Adoption of New Information and Communications Technologies in the Workplace Today

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I. Introduction

For decades, new information and communications technologies (ICTs) have been coming into the workplace. The application of ICTs is most of modern technical progress in the services sector (most of modern employment) and in the management and marketing functions of the reset of the economy (most of the rest of modern employment). Today, a new wave of novel ICTs are moving into the workplace, both replacing and complementing existing technologies. This paper takes up two simple to state, if hard to answer, questions: What valuable impacts will come from application of these new ICTs, and what impacts will these have on labor demand, and therefore on income inequality, going forward? Today there is a large academic and public policy debate about these questions, based on an enormous amount of speculation and uninformed by any actual examination of the actual application of these new ICTs in the workplace. In this paper, we examine that actual application and find that we disagree with all sides in the current debate.

In the language of engineering, ICTs are "enabling technologies": they permit, but do not direct, the invention of applications. Instead, a complex process of "co-invention"(in the language of economics) creates applications that address market demands and organizational supply processes. These applications define the economic value and impacts on labor demand of the enabling technologies. For example, the Internet is a wonderful group of inventions. It permitted, but did not direct, valuable inventions in E-commerce such as online stores. The value-creation and labor-demand implications of online stores depend mostly on the economics of stores (online or not) and only indirectly on the fact that the Internet uses computers and communications equipment.

The systematic study of ICT co-invention, discussed in the next section, has revealed at least three critical features. (1) Co-invention of ICT applications often increases product quality. They do not simply decrease production costs at the status quo. The automatic teller machine (ATM) network is a familiar example. ATMs did not merely replace human tellers. They allowed consumers to make deposits and (especially) withdrawals when the bank was closed. Once ATMs were networked, they allowed cash access even while far away from any branch of their bank. These increases in convenience increased the quality of banking services. (2) Co-invention of ICT applications often changes communication and/or incentives throughout an organization or even an entire supply chain. A familiar example is Uber, which has a different form of communication between driver and passenger than hailing or calling for a cab and which changes incentives by requiring drivers to rate passengers and passengers to rate drivers. Many other applications change more kinds of workers', suppliers', or customers' incentives and communication and are comparatively complicated. (3) Much co-invention of ICT applications is very difficult, requiring both brainpower and experimentation to create value. ICT co-invention is not just a matter of buying servers, PCs, and phones. Instead, it involves the incremental improvement of applications at a particular using firm. The applications grow steadily more complex and valuable because they build upon the learning that results from their earliest, simple, variants. Achieving (1) and (2) require figuring out exactly how to change the incentives of a large number of workers, customers, and suppliers in order to make a new organization that can supply improved product quality.

As new waves of ICT have come into the workplace, from mainframes to mobile phones, they have enabled new rounds of ICT application co-invention. In this paper, we exam the round of co-invention which is just now beginning. A very large number of firms are taking up the opportunity to co-invent ICT applications which draw on such new technologies as Big Data, Analytics, Mobile, and the Cloud. These are being treated, not surprisingly, as important technologies. What is striking in our investigations is how much co-invention today looks like earlier rounds of co-invention. In short, while there has been terrific technical progress in ICT, there has been little maturation of ICT application co-invention process. Co-invention still requires considerable brainpower and experimentation. Co-invention still looks for ways to change whole organizations. Indeed, modern co-invention often looks for ways to change whole supply chains. That is still very difficult. And co-invention still seeks to improve product quality in a way that aligns the new applications with the firm's strategic goals. That, too, is still difficult. The main features of co-invention over the last 50 years are still present today.

The three key features of ICT co-invention have important implications for value creation and for labor demand. (1) The need for brainpower and experimentation to translate ICT into new and valuable products and services provides a very simple explanation of why co-invention of ICT applications has raised the demand for smart managers and professionals. (2) The organizational change involved in ICT co-invention increases demand for workers with "organizational participation skills (OPS)" in all wage brackets. (3) The complexity of ICT co-invention renders it a long and sustained process, so these labor demand implications will sustain many of important changes in the labor market over the last 40 years (changes which many observers have rightly found alarming).

A widespread and noisy debate among scholars and those interested in public policy has taken up a question you might think is related to our enquiry: the extent to which computer work has been substituted for human work over the last 40 years and the possibility that various developments, such as improvements in Artificial Intelligence (AI) will accelerate that substitution. All readers of this paper will have seen articles such as "Why the Final Game between AlphaGo [an AI machine] and Lee Sedol [a human grandmaster in the game of Go] Is Such a Big Deal for Humanity."[1] Klaus Schwab, of the World Economic Forum argues that we are at the start of the "fourth industrial revolution" and that "[t]here has never been a time of greater promise, or one of greater potential peril." Others see the Google driverless car as the sign that there is about to be an acceleration of substitution of computer intelligence for human intelligence. Given the breathless and overblown nature of these claims ("such a big deal for humanity") others have started to argue that computer intelligence won't be substituted for human intelligence in all work (e.g. Remus and Levy (2015))[2] or that that substitution will occur but it

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[1] Cade Metz, "Why the Final Game between AlphaGo and Lee Sedol Is Such a Big Deal for Humanity" Wired (online) 3/14/2016.

[2] Remus, Dana and Levy, Frank S., Can Robots Be Lawyers? Computers, Lawyers, and the Practice of Law (December 30, 2015). Available at SSRN: http://ssrn.com/abstract=2701092 This paper makes the excellent point that "the existing literature's narrow focus on employment effects should be broadened to include the many ways in which computers are changing (as opposed to replacing) the work of lawyers."

will take a long time (e.g. Autor (2015))[3]. We think this debate simply misses the point about the future of ICT based applications in the workplace. Applications have not rendered human beings useless historically, and there are no indications in current applications will be any different.

What will happen going forward? The early stages of importing new ICT technologies into the workplace look, so far, remarkably like the early stages of all of the earlier waves in which valuable new ICT invented outside the realm of workplace computing has been brought into the workplace. A sensible forecast would be built around the point that the workplace is, once again, importing new ICT technologies. There will be renewed opportunities for the invention of profitable ways to use ICT in the workplace – with new products and services of improved quality and new and better incentives in organizations and markers begin the forecast. There will also be, this reasonable forecast goes on, continuity in the labor demand implications of the use of ICT. There will continue to be increased demand for managers and professionals as their skills are complementary to ICT application co-invention. There will continue to be increasing spread across firms in wages paid. In short, the near term future will look like the recent past, both the good parts and the bad parts.

