Global Economic Impacts Associated with Artificial Intelligence

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I. Introduction

Artificial intelligence ("AI"), a term first coined in 1956, is a branch of computer science that aims to create intelligent machines that work and react like humans.[2] At the beginning of the study of AI, British mathematician Alan Turing proposed the true indication of computer intelligence to be when a question-asker could not distinguish between answers from a human and those from a computer.[3] In contrast, today, 60 years later, AI is characterized by a number of applications, including computers playing games against humans and understanding human languages, virtual personal assistants, and robotics which involve computers seeing, hearing, and reacting to sensory stimuli.[4] Looking forward to the next decade, technologists have offered a wide array of predictions for AI, ranging from AI being used as a tool to aid relatively simple processes (which some refer to as weak AI) to robots with human-like mental capabilities (which is sometimes referred to as strong AI).[5] According to AI expert Sir Nigel Shadbolt: "What we really have in AI is a whole spectrum of abilities, from programs that are smart but they are not smart like us, to programs that are super clever in specific areas."[6]

For the purposes of our study, we consider AI to broadly be computational devices and systems made to act in a manner that can be deemed intelligent.[7] In other words, AI is technology that appears to emulate human performance by learning, coming to its own conclusions, understanding complex content, engaging in dialog with people, enhancing human cognitive performance, or replacing humans in executing both routine and non-routine tasks. Because of the uncertainty of the future development and diffusion of AI, this view is intentionally broad, covering the AI existing today, such as targeted advertising and virtual personal assistants, as well as the AI that may exist in the future, such as robots with human-like processing capabilities. The range of AI's progress in the future will determine

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[1] The authors are all employed by Analysis Group, Inc. Funding for this study was provided by Facebook, Inc.
[2] Miller, Stephen. "Computer Scientist Coined 'Artificial Intelligence'." WSJ, 26 Oct. 2011.
[3] Turing, A. "Computing machinery and intelligence." Mind 1950. Reprinted in Computation and Intelligence by G. Luger, ed. MIT Press, Cambridge, 1995, pp.23-46.
[4] Pareek, Rahul. "Web Intelligence-An Emerging Vertical of Artificial Intelligence." International Journal Of Engineering And Computer Science 3.12 (2012): 9430-436.
[5] For example, "However, the characteristic of [AI's current] success is what I call the combination of brute force and a little insight" (Shadbolt, Nigel, "Why We Should Not Fear AI. Yet." Wired. May 8, 2015) and "If you think Siri is useful now, the next decade's generation of Siri will be much more like JARVIS from Iron Man, with expanded capabilities to understand and answer… In a decade, it will be normal for you to give your AI access to listen to all of your conversations, read your emails and scan your biometric data because the upside and convenience will be so immense. (Diamandis, Peter, "The World in 2025: 8 Predictions for the Next 10 Years." Singularity Hub, May 11, 2015.
[6] "The Life Scientific-Nigel Shadbolt." Interview by Jim Al-Khalili. BBC Radio 4. 14 Apr. 2015. Radio.
[7] McCarthy, John. "What Is Artificial Intelligence?" Computer Science Department Stanford University, 28 Sept. 2001, Revised 12 Nov. 2007; Thomason, Richmond. "Logic and Artificial Intelligence." Department of Philosophy University of Michigan, 27 Aug. 2003.

the economic impact of AI on the global economy, with more limited advances and applications (i.e., weak AI only) corresponding to more limited economic impacts, and more substantial progress (i.e., strong AI) corresponding to more significant economic impacts.

This study estimates the projected global economic impacts associated with the use, development, and adoption of AI over the next ten years, and finds a reasonable range of AI's economic impact over the next 10 years to be between $1.49 trillion and $2.95 trillion. During this time period, AI is predicted to have wide-ranging applications, including, but not limited to:

- Machine learning that automates analytical model building by using algorithms that allow machines to operate without human assistance.[8] Potential applications include predicting cause-and-effect relationships from biological data, identifying new drugs,[9] self-driving cars,[10] and protecting against fraud.[11]
- Improved natural language processing that allows computers to continue to better analyze, understand, and generate language to interface with humans using natural human languages.[12] Examples of applications include transcribing notes dictated by physicians, automatically drafting articles, and translating text and speech.[13]
- Virtual personal assistants that help users by providing reminders, scheduling appointments, organizing their personal finances, and finding providers of various services.[14]
- Machine vision that allows computers to identify objects, scenes and activities in images. Current applications of machine vision include providing object descriptions for the blind,[15] realistic facial reconstructions,[16] car-safety systems that detect pedestrians and bicyclists,[17] and street-view maps.[18]

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[8] Yeomans, Mike. "What Every Manager Should Know About Machine Learning." Harvard Business Review, 7 July 2015.

[9] Naz, Mufassra, Alpha Tom Kodamullil, and Martin Hofmann-Apitius. "Reasoning over Genetic Variance Information in Cause and-effect Models of Neurodegenerative Diseases." Briefings in Bioinformatics Advance Access, 5 Aug. 2015.

[10] Rettinger, Jonathan. "How Close Are We to a Real Self-Driving Car?" The Huffington Post, 21 Oct. 2015; Mui, Chunka. "Google's Trillion-Dollar Driverless Car -- Part 2: The Ripple Effects." Forbes Magazine, 24 Jan. 2013.

[11] Nash, Kim S. " PayPal Fights Fraud with Machine Learning." WSJ 25 Aug. 2015.

[12] Nadkarni, Prakash M., Lucila Ohno-Machado, and Wendy W. Chapman. "Natural Language Processing: An Introduction." Journal of the American Medical Informatics Association (2011): 544-51; B. H. Juang, L. R. Rabiner, "Automatic speech recognition - A brief history of the technology development." Elsevier Encyclopedia of Language and Linguistics, 2005.

[13] Somaiya, Ravi. "The A.P. plans to automate quarterly earnings articles." New York Times, 30 June 2014; Deangelis, Stephen F. "The Growing Importance of Natural Language Processing." Wired; "Natural Language Processing." Microsoft Research, 2015.

[14] Berger, Rob. "7 Robo Advisors That Make Investing Effortless." Forbes Magazine, 5 Feb. 2015; Aggour, Kareem S., Piero P. Bonissone, William E. Cheetham, and Richard P. Messmer. "Automating the Underwriting of Insurance Applications." AI Magazine 2006; Dougherty, Conor. "Insurance via Internet Is Squeezing Agents." The New York Times, 18 Jan. 2015.

[15] Kulkarni, Nitish. "Computer Vision Startup ThirdEye Pivots From Google Glass To Mobile." TechCrunch, 05 Jan. 2016.

[16] "Realistic Facial Reconstructions Enhanced by Combining Three Computer Vision Methods." Phys.org, 8 Dec. 2015.

[17] Markoff, John. "A Learning Advance in Artificial Intelligence Rivals Human Abilities." The New York Times, 10 Dec. 2015.

We expect the economic effects of AI to include both direct GDP growth from sectors that develop or manufacture AI technology, and indirect GDP growth through increased productivity in existing sectors that employ some form of AI. Growth in AI producing sectors could lead to increased revenues, and employment within these existing firms, as well as the potential creation of entirely new economic activity. Productivity improvements in existing sectors could be realized through faster and more efficient processes and decision making as well as increased knowledge and access to information.

The extent of these economic gains will be driven in large part by the rate of the advancement and diffusion of AI. If AI is an increasingly critical component of more products, it will become an integral part of many people's lives. As our definition of AI is intentionally broad, our definition of the diffusion of AI is necessarily broad as well. We generally conceive of the level of AI diffusion as the portion of an individual's activities in an average day that are produced or shaped AI in any manifestation. As AI is increasingly incorporated into more applications, or AI is relied on more heavily in existing applications, AI will become a more integral part of daily life, increasing AI's level of diffusion.

The extent of AI's economic effect is also likely to vary from region to region, though this variation may be more dependent on the predominate economic activity of a region, and thus AI's ability to influence economic activity, rather than the economic or developmental status of the region. In fact, with the current move towards accessibility and open source development, AI has the potential to transcend income classes and to bring significant gains to both developed and developing countries. For example, AI has the potential to optimize food production around the world by analyzing agricultural regions and identifying what is necessary to improve crop yields. In total, the broader and deeper the applications of AI in a given region or economic sector, the greater economic impact it is expected to have.

In estimating the future economic effects associated with an innovation such as AI, it is important to note that it is challenging to accurately predict which applications of AI will ultimately be commercially successful. Further, even if one could predict successful commercial applications, it is difficult to predict to what extent AI will be adopted in its successful applications, the precise ways in which they will be deployed, and the resulting economic effects.

Given these challenges, calculating a single accurate estimate of AI's economic effect is difficult (if not impossible). Instead, we utilize several approaches to construct a reasonable range of estimates of the potential economic effects associated with AI, concluding that this reasonable range is between $1.49 trillion to $2.95 trillion over the next ten years. However, and as we discuss in more detail below, if AI is ultimately not as successful as some are currently predicting, or if AI develops as quickly and is as widely adopted as its strongest proponents suggest, the economic impacts could be either smaller or larger than our initial estimated range of $1.49 trillion to $2.95 trillion. Our analysis accounts for the uncertainty associated with AI's economic impacts and yields results

[18] Miller, Greg. "The Huge, Unseen Operation Behind the Accuracy of Google Maps." Wired.com, 12 Aug. 2014.

which we consider supplemental lower and upper bound estimates to our range. Our first approach for estimating the economic impact of AI is a "bottom up" approach, which is described in the paragraph immediately below, and provides a lower bound estimate of $359.6 billion for AI's economic effect if AI ultimately does not develop at the rate some are currently predicting. Our second approach, as described in the subsequent paragraph, is more of a "top down" approach. This approach focuses on the global impacts of past technological innovations as potential benchmarks for AI and provides both our reasonable range of $1.49 trillion to $2.95 trillion in economic impact as well as an upper bound estimate, should the adoption and development of AI follow the more optimistic predictions, of $5.89 trillion. As detailed in the following sections, a careful evaluation of these methodologies leads us to conclude that our bottom up approach is likely too conservative, while some of our benchmarks in the top down approach are likely too optimistic. Therefore, we conclude that a reasonable range for AI's economic impact is unlikely to include either one of these extremes, but may instead range between $1.49 trillion and $2.95 trillion over the next decade.

In our first bottom up approach we apply methodologies to estimate the economic effects of investments in firms developing AI technology since investment levels in a technology are a telling sign of the future potential of that technology. We use two measures of investment: private sector and venture capital. For our private sector investment analysis, we rely on historical investment in AI to forecast future investment and economic literature to estimate the economic effects of these investments. Using this approach, we estimate that AI will lead to an increase of between $296.5 billion and $657.7 billion in the GDP of high-income countries in the next ten years. Under a similar methodology focusing on venture capital investment, we estimate that AI will lead to between $63.1 billion and $115.5 billion in GDP of high-income countries in the next ten years.[19] Acknowledging that there may be some overlap between these two approaches, we estimate that the total economic impact of investments by these two sectors alone (i.e., not including other forms investment in AI such as capital investment) would imply $359.6 billion to $773.2 billion in economic growth over the next ten years. We conclude, however, that these two sectors are unlikely to sufficiently represent the future potential of AI. We therefore turn to the top down approach to allow for a more comprehensive analysis of AI's potential.

Our top down approach applies the history and estimated impacts of prior technologies as benchmarks for how AI's development and diffusion may affect the global economy over the next ten years. AI has the potential to affect business across the globe in a wide range of industries in ways only a number of technologies have done in the past. For example, AI is expected to be a useful tool for enhancing human capabilities and in some instances replacing functions such as driving a car. Similarly, past technological innovations and investments such as the investment in information technology (IT), the development and adoption of broadband internet, the development and adoption of mobile telephony, and industrial robotic automation have served to enhance human capabilities and in some cases, replace humans. In this approach, we rely on academic research on the economic impact of IT investment, broadband internet, mobile phones, and industrial robotics to

[19] High-income countries are the 80 countries identified by the Worldbank with gross national income per capita of $12,736 or more as of 2014.

establish benchmarks for the potential impacts of AI. The most reasonable benchmarks suggest a boost to global economic output of between $1.49 trillion and $2.95 trillion. Given the potential range of AI's development over the next decade, we also include the possibility of more optimistic scenarios which result in an upper bound estimate as high as $5.89 trillion over the next ten years.

This report focuses on the potential net economic effects of AI and not on the specific mechanisms that lead to economic outcomes. While AI is likely to affect both the productivity and employment components of economic growth in many sectors, parsing these effects independently is beyond the scope of this analysis. Significant public debate has focused on projections of AI's effect on the labor force, however. For instance, some researchers have argued that the rise of AI and automation will lead to significant unemployment as capital is substituted for labor. In doing so, they point to the concern that the increasing sophistication of AI may jeopardize skilled and semi-skilled workers and reduce the size of the middle class.[20] This is not a new argument, as the fear of technology negatively affecting the labor force and leading to mass unemployment has been articulated as early as the Industrial Revolution when economist David Ricardo wrote that the "substitution of machinery for human labor, is often very injurious to the interests of the class of laborers."[21] The alternative view, however, is supported by the economic history of previous "disruptive" technologies. Although employment in certain industries has been reduced in the past due to technological advancements, the net effect of technological advancement has not appeared to lead to a reduction in long-term total employment.[22] To date, the labor market has adapted to the introduction of new technologies, giving rise to new jobs in new areas. If the labor market continues to demonstrate its historical resilience, then the advancement of AI may also be accomplished without a reduction to total-employment in the long-run.

This paper proceeds as follows. Section II provides additional detail on the methodology behind our first, bottom-up approach, reviewing the academic literature and available data on current investment levels in AI. Section III then discusses our second, top-down approach taking each of the four benchmark technologies in turn, reviewing the academic literature on each, and weighing their relative strengths and weaknesses as an appropriate benchmark for AI. Section IV then summarizes these findings and concludes with the estimated reasonable range of economic impact for AI over the next ten years.

II. Benchmarking AI using Sector Investments

A prerequisite for the widespread adoption of any technology is the large amount of research, development, and investment that it takes to bring that technology to market.[23] Therefore, the high levels of current investment by industry players and venture capital

[20] Frey, Carl Benedikt and Michael A. Osborne. "The Future of Employment: How Susceptible are Jobs to Computerisation." Oxford Martin School, September 17, 2013.
[21] Ricardo, David. "On the Principles of Political Economy and Taxation" John Murray, 3rd. ed., Chapter 31.3.
[22] Atkinson, Robert. "Stop Saying Robots are Destroying Jobs- They Aren't." Technology Review, Sept. 3, 2013.
[23] For example, Bloomberg reports that Apple spent $2.7 billion dollars to bring the first iPhone to market. "How Much Did Apple Spend on R&D for the iPhone?" Bloomberg, Feb. 7, 2016.

firms in AI provide a telling sign of the current state of, and impending advances in, AI. In 2014 and 2015 alone, eight major global tech firms made at least 26 acquisitions (totaling over $5 billion) of companies developing AI technology.[24] Private investment in AI has also taken the form of in-house spending in addition to startup acquisitions. For example, Facebook's AI Research lab, Google's Machine Intelligence lab, and Microsoft's Machine Learning and Artificial Intelligence research division are all making advances in AI technology and investing in the industry's top talent.[25] Additionally, between 2010 and 2015, nearly $5 billion in venture capital funding was invested in firms across the globe developing and employing AI technology.[26]

Below, we use a methodology based in academic literature to estimate the potential global economic impacts of private industry and venture capital investment in AI. In doing so, we note that we have thoroughly reviewed the limited economic literature surrounding the macroeconomic effects of R&D and venture capital investment. Based on the available research, we estimate that industry investment in AI over the next ten years could lead directly to a net economic impact of $296.5 billion to $657.7 billion, while venture capital investment could lead to an additional net economic impact of $63.1 billion to $115.5 billion over the next ten years. Taken together, we estimate that the total economic impact of investments by these two sectors alone could lead to between $359.6 billion and $773.2 billion in economic growth over the next ten years. These estimates reflect the impacts of AI due to investment by only a portion of the global economy, excluding investments and research conducted by government and higher education, for example. Nonetheless, they provide a signal of the potential of AI to have large global impacts over the next ten years.

Implied Impact of Private Industry Investment

As noted above, private investment in AI has been growing rapidly in recent years. Romain and van Pottelsberghe (2004) provide a methodology that we use to estimate the net economic impacts of that investment.[27] The researchers find that private R&D, venture capital, and public R&D investment all have strong net effects on economic growth with venture capital funding having the strongest such effect. The researchers hypothesize that venture capital investment contributes to economic growth through innovation and by bolstering the capacity of an economy to use existing knowledge to increase productivity. Using a panel regression framework to analyze historical data from 16 OECD countries, they estimate the impacts of venture capital, business R&D, and public R&D intensities on multi factor productivity. The paper finds that the elasticities of output in relation to

[24] The eight firms included are Google, Microsoft, Apple, Amazon, IBM, Yahoo, Facebook, and Twitter. 2014 and 2015 acquisitions spanned services including speech and image recognition, healthcare analytics, home automation, data security, cognitive computing, and machine learning. $5 billion is a conservative estimate as deal values were not published for more than half of these acquisitions.

[25] Facebook AI Research available at https://research.facebook.com/ai; Research at Google – Machine Intelligence available at http://research.google.com/pubs/MachineIntelligence.html; Microsoft Research – Machine Learning and Artificial Intelligence available at http://research.microsoft.com/en-us/research-areas/machine-learning-ai.aspx.

[26] According to ThomsonOne Private Equity screener searching for firms with the keywords 'Artificial Intelligence,' 'Machine Learning,' 'Natural Language Processing,' 'Self-Driving,' and 'Image Recognition' in their business descriptions.

[27] Romain, Astrid, and Bruno Van Pottelsberghe. "The Economic Impact of Venture Capital." Université Libre De Bruxelles, Solvay Business School, Centre Emile Bernheim, Apr. 2004.

business R&D, venture capital, and public R&D intensities are 19.9%, 0.9%, and 13.6%, respectively. They then calculate that the effect on output, one year later, of one dollar of business R&D, venture capital, and public R&D spending to be $1.99, $3.33, and $2.69, respectively.[28]

These findings represent net impacts on the economy, taking into account the sum of any positive and negative impacts the funding or investment might have. For example, imagine a venture capital firm invests in a company that helps farms that produce a certain crop to convert to the production of a more lucrative crop. In this example the loss of the output of the less lucrative crop has a negative economic impact, but the gain of the output of the more lucrative crop has a greater positive effect on the economy representing a net positive impact on economic output of the venture capital funding that led to the crop switch. These impacts are not realized solely by the firms that receive venture capital investments, but could also take the form of output growth attributable to widespread adoption of a new technology developed by a venture funded firm. This broad, net impact multiplier methodology is especially appropriate for AI because of the large potential for spillover effects of investments in the technology as it gains traction.

According to industry analysts at the Institute for the Future, private investment in AI has grown from $1.7 billion in 2010 to $14.9 billion in 2014.[29] To estimate the global economic impacts of this rapidly growing private investment in AI technology, we use Romain and van Pottelsberghe's 2004 finding that the marginal impact of one dollar invested in business R&D is a $1.99 increase in output.[30] Specifically, we assume two different scenarios about the trajectory of private investment in AI over the next ten years. First, taking the conservative assumption that the amount of private industry investment over the next ten years remains constant at the 2014 level of $14.9 billion per year, then using Romain and van Pottelsberghe's findings, we estimate those investments would lead to approximately $296.5 billion of economic growth over the next ten years.[31] Alternatively, if we take the more optimistic view that private industry investment in AI technology increases at a linear rate[32] equal to the average increase in the level of investment between

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[28] The findings of Kortum and Lerner (2000) provide robustness support for this finding indicating that venture capital is a more potent impetus for patent creation than R&D spending. Kortum and Lerner. "Assessing the Contribution of Venture Capital to Innovation." Rand Journal of Economics, Winter 2000.
[29] Trabulsi, Andrew. "The Future of Artificial Intelligence." Institute for the Future, via Quid, June 2015. These figures are not limited to private R&D spending in AI, but aim to include all private sector investment in AI technology, not including mergers and acquisitions.
[30] Romain and van Pottelsberghe's study specifically estimates the net economic impacts of private R&D spending. The levels of private investment we have cited above are not strictly limited to R&D spending, but could also include capital expenditures or other investments. Therefore, our estimates of the net economic impacts of private investment AI technology over the next ten years rely upon the assumption that all private investment will effect similar net economic impacts as private R&D spending specifically. (Romain, Astrid, and Bruno Van Pottelsberghe. "The Economic Impact of Venture Capital." Université Libre De Bruxelles, Solvay Business School, Centre Emile Bernheim, Apr. 2004.)
[31] Assuming the $14.9 billion of industry investment in AI technology observed in 2014 continues through 2024. Romain and van Pottelsberghe find that the marginal impact of one dollar invested in business R&D in year t is a $1.99 increase in economic output in year t + 1. Calculated as ($14.9 billion invested * 1.99 marginal impact of a dollar invested in business R&D) * 10 years from 2015 - 2024 = $296.5 billion.
[32] Referencing R&D data of U.S. firms compiled by the National Science Foundation as part of its annual Science and Engineering Indicators, we observe linear type increases in R&D spending by public U.S. firms

2010 and 2014 (an increase of $3.3 billion per year) for the next ten years, then based on Romain and van Pottelsberghe's findings, and assuming that private industry investment in AI specifically results in the same increase in economic output as general private sector R&D, we estimate that private investment in AI will lead to approximately $657.7 billion in economic growth over the next ten years.[33]

Implied Impact of Venture Capital Investment

As an alternative to estimating the economic impact of AI by way of private investment, we can also examine levels of venture capital investment in the sector. Within the academic literature, there is general consensus that increases in venture capital funding lead to increases in macroeconomic indicators such as the number of firms, employment, and wages. The theory behind this line of research is that venture capitalists contribute to economic growth in several important ways. First, venture funding spurs innovation.[34] Second, venture capitalists alleviate capital constraints, thereby allowing individuals otherwise lacking sufficient capital to engage in entrepreneurship. Third, venture capitalists can encourage further entrepreneurship simply by being active in the market and increasing entrepreneurs' expectations of receiving funding. Finally, venture capitalists can affect the economy by increasing the probability of spinoff companies as venture funded firms inspire outsiders to begin their own companies, and potentially prepare their employees to start their own firms by exposing them to the rigors of running a start-up firm.[35] For example, in a study of the 329 metropolitan statistical areas in the U.S., Samila and Sorensen (2011) found that doubling the number of firms receiving venture capital funding across all industries in a region increased the number of firms by between 0.48% and 2.21%, increased the number of jobs in that area by up to 1.24%,[36] and increased aggregate income by between 0.48% and 3.78% five years following the investment.[37]

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from 1994 - 2000 on developing technologies (similar to AI's current state) like mobile phones and computer storage devices. Alternatively, during the same time frame, we observe flat R&D spending in mature and stable industries such as chemical manufacture and aerospace. These historical observations make flat R&D spending in AI over the next ten years a conservative assumption as the field is still developing. "U.S. and International Research and Development: Funds and Technology Linkages – National R&D Trends" National Science Board Science and Engineering Indicators 2004, May 2004 at Chapter 4, Appendix table 4-22.

[33] From 2010 through 2014, the amount of venture capital investment in firms developing AI technology increased at the average linear rate of $3.3 billion per year, calculated as ($14.9 billion invested in 2014 - $1.7 billion invested in 2010) / (4 years from 2010 – 2014). Let us assume the $14.9 billion of private investment observed in 2014 increases at this rate of $3.3 billion each year through 2024, Romain and van Pottelsberghe find that the marginal impact of one dollar of business R&D in year t is a $1.99 increase in economic output in year t + 1.The total economic impact of venture capital investment in firms developing AI technology over the next ten years is calculated as the sum of projected future investments in the sector increasing at the linear rate of $3.3 billion per year over the years 2015 – 2024 multiplied by $1.99 in growth for each dollar invested, yielding an estimated total economic impact of $657.7 billion.

[34] The findings of Kortum and Lerner (2000) provide robustness support for this finding indicating that venture capital is a more potent impetus for patent creation than R&D spending.

[35] Samila, Sampsa, and Olav Sorenson. "Venture Capital, Entrepreneurship and Economic Growth." The Review of Economics and Statistics, February 2011.

[36] It is important to note here that VC funding for firms developing AI technology has the potential to induce a net negative employment impact as AI often takes on tasks that otherwise would be conducted by a human, potentially displacing workers. To date, no academic studies have been conducted estimating the broader economic effects of VC investment in AI specifically.

[37] Samila, Sampsa, and Olav Sorenson. "Venture Capital, Entrepreneurship and Economic Growth." The Review of Economics and Statistics, February 2011.

Like private industry investment in AI, an increasing level of venture capital investment in AI is an indicator of the future potential of the technology. Table 1 below, assembled from the ThomsonONE private equity database, shows the amount of venture capital funding that has been invested since 2010 across the globe in firms that are employing and developing AI technology.[38] In compiling this estimate, we identified this set of firms receiving venture capital funding by searching firm descriptions for the targeted key words in the table. These key words are representative of the branches of AI that are considered by technologists as likely to have an effect on the global economy in the near future. As evident in Table 1, the amount of venture capital funding flowing to firms developing AI technology has increased dramatically since 2010, with the largest annual amount, $1.9 billion, being invested in 2015. AI's relative share of venture capital investment has also increased substantially; according to Ernst and Young, global venture capital investment totaled $46.6 billion in 2010 and had nearly doubled to $86.7 billion in 2014.[39] By comparison, during that time venture capital investment in firms developing AI technology has increased over eight times.

Table 1: Venture Capital Investment in Firms Developing AI Technology

$ in Millions

Keyword Searched	2010	2011	2012	2013	2014	2015	Total
Artificial Intelligence	31.2	47.7	86.6	58.9	419.0	211.7	**855.2**
Machine Learning	81.2	386.5	215.5	419.6	792.7	1,529.8	**3,425.3**
Natural Language Processing	21.2	33.8	52.5	68.2	80.7	88.3	**344.8**
Self Driving	-	-	3.5	-	12.6	15.5	**31.6**
Image Recognition	4.9	7.1	16.3	38.3	53.2	127.8	**247.5**
Computer Vision	22.9	10.1	22.7	18.7	92.1	80.0	**246.5**
Total	**148.5**	**456.0**	**369.5**	**546.8**	**1,294.6**	**1,895.6**	**4,711.0**

Notes:

[1] AI firms identified in the ThomsonONE database by searching business descriptions for the keywords in the table above.

[2] Sum of rows within each year do not add up to the total for that year becase some firms that received funding appear in multiple categories.

Source:

ThomsonONE private equity screener.

Similar to our methodology for estimating the economic impact of private spending on AI, we use the results from Romain and van Pottelsberghe (2004) to estimate the potential global economic impact of venture capital funding for firms developing and employing AI technology. Using the same methodology of projecting private investment in AI over the next ten years, we estimate the global economic effects of venture capital investment in AI.

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[38] Given the difficulty of identifying firms developing and employing AI technology from Thomson ONE's extensive database tracking tens of thousands of venture capital investments, this is likely a conservative estimate.

[39] Pearce, Bryan, Jeff Grabow, Sandra Feldner Vandergriff, Shanta Kumari, and Vidhi Gupta. "Venture Capital Insights® – 4Q14." Global VC Investment Landscape. Ernst & Young, Jan. 2015.

The Romain and van Pottelsberghe (2004) study estimates that the marginal impact of one dollar invested by venture capitalists is a $3.33 increase in economic output. Assuming that the amount of venture capital investment over the next ten years remains constant at the 2015 level of $1.9 billion per year, then using Romain and van Pottelsberghe's (2004) findings, we estimate those investments would lead to approximately $63.1 billion of economic growth over the next ten years.[40] Alternatively, if we take the more optimistic assumption that venture capital investment in firms developing AI technology increases at a linear rate[41] equal to the average increase in the level of investment between 2010 and 2015 (an increase of $349.4 million per year) for the next ten years, then assuming that VC investment in AI specifically result in the same increase in economic output as general VC investment, Romain and van Pottelsberghe's findings suggest that investment in AI firms will lead to approximately $115.5 billion in economic growth over the next ten years.[42]

Accepting that our estimations of the economic impact of AI over the next ten years based on private sector and venture capital investments in the technology may have some overlap, we estimate that the sum total economic impact of AI as a direct result of these two sources of investment to be between $359.6 billion and $773.2 billion over the next ten years. In interpreting these estimates of the economic impact of AI, it is important to consider that private industry and venture capital investment are only a portion of the global economy. Thus, our estimates of the economic impacts of these two sources of investment in AI technology represent only a portion of the total economic contributions that AI is likely to generate.

Furthermore, the methodology used here to estimate the economic impact of AI only reflects the social return on investment dollars one year after the investment has been made. It is very likely that a dollar of investment will generate returns over a longer time period than one year suggesting larger economic impacts than we have calculated above. Nonetheless, current levels of private industry expenditure and venture capital investment in AI send a very clear message about AI; in particular, AI is already a contributing factor of

[40] Assuming the $1,896 million of venture capital investment in firms developing AI technology observed in 2015 continues through 2024. Romain and van Pottelsberghe find that the marginal impact of one dollar invested by venture capital in year t is a $3.33 increase in economic output in year t + 1. Calculated as ($1,896 million invested * 3.33 marginal impact of a dollar invested by venture capital) * 10 years from 2015 - 2024 = $63.1 billion

[41] Gompers, et al. "Venture capital investment cycles: The impact of public markets." Journal of Financial Economics 87 (2008) 1–23. Web. The authors analyze venture capital investment from 1975 – 2003 and classify each investment into one of nine industry categories. The authors show the amount of venture capital investment in four of those nine industries over time and each industry exhibits periods of prolonged linear type venture capital investment growth supporting our assumption.

[42] From 2010 through 2015, the amount of venture capital investment in firms developing AI technology increased at the average linear rate of $349.4 million per year, calculated as ($1,896 million invested in 2015 - $148.5 million invested in 2010) / (5 years from 2010 – 2015). Let us assume the $1,896 million of venture capital investment observed in 2015 increases at this rate of $349.4 million each year through 2024, Romain and van Pottelsberghe find that the marginal impact of one dollar invested by venture capital in year t is a $3.33 increase in economic output in year t + 1. The total economic impact of venture capital investment in firms developing AI technology over the next ten years is calculated as the sum of observed 2015 venture capital investment ($1,896 million) and projected venture capital investments in the sector increasing at the linear rate of $349.4 million per year over the years 2016 – 2024 multiplied by $3.33 in growth for each dollar invested, yielding a total economic impact of $115.5 billion.

the global economy and will likely have large and wide-ranging impacts over the next ten years. In the section that follows, we aim to more comprehensively estimate the full extent of AI's potential economic impacts.

III. Benchmarking AI using Past Technological Advancement

During the last half century, technological innovations have been large drivers of growth in economic output as well as in labor and capital productivity. Innovations such as the personal computer, broadband internet, mobile phones, and industrial robots have all had measurable and significant effects on the global economy. Applications of these technological innovations are wide-ranging, and so are their economic benefits. These technological tools have reduced costs, increased productivity, expanded output, spurred further innovation, and given rise to new and significant sectors of the current global economy which, in turn, affected the allocation of labor in the modern economy. AI has the potential to affect the global economy in these same ways.

As an alternative to the bottom-up approach taken in Section II, this section estimates the potential economic impact by using previous technological innovations whose effects may be similar to those AI will have over the next ten years. Specifically, in the following sub-sections, we examine four benchmarks to inform AI's potential economic impact: general IT investment, broadband internet, mobile phones, and industrial robotics. These benchmarks each represent recent and significant technological innovation that experienced rapid and extensive adoption, and had significant global economic effects through the mechanisms discussed above. As pre-cursors to AI, the benchmark technologies are appropriate in part because their method and rate of diffusion may be representative of the future diffusion of AI.[43]

A baseline of computing power, internet access, mobile phone penetration, and basic robotic integration is likely necessary to allow the subsequent adoption of AI technology, and the changes that industries underwent as these previous technologies were adopted and leveraged serve as a good indication of the industries' ability to respond flexibly to future technological advances such as AI. Furthermore, the mechanisms through which these benchmarks influenced the global economy are similar to the mechanisms through which AI is anticipated to affect productivity and growth. Therefore, our benchmarks represent a range of economic effects to appropriately reflect the uncertainty of AI in the future.

In undertaking this approach, we summarize the academic literature that has estimated the contribution of each technology to economic growth, evaluate these benchmarks' relative strengths and weaknesses, and use these studies to inform a potential range for the

[43] As discussed in Section I, this paper takes an intentionally broad view of AI in terms of both defining the technology and describing its potential trajectory of development over the next decade. A correspondingly broad view of what the diffusion of AI will mean, and how it will come about is therefore also necessary. We generally define the level AI diffusion as the portion of an individual's activities in an average day that are produced or shaped AI in any manifestation.

economic effect of AI through 2025. As summarized in Table 2 and discussed in more detail below, these benchmarks imply a full range of economic effects for AI of between $1.49 trillion and $5.89 trillion (0.2% to 1.0% of GDP), with the more likely estimates, which excludes the more highly optimistic scenarios relying instead on more conservative methodologies and closer parallels between AI and the benchmark technology, ranging between $1.49 trillion and $2.95 trillion.

Table 2: Summary of Benchmark Estimates for AI's Economic Effect 2016-2015
$ in Trillions

Benchmark Technology	Implied Economic Effect of AI
IT Investment	$4.78
Broadband Internet	$1.49 – $5.89
Mobile Phones	$2.95 – $4.24
Industrial Robotics	$2.23

Notes:
[1] Dollar amounts are reported in 2014 USD.
[2] Mobile benchmarking studies do not differentiate between high income and other countries, so estimates are based on global projected GDP. All other benchmarks present estimates based on GDP for high-income countries.

Sources:
World Bank 2014 Gross Domestic Product, available at http://databank.worldbank.org/data/download/GDP.pdf; Conference Board GDP Projection Estimates 2015-2025, available at https://www.conference-board.org/pdf_free/workingpapers /EPWP1502.pdf; OECD Communications Outlook 2013, Broadband Subscriptions per 100 Inhabitants in the OECD Area 1997-June 2012; World Bank, Mobile cellular subscriptions (per 100 people) 1983-2003; Czernich et al. (2011); Qiang and Rossotto (2009); Koutroumpis (2009); O'Mahony and Timmer (2009); Graetz and Michaels (2015); Gruber and Koutroumpis (2011); Vu (2011).

For each benchmark in the following sub-sections, we incorporate the most relevant available academic literature on the topic, but note several limitations of this approach. First, while we have conducted a thorough review of research on the benchmarks, some benchmarks have been more comprehensively studied than others. For instance, both IT investment and broadband have been well studied. As discussed in the following sub-sections, while the results of the IT and broadband studies do not all agree on the exact magnitude of the economic effect generated by these technologies, the volume of research available on these topics does serve to generally confirm the presence and range of the potential economic effects. In contrast, there are relatively fewer papers that attempt to assess the economic effect of robotics or mobile phones. Therefore, we have less certainty about the range of economic effects created by robotics and mobile phones, and future research may reveal a different magnitude than the basis for our current estimates.

Second, as is the case with any benchmarking exercise, benchmarks can serve as informative approximations but are not intended to represent an identical scenario to AI. AI is unlikely to manifest identically to any particular benchmark. Our intention is, instead, to employ benchmarks that share certain characteristics of AI, and from these potential similarities assess a range of effects that are possible for AI should AI manifest in ways more comparable to one or another benchmark.

A. Economic Effects Using Information Technology Investment as a Benchmark

The first benchmark we consider is the rapid investment in IT that occurred during the 1990s and early 2000s. During these years, IT investment was largely composed of investments in computing hardware and software which caused a dramatic increase in computing prevalence in businesses.[44] AI is already pushing electronics growth into markets not previously penetrated by advanced computing with innovations such as smart appliances and robo-advisors.[45] These current achievements are a strong indication that AI has the potential to substantially change how entire sectors of the economy use technology, just as IT investment did during the 1990s and early 2000s. As a benchmark, IT also has the advantage of several similarities with our functional definition of AI. For instance, IT investment resulted in a wide range of economic benefits including reduced costs, increased productivity, expanded output, and spurring further innovation, all of which mirror AI's potential. Furthermore, IT is a bundled term that refers to a wide array of technology, some of which were individually very substantial contributors to economic growth (such as personal computers) while the majority of the technology encompassed in the IT category were likely contributing to economic output at a much lower rate. The effect of this blend is essentially a weighted average assessment of the potential impacts of IT. This blend may appropriately reflect AI's range of applications, as some are likely to be substantial contributors to output while others may have a smaller economic effect.

The effects of IT on increasing productivity and output have been studied extensively. A widely-cited meta-analysis conducted by Dedrick et al. (2003) examined over 50 papers in the preceding decade and a half and concluded that "[a] number of major studies have documented the significant impact of IT investment on the productivity of firms, industries, and countries, showing that computers do, in fact, show up in the productivity statistics."[46] Furthermore, they write: "IT investments actually have been increasing productivity for

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[44] During the 1990s and 2000s particularly substantial investment was made in computing hardware and software which was in part made possible by rapid declines in prices during this period. (See e.g., "The Diffusion of Personal Computers across the U.S.," FRBSF Economic Letter, 2005-37; Schreyer, Paul. "Computer Price Indices and International Growth and Productivity Comparisons." Review of Income and Wealth (2002) 48:1.)

[45] Smart appliances such as the Nest thermostat are bringing increased demand for computer processing to household appliances that previously did not utilize much computing power. Similarly, robo-advisors bring increased computing to the financial advising sector as they are becoming a product in and of themselves rather than computer programs just being used as a tool by human financial advisors. Hardawar, Devindra. "Google Buys Nest for $3.2B – Its Key to the Connected Home." VentureBeat, Jan. 13, 2014; Prince, Russ "Many Financial Advisors are Note Concerned about Robo-Advisors Even Though They Should Be." Forbes, Jan. 19, 2016.

[46] Dedrick, Jason, Vijay Gurbaxani, and Kenneth L. Kraemer. "Information technology and economic performance: A critical review of the empirical evidence." ACM Computing Surveys (CSUR) 35.1 (2003): 1-28.

more than three decades."[47] IT investments have been tied to significant gains in economic output in Asia, Europe, and North America.[48]

For the purposes of this benchmarking exercise, we focus on several more recent studies that estimated IT's net contribution to economic growth. For example, O'Mahony and Timmer (2009) estimated that from 1995-2005, investments in ICT contributed to EU and U.S. annual output growth by 0.6 and 1.0 percentage points respectively.[49] While other studies support the magnitude of these findings, some indicate that gains from technology may have slowed. For example, Oliner et al. (2007) found that from 1995-2000, IT capital investments contributed 1.09 percentage points to annual U.S. productivity growth, but its contribution subsequently dropped to 0.61 percentage points from 2000-2006.[50] Similarly, Jorgenson et al. (2011) found that IT capital was responsible for 1.02 percentage points of the annual output growth experienced from 1995-2000 in the U.S., and then only 0.49 percentage points of annual output growth from 2000-2007.[51]

Applying the results of this literature, we estimate the potential economic effect from AI, should AI perform as IT did during the 1990s and 2000s. We choose to rely on the results of O'Mahony and Timmer (2009) because (1) their study had a broader scope by covering more countries, (2) their results for the U.S. were consistent with other studies, and (3) their analytical approach yielded more conservative estimates.[52] However, the study does not assess IT's impact on employment or productivity independently from IT's net effect on economic growth.[53]

To calculate a single economic effect we blend O'Mahony and Timmer's U.S. and EU estimates (weighted by GDP), yielding an estimated IT effect on annual GDP growth of 0.79%.[54] To convert this estimated annual contribution to GDP growth into dollars, we

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[47] Ibid.
[48] Kraemer, Kenneth L., and Jason Dedrick. "Information technology and productivity: results and policy implications of cross-country studies." Center for Research on Information Technology and Organizations (1999); Kraemer, Kenneth L., and Jason Dedrick. "Payoffs from investment in information technology: Lessons from the Asia-Pacific region." World Development 22.12 (1994): 1921-1931; Jorgenson, Dale W. "Information technology and the US economy." American Economic Review (2001): 1-32.
[49] O'Mahony, Mary and Marcel Timmer. "Output, Input and Productivity Measures at the Industry Level: The EU KLEMS Database." The Economic Journal (2009) 119:F374-F403.
[50] Oliner, Stephen D., Daniel E. Sichel, and Kevin J. Stiroh. "Explaining a Productive Decade." Brookings Papers on Economic Activity. (2007) 1:81-137.
[51] Jorgenson, Dale W., Mun S. Ho, and Jon D. Samuels. "Information technology and US productivity growth: evidence from a prototype industry production account." Journal of Productivity Analysis 36.2 (2011): 159-175.
[52] In contrast to studies such as Oliner et al. (2007), the O'Mahony and Timmer (2009) results do not include an explicit assessment of the economic gains from the growth and improved productivity in the IT-producing sector itself, focusing instead on the effect of investment in IT capital. This omission is appropriately conservative because, given the current size of the AI industry, it is unlikely that productivity gains and output growth within the AI industry in the next ten years could rival those of the entire IT sector, which contributed over $1 Trillion to 2014 U.S. GDP (approximately 6% of the aggregate) and has consistently grown at almost 4% per year in the past decade. (See Bureau of Economic Activity).
[53] IT's effect on productivity or employment are captured in the benchmark estimates of net economic impact, but these components of economic impact are not measured in isolation by the benchmark studies.
[54] In 2014, the EU and US approximately represented a combine 45% of world GDP (52% EU and 48% U.S.).

combine data from the Conference Board and the World Bank to estimate GDP for 2015-2025.[55] Because the benchmark papers focus on high-income, developed nations, we focus on the implied impacts of AI for high-income countries. As discussed in Section I, AI is likely to generate economic benefits for both developing and developed nations. However, since the benchmark papers do not include developing countries in their estimates we are unable to estimate AI's potential effect for these countries so we conservatively assume AI has no impact in these regions. Multiplying the projected GDP estimates through 2025 by the 0.79% estimated economic contribution of IT, we calculate that if AI performs equivalently to historical IT, then AI could have a cumulative economic effect of $4.78 trillion through 2025, or 0.8% of GDP.[56]

While there are technologists who believe that AI is likely to mimic past IT revolutions and drive a corresponding increase in IT investment such as the investment analyzed in the benchmark studies,[57] an economic effect due to AI on the scale of the 1990's IT experience is likely too optimistic, as this would imply AI singularly attaining the same level of significance as the entire IT sector of the 1990s within the next ten years. In addition, as indicated by the academic literature, the contribution of IT may have declined over time as the gains from IT decreased. Given this likely decline in IT's effect, the difference in timing between the anticipated adoption of AI and the previous diffusion of IT (2016-2025 versus 1997-2007) is likely to reduce the effects of investment below those documented in the benchmark studies. Thus the $4.78 trillion in economic impact implied by this benchmark is likely only reasonable if the development and diffusion of AI over the next decade matches or exceeds expectations of AI's strongest proponents.

B. Economic Effects Using Broadband Internet as a Benchmark

The second benchmark we consider is broadband internet which realized a rapid and pervasive diffusion in the late 1990s and early 2000s. As a benchmark, broadband has the advantage of several similarities with our functional definition of AI. In particular, broadband internet increased the speed and availability of information, resulting in a wide range of economic benefits including reduced costs, increased productivity, expanded output, and spurring further innovation, all of which mirror AI's potential. Relative to IT investment, broadband internet has the advantage of being only a component of IT while still being broadly applicable to essentially all sectors of the economy. This is likely a closer corollary for AI within the next ten years, as AI is likely to be broadly applicable to many economic sectors, but less likely to grow rapidly enough in the next decade to rival the magnitude of the full IT sector. In addition, the economic effects of broadband have been relatively well studied within the academic literature.

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[55] World Bank 2014 Gross Domestic Product, available at http://databank.worldbank.org/data/download/GDP.pdf; Conference Board GDP Projection Estimates 2015-2025, available at https://www.conference-board.org/pdf_free/workingpapers/EPWP1502.pdf

[56] If we take an alternate approach and assume that the estimated economic effect of IT for the U.S. and EU holds for all countries globally, not just high-income countries, then AI could have a cumulative economic effect of $7.46 trillion.

[57] Brynjolfsson and McAfee. *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies.* W.W. Norton & Company (2014).

Studies of the effects of broadband penetration have found that in a wide range of economies, a modest increase in broadband penetration can have significant effects on GDP. The exact magnitude of the impact on GDP, however, varies across studies. At the high end, Czernich et al. (2011) found that for 25 OECD countries between 1996 and 2007, a 10% increase in broadband penetration increased annual per-capita GDP growth by 0.9-1.5 percentage points.[58] We use the more conservative, lower bound of this estimated range to inform our benchmark. Similarly, Qiang and Rossotto (2009) found that from 1980-2006, high-income economies realized increases in average annual per-capita GDP growth of 1.21 percentage points per 10% increase in broadband penetration. However, for low and middle income economies Qiang and Rossotto (2009) found that broadband was an insignificant determinant of growth. Alternatively, more conservative estimates such as Koutroumpis (2009) found that for 22 OECD countries between 2002-2007, a 10% increase in broadband penetration increased average annual economic growth by 0.25 percentage points.[59] Similarly to Qiang and Rossotto (2009), Koutroumpis' results also indicate that level and speed of broadband diffusions effect the returns on growth, such that broadband would have a smaller effect on countries with relatively low levels of broadband penetration or diffusion. As with the IT investment benchmark, the benchmark studies on broadband do not explicitly address broadband's impact on employment or productivity (i.e., these components of economic impact are not measured in isolation, only reflected as components of the net effect of economic output) so these benchmarks serve only to anchor net economic effects not more specific employment effects.

Applying the results of this literature, we estimate a potential economic effect from AI, should AI perform as broadband internet did during the 1990s and 2000s. To do so, we first require an approximation of AI's potential diffusion over the next decade. Broadband internet penetration increased rapidly during the decade 1997-2007 covered by this literature, rising from approximately 0% to 20% in the OECD countries.[60] For the purposes of this study we are focused on AI during its early years as well. Importantly, the typical rate of adoption for new technologies tends to exhibit an "S" curve shape, with slow increases in prevalence in early years, followed by a rapid increase in diffusion speed, which subsequently levels out as the saturation point is neared.[61] Broadband's experience in the 1990s and 2000s matches this expected shape well. While AI is unlikely to follow an identical pattern to any benchmark, AI developments could follow a similar dissemination path to broadband given their potential similarities discussed above. Therefore, we employ broadband's actual experienced diffusion rate from 1997-2007 as an estimate of the path AI may follow from 2016-2025. These results are presented below in Table 3.

Estimates of economic effect of broadband from the academic literature are presented relative to a 10% increase in broadband penetration. A 10% presence of AI is not applicable for all years of our projection, therefore we use the ratio of the estimated

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[58] Czernich, Nina, Oliver Falck, Tobias Kretschmer, and Ludger Woessmann. "Broadband Infrastructure and Economic Growth." The Economic Journal 505-530 (2011).
[59] Koutroumpis, Pantelis. "The Economic Impact of Broadband on Growth: A Simultaneous Approach." Telecommunications Policy, 2009. 471-485. Print.
[60] OECD Historical Broadband Penetration Data.
[61] In economics, market saturation is used to describe the situation where a product has become fully diffused.

diffusion rates of AI over 10% to adjust the economic effect of broadband as estimated by the above literature and summarized in Table 3. Finally, as with the IT benchmark, the broadband benchmark papers focus on high-income, developed nations. Therefore we focus on the implied impacts of AI for high-income countries as well, multiplying the adjusted annual contribution to economic growth by projected GDP estimates for these countries through 2025.[62] The resulting range implies that if AI performs equivalently to historical broadband, then AI could have a cumulative economic effect between $1.49 trillion and $5.89 trillion through 2025, or alternatively, between 0.2% and 1.0% of GDP for high-income countries during those same years.[63] These calculations and results are summarized in Table 3.

[62] Since the benchmark papers do not include low-income or developing countries in their estimates (with the exception of Qiang and Rossotto (2009), who find insignificant results) we are unable to estimate AI's potential impact for these countries so we conservatively assume AI has no impact.

[63] As with the preceding IT benchmark, the academic literature on broadband has focused on the effects of broadband in relatively high-income countries. Therefore, it may be inappropriate to apply these benchmark estimates to lower-income or developing countries. However, if global GDP estimates are used in place of high-income estimates, the resulting economic effect of AI would range from $2.32 to $9.41 trillion.

Table 3: Estimated Economic Effect of AI from Potential Broadband Benchmarks 2016-2025
$ in Millions

	High Income GDP	Estimated AI Diffusion Rate (per Broadband)	Qiang and Rossotto	Czernich et al. (Lower)	Koutroumpis
Annual %Pts. of GDP Growth			**1.21%**	**0.90%**	**0.25%**
2015	53,868,829	0.01%			
2016	55,000,074	0.06%	3,993	2,970	--
2017	56,155,075	0.30%	20,384	15,162	--
2018	57,334,332	1.21%	83,943	62,437	--
2019	58,538,353	2.93%	207,536	154,366	--
2020	59,767,658	4.87%	352,193	261,962	--
2021	60,843,476	7.28%	535,958	398,646	--
2022	61,938,659	10.34%	774,939	576,401	--
2023	63,053,555	13.78%	1,051,342	781,990	--
2024	64,188,519	16.79%	1,304,048	969,953	--
2025	65,343,912	19.65%	1,553,650	1,155,607	--
Total	**602,163,614**		**5,887,986**	**4,379,494**	**1,485,122**
Percent	**100%**		**0.98%**	**0.73%**	**0.25%**

Notes:
[1] GDP is in real dollars and is estimated by applying the Conference Board's projected growth for "mature economies." All dollar amounts are in millions of 2014 USD.
[2] Benchmark estimates from Koutroumpis (2009) are the compound annual growth effect of broadband (as calculated from diffusion rates and estimated elasticities), and report the average impact on GDP growth. It is therefore inappropriate to apply a diffusion rate to this estimate of economic impact.
[3] The estimated AI diffusion rate is the actual diffusion rate of fixed broadband internet in OECD countries from 1997-2007.

Sources:
World Bank 2014 Gross Domestic Product, available at http://databank.worldbank.org/data/download/GDP.pdf; Conference Board GDP Projection Estimates 2015-2025, available at https://www.conference-board.org/pdf_free/workingpapers/EPWP1502.pdf; OECD Communications Outlook 2013, Broadband Subscriptions per 100 Inhabitants in the OECD Area 1997-June 2012; Czernich et al. (2011); Qiang and Rossotto (2009); Koutroumpis (2009).

In interpreting these results, it is important to understand what the broadband benchmark implies for AI. Today, after 20 years, broadband has significant penetration in high-income countries. AI, in contrast may take a more gradual diffusion path than the rapid escalation experience by broadband. In addition, broadband is such a general tool that it was quickly applicable to essentially every sector of the economy. Though AI certainly has the potential to affect many sectors of the economy, specific realizations of AI in the next ten years may have more focused applications. Finally, the larger estimates found in the academic literature may over-attribute the growth that occurred due to broadband during the period analyzed. There were several nearly simultaneous innovations that occurred in these years, and thus it is very difficult to assess the portion which broadband specifically contributed.

This difficulty may explain, at least in part, the wide range of estimates provided by these benchmark papers. For example, the highest implied estimates for AI's economic impact from the broadband internet benchmark (derived from Qiang and Rossotto (2009)) exceeds even the estimate implied by IT investment, while the middle estimate (derived from Czernich et al. (2011)) is nearly equivalent to the IT benchmark. Since it is our view that the IT benchmark is likely too optimistic, we consider these two broadband benchmark estimates as equally optimistic estimates for AI's economic impact. In contrast, the more conservative broadband benchmark (derived from Koutroumpis (2009)) implies that AI could have a cumulative economic effect of $1.49 trillion through 2025. As this estimate relies on a benchmark technology which offers qualitative improvements over IT investment as discussed above, and as the resulting estimate falls above our likely too conservative approach in Section II (yielding $359.6 to $773.2 billion) and below the likely too optimistic IT benchmark (yielding $4.78 trillion), we find this a potentially reasonable benchmark for AI's economic impact.

C. Economic Effects of Mobile Phones as a Benchmark

The third benchmark we consider for AI is mobile phone technology. Mobile phones are another recent ICT development that experienced a rapid diffusion rate. Similar to IT, broadband, and AI's potential, mobile phones are considered a general purpose technology as there are many available mechanisms for this technology to affect economic growth.[64] Mobile phones have changed the way users interact, and increased users' accessibility and the speed and reliability with which contact can be made and information shared. By improving communication, mobile phones have resulted in an increase in productivity, efficiency, and innovation in applications from improving government tax collection to fostering new types of services and business structures. Similarly, current manifestations of AI are already working to increase our ability to collect, share, and communicate information efficiently with innovations like smart medical repositories and real-time business analytics. These current achievements are a strong indication that AI has the potential to substantially increase the speed and accessibility of information just as mobile phones have done in the last decade. In addition, mobile phones share broadband's potential improvement over IT as a benchmark for AI by representing a substantial, but not all encompassing portion of IT. Finally, and in contrast to the previous IT and broadband benchmark papers, mobile phones have been found to have a disproportionate effect on developing countries because significant infrastructure investment is not necessary for a population to effectively employ mobile phone technology. For example, by 2009, mobile phone subscribers in developing countries represented nearly 70% of global mobile phone subscriptions (3.2 out of 4.6 billion).[65] As is already being exhibited with current AI developments such as Apple's Siri or Microsoft's Cortana, it is likely that some future AI improvements will be accessed through mobile phone technology. Thus, if AI were to continue to enter the market through mobile phone technology, it is possible that AI could have similarly differential effects on developing countries.

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[64] Gruber, Harald, Pantelis Koutroumpis. "Mobile Telecommunications and the Impact on Economic Development." Economic Policy (2011) 387-426.
[65] Gruber and Koutroumpis (2011).

Researchers have found that mobile phones have a positive impact on economic growth in both developing and developed economies.[66] Two studies examine the effect of mobile telecommunication technology during its development from the mid-1990s into the early 2000s. Gruber and Koutroumpis (2011) study 192 countries from 1990-2007 and find a positive and statistically significant impact of mobile phone lines on growth, with a 10% increase in the mobile penetration rate increasing annual average economic growth by 0.33-0.89 percentage points.[67] As with the broadband benchmark studies, we use the more conservative, lower bound of this estimated range to inform our benchmark. Similarly, Vu (2011) studied 102 countries from 1996-2005 and finds that a 10 percentage point increase in the mobile phone penetration rate increases economic growth by at least 0.55 percentage points.[68]

Applying the results of this literature, we estimate a potential economic effect from AI should AI perform as mobile phones did during the 1990s and 2000s. Similar to the broadband benchmark, in order to estimate the effect of AI we require an approximation of AI's potential diffusion over the next decade. Using data from the World Bank, we select the second decade of mobile phone data as representative of mobile phone's first significant period of adoption. During the decade from 1993-2003, subscribers of mobile phones increased from 0.6% of the population to 22%. While AI is unlikely to follow an *identical* pattern to any benchmark, AI developments could follow a *similar* dissemination path to mobile phones given the potential similarities discussed above. Therefore, we employ mobile phone's actual experienced diffusion rate from 1993-2003 as an estimate of the path AI may follow from 2016-2025.

Applying this assumed diffusion pattern, we calculate that the finding of Gruber and Koutroumpis (2011) would yield an annual average increase in GDP growth of 0.31% over the next decade. Similarly, we estimate the economic effect of AI using the results from Vu (2011) by applying this study's regression equation to the level of mobile phone diffusion each year and calculating the percentage points of GDP growth attributable to mobile phones, indicating an average of 0.43% over the next decade.[69] As both benchmark studies included a wide range of countries we multiply projected global GDP estimates through 2025 by the range of 0.31% to 0.43% for the estimated economic effect of mobile phones. We calculate that if AI performs equivalently to historical mobile phones, AI could have a

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[66] Gruber and Koutroumpis (2011) find that mobile technology had a positive effect on economic growth in both high- and low-income countries from 1990-2007. Lee, et al. (2012) find that the diffusion of mobile technology in sub-Saharan Africa is an important determinant of economic growth. (Lee, Sang, John Levendis, and Luis Gutierrez. "Telecommunications and Economic Growth: an Empirical Analysis of Sub-Saharan Africa." Applied Economics (2012) 44, 461-469).

[67] Two different methodologies are used to estimate the effect of mobile phones on economic growth, resulting in estimates of 0.33% and 0.89%.

[68] Vu, Khuong M. "ICT as a Source of Economic Growth in the Information Age: Empirical Evidence from the 1996-2005 Period." Telecommunication Policy (2011) 35:357-372. Vu finds that the effect of mobile penetration on growth declines as penetration levels increase. When mobile penetration first begins, it increases economic growth by 0.55 percentage points, but this effect decreases slightly as the penetration rate continues to increase. This result contrasts with the findings of Gruber and Koutroumpis (2011), who find that mobile has a stronger effect on economic growth as penetration rises.

[69] These estimates already incorporate the diffusion of mobile phones that we assume AI will mirror over the next decade, so no further use of the diffusion rate is necessary.

cumulative global economic effect of $2.95 trillion–$4.24 trillion through 2025, or 0.31% to 0.45% of global GDP during that period.

As with broadband, we acknowledge that there were several nearly simultaneous innovations that occurred in these years, and thus it is difficult to assess the portion which mobile phones specifically contributed. The estimates of AI's potential economic impact produced by mobile phone benchmarking studies fall within the range of estimates generated by the broadband benchmark, thus we evaluate them similarly. Again, the highest implied estimates for AI's economic impact from the mobile phone benchmark (derived from Vu (2011)) is nearly equivalent to the IT benchmark. As we have determined that the IT benchmark is likely too optimistic, we consider this mobile phone benchmark estimate as equally optimistic about AI's economic impact. That is, an economic impact of $4.24 trillion is likely only reasonable if the development and diffusion of AI over the next decade matches or exceeds expectations of AI's strongest proponents. In contrast, the more conservative mobile phone benchmark (derived from Gruber and Koutroumpis (2011)) implies that AI could have a cumulative economic effect of $2.95 trillion through 2025. As this estimate relies on a benchmark technology which offers qualitative improvements over IT investment as discussed above, improved scope over the broadband benchmark (by also considering the effects on developing countries), and as the resulting estimate falls above our likely too conservative approach in Section II (yielding $359.6 to $773.2 billion) and below the likely too optimistic IT benchmark (yielding $4.78 trillion), we find this a potentially reasonable benchmark for AI's economic impact.

D. Economic Effects of Robotic Automation as a Benchmark

The final benchmark we consider for AI is robotic automation. As with broadband, robotics technology shares several components of our definition of AI. Specifically, robotic automation is a tool that enabled productivity growth just as AI, in the words of Sir Nigel Shadbolt, is "an aid to augment our intelligence. It's making us smarter and quicker at what we do."[70] Robotic automation is potentially a more appropriate benchmark than IT investment, broadband internet, or mobile phones for several reasons. First, while both IT investment and broadband internet were economy-wide phenomena, robotics, while still applicable to a wide sector of the economy, is more focused in a few sectors. This is likely a closer corollary for AI within the next ten years, when realizations of AI are likely to have more targeted, sector-specific, applications. Second, relative to broadband, robotics may be considered a more "disruptive" technology that leads to reconfiguring systems in order to leverage the technology's benefits in an optimal way. AI also has the potential to cause disruption as it may introduce new ways to perform a task, not just increasing the speed at which the previous method can be performed.

Data, and therefore academic research, on robotics are limited. However, a recent paper by Graetz and Michaels (2015) examines the effects of increased use of robotics across 14 industries in 17 developed countries from 1993-2007.[71] They find that the adoption of

[70] Jee, Charlotte. "Artificial Intelligence Fears Overblows, Says AI Expert Sir Nigel Shadbolt." Techworld. August 6, 2015.
[71] Graetz, Georg and Guy Michaels. "Robots at Work." CEP Discussion Paper No. 1335 (2015).

robotic technologies over this period increased annual average GDP growth by about 0.37 percentage points and improved labor productivity by 0.36 percentage points.[72] This accounted for one tenth of the aggregate GDP growth during this period for the countries examined, even though industrial robotics accounted for only roughly 2.25% of capital stocks in robotic-using industries as of 2007 and much less in the earlier years analyzed. Graetz and Michaels also conduct several sensitivities and determine that their results are generally robust to changes in capital and labor (including both employment and productivity effects) which might be induced by an increased use of robots in these industries.

Applying the results of this study, we estimate a potential economic effect from AI, should AI perform as industrial robotics did during the 1990s and 2000s. This estimate is calculated using a similar approach to the IT investment benchmark. As with the preceding IT and broadband benchmarks, the benchmark study on robotics focused on the effects of robotics in relatively high-income countries. Thus, multiplying the projected GDP estimates for high-income countries through 2025 by the 0.37% estimated economic impact of industrial robotics, we calculate that if AI performs equivalently to historical robotics, then AI could have a cumulative economic effect of $2.23 trillion through 2025, or 0.4% of GDP during that period.[73]

As discussed above, robotic automation as a benchmark is potentially preferable to any of IT investment, broadband, or mobile phones because robotics is likely to more closely reflect AI's more sector-targeted effects, and potentially disruptive nature. In addition, the results associated with applying industrial robots to AI yield estimates of AI's economic effect which fall between previous benchmarks that we assess as likely under-estimates (i.e. venture capital and private investment) and below estimates which we assess as likely over-estimates (i.e. IT investment and the upper bounds implied by broadband and mobile phones). We therefore find this a potentially reasonable benchmark for AI's economic impact.

IV. Conclusion

Our study of the economic impacts of AI during the next decade relies on two methodologies. First, a narrow and conservative analysis of private sector and venture capital investment indicates that the economic impact of AI could be between $359.6 billion and $773.2 billion over the next ten years. At a minimum, the current levels of investment in AI are a signal of the economic potential of AI. However, given limitations of the available data on current investment levels in AI and other potential mechanisms beyond return on investment through which AI may also affect economic growth which are

[72] Graetz and Michaels (2015) calculate robotic density as the number of delivered robotic units per million hours worked in robotic using industry.

[73] As the estimate from Graetz and Michael (2015) is an average annual effect from the observed change in robot density that occurred during the full period analyzed, it is inappropriate and redundant to apply a diffusion rate for AI as was done for the broadband benchmark estimates. Applying these estimates to all countries results in estimated global GDP effects of $3.48 trillion.

not captured by this approach, we conclude that this approach likely yields an under estimate of AI's economic effects over the next ten years.

Second, a set of benchmarks of recent and significant technologies that share similar characteristics with AI including general IT investment, broadband internet, mobile phones, and industrial robotics, provides a useful framework for estimating AI's potential economic effects. The most reasonable benchmarks suggest that the economic impact of AI could be between $1.49 trillion and $2.95 trillion over the next ten years. These estimates are derived from the more conservative studies of broadband internet, mobile phones, and the study of industrial robotics. At a high level this range is conceptually reasonable. It falls well above our first, investment driven approach which we conclude is a likely under-estimate, as noted above. It also falls well below the IT benchmark (implying $4.78 trillion in economic effect) which we conclude is a likely over-estimate given the improbability of AI singularly attaining the same level of significance as the entire IT sector of the 1990s within the next ten years.

At a more detailed level we also conclude that broadband, mobile phones, and robotics technology represent reasonable benchmarks for AI. All three technologies embody close parallels with AI's potential mechanisms for economic impact, and potential diffusion rates. For example, similar to AI's potential both broadband internet and mobile phones increased the speed and accessibility of information allowing for increased productivity across many sectors. Relative to broadband, mobile phones have the advantage of being studied globally, and not just in developed, high-income countries. This benchmark correspondingly yields the upper bound in our range of reasonable estimates at $2.95 trillion. Relative to both broadband and mobile phones, robotics offers several further advantages which make it a reasonable benchmark. Namely, robotics is likely to more closely reflect AI's more sector-targeted effects, and AI's potentially disruptive nature.

Given the range of potential for AI's development over the next decade we also rely on our benchmarks to provide an estimate for AI's economic impact should AI's development and diffusion meet or exceed its strongest proponents current projections. This optimistic upper bound is estimated to be as high as $5.89 trillion over the next ten years.

It is important to note that the benchmarks serve as informative approximations of AI's potential, but are not intended to perfectly predict the future economic effects of AI. We caveat our results with the points that AI's future diffusion, impacts on developing countries, and effects on employment are wide-ranging and much-debated. Our study is not anchored on any specific future of AI but rather serves to introduce a range of possibilities for AI going forward. In the course of its 60 year history, AI has frequently been heralded as on the cusp of being a significant contributor to global economic growth. Given the AI that exists today and the availability of data and computing power, AI may be on the verge of starting to realize its much anticipated potential.