, human-computer interaction, robotics, operating systems, networking, and aerospace. Dr. Horvitz has been awarded the Feigenbaum Prize and the AAAI-Association for Computing Machinery (ACM) Allen Newell Award for contributions to artificial intelligence and human-computer interaction. He has been elected fellow of the AAAI, the ACM, the American

Academy of Arts and Sciences, and the NAE, and he has been inducted into the CHI Academy.

RUTH M. MILKMAN is a distinguished professor of sociology at the City University of New York (CUNY) Graduate Center and at the Joseph F. Murphy Institute for Worker Education and Labor Studies, where she also serves as research director. She is a sociologist of labor and labor movements who has written on a variety of topics involving work and organized labor in the United States, past and present. Her early research focused on the impact of economic crisis and war on women workers in the 1930s and 1940s. She then went on to study the restructuring of the U.S. automobile industry and its impact on workers and their unions in the 1980s and 1990s; in that period she also conducted research on the labor practices of Japanese-owned factories in California. More recently Dr. Milkman has written extensively about low-wage immigrant workers in the United States, analyzing their employment conditions as well as the dynamics of immigrant labor organizing. She helped lead a multi-city team that produced a widely publicized 2009 study documenting the prevalence of wage theft and violations of other workplace laws in Los Angeles, Chicago, and New York. She also recently co-authored a study of California's paid family leave program, focusing on its impact on employers and workers. After 21 years as a sociology professor at UCLA, where she directed the Institute for Research on Labor and Employment from 2001 to 2008, she returned to New York City in 2010. Dr. Milkman received her Ph.D. in sociology from the University of California, Berkeley, in 1981.

EDUARDO SALAS is a professor and the Allyn R. and Gladys M. Cline Chair in Psychology at Rice University. Previously, he was a trustee chair and the Pegasus Professor of Psychology at the University of Central Florida where he also held an appointment as program director for the Human Systems Integration Research Department at the Institute for Simulation and Training (IST). Before joining IST, he was a senior research psychologist and head of the Training Technology Development Branch of Naval Air Warfare Center Training Systems Division for 15 years. During this period, Dr. Salas served as a principal investigator for numerous research and development programs that focused on teamwork, team training, simulation-based training, decision making under stress, safety culture, and performance assessment. He has co-authored more than 450 journal articles and book chapters and has co-edited 27 books. His expertise includes assisting organizations in how to foster teamwork, design and implement team training strategies, facilitate training effectiveness, manage decision making under stress, develop performance measurement tools, and create a safety culture. Dr. Salas is a past president of the Society for Industrial/Organizational Psychology and the Human Factors and Ergonomics Society, a fellow of the American Psychological Association and a recipient of the Meritorious Civil Service Award from the Department of the Navy. He is also the recipient of the 2012 Society for Human Resource Management Losey Lifetime Achievement Award and the 2012 Joseph E. McGrath Award for Lifetime Achievement.

NICOLE SMITH is a research professor and senior economist at the Georgetown University Center on Education and the Workforce where she leads the center's econometric and methodological work. Dr. Smith has developed a framework for restructuring long-term occupational and educational projections. This framework forms the underlying methodology for *Help Wanted*, a report that projects education demand for occupations in the U.S. economy through 2020. She is part of a team of economists working on a project to map, forecast, and monitor human capital development and career pathways. Dr. Smith was born in Trinidad and Tobago and graduated with honors in economics and mathematics from the University of the West Indies (U.W.I.), St. Augustine campus. She was the recipient of the Sir Arthur Lewis Memorial Prize for outstanding research at the master's level at the U.W.I. and is co-recipient of the 2007 Arrow Prize for Junior Economists for educational mobility research. Prior to joining the center, Dr. Smith was a faculty member in economics at Gettysburg College in Pennsylvania, and the University of the West Indies, St. Augustine campus. Dr. Smith taught classical and modern econometrics, introductory and advanced level courses in microeconomics, macroeconomics, statistics, mathematics for economists, and Latin American economic development. Her previous macroeconomic research focused on the political economy of exchange rates and exchange rate volatility in the Commonwealth Caribbean, the motivation for her M.S. thesis and a joint-publication at the Inter-American Development Bank. Her current research investigates the role of education and socioeconomic factors in intergenerational mobility. She is a co-author of *The Inheritance of Educational Inequality: International Comparisons and Fifty-Year Trends* (2007). She received her Ph.D. in economics from American University.

CLAIRE J. TOMLIN is a professor of electrical engineering and computer sciences at the University of California, Berkeley, where she holds the Charles A. Desoer Chair in Engineering. Dr. Tomlin held the positions of assistant, associate, and full professor at Stanford University from 1998 to 2007, and in 2005 joined Berkeley. She received the Erlander Professorship of the Swedish Research Council in 2009, a MacArthur Fellowship in 2006, and the Eckman Award of the American Automatic Control Council in 2003. She works in hybrid systems and control, with applications to air traffic systems, robotics, and biology. Dr. Tomlin received her Ph.D. in electrical engineering and computer science at the University of California, Berkeley, in 1998.

NATIONAL ACADEMIES STAFF

JON EISENBERG is director of the Computer Science and Telecommunications Board (CSTB) of the National Academies. He has also been study director for a diverse body of work, including a series of studies exploring Internet and broadband policy and networking and communications technologies. From 1995 until 1997, he was an AAAS Science, Engineering, and Diplomacy Fellow at the U.S. Agency for International Development, where he worked on technology transfer and information and telecommunications policy issues. Dr. Eisenberg received his Ph.D. in physics from the University of Washington in 1996 and B.S. in physics with honors from the University of Massachusetts, Amherst, in 1988.

EMILY GRUMBLING is a program officer with the CSTB, where she coordinates projects addressing the societal impacts of emerging information and communication technologies. She previously served as an AAAS Science and Technology Policy Fellow in the Directorate for Computer and Information Science and Engineering at the National Science Foundation (2012-2014) and as an American Chemical Society (ACS) Congressional Fellow in the U.S. House of Representatives (2011-2012). Dr. Grumbling currently serves as a volunteer associate of the ACS Committee on Environmental Improvement. She received her Ph.D. in physical chemistry in 2010 from the University of Arizona, where she was the 2008 Marvel fellow, and her B.A. with a double-major in chemistry and film/electronic media arts from Bard College in 2004.

MARGARET HILTON is a senior program officer of the Board on Science Education (BOSE) of the National Academies where she is currently directing a study on assessing intrapersonal and interpersonal competencies and a study on developing indicators for undergraduate STEM education. Her previous studies, *Enhancing the Effectiveness of Team Science* (2015) and *Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century* (2012) drew widespread interest in the scientific and education communities. In 2011 and 2012, she directed two large national summits—one on community college STEM education and one on assessment of informal and afterschool science learning. She contributed to the BOSE study *Discipline-Based Education Research: Understanding* *and Improving Learning in Undergraduate Science and Engineering*, was a primary author of the report *Learning Science through Computer Games and Simulations*; and directed a study of high school science laboratories. For the National Academies' Committee on National Statistics, she directed a study of a large database of occupational information. Prior to joining the National Academies staff, as an analyst at the Congressional Office of Technology Assessment, Ms. Hilton directed studies of workforce training, work reorganization, and international competitiveness. She earned a B.A. in geography, with high honors, from the University of Michigan, an M.A. in regional planning from the University of North Carolina, Chapel Hill, and an M.A. in education and human development from George Washington University.

SHENAE BRADLEY is an administrative assistant for the CSTB. She currently provides support for multiple projects, including Continuing Innovation in Information Technology; Information Technology, Automation, and the U.S. Workforce; and Toward 21st Century Cyber-Physical Systems Education, to name a few. Prior to this, she served as a senior project assistant with the board. Prior to coming to the National Academies, she managed a number of apartment rental communities for Edgewood Management Corporation in the Maryland/DC/Delaware metropolitan areas.

KATIRIA ORTIZ is a research associate for the CSTB. She previously served as an intern under the U.S. Department of Justice and as an undergraduate research assistant at the Cybersecurity Quantification Laboratory at the University of Maryland College Park. She received a B.S. in cell biology and molecular genetics and a B.A. in criminology and criminal justice from the University of Maryland College Park, in 2014. She recently completed her M.A. in international science and technology policy from George Washington University.

D

Acronyms and Abbreviations

ACS	American Community Survey
AI	artificial intelligence
ATM	automated teller machine
BDS	Business Dynamic Statistics
BEA	Bureau of Economic Analysis
BED	Business Employment Dynamics
BLS	Bureau of Labor Statistics
BPP	Billion Prices Project
CES	Current Establishment Survey
CPI	Consumer Price Index
CPS	Current Population Survey
DOT	Dictionary of Occupational Titles
EHR	electronic health record
GDP	gross domestic product
GPS	Global Positioning System
IDT	interdisciplinary team
IT	information technology

JOLTS	Job Openings and Labor Turnover Survey
LEHD	Longitudinal Employer Household Dynamics
MOOC	massive open online course
NCHS	National Center for Health Statistics
O*NET	Occupational Information Network
QCEW	Quarterly Census of Employment and Wages
QWI	Quarterly Workforce Indicators
R&D	research and development
STEM	science, technology, engineering, and mathematics
VoIP	Voice-over Internet Protocol