II. ICT co-invention: organizational change and product quality

Contemporary observers emphasize substitution of machine for the *individual* worker at the task level. The literature on ICT application co-invention suggests that these observations are made at the fundamentally wrong unit: ICT co-invention induces *organizational* change, since firms do not cleanly separate into the sum of their individual workers. Furthermore, firms respond to customer demand, competition, and internal organizational processes. The rate and direction of application development is therefore shaped by the competitive market, which forces efficiency on the production side and product/service quality improvements for the consumer side.

A. Organization as fundamental unit of analysis

While co-invention of ICT applications does increase in the demand for computer scientists, data scientists, and a large number of other technical disciplines, the literal computer programmers (however broadly understood) cannot explain most of the technical change that has been contributing to spreading income distributions, simply because there are not enough of them. As a result, scholars have looked for broader categories of workers whose work is complementary to ICT. Reich (1993) suggested that there was another important element of skill-biased technical change in the use of computers by “symbolic analysts” or “knowledge workers” who use computers, especially PCs. Enough attention has now been focused on this story that it has become a standard. It is a theory of complementarity between computers and the human capital of *individual* computer users. This particular story has guided much of the labor economics literature on skill-biased technical change to measure “technical change” as “computer-use by the individual”. Few theories in economics have been rejected by as much evidence as the idea that technical change should be measured as “computer use by the individual” while retaining such enormous influence.

An understanding of the process of co-invention of ICT applications should compel scholars to recognize that the minimum divisible unit at which we can analyze technical change is at the level of the

[3] Autor, David H. 2015. "Why Are There Still So Many Jobs? The History and Future of Workplace Automation." Journal of Economic Perspectives, 29(3): 3-30.

organization. ICT co-invention involves brainpower and experimentation at the organizational level.[4] The literature on co-invention emphasizes the cognitive difficulty of inventing new business computer systems, and their complementarity with changes in organization and new services at the firm level.[5] Typically the co-invention process is directed by managers (decision-makers with control-authority at various levels of leadership in a firm) because of its high potential value, i.e., changing the nature of the organization or improving product/service quality. Managers and professionals do more research as a result, and turn their results into operations more systematically. This calls for new cognitive skills, having a deep understanding of one's own organization and one's customers' needs. It calls for brainpower in finding ways to adapt to change.[6] Thus, the real driver of spreading income distributions is the increase in the demand for smart co-inventors in the form of managers (leaders) and professionals who complement ICT.

A. Accounting for quality improvements

Of course, as ICT-based production has spread, some tasks formerly undertaken by people are indeed now done by machines. This limited substitution of capital for labor is most pronounced in routine work in white-collar bureaucracies.[7] Few large firms today employ people to look up an account balance in a paper register and write bills. Instead, the system generates the bill automatically. The demand for billing clerks, at least billing clerks who do no more than process bills, is reduced. And, of course, this is not just the billing clerks, but the clerks in a number of different functions in white collar bureaucracies.

What we have learned from the literature on co-invention, however, is that the business value from automation of such routine white collar work functions is not the cost savings from removing the (few, and comparatively cheap) humans from the production process. Instead, the automation opens opportunities for improving the process itself to create better quality products and services. For example, once there is a billing database, smart billing can produce information to for a "decision support" system that improves quality.[8] Getting from a simple transactional system to a decision support system requires managers and professionals and OPS workers to continue the process of co-invention.

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[4] A summary of the management implications of the organizational focus can be found in Hammer M (1990) " Harvard Bus. Rev. 68(4):104–112

[5] See Barras (1990), Bresnahan & Saloner (1996), Bresnahan and Greenstein (1996), Brynjolfsson and Hitt (1996), and Friedman and Cornford (1989).
Barras, Richard (1990), "Interactive Innovation in Financial and Business Services", Research Policy, v 19, n 3, pp. 215-237.
Brynjolfsson, Erik and Lorin Hitt (1996), "Paradox Lost? Firm-Level Evidence on the Returns to Systems Spending", Management Science, v 42, n 4, pp. 541-558.
Friedman, Andrew L. and Dominic Cornford (1989), Computer Systems Development: History, Organization, and Implementation, Chichester, England: New York : Wiley.

[6] Bartel and Lichtenberg (1987) suggest that high levels of cognitive skills may be particularly important in creating and adapting to change, notably in implementing new technology. The managerial side of computer-based production processes is an excellent example of this story.

[7] See Bresnahan (1999) for details.

[8] Keen(1981) lists eleven different kinds of decision support systems coming into widespread use decades ago . Rather than reducing cost, he writes, they tend to add value. This is typical of assesments of DSS over a long period.
"Value Analysis: Justifying Decision Support Systems," by Peter G. W. Keen, MIS Quarterly Vol. 5, No. 1 (Mar., 1981), pp. 1-15.

A series of famous consumer banking innovations associated with demand deposits illustrate the product quality point and its ongoing importance. All make it more convenient for the customer. The first was the ATM, which let the customer withdraw, check balances or deposit even when the bank was closed. The next was the ATM network, which let the customer do those activities even if away from any of her bank's branches. Both of these increase convenience.

The increase in convenience is a product quality improvement, and should expand output. As James Bessen has pointed out, the ATM also represents automation of a function formerly performed by human tellers if the customer uses an ATM for deposits or withdrawals that otherwise would have been done in the bank. Some replacement of human work, some expansion of output through the convenience / product quality improvements. But as Bessen also points out, bank teller demand did not fall. What happened is that tellers moved to more valuable services, like selling other products to the customers. While the example may be extreme, it points out an important feature of product-quality improvement: expanding the demand for labor while potentially changing the nature of the ideal worker.

B. Complementarity between ICT co-invention and organizations

The adaption at the organizational level to exploit ICT means that skills related to organizational activity become complementary. One systematic use of ICT is to measure and monitor work and the output of work so as to improve incentives and communications within firms.[9] This has systematically changed the demand for workplace social skills.[10] Demand is up for workers who can work effectively in teams, can accept incentives from the system, can function effectively if their manager is offsite, etc. Demand is down for workers who want to do their task and who tend to drift off task if not overseen by a manager. We call these "organization participation skills (OPS)", to reflect the importance of efficient interaction and communication between members of the organization. All of these OPS are demanded as part of a <u>bundle</u> – a worker has to be able to perform a particular task or tasks and also has to be able to work in a team, accept incentives, or communicate with a distant manager (or a customer or supplier).

Managers, for their part, have new demands for OPS as well in ICT-based production. They need to be able to work with teams, to design formal incentive systems, to get effective work out of people at far off locations, and so on. On top of increased brainpower and increased knowledge (e.g. of customers) managers in ICT based production often need new social skills. Here, too, we see an important element of bundling of different skills in the same person.

Note that workers in any level of the organization that can exploit OPS in conjunction with the ICT co-invention process will experience increased demand for their labor.

C. A Long and Sustained Process of Experimentation

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[9] See, for example, Hubbard, Thomas N. 2003. Information, Decisions, and Productivity: On Board Computers and Capacity Utilization in Trucking. <u>American Economic Review</u>. 93(4): 1328-1353 Susan Athey & Scott Stern, The Impact of Information Technology on Emergency Health Care Outcomes, 33 RAND J. Econ. 399 (2002); Ann Bartel, Casey Ichniowski & Kathryn Shaw, How Does Information Technology Affect Productivity? Plant-Level Comparisons of Product Innovation, Process Improvement, and Worker Skills, 122 QUART. J. ECON. 1721 (2007);.

[10] Social skills are very important in labor markets, though they are badly measured by education, occupation, or income, the three most common skill proxies in the empirical labor economics literature.

This increase in the demand for managers and professionals flowing through co-invention is ongoing and perennial. One might have thought that co-invention is a one-time thing, and that firms needed a one-time burst of brainpower to figure it out. On the contrary, two different forces have worked to create a sustained, increasing shift in demand for smart managers and professionals over decades.

Once force is the nature of individual “projects” of co-invention in individual firms. Much of co-invention is experimental, spread out over a large number of rounds of improvements, and thus ongoing. Experimentation and improvement in the business aspects of a particular ICT-based system can go on for years or even decades.[11]

Another important force is that new opportunities for co-invention have been created by invention, especially by the improvements in ICT brought into the workplace. In Figure 1, we show a number of technologies that were originally developed outside the workplace, most but not all in scientific/engineering computing, which have migrated to use in the workplace. Each wave of migration creates new opportunities for ICT applications co-invention in the workplace (as does the ongoing improvement in ICT, though typically not in such dramatic fashion.) There is, in short, a pattern of renewal of enabling technologies setting off new rounds of co-invention of ICT application.

As these cycles of renewal have brought a wider range of ICT technologies, what has been enabled is not just new applications but also the possibility of larger and more complex applications. Early applications were typically at the level of the firm. Over time, applications have expanded beyond firm boundaries to the level of the firm-and-its-customers, the-firm-and-its-suppliers, whole markets, or whole supply chains.

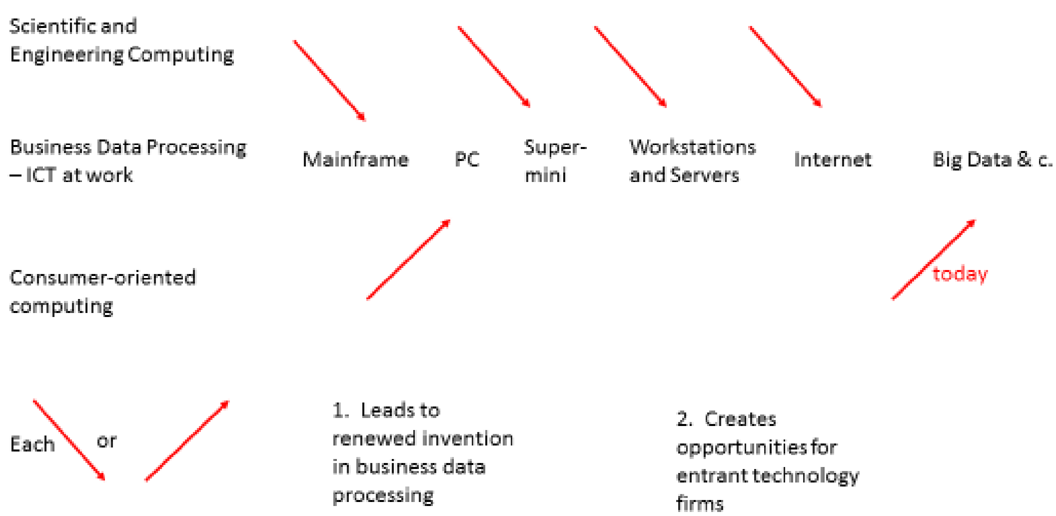

Figure 1

[11] The airline reservation system is a famous example.

The analytical literature on co-invention suggests that the complexity brought by increasing potential scope of the application (firm to market to supply chains) will slow the advance of the most complex apps[12], leading to a renewed cycle of experimentation in the co-invention of ICT applications, raising the demand for skilled engineers and especially for managers and professionals. Co-invention of ICT applications has also grown more difficult as it has spread out to organizations such as those in healthcare, where the problems of changing decision rights in the organization are daunting.[13]

Of course, part of the punchline of Figure 1 is that this cycle has continued into the present.

III. ICT Co-invention Today:

We turn now to the ICT technologies that are coming into use in the workplace today. Many of these, such as mobile apps and devices, cloud computing, big data, and analytics, have been widely used in consumer-facing computing, but are still new enabling technologies in the workplace. While these technologies are new to the workplace, new technologies have come into workplace computing before. Our question in this section will be whether (A) there is a radical transformation underway or (B) these new technologies are setting off a new round of co-invention of ICT applications like the earlier waves of technology shown in Figure 1. We will conclude that the current round shares the three key features of early waves. The need for brainpower and experimentation to (co-)invent new applications is slowing and directing the co-invention process. The locus of change is the organization, not the individual worker. And product/service quality improvements are central. This is a story of taking up another important opportunity, not a story of radical change.

We start with the World Economic Forum's survey of multinational enterprises. "The Future of Jobs Report" January 2016.[14] We start here for two reasons. First, the WEF report concludes that we are living in a time of radical change in the workplace. Second, the actual results of the survey are broadly similar to those of other contemporary primary research.

The results of interest to us are reported in Table 1, below. A more complete version of this table, with the specific questions asked and other details, is in our Appendix. Briefly, the survey asked HR or strategy executives to respond to a list of potential areas of co-invention, called "drivers of change," ranking each area as a "top trend" or not and specifying to time frame in which it will be relevant to application. While the WEF has a longer list, we restrict attention to the subset of "drivers of change" which have an ICT basis. Following the WEF, we rank these by the percent of respondents who feel that the particular the area is a "top trend".

The first thing to note about this table is that the two technologies which are getting the most discussion – robotics and AI – are far down the list ordered by how many users think of the technology as a top trend, with 9% and 6% of users agreeing to the "top trend" designation, respectively. These

[12] This appears to be entirely correct. See, e.g., "Do Market Leaders Lead in Business Process Innovation? The Case(s) of E-business Adoption" by Kristina McElheran, Management Science (2015)

[13] See, e.g., Dranove et al 2014, which discuss the difficult but ultimately successful efforts to bring Electronic Medical Records to the hospital sector.
Dranove, David, Chris Forman, Avi Goldfarb, and Shane Greenstein. 2014. "The Trillion Dollar Conundrum: Complementarities and Health Information Technology." American Economic Journal: Economic Policy, 6(4): 239-70

[14] World Economic Forum, "The Future of Jobs Report," January 2016.

two technologies are significantly less likely to get that designation than the technology-based reorganization of work, mobile internet and cloud, or big data, all rated as "top trends" by between a quarter and a half of respondents. Second, those same two technologies are placed firmly in the future by these respondents, with the timing of their impact three years off as of the survey.

Table 1

"Driver"	% rating as "top trend"	Timing
Changing work environments and flexible working arrangements	44%	already
Mobile internet and cloud technology	34%	2015-2017
Advances in computing power and Big Data	26%	2015-2017
The Internet of Things	14%	2015–2017
Crowdsourcing, the sharing economy and peer-to-peer platforms	12%	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

The many public statements that these new technologies are changing everything contrast with the empirical fact that these technologies are, in round numbers, not changing anything yet.

Second, the same survey reveals that there are other important ICT technologies which are having an impact on the workplace or which respondents see as about to have an impact (vs being years off). The important technologies enabling co-invention today are ones that support ongoing organizational change and the new imports from consumer computing – mobile, cloud and big data.

With this influx of new applications and this increase in the complexity and scope of the applications of ICT has come a remarkable development. Rather than becoming simpler, the invention of the applications of ICT has retained the strategic, organizational and creative aspects of co-invention first noticed decades ago. 1) Innovation and experimentation are required to apply ICT technologies in the workplace. 2) Organizational adaptions are required to both create and implement ICT applications in the workplace. 3) The resulting new services and products from this co-invention process represent simultaneously higher quality and lower cost changes to the economy. There has been little maturation of the co-invention process. Instead, the need to change complex organizations, align the new application with firm goals, and have an implementation that specifically achieves what the grand strategy expected remain centerpieces of co-invention. These three properties all enhance and increase demand for human labor.

I. Innovation and experimentation

One part of what is actually going on today is connected to Artificial Intelligence, but not through replacing human thinking with machine thinking.

A cluster of technologies has emerged associated with "big data." "Big" data sets – sometimes called data streams – are typically gathered automatically. Many ordinary consumer activities contribute to these data streams already, such as searching on the web, looking through an online store before buying things, online social interaction or other communication, mobile app usage, and so on. Big data techniques have been pushed very far forward in the largest consumer-oriented ICT firms. Many of these technologies have so far had their main value-add as specialization recommendation-engine technologies. Google, for example, uses complex algorithms both to decide what search results to show a particular person and what advertisement to show a particular person after a particular search. Amazon does not recommend the same products to everyone, nor Netflix (nor Pandora) the same entertainment, just as Google returns different search results to people it "decides" have different interests. A great deal of machine learning is involved in making that "decision. Note, however, that these technologies enhance, rather than replace, human decision-making by providing information in a useful manner to the human decision-maker.

These consumer-facing applications have led to a large volume of technical progress -- the new technologies that are now coming into the workplace. It has proved difficult to manage these data streams with traditional relational data base management software and associated programming tools, both because the scale of "big" data can be quite large and because it is difficult to impose definitions on large, cheaply gathered data streams. (In contrast, traditional DBMS software dealt with transactions datasets, where there can be a known and enforced definition of all the fields associated with a transaction.) Not surprisingly, "predictive analytics" which are statistical techniques with a data-mining flavor, are closely associated with big data. Some of these techniques involve machine learning while others do not.

The potential application of these techniques in the workplace today is generating tremendous interest among employers. A number of surveys report that large US firms fall into three roughly equally-sized groups: those that already have a big data co-invention project under way, those that have identified and are capturing big data streams (but don't yet have a co-invention project underway) and others.[15] Penetration of the big data techniques out of a co-invention project phase into production applications is perhaps a bit slower: In a recent survey Dresner Advisory Services reported that 83% of 3000 firms were not currently using big data, despite 59% of the firms responding that application of big data is "critically important."[16] The technical disciplines associated with big data and analytics, such as data scientists, are in very hot demand, and the supply-side response of trying to train more data scientists in statistics, computer science, and economics departments is very large.[17]

The co-invention wave associated with big data involves, like the earlier waves of co-invention, substantial amounts of experimentation, exploration, and the deployment of managers with the brainpower to understand management, statistics (!), and their customers, workers or suppliers.[18]

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[15] Dresner Advisory Services, *Big Data Analytics Market Study*, November 2015, http://www.bigdataanalyticsreport.com/

[16] http://www.datamation.com/applications/thesurprisingtruthaboutbigdata.html, James Maguire, February 2, 2016, citing Dresner Advisory Services, *Big Data Analytics Market Study*, November 2015.

[17] We can't resist one "only at Stanford" remark; our colleagues in Political Science have added a "big data" track to their B.A. curriculum.

[18] Susan Athey has suggested a set of implications for the education of managers rooted in a deep understanding of the (https://www.gsb.stanford.edu/insights/susan-athey-how-big-data-changes-business-management) possibilities for new work in the "big data" era.

The pattern of experimentation is taking time and multiple rounds to lead to value creation in this round as in earlier rounds of co-invention. This pattern has not changed in modern times. Harnessing the benefits of new technology is hard, so the realization of its benefits are often delayed far beyond the date when its applications are envisioned. This has been observed historically, and the impending technologies of today are no different. According to McKinsey Quarterly, January 2015,

> "we recently assembled a group of analytics leaders from major companies that are quite committed to realizing the potential of big data and advanced analytics. When we asked them what degree of revenue or cost improvement they had achieved through the use of these techniques, three-quarters said it was less than 1 percent."[19]

Even more simplistic data involved in back-end production processes poses application challenges. The measurement and networked communication opportunities from ubiquitous sensors have created excitement over the possibilities from an Internet of Things (IoT). However, as a June 2015 McKinsey report discovered, "Most IoT data are not used currently. For example, only 1 percent of data from an oil rig with 30,000 sensors is examined. The data that are used today are mostly for anomaly detection and control, not optimization and prediction, which provide the greatest value." [20]

The ultimate value of "analytics" based on big data is clear to these adopters at an early stage. What is not clear is how that ultimate value will be realized. Only after the initial applications have been built, and their potential role in the organization assessed based on evidence, will the value proposition and the labor demand impact become clear. Until then the process of innovation and experimentation to discover those applications will require more human labor, not less.

Big data applications development hits two very different bottlenecks when it moves into more ordinary businesses. It can be difficult to decide what are the profitable applications for big data. Those organizations which have gathered big data but are not yet using it typically report that as the bottleneck. A Dell survey reported that for organizations that have big data but no applications using it "the top barrier is not knowing if the benefits are worth the costs."[21] Typically, it is a business person, not an IT person who leads the effort to define big data projects. Those organizations which are using big data typically identify the costs of the IT infrastructure for big data processing. This is much like the early stages of many important ICT technologies of the past. Inventing the uses is a bottleneck at the beginning, when the costs (data scientists are expensive as well) make the risk/benefit/cost calculation difficult.

Many big data applications go to places where risks are low because co-invention costs are low. One current example of ICT co-invention is security applications in finance, such as fraud-detection in credit cards and related systems. These are low-risk applications for big data because they are already statistical – the output of a fraud detection system is a probabilistic assessment of a particular transaction – fraud or legit? Thus a big-data based system need only provide a better prediction of fraud in a statistical sense, and it can be plugged into the existing people- and computer-based system for fraud detection without altering it fundamentally. Paypal, for example, uses big data and machine

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[19] David Court, "Getting Big Impact from Big Data", *McKinsey Quarterly*, January 2015.
[20] "The Internet of Things: mapping the value beyond the hype, "June 2015, McKinsey Global Institute.
[21] Dell, *Global Technology Adoption Index,* 2015, Slide 4, https://powermore.dell.com/wp-content/uploads/2015/10/GTAI_2015_Results_Deck_Final_for_Web_101115.pdf .

learning for fraud detection.[22] Paypal uses a linear fraud prediction algorithm, a neural network based algorithm, and deep machine learning and data mining – alongside human intelligence. Dr. Hui Wang, Senior Director of Risk Sciences at PayPal, notes,

"I never worry that these machines will replace humans. Yes, we can add layers, but you can talk to any machine learning scientist and they will say that the algorithm is important, but at the end of the day what really makes the difference is that a machine cannot find data automatically…. There is so much data, so much variety, but the flip side is: What is useful? We still rely on human oversight to decide what ingredients to pump into the machine."[23]

Another current day example of ICT co-invention is risk analysis in insurance, which was, of course, already analytic, so adding big data analytics is not a radical change. Practitioners confirm that the path of invention in this area is to undertake the low-risk, low change part of the application first. Only later do more profound changes follow.[24] As the applications mature, they tend to enhance rather than replace the efforts of workers: insurance industry analytics modelers work with claims staff to design effective models. [25]

Related examples can be found throughout the current co-invention wave. Ram Narasimhan of GE emphasized the change from consumer applications – co-invention – when he said "What data scientists do at Google or Yahoo or Facebook is a little different from what we at GE do." But he also emphasized the continuity with previous applications, such as detecting and predicting engine failures. These were already statistical; early big data applications permit doing a better job because there is more data about more GE-manufactured engines and "[t]hese engines are becoming smarter, and they generate a lot more data." Like fraud detection in finance, failure prediction in operations was already statistical and it is a natural move to go to machine learning on top of big data – statistical analysis that, because of the larger and more detailed data streams, can be faster and more detailed.

This pattern of undertaking experiments where it is comparatively easy to see that they might go well is an element of co-invention that is familiar from earlier rounds of co-invention (see, e.g. Bresnahan-Greenstein (1996) for much earlier rounds). The next round of co-invention will be based on the early experiments in their specific business context. How that next round will create value will depend on what is learned (ahem, by humans) from the experiments, not on some pre-determined substitution of ever smarter computers for the next-smarter kind of human worker.

Indeed, like traditional database applications before them, big data applications are not primarily based on substituting new and improved machine intelligence to do something that human intelligence did before. Instead, there is expansion. People are using computers to do many things, and machines have more and more embedded computers, so more "data streams" are feasible to capture cheaply. Cheap

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[22] How PayPal beats the bad guys with machine learning, Eric Knorr, April 13, 2015 http://www.infoworld.com/article/2907877/machine-learning/how-paypal-reduces-fraud-with-machine-learning.html.

[23] "What Data Scientists Do All Day at Work: Ram Narasimhan of GE talks about the importance of curiosity and what makes his day" by Deborah Gage, Wall Street Journal March 13, 2016.

[24] "Transforming into an analytics-driven insurance carrier," Ari Chester, Richard Clarke, & Ari Libarikian write "In the initial phase, carriers develop models that demonstrate early evidence of success."

[25] "As the analytics function matures, model builders work closely with frontline staff, who become involved in the nuts and bolts of building the model." Op cit.

computers, cheap communications, and especially cheap storage make it cost-effective to make "data streams" that capture information that it was never cost effective to capture before.

The increase in demand such that there is now a shortage of data scientists and programmers is the most obvious labor market effect of this new co-invention. However, the human element is not limited to those technical specialties who develop the new applications. Instead, there are a large number of managers who decide on the experiments to do in the course of co-inventing ICT applications based on big data. This creates opportunities for managers who understand not only their business but also some statistics and machine learning – a new bundle of skills – to create value.[26] Like earlier rounds of co-invention, this round is creating new valuable bundles of different human skills and rewarding them highly.

This effect of increasing the value of human work need not be limited to managers and professionals, though if the earlier pattern of co-invention's impact on the workplace is followed, it will be stronger there. Firms that effectively execute strategies today have organizations comprised of integrated departments and workers, so the critical knowledge and decisions necessary for a successful ICT application are found in consumer-facing staff. Mid-range participants in that staff that embrace the opportunity to make decisions based on machine learning and have the OPS to participate effectively in the co-invention of new systems will find the demand for their services raised.

II. Organizational adaption

What we learned in the review of co-invention above is that organizational adaptions have long been required to both create and implement ICT applications in the workplace. This is also true in the present. The wave of new ICT application co-invention set off by today's new technologies has set many companies off on a path of organizational change. As in earlier waves of co-invention, the ICT often augments how people in firms interact with one another or with suppliers and customers, rather than replacing those humans. The replacement of ever-smarter humans by ever-smarter machines does not appear as an important part of this dynamic, much less as its central thrust.

One well-known contemporary example is Uber. Compared to a traditional taxi company, Uber does indeed involve some limited aspects of automation. The task of taking customer orders and dispatching vehicles was traditionally done by (human) dispatchers on the telephone, more recently by order-taking websites plus human dispatchers on the telephone. It is a critical element of this part of Uber, however, that the automatic scheduling, combined with the flexible work schedule of Uber drivers, raises the efficiency of drivers and cars. Ubers wait less time between rides for their next fare. This increase in efficiency raises marginal physical product of an hour of driver time (more of it is spent productively) and is one key to the labor-demand expansion effect of Uber.

Uber also involves a significant change in organizational incentives compared to traditional taxi companies. Uber drivers, unlike cab drivers, are rated by their customers – Uber is set up to make rating nearly universal. This changes the incentive of a driver to be on time, courteous, and safe (not all of which are famous features of cab drivers.)[27] Uber drivers who are rated as weak on these attributes

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[26] Athey, op cit, describes managers that have this bundle of skills as "rock stars" on the labor market.

[27] Wallsten (2015) undertakes an empirical investigation of taxicab complaints and concludes that competition from Uber has a positive impact on cab driver behavior.

soon leave the service. Similarly, drivers rate passengers on Uber, changing passenger incentives. Passengers who are abusive in the car, are late to come out to the street, and so on, are rated down. Uber also makes it easy for driver and rider to communicate by cellphone to, for example, settle on an exact pickup location. These coordination and incentive terms cut across rider, platform (Uber) and driver – changing the organizational structure of the market. Einav, Farronato and Levin (2015) have a very interesting analysis of Uber and other "peer to peer" networks from a market-design perspective, emphasizing the changes in the organization of the entire market and its new incentives and information structures.

Bank of America recently adopted wearable technologies for its workers with the intent to monitor and improve productivity. They successfully achieved their goals. However, the way in which these productivity gains were achieved were based on changes in organizational structure to enhance human interaction within the firm, not outside of the firm:

"When they began studying the reps they figured the key indicator would be how they talked to customers, but they found that it was actually how the talked to one another that was most important because employees shared information and techniques.

They learned that employees talked most during the 15 minutes their lunches overlapped, so they tried giving one group lunch all at the same time and let the other group continue to have lunch according to the old staggered schedule. What they found surprised them.

Network cohesiveness, which measures how well they communicate went up 18 percent. This reduced stress (as measured by tone of voice) by 19 percent. All of this led to happier employees and lower turnover rates, which went down 28 percent. The key metric though, call completion time improved by 23 percent. These are numbers that on a scale of Bank of America could translate into billions in savings."[28]

The process of co-invention requires innovation and experimentation by the entire organization, so it is no surprise that the first step in co-invention is the enhancement of communications within the organizations to spur innovation and experimentation.

As co-invention successfully creates workplace applications, the organization must also adapt to implement those applications. Current explanations of the co-invention processes written by leading practitioners, relating to current applications of the newly imported consumer oriented technologies, could easily have been written when servers were coming into business data processing in the early 1990s. Here is a representative discussion of the difficulties of co-invention in Big Data and Analytics (a close complement) applications.

> "capturing the potential of data analytics requires the building blocks of any good strategic transformation: it starts with a plan, demands the creation of new senior-management capacity to really focus on data, and, perhaps most important, addresses the cultural and skill-building challenges needed for the front line (not just the analytics team) to embrace the change. ….

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[28] Miller, Ron. "New Firm Combines Wearables And Data To Improve Decision Making." TechCrunch. N.p., 24 Feb. 2015. Web. 24 Feb. 2016. <http://techcrunch.com/2015/02/24/new-firm-combines-wearables-and-data-to-improve-decision-making/>.

> Existing organizational processes are unable to accommodate advancements in analytics and automation, often because protocols for decision making require multiple levels of approval…[29].

These large organizational changes go beyond just needing to invent new applications software. More critically, the cost of fully integrated technology adoption requires adaption by the entire organizational structure, from incentives, to routines, to culture, to redefining job descriptions. Thus the impact on labor demand is more or less the opposite of the simple task-substitution model. As the practitioner we just cited wrote, "Automating part of the jobs of employees means making a permanent change in their roles and responsibilities." What is particularly interesting here is that the practitioner is discussing, not the use of "big data" to have better data, but the use of "analytics" running on top of "big data" to make better decisions. It is precisely this substitution, of machine for human decision making, that makes the application the most difficult to implement organizationally.[30]

III. Improving product quality=more demand.

The resulting new services and products from this co-invention process represent simultaneously higher quality and lower cost changes to the economy. Higher quality implies that demand for these innovations will increase, potentially increasing the demand for complementary human labor. Lower cost may lead to lower prices, which would also lead to higher demand for these innovations, again increasing the demand for complementary human labor.

For example, one aspect of consumer-oriented computing has been rapidly taken up in corporate sector, the mobile app. Originally introduced as an entrepreneurial technology to replace existing firms and markets (and with a few important successes in that arena out of the many millions of mobile app entrepreneurs) the technology for making and distributing mobile apps was quickly adapted by existing companies.[31] The corporate mobile app – whether from an airline, a retailer, or Starbucks – quickly took on one of the classical attributes of computing at work, product quality improvement. The implication of technical change that leads to product quality improvement is different from automation. Automation substitutes capital for labor (and the resulting cost rise may lead to some price falls and thus output expansion). Product quality improvement leads directly to output expansion.

In the case of the corporate mobile app, firms typically adapted the technology to deepen customer relationships. Airlines were able to give travelers more information about their flight, give them a boarding pass that didn't need to be printed, and let them check the upgrade list as often as they liked. Rather than replacing the functions of gate agents and customer service agents, the app lets the traveler interact with the airline more frequently. Starbucks was able to provide a convenient way to store loyalty rewards, which increased customer retention and necessitates more, rather than less, baristas.

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[29] "Getting Big Impact from Big Data," David Court, McKinsey Quarterly, 1/15

[30] "For example, it's great to have real-time data and automated pricing engines, but if management processes are designed to set prices on a weekly basis, the organization won't be able to realize the full impact of these new technologies." And "If you automate pricing, for instance, it is hard to hold the affected manager solely responsible for the profit and loss of the business going forward, since a key part of the profit formula is now made by a machine."

[31] A much fuller account of the origins of the corporate mobile app can be found in Bresnahan-Davis-Yin(2014).

ICT innovations are more likely to redefine jobs to higher quality services and activities at lower costs, as some tasks are automated.[32] "Even where automation has made significant progress, its impact has been far less than the headlines would have us believe."[33] In the legal profession, automation of scanning and preparing legal documents means that those services are cheaper and scalable, so demand could increase among previously unserved markets.[34] In the medical profession a robot pharmacists at UCSF allows the current 100 staff pharmacists to improve services:

"…now nearly all have been reassigned to different parts of the hospital, where they make IVs, help adjust patients' drug regimens, and perform other tasks that had been neglected when they were simply filling prescriptions.

There is a theory among pharmacists that robots will ultimately benefit the profession. The more automation that enters the field, the more pharmacists can focus on uniquely human tasks: counseling patients and working with doctors to ensure the proper medicine gets prescribed. This is especially true of pharmacists who work in hospitals. UCSF hasn't laid off any human pharmacists since installing its robotic dispenser." [35]

The next was the mobile banking app, which let the customer deposit checks and check balances from anywhere – and which, when coupled with a smartphone payment system (Apple pay or its many competitors) lets the customer do transactions out of her demand deposit account without cash. At each stage, convenience increases. Of course, the same can be expected of the modern, mobile-based "tellers in your pocket." They increase convenience, substitute some routine human tasks, and create opportunities to move the human worker to higher-value tasks.

Other corporate mobile apps have similar flavors. "Multichannel marketing" apps from retailers permit the customer to buy on her mobile device as well as online or in the store. This has some elements of automation – a purchase made online or on the mobile device does not require an instore sales person. Yet it also has elements of complementarity. If the purchases suggested online or on the mobile app take advantage of the information gleaned about the customer from an in-store visit, the efforts of the store sales rep to learn the customer's size or tastes are thereby spread out over more transactions than the salesperson personally attends. That leverage raises the demand for particularly effective salespeople.

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[32] McKinsey Quarterly, 11/15, "Four fundamentals of workplace automation, Michael Chui, James Manyika, & Mehdi Miremadi. "According to our analysis, fewer than 5 percent of occupations can be entirely automated using current technology. However, about 60 percent of occupations could have 30 percent or more of their constituent activities automated."

[33] "Can Robots Be Lawyers? Computers, Lawyers, And The Practice Of Law" Dana Remus and Frank Levy

[34] http://www.slate.com/articles/technology/robot_invasion/2011/09/will_robots_steal_your_job_5.html"instead of serving just a handful of high-paying clients, this maestro might be able to use machines to help serve thousands of clients over the Web, providing legal help to those who can't access it today." "The End of Lawyers? Not So Fast." By John Markoff http://mobile.nytimes.com/blogs/bits/2016/01/04/the-end-of-work-not-so-fast/?_r=1&referer=http://www.msn.com/en-us/money/technologyinvesting/a-plan-in-case-robots-take-the-jobs-give-everyone-a-paycheck/ar-BBqf3Id?li=BBnb7Kz

[35] http://www.slate.com/articles/technology/robot_invasion/2011/09/will_robots_steal_your_job_2.html

By far the most important lesson of the product-quality point is that ICT-based production processes are not merely automated versions of the previous processes. Just as with the organizational-change point, the mechanism by which ICT-based production processes have saved more low-wage labor than high-wage labor is not one of automation.

A. Labor Market Outcomes

One implication of a risky and uncertain process of ICT application co-invention is that firms should be spreading out in their success, with the more successful firms showing the major indicia of co-invention, such as changes in skill demand and higher ICT use. Such firm-level effects follow from the difficulty of co-invention (not all firms succeed equally in this invention) and from the organization-level implications of co-invention. This is, indeed, the case in organization/firm level studies. By now, there have been a large number of these studies.[36]

James Bessen has provided valuable new information on the implications of computer use in organizations.[37] He predicts employment growth from 1980 to 2013 in an occupation in an industry (accountants in insurance...). He includes two predictors relevant to our enquiry: (1) to what extent do people in this occupation in this industry report that they use a computer at work, and (2) to what extent do people in other occupations in this industry report that they use a computer at work? Use of computers within an occupation in an industry predicts higher employment growth in that occupation /industry. It is use of computers in other occupations in the industry that predicts lower employment growth. Since the "computer use" variables are the only ICT measures included, this points to an organizational, rather than a task-substitution, model of computer-based productivity change.[38] More interesting is the pattern of impacts of organizational computing that this suggests. There is little evidence that either own-computer-use or others'-computer-use impacts employment growth in employment growth in routine-intensive occupations, an unhappy fact for the computer-human substitution hypothesis. However, when Bessen looks across the wage distribution, he finds that others'-computer-use lowers employment growth in the bottom three quartiles of the wage distribution significantly, but has a positive (if imprecisely estimated) impact on the top wage quartile. This is consistent with the idea that organizational changes in computing allow better or smarter management of the overall organization, raising the productivity of comparatively rich workers.

Another implication is that firms should be spreading out in the wages they pay; successful co-inventing firms expand, typically because of the increase in product quality, and demand more labor, especially more capable labor. This implication, too, is borne out in the data. Song, Guvenen and Bloom (2015) examine the sources of the substantial increase in earnings dispersion across workers in the US from

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[36] The complementarity between ICT adoption and organizational and skills change can be found in, for example, Bresnahan and Greenstein (1996); Bresnahan, Brynjolfsson, and Hitt (2002); Forman, Goldfarb and Greenstein (2005); and Bloom et al. (2009). All of these papers document the variety across firms, indeed, that variety is their measurement frame.

[37] "How Computer Automation Affects Occupations: Technology, Jobs, and Skills" by James E. Bessen Boston University - School of Law; Research on Innovation January 16, 2016

[38] It also shows that the long literature based on individuals' computer use at work is irrelevant to the assessment of the labor-demand impact of ICT-based production. Both the part of the literature that finds impacts of computer use on wages (starting with Krueger (1993)) that the part of the literature that casts doubt on that finding (DiNardo and Pischke (1993) "pencils") are irrelevant to assessing the labor demand impact of ICT in the workplace.

1978 to 2012. They find that "virtually all" of the increase in earnings dispersion between workers is accounted for by an increase in the dispersion across employers (firms). In a study looking at the same phenomenon but on a narrower range of firms (only manufacturing firms) Dunne et al. 2004[39], find that "the bulk of overall wage dispersion is accounted for by between-plant dispersion, and the contribution of this component has been growing over time." An advantage of the narrower frame of the Dunne et al. work is that they have ICT variables, and find that the increase in wage dispersion across plants is highly correlated with ICT adoption.

The right level of analysis is not the individual job, but the entire organization, including today parts of the organization that extend beyond firm boundaries to customers or suppliers. The impact of ICT adoption and ICT application co-invention at the firm level has been to raise the demand for workers and their wages. The story that ICT is substituting for smarter and smarter human jobs as computers grow smarter is just wrong. ICT capital-intensive production replaces a wide range of workers, but is complementary to skilled workers, both in the sense of smart people and people with OPS.

IV. Concluding Remarks

The use of ICT in white collar organizations and in markets has, over the last 50 years, had two important economic consequences. It has been valuable, particularly through improving organizations and through improving product quality. It has contributed to the spread out in the income distribution, particularly through increasing the demand for various kinds of skills. The current state of ICT application co-invention, bringing in a number of technologies, some with a machine-learning flavor, suggests strongly that both of those trends will continue. There are two deep reasons for this. One is the renewal of technical opportunity that invention in ICT itself brings. The other is the process by which all the thousands of different advances in ICT are converted into valuable applications in organizations. Today, the renewal of technical opportunity is as valuable new technologies such as Big Data and Mobile come into the workplace from the consumer computing world. Today, the labor demand implications of co-invention of ICT applications are largely the same as before. The thing to like about digitization – valuable technical progress – and the thing to worry about – spreading out of the income distribution – will be the same in the near future as in the recent past.

In reaching this assessment, we are acutely aware that we disagree with pretty much everybody else who is trying to assess the implications of current technical developments for future wages and work. We disagree with those who say that that smarter and smarter computers, including "robots" and artificial intelligence, are about to substitute for more and more human jobs sooner or later. Substitution is not the first order effect in the co-invention process. The most important ICT applications today change large systems across whole organizations, markets, or supply chains. Any particular advances in ICT – including "smart machines," "robots," or AI, will be transformed itself as it is brought into productive use as much as it transforms production.

V. Appendix

[39] Dunne, Timothy, Lucia Foster, John Haltiwanger, and Kenneth R. Troske,"Wage and Productivity Dispersion in United States Manufacturing: The Role of Computer Investment," Journal of Labor Economics, April 2004, 22 (2), 397–430.

"Driver" [40]	% rating as "top trend"	Timing
Changing work environments and flexible working arrangements [41]--	44%	already
Mobile internet and cloud technology[42]	34%	2015-2017
Advances in computing power and Big Data[43]	26%	2015-2017
The Internet of Things[44]	14%	2015–2017
Crowdsourcing, the sharing economy and peer-to-peer platforms[45]	12%	already
Advanced robotics and autonomous transport[46]	9%	2018-2020
Artificial intelligence and machine learning[47]	7%	2018-2020
Advanced manufacturing and 3D printing[48]	6%	2015-2017

[40] Source: World Economic Forum, "The Future of Jobs Report," January 2016.This survey was filled in by senior "talent and strategy" executives at 371 companies in the first half of 2015.

[41] "New technologies are enabling workplace innovations such as remote working, co-working spaces and teleconferencing. Organizations are likely to have an ever-smaller pool of core full-time employees for fixed functions, backed up by colleagues in other countries and external consultants and contractors for specific projects."

[42] "The mobile internet has applications across business and the public sector, enabling more efficient delivery of services and opportunities to increase workforce productivity. With cloud technology, applications can be delivered with minimal or no local software or processing power, enabling the rapid spread of internet-based service models."

[43] "Realizing the full potential of technological advances will require having in place the systems and capabilities to make sense of the unprecedented flood of data these innovations will generate."

[44] "The use of remote sensors, communications, and processing power in industrial equipment and everyday objects will unleash an enormous amount of data and the opportunity to see patterns and design systems on a scale never before possible."

[45] "With peer-to-peer platforms, companies and individuals can do things that previously required large-scale organizations. In some cases the talent and resources that companies can connect to, through activities such as crowdsourcing, may become more important than the in-house resources they own"

[46] "Advanced robots with enhanced senses, dexterity, and intelligence can be more practical than human labour in manufacturing, as well as in a growing number of service jobs, such as cleaning and maintenance. Moreover, it is now possible to create cars, trucks, aircraft, and boats that are completely or partly autonomous, which could revolutionize transportation, if regulations allow, as early as 2020."

[47] "Advances in artificial intelligence, machine learning, and natural user interfaces (e.g. voice recognition) are making it possible to automate knowledge-worker tasks that have long been regarded as impossible or impractical for machines to perform."

[48] "A range of technological advances in manufacturing technology promises a new wave of productivity. For example, 3D printing (building objects layer-by-layer from a digital master design file) allows on-demand production, which has far-ranging implications for global supply chains and production networks."