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The Impacts of Technological Invention on Economic Growth – A Review of the Literature

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I. Introduction

In their recently published book, *The Second Machine Age*, Erik Brynjolfsson and Andrew McAfee rely on economist Paul Krugman to explain the connection between invention and growth:

> Paul Krugman speaks for many, if not most, economists when he says, "Productivity isn't everything, but in the long run it's almost everything." Why? Because, he explains, "A country's ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker"—in other words, the number of hours of labor it takes to produce everything, from automobiles to zippers, that we produce. Most countries don't have extensive mineral wealth or oil reserves, and thus can't get rich by exporting them. So the only viable way for societies to become wealthier—to improve the standard of living available to its people—is for their companies and workers to keep getting more output from the same number of inputs, in other words more goods and services from the same number of people. Innovation is how this productivity growth happens.[2]

For decades, economists and economic historians have sought to improve their understanding of the role of technological invention in economic growth. As in many fields of inventive endeavor, their efforts required time to develop and mature. In the last five years, these efforts have reached a point where they are generating robust, substantive, and intellectually interesting findings, to the benefit of those interested in promoting growth-enhancing invention in the U.S.

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[1] The author is research professor at the George Washington Institute of Public Policy. This paper is the public version of one delivered under contract to the Lemelson Foundation of Portland, Oregon for its internal use. The foundation's mission is to support inventors and invention-based enterprises in the U.S. and developing nations. The content of the paper is entirely the author's responsibility.

[2] Erik Brynjolfsson and Andrew McAfee, *The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies*, New York: W.W. Norton & Co. (2014), pp. 72-73.

This paper organizes, summarizes, and assesses findings for six types of analyses.

- Economic History – review of the history of invention in the West to determine the impact of invention on economic growth and the conditions that enable invention.
- Innovation Accounting – statistical methods for calculating the contribution of innovation-related factors (such as research and development, technological change, greater capital intensity, and greater human capital) on growth in economic output.
- Macroeconometric Analysis – statistical analyses that estimate the influence of the size and type of R&D expenditures on economic growth.
- Microeconometric Analysis – statistical analyses that measure the economic outcomes of innovation-driven firms compared to other firms.
- Economic Theory and Models – theories that predict and complex models that test hypotheses about the relationship between invention/innovation and economic growth.
- Future Scenarios – examination of the expected economic impacts of technological invention over the coming years.

This paper relies on the definitions below, drawn from a summary of a Lemelson-MIT Program-sponsored workshop held in March 2003.[3]

- Invention is the process of devising and producing by independent investigation, experimentation, and mental activity something which is useful and which was not previously known or existing. An invention involves such high order of mental activity that the inventor is usually acclaimed even if the invention is not a commercial success.
- Innovation, which may or may not include invention, is the complex process of introducing novel ideas into use or practice and includes entrepreneurship as an integral part. Innovation is usually considered noteworthy only if it is a commercial success. Thus society benefits from innovation, not from invention alone, and often there is a significant lapse of time from invention to innovation.
- Technology is the body of knowledge of techniques, methods, and designs that work, and that work in certain ways and with certain consequences, even when one cannot explain exactly why. Technology may also be defined as the effort to organize the world for problem solving so that goods and services can be developed, produced, and used.

[3] The Lemelson-MIT Program, "Historical Perspectives on Invention & Creativity," Massachusetts Institute of Technology, 2004.

Joel Mokyr, a member of the Lemelson-MIT group, notes elsewhere that "without invention, innovation will eventually exhaust itself."[4]

The Lemelson-MIT workshop definition of invention cited above is quite broad in scope—the operative noun, after all, is "something." Looking over the historical arc of invention, one can discern five types of invention:

- Symbolic—such as the alphabet, arithmetic notation, and software code
- Domestication—of wild animals and plants
- Technological—new organizations and combinations of matter
- Institutional—such as
  - rituals (e.g., rites of passage)
  - belief systems (e.g., spiritual practices)
  - methods (e.g., double-entry bookkeeping, just-in-time inventory)
  - organizational formats (e.g., the corporation)
  - forms of governance (e.g., the Constitution)
  - product standards (e.g., to be labelled "organic")
  - practice standards (e.g., professional ethics, accounting principles)
- Explanations—of how the world and the universe work (e.g., Newton's "Mathematical Principles of Natural Philosophy," Darwin's theory of evolution, Einstein's theory of relativity)

Each type of invention facilitates and is facilitated by the other. This paper examines in particular approaches to understanding the relationship between technological invention and economic growth.

The definition of economic growth is deserving of discussion as well. Traditionally, economic growth has been measured in terms of change in Gross Domestic Product (GDP) or GDP per capita over time. GDP itself has been lauded as "one of the great inventions of the 20th century."[5]

> While the GDP and the rest of the national income accounts may seem to be arcane concepts, they are truly among the great inventions of the twentieth century. . . .
>
> Much like a satellite in space can survey the weather across an entire continent so can the GDP give an overall picture of the state of the economy. It enables the President, Congress, and the Federal Reserve to judge whether the economy is contracting or expanding, whether the economy needs a boost or should be reined in a bit, and whether a severe recession or inflation threatens.

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[4] Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress*, New York: Oxford University Press, 1990, p. 292.
[5] "GDP: One of the Great Inventions of the 20th Century," *Survey of Current Business*, January 2000, pp. 6-14.

> Without measures of economic aggregates like GDP, policymakers would be adrift in a sea of unorganized data. The GDP and related data are like beacons that help policymakers steer the economy toward the key economic objectives.[6]

However, traditional GDP is more a measure of production, as currently valued by the market, than it is a more general measure of economic well-being. In recent years, the shortcomings of GDP has been an increasingly popular topic of policy and scholarly conversation. For the purposes of this paper, two types of issues are relevant.

First, many aspects of the nation's economic well-being are difficult to measure. On the positive side, examples include lower search costs for information and goods, radical jumps in computing power at no extra cost, the availability of free smartphone apps, significantly lower transaction costs for information search, and increases in educational attainment. On the negative side, examples include climate change effects and the emotional, health, and financial costs of high unemployment.[7]

Second, GDP and GDP per capita do not indicate how the benefits of economic growth, however measured, are distributed across society.

> When there are large changes in inequality (more generally a change in income distribution) gross domestic product (GDP) or any other aggregate computed per capita may not provide an accurate assessment of the situation in which most people find themselves. If inequality increases enough relative to the increase in average per capital GDP, most people can be worse off even though average income is increasing.[8]

As shorthand, Brynjolfsson and McAfee distinguish between the "bounty" (GDP) and the "spread" (distribution).[9] Useful measures of distribution include median income per capita, median household income, and the distribution of income and wealth by percentile (e.g., the percent of the nation's income earned by the highest-earning 10 percent of households).

In a recent article, Nick Hanauer and Eric Beinhocker offer an alternative measure of economic well-being that, coincidentally, neatly describes the relation between invention and economic growth: "Prosperity in a society *is the accumulation of solutions to human problems*." They explain their thinking:

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[6] Paul Samuelson and William Nordhaus, Economics, 15th edition, New York: McGraw-Hill, 1995, as cited in "GDP: One of the Great Inventions of the 20th Century," *Survey of Current Business*, January 2000, p. 7.
[7] An extensive discussion of issues regarding GDP measurement can be found in Brynjolfsson and McAfee, *op.cit.*, Chapter 8: "Beyond GDP."
[8] Joseph E. Stiglitz, Amartya Sen, and Jean-Paul Fitoussi, *Report by the Commission on the Measurement of Economic Performance and Social Progress*, 2009, p. 7.
[9] Bryjolfsson and McAfee, *op.cit.*

> Ultimately, the measure of a society's wealth is the range of human problems that it has found a way to solve and how available it has made those solutions to its citizens. Every item in the huge retail stores that Americans shop in can be thought of as a solution to a different kind of problem—how to eat, clothe ourselves, make our homes more comfortable, get around, entertain ourselves, and so on. The more and better solutions available to us, the more prosperity we have.[10]

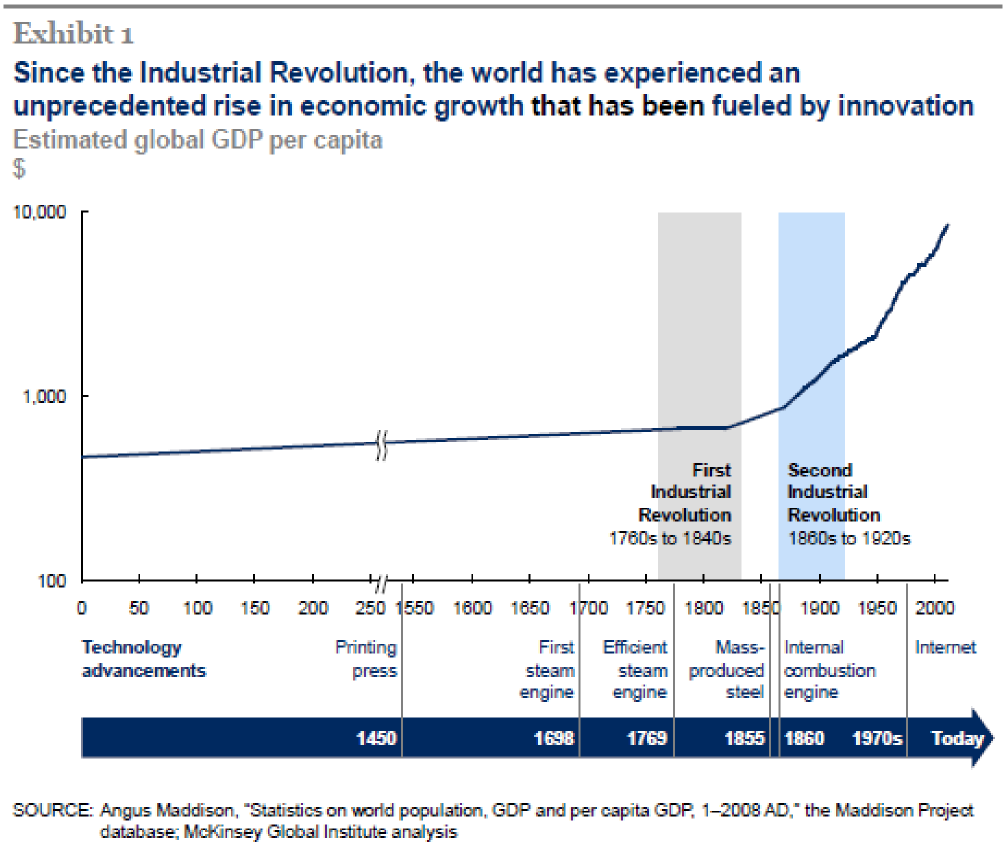
The five types of invention offered earlier collectively provide "solutions to human problems." While no measure presently exists that fully reflects Hanauer and Beinhocker's definition of prosperity, such a measure certainly can be deemed aspirational.

[10] Nick Hanauer and Eric Beinhocker, "Capitalism Redefined," *Democracy: A Journal of Ideas*, No. 31, Winter 2014, p. 34.

II. Economic History

Technological Invention and Global and National Economic Growth

It is generally understood and accepted that the unprecedented material bounties of modern human life are fully the result of invention. That conclusion is clear from personal experience and across multiple academic disciplines. From a long-term historical perspective, this can be seen in one image, the following graph from a recent McKinsey Global Institute report.[11]



One can see an unprecedented and dramatic upturn in the global standard of living that was initially catalyzed by the First Industrial Revolution, greatly magnified by the Second Industrial Revolution, and further heightened in the recent age of information and computer technology.

> [S]ince the Industrial Revolution of the late 18th and early 19th centuries, technology has had a unique role in powering growth and transforming economies. Technology represents new ways of doing things, and, once mastered, creates lasting change, which businesses and cultures do not 'unlearn.' Adopted technology

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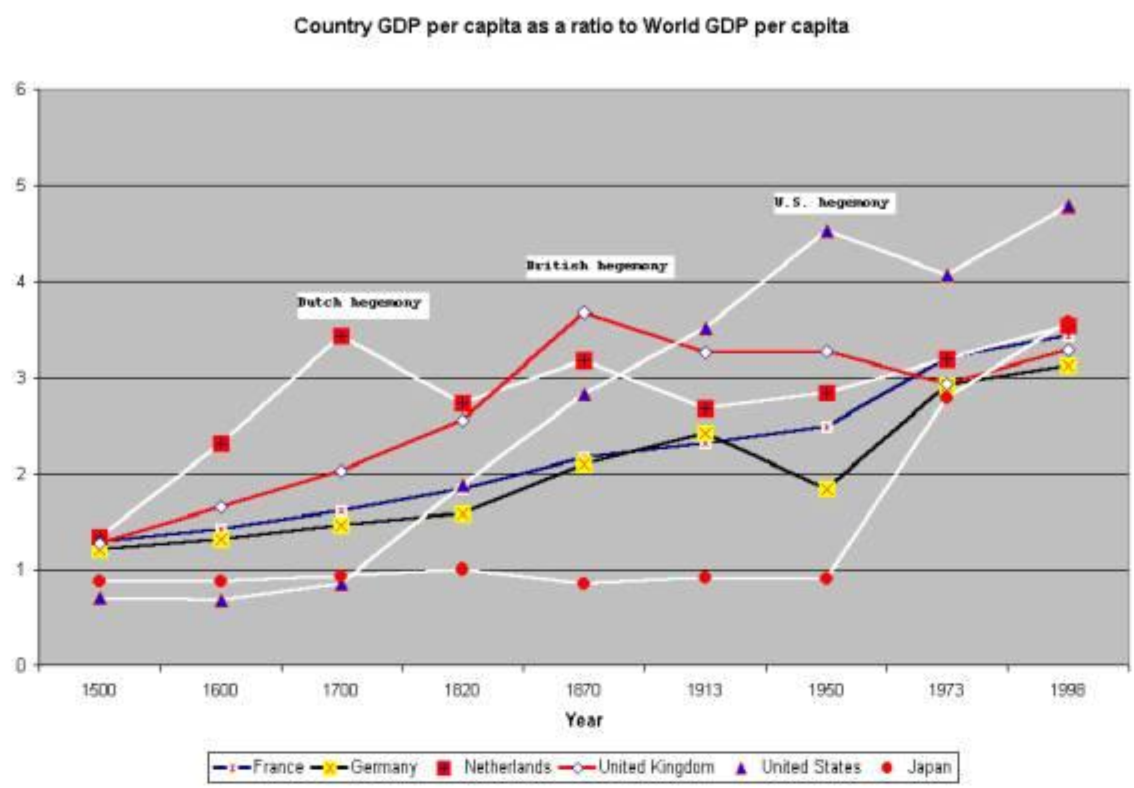
[11] James Manyika et al., "Disruptive technologies: Advances that will transform life, business, and the global economy," McKinsey Global Institute, May 2013, p. 24. "

becomes embodied in capital, whether physical or human, and it allows economies to create more value with less input. [12]

The growth that began in the 19th century is much more rapid than anything seen previously and shows signs of being self-sustaining in ways that past growth was not.[13] Note that the graph is on a log scale—the actual slope of the line after World War II is much steeper than visually depicted.

The McKinsey graph masks what historians call "The Great Divergence," the concentration of economic growth at the sites of the technological inventions, that is, Western Europe—particularly Great Britain, catalyst for the First Industrial Revolution—and North America—particularly the United States, primary catalyst for the Second Industrial Revolution and the advances in information technology. The nature of The Great Divergence can be seen in the following graph.



Source: Christopher Chase-Dunn, Rebecca Giem, Andrew Jorgenson, Thomas Reifer, John Rogers and Shoon Lio, "The Trajectory of the United States in the World-System: A Quantitative Reflection," Institute for Research on World-Systems, University of California, Riverside, IROWS Working Paper # 8, 2002.

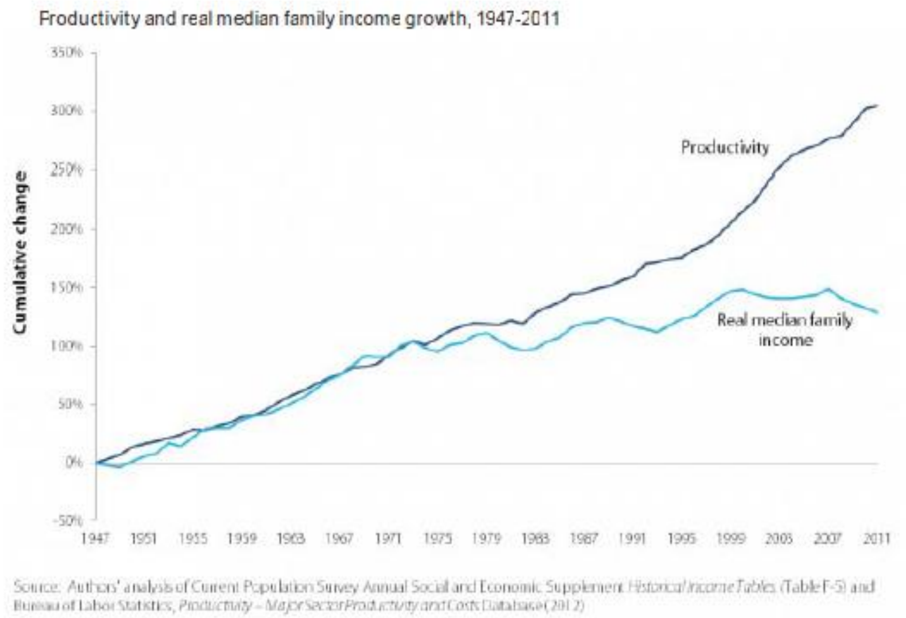
[12] *Ibid.*, p. 1.
[13] Richard Lipsey, Kenneth Carlaw, and Clifford Bekar, *Economic Transformations: General Purpose Technologies and Long Term Economic Growth*, New York: Oxford University Press, 2005, p. 221.

More recently, of course, the developing world has experienced great benefits from technological change. Ezra Klein:

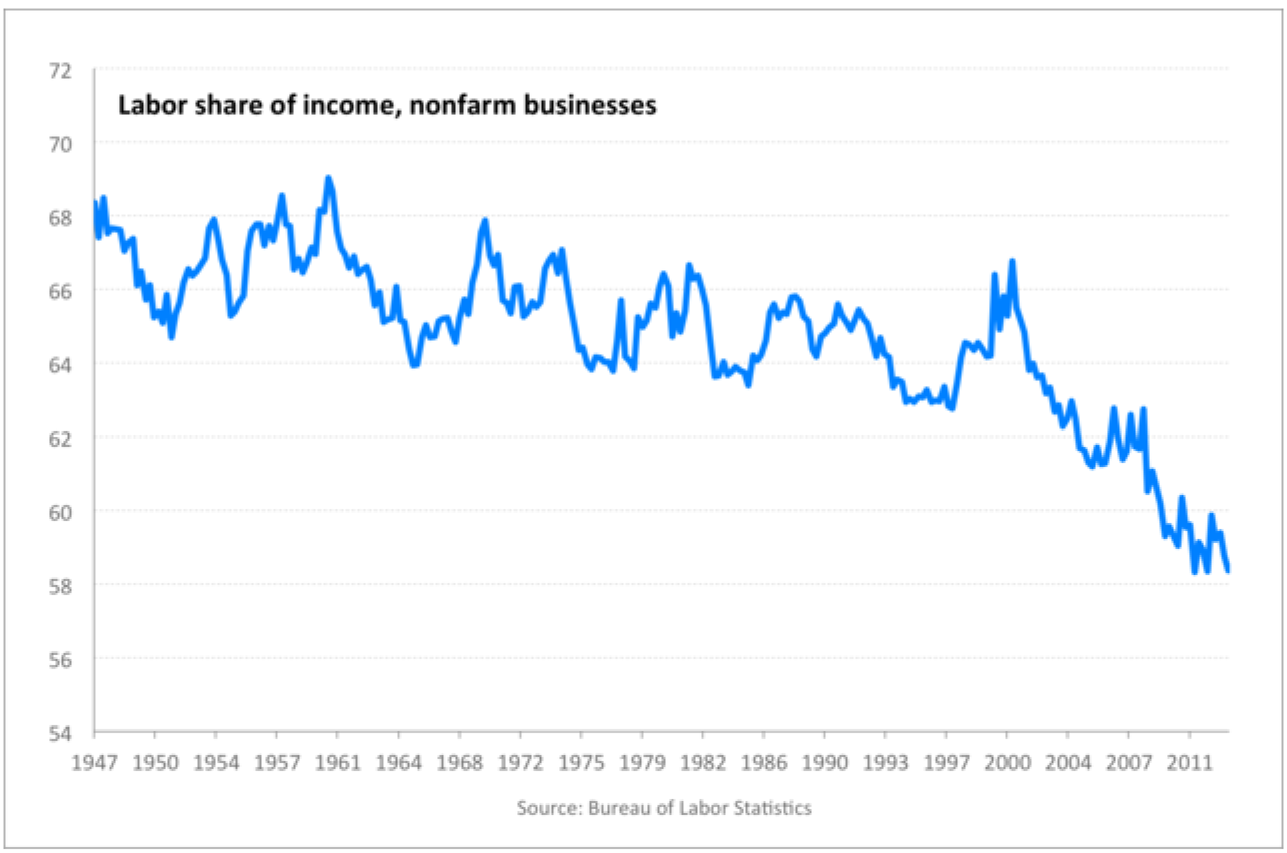
> In terms of human welfare, the most important changes are happening outside our borders. More people have seen their lives improve more quickly in the past few decades than perhaps at any time in human history. In 1990, more than 40 percent of the world lived in extreme poverty. By 2015, the World Bank predicts, the figure will be just 16 percent. Among people who work in global development, the goal of eradicating extreme poverty by 2030 is now controversial because it's not considered ambitious enough. . . .
>
> Rapid development in China, and India is among the best news in the history of the human race. It will also profoundly alter the U.S. role in the world -- and its sense of mission and place -- as the century wears on. The U.S. will not be, and should not be, the world's largest economy for long. . . .
>
> I take the optimist's view, which is that global development is good for the world and good for the U.S. . . . The rising power of autocratic governments is a real concern. But we have even greater cause to be thrilled that billions of people will be better able to develop and use their talents as economic demand increases and technology advances.[14]

A different type of divergence has been taking place within developed nations. Invention leads to economic growth by increasing labor productivity—new technologies allow each worker to produce a greater amount of goods and services. The following graphs show that between the end of World War II and the mid-1970s, U.S. households fully benefited from steadily increasing productivity. However, while productivity increases have continued apace over the last four decades, median household income has been relatively stagnant and labor's share of income has declined. This suggests that of late the benefits of invention have not been evenly distributed in the U.S.

[14] Ezra Klein, "The Future Looks Dull from Here," Bloomberg View website, February 19, 2014, http://mobile.bloomberg.com/news/2014-02-19/the-future-looks-dull-from-here.html (accessed February 20, 2014).



Updated October 5, 2012



The remainder of this chapter explores the nature of and reasons for the remarkable stream of technological innovations and its effects on economic growth.

The Foundations of Technological Invention in the West

In the early Middle Ages in the West, life was organized around immediate sensory experiences of cyclical (not linear) time and very finite space; experience was constantly interpreted through a lens of religious symbolism; the Earth was believed to be the center of universe and Jerusalem the center of the Earth. The transformation of Western civilization in 600 years from this state to the First Industrial Revolution required the development and diffusion of multiple discrete innovations, many of which were outside of technology, including writing, mathematics, critical thinking, and research methods:

- Literacy: Ready access to, and ability to read, the written word was fundamental to mathematical analysis, scientific research, engineering, and invention. Key developments include:
    - Writing—Cuneiform writing first appears in Sumer around 3100 BCE and hieroglyphics in Egypt soon after. These writing systems allowed for a substantial extension of commerce and government.[15]
    - Alphabet—Around 1400 BCE, the first alphabet—25 letters representing the basic consonant sound units of speech—was invented, enabling the spread of commerce, religion, and empire. The Greeks created vowels in the middle of the first millennium BCE, "eliminating the phonemic ambiguity of . . . the older alphabetic systems" and making the creation of new philosophical and logical analyses and histories much easier.[16]
    - Writing surfaces—Papyrus was developed by the Egyptians around 2000 BCE, parchment around 200 BCE, and paper by the Chinese around 0 CE. The physical form of a book ("codex"), which has multiple advantages over a scroll, was invented around 500 CE. Paper mills came to Christian Europe around 1100 CE.[17]
    - Organization of text: Irish monks created spaces between words in the sixth century CE to facilitate reading and writing—this invention took 500 years to spread across Europe.[18] Spaced text led to a substantial increase in solitary reading and writing and greatly improved the educational process. European universities in the 1200s-1300s created punctuation, further facilitating reading, and developed cursive writing, which sped that process.[19]

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[15] William J. Bernstein, *Masters of the Word: How Media Shaped History from the Alphabet to the Internet*, New York: Grove Press, 2013.
[16] Bernstein (2013) says that syllabic writing systems took a decade to learn, consonant-only alphabetic writing systems five years, and consonant-vowel alphabetic writing systems one-to-two years.
[17] Ibid.
[18] According to Bernstein, for more than a millennium writing was *scriptura continua*, words with no separation, which required substantial concentration and reading aloud, greatly slowing reading speed.
[19] Alfred W. Crosby, *The Measure of Reality: Quantification and Western Society, 1250-1600*, Cambridge University Press, 1997.

  - Organization of literature: To facilitate learning of ancient texts, European universities in the 1100s-1300s developed alphabetization, chapter titles, citations, cross-references, concordances, indices, and tables of contents.[20]
  - Printing: The development of the printing press (Germany, 1440) enabled, for the first time in history, the widespread distribution of information.[21]
- Numeracy: Between 1200 and 1700, the West developed arithmetical and mathematical tools capable of performing the complex analyses needed to carry out scientific research.
  - Counting tokens representing units of agricultural goods were invented around 10,000 BCE in the Fertile Crescent.
  - In the Middle Ages, the West still relied on Roman numerals and the abacus for calculation. Key arithmetic developments include the adoption of Hindu-Arabic numbers (Italy, 1202); zero (non-existent in the Roman system); place value; plus and minus signs (Germany, 1489); equal sign (England, 1550); decimals (Flanders, 1585); multiplication sign (England, 1631); and division sign (Switzerland, 1659).
  - With basic conventions for manipulating numbers in place, more sophisticated mathematics quickly developed, including symbolic algebra (France, 1591); logarithms (Scotland 1614), analytic geometry (France, 1637); and calculus (England and Germany, 1687).[22]
- Mechanization, measurement, and commerce: In the Middle Ages, the West developed a passion for machines and standardized measures of the world and activities within. These, in turn, allowed commerce to flourish.
  - Between 1275 and 1325, the striking mechanical clock, cannon, marine charts, and double-entry bookkeeping were developed.
  - Invention of the mechanical clock lead to the creation of the standard hour (Germany 1330). The notion that the universe behaves like a mechanical clock (a precursor to Newtonian physics) started to become popular in the mid-1350s. Clocks with an hour hand appeared in the late 1300s (those with a minute hand not until 1690).
  - Marine charts led to maps with longitude and latitude (Germany, 1477). Clocks, bookkeeping, and maps in turn stimulated commerce and trade.

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[20] *Ibid.*

[21] A prerequisite invention for the printing press was the technology to rapidly produce thousands of bits of letter type "so finely made that the few thousand blocks required for the average page fitted perfectly together. . . . Unless the type caster manufactures all the type blocks so that the printer can align them exactly, the result will be an unreadable jumble . . . ." Bernstein, *op.cit.,* pp. 142-143.

[22] Sources for this information include Crosby, *op.cit.*; James Gleick, *The Information: A History, A Theory, A Flood*, New York: Pantheon Books, 2011; and various entries in Wikipedia.

    - The Western passion for measuring everything was reflected in the coining of the work "pantometry," or universal measurement, in 1571.[23]
- Logic: The Schoolmen of the Middle Ages developed the habits and processes of precise definition, meticulous reasoning, and rigorous logic and applied these to all intellectual matters, not just ones of faith. These were necessary foundations for the development of science and engineering in later centuries.[24]
- Retention of Scientific Advances: Europe "institutionalized memory for scientific advances in the form of the autonomous universities and their libraries."[25]
- Scientific Revolution: The development and diffusion of literacy, numeracy, measurement, and logic enabled major scientific discoveries in the 1500s and 1600s. Key aspects of the Scientific Revolution included mechanical philosophy (understanding the machine-like workings of the universe); chemistry (understanding the active powers of matter); empiricism (scientific method); and mathematics (quantitative measurement of physical phenomena). Key actors included:
    - Nicolaus Copernicus developed his heliocentric theory of the solar system in 1532.
    - Galileo Galilei, considered by many to be the father of modern science through his pioneering use of mathematics and experimentation in research, made key findings in the realms of basic and applied sciences, including astronomy, physics, and technology, between 1590 and 1642.
    - Francis Bacon articulated the scientific method in 1620.
    - Johannes Kepler made numerous astronomical discoveries between 1596 and 1621.
    - Robert Boyle developed the foundations of modern chemistry in the 1660s.
    - Isaac Newton published *Principia* in 1687, which provided a set of laws about the machine-like workings of the universe.
    - Newton and Gottfried Leibniz independently invented calculus, an analytic method that allowed Newton's universal laws to be applied to engineering and technology.
    - Newton and Christian Huygens, among others, created the norm of using numbers to test a scientific theory's validity.[26]

Newton's work enabled Great Britain in the 1700s to become the locus of a cumulative set of invention activities never before seen in human history. Only in Britain was Newtonian mechanics widely understood, taught, and practiced. "[T]hanks primarily to Newton's work,

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[23] Crosby, *op.cit*.
[24] *Ibid.*, p. 64-65.
[25] Lipsey, Carlaw, and Bekar, *op.cit*.
[26] I. Bernard Cohen, *The Triumph of Numbers: How Counting Shaped Modern Life*, New York: W.W. Norton & Co., 2005, p. 35.

mechanics became an organized body of readily accessible knowledge" that allowed British scientists, engineers, and entrepreneurs to easily communicate.[27] Public interest in and understanding of mathematics and Newtonian mechanics became widespread. "In an unprecedented turn, the once exclusive domain of scholars became the science of the educated layperson. . . . 'Newtonianism was soon represented in the public world as holding the keys to the solution to a wide range of obstacles in mechanics, mining, hydraulics, and various technical enterprises.'"[28]

> The degree to which Newton's new mechanical science permeated British society and was used by innovators and entrepreneurs, such as the Watts and the Boultons, separated England from all other European countries—only the Netherlands came close. This knowledge entered into the public domain in a world in which science was 'all the rage.' It was in the air and practical engineers and inventors breathed it every day. By 1750 the scientific revolution had created in Britain 'a new person, generally but not exclusively a male entrepreneur, who approached the productive process mechanically, literally by seeing it as something to be mastered by machines, or on a more abstract level to be conceptualized in terms of weight, motion, and the principles of force and inertia' . . . .
>
> The influence of mechanistic science was felt not just in the development of machinery but also in canals, harbours, mines, and a host of other applications. The role of science in all of this was not that of general laws leading to the development of specific applications. Instead, it permeated the thoughts and attitudes of ordinary people, providing them with the theoretical mechanics and practical mathematics that facilitated technological change. This illustrates the fusion of theoretical and applied science, as well as engineering, which characterized the scientific world well into the nineteenth century.[29]

The advent of the First Industrial Revolution was most visible in the British textile industry, brought on by the connection of water power, textile machinery, and factory organization. It also could be seen in the development of the steam engine (1712), the first new major power source since the windmill. The Industrial Revolution was the culmination of a long series of discoveries and was not predictable or pre-ordained in terms of timing, place, new technologies, or industry focus.

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[27] Margaret C. Jacob, *Scientific Culture and the Making of the Industrial West*, Oxford: Oxford University Press, p. 8, as quoted in Lipsey, Carlaw, and Bekar, *op.cit.*, pp. 241.
[28] Lipsey, Carlaw, and Bekar, *op.cit.*, pp. 241, including quote from Larry Stewart, *The Rise of Public Science: Rhetoric, Technology, and Natural Philosophy in Newtonian Britain, 1660-1750*, Cambridge: Cambridge University Press, 1992, pp. xxxi-xxxii.
[29] Lipsey, Carlaw, and Bekar, *op.cit.*, pp. 242-243, including quote from Jacob, *op.cit.,* pp. 6-7.

Historical Phases of Technological Invention

Lipsey, Carlaw, and Bekar identify four phases of industrial mechanization between 1450 and 1975:[30]

- The early modern mechanization phase (1450~1750), predates the First Industrial Revolution and involve cottage-based "putting out," sheds and cottages with hand-powered textile machines, and a few water-powered textile "manufactories."
- The early factory phase (1770~1820) saw "proto-factories" grow in number and size, largely powered by waterwheels, with a few powered by steam engines. The focus continued to be textile production.
- The steam-driven factory phase (1820~1880) involved the widespread diffusion of steam engines in factories and transportation, including railways and ships, as well as the substantial expansion of the number and amount of goods produced in factories.
- The science-led industrial phase (1880~1975) was characterized by inventions, derived from scientific laws, which provided a material foundation for massive economic growth. Key inventions included steel, chemicals, internal combustion engines, and electric motors.[31]

The last quarter of the 20th century saw the emergence of the information and computer technology (ICT) revolution, the development of products and processes that rely on managing the movement of electrons for communications and analysis.[32] If mechanization provided means to extend and magnify human brawn, information technology offers the means to extend and magnify the workings of the brain. Brynjolfsson and McAfee say:

> Now comes the second machine age. Computers and other digital advances are doing for mental power—the ability to use our brains to understand and shape our environments—what the steam engine and its descendants did for muscle power. They're allowing us to blow past previous limitations and taking us into new territory. . . . [W]hether or not the new machine age bends the curve as dramatically as Watt's steam engine, it is a very big deal indeed. . . . [M]ental power is at least as important for progress and development—for mastering our physical and intellectual environment to get things done—as physical power. So a vast and unprecedented boost to mental power should be a great boost to humanity, just as the earlier boost to physical power so clearly was.[33]

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[30] Roughly corresponding to Brynjolfsson and McAfee's "first machine age," *op.cit.*

[31] Lipsey, Carlaw, and Bekar, *op.cit.*, pp. 238-239.

[32] Nicholas Crafts and Kevin O'Rourke, "Chapter 6: Twentieth Century Growth," *Handbook of Economic Growth*, Volume 2A, Oxford, UK: North Holland, 2014.

[33] Brynjolfsson and McAfee, *op.cit.*, pp. 7-8.

Up to the late 19th century, Great Britain was the lead industrial innovator. That leadership then transferred to the United States, where it has remained until the present. During the science-led industrial phase, the U.S. was the site for key new technologies such as the internal combustion engine, electricity, petrochemicals, aviation, transistors, and integrated circuits. In the current ICT revolution, eight of the 14 largest IT companies and seven of the ten largest Internet companies worldwide are based in the U.S.[34]

Classes of Technological Invention

In light of the essential role of invention in economic growth, scholars of invention activity have developed typologies that distinguish among technological inventions in terms of their nature, importance, and impact, with the aim of facilitating greater understanding of the phenomenon. This section briefly reviews four approaches to classification and then focuses on the one currently most widely adopted. The four classification schemes are:

- Radical (or revolutionary, breakthrough, discontinuous) invention vs. incremental (or evolutionary, continuous) invention, suggested by sociologist S. Colum Gilfillan (1935), mid-20th century economist Joseph Schumpeter, economist Brian Arthur, and many others.
- Macroinvention vs. microinvention, proposed by technology historian Joel Mokyr (1990).
- Disruptive vs. sustaining innovation, suggested by Clayton Christensen, business professor (1997).
- General purpose technologies (GPTs), proposed by economists Timothy Bresnahan and M. Trajtenberg (1995).

The notion of radical, or somehow dramatically different, invention, innovation, and technology is the most popular, and least well defined, framing. The lack of fixed definition in part is due to the fact that it emerges from diverse scholarly disciplines. A common theme is that radical innovations "could not have evolved through improvements to, and modifications of, the existing technology" or are based on a new set of science and engineering principles, while "incremental innovations . . . improve upon and extend existing technology."[35]

To Mokyr, "[m]acroinventions are those inventions in which a radical new idea, without clear precedent, emerges more or less ab nihilo [from nothing]" while microinventions are "the small, incremental steps that improve, adapt, and streamline existing techniques already in use, reducing costs, improving form and function, increasing durability, and reducing energy and raw material requirements." Mokyr goes on to distinguish between a radical macroinvention

[34] Ranked by revenue. U.S. IT firms: Apple, HP, IBM, Microsoft, Amazon, Dell, Google, Intel. U.S. Internet firms: Amazon, Google, eBay, Facebook, Priceline, Yahoo, Salesforce. Source: Wikipedia.
[35] Amanda Slocum and Edward S. Rubin, "Understanding Radical Technology Innovation and its Application to CO2 Capture R&D: Interim Report, Volume One—Literature Review," Department of Engineering and Public Policy, Carnegie Institute of Technology, May 30, 2008.

("a new idea is conceived and implemented") and a hybrid macroinvention ("separate and previously known elements are combined in a novel way"). He offers the mechanical clock as an example of the former and the windmill as an example of the latter. Mokyr has a particular perspective on the process by which macroinventions develop:

> Macroinventions . . . do not seem to obey obvious laws, do not necessarily respond to incentives, and defy most attempts to relate them to exogenous economic variables. Many of them resulted from strokes of genius, luck, or fortunate misunderstandings. Technological history, therefore, retains an unexplained component which makes a purely economically oriented explanation difficult to maintain. In other words, luck and inspiration mattered and thus individuals made a difference.[36]

Christensen's primary focus is on the disruptive impacts of a new technology rather than its inherent technological uniqueness.

A disruptive innovation is an innovation that helps create a new market and value network, and eventually goes on to disrupt an existing market and value network (over a few years or decades), displacing an earlier technology. The term is used in business and technology literature to describe innovations that improve a product or service in ways that the market does not expect, typically first by designing for a different set of consumers in a new market and later by lowering prices in the existing market.

In contrast to disruptive innovation, a sustaining innovation does not create new markets or value networks but rather only evolves existing ones with better value, allowing the firms within to compete against each other's sustaining improvements. Sustaining innovations may be either "discontinuous" (i.e. "transformational" or "revolutionary") or "continuous" (i.e. "evolutionary").[37]

Disruptive innovation helps firms and economies grow through the creation of new businesses and the development of new product markets. But disruptive innovation also provides users with important products that were previously out of their reach. It does this by bringing technology to lower cost providers and users so they can have access to products that improve their living standards and productivity.[38]

Scholars working with Christensen's framework have integrated it with the older notion of a radical technology.

> [Scholars] distinguish disruptive innovations further based on their radicalness, or new products based on a new technology relative to what already exists in the

[36] Mokyr, *op.cit.*, p. 7.
[37] "Disruptive Innovation," Wikipedia (accessed January 3, 2014).
[38] David Ahlstrom, "Innovation and Growth: How Business Contributes to Society," *Academy of Management Perspectives*, 24(3): 11-24, August 2010.

> industry. Their empirical research shows that all disruptive innovations are not necessarily radical (e.g., Schwab's discount brokerage business model), nor are all radical innovations necessarily disruptive (e.g., cordless phones relied on substantially new technology relative to wired phones but were not disruptive to the industry). Some can be both radical and disruptive (e.g., cellular phones).[39]

Each of these three typologies is problematic for the purposes of exploring the impacts of invention on economic growth. Not only is the first not consistently defined, no one has combed through history to identify which inventions are radical and which are not and systematically explore the relationship among them. The second depends on a notion that macroinventions emerge outside the dynamics of social science —I don't believe this to be so, but in any case it is not a framework amenable to analysis.[40] Further, Mokyr has not developed a comprehensive list of macroinventions nor has he prepared a rigorous testable framework for understanding the relationship between macroinventions, microinventions, and economic growth. While Christensen's approach is useful for understanding the relationship between invention, product markets, and industry structure, proponents have not come up with a definitive listing of disruptive technologies and mapped the relation between them, sustaining technologies, and economic growth.

On the other hand, scholars in several disciplines have found that the concept of general purpose technologies (GPTs) has qualities amenable to useful analysis, particularly in relation to economic growth. The concept has increased its reach over the last 20 years to the point that scholars regularly extend, enhance, and experiment with it, using a shared GPT-related language and framework.

In 1995, Bresnahan and Trajtenberg published a seminal article, "General purpose technologies: Engines of growth?," in which they argue:

> The central notion is that, at any point in time, there are a handful of 'general purpose technologies (GPT's) characterized by the potential for pervasive use in a wide range of sectors and by their technological dynamism. As a GPT evolves and advances it spreads throughout the economy, bringing about and fostering

[39] Stanley F. Slater and Jakki J. Mohr, "Successful Development and Commercialization of Technological Innovation: Insights Based on Strategy Type," *The Journal of Product Innovation Management*, 23(1): 26-33, January 2006.

[40] Mokyr, *op.cit.*, p. 13: "*Macroinventions* . . . are those inventions in which a radical new idea, without clear precedent, emerges more or less ab nihilo [out of nothing]. . . . Macroinventions . . . do not seem to obey obvious laws, do not necessarily respond to incentives, and defy most attempts to relate them to exogenous economic variables. Many of them resulted from strokes of genius, luck, or serendipity. Technological history, therefore, retains an unexplained component that defies explanation in purely economic terms."

generalized productivity gains. Most GPT's play the role of 'enabling technologies', opening up new opportunities rather than offering complete, final solutions.[41]

In this way, the authors say, GPTs have served and will continue to serve as the foundation for economic growth. Lipsey, Carlaw, and Bekar offer perhaps the most thorough definition of a GPT. They indicate that:

- A GPT may be a product technology (e.g., airplane), a process technology (e.g., writing), or an organizational technology (e.g., the factory system).
- Any GPT must satisfy four criteria:
  - It must have a wide range of uses, that is, it must be applicable in many different industries and used in a high proportion of economic activity.
  - It must have a wide variety of uses, that is, a substantial number of distinct uses.[42]
  - It must have scope for improvement and evolution: "As the technology is developed, its costs of operation in existing uses fall, its value is improved through the inventions of ancillary supporting technologies, and its range and variety of uses increases."
  - It must generate "spillovers," that is, affect the nature of existing technologies and create the opportunity for new product, process, and organizational technologies.[43]
- Any technology sits along a continuum in relation to the four criteria; therefore some technologies are almost, but not quite, GPTs.
- GPTs fall into six main classes:
  - Materials technologies (e.g., bronze, biotechnology)
  - Power (e.g., waterwheel, steam engine)
  - Information and communications technologies (e.g., writing, Internet)
  - Tools (e.g., wheel)
  - Transportation (e.g., steamship)
  - Organization: (e.g., mass production)
- A GPT is rarely born as such, rather, it evolves to become one. Once developed, the economic impact of a GPT is not likely to be immediate, for it requires business to develop appropriate intermediate goods before it can be implemented, e.g., the building of gas stations allowed the auto market to grow.[44] As a result, the

[41] Timothy Bresnahan and M. Trajtenberg, "General purpose technologies: "Engines of growth?," *Journal of Econometrics*, 65(1): 83-108, January 1995.
[42] For instance, while a light bulb has a wide range of uses, it does not have a wide variety of uses.
[43] Bresnahan and Tratjenberg called these "innovational complementarities."
[44] Philippe Aghion, Ufuk Akcigit, Peter Howitt, "Chapter 1: What Do We Learn From Schumpeterian Growth Theory?," *Handbook of Economic Growth*, Volume 2B, Oxford, UK: North Holland, 2014.

> appearance of a GPT may result in a short-term slowdown in economic growth as the economy adjusts.[45]

Brynjolfsson and McAfee summarize the relation between GPTs and economic growth:

> [The] benefits of [a GPT] start small while the technology is immature and not widely used, grow to be quite big as the GPT improves and propagates, then taper off as the improvement—and especially the propagation—die down. When multiple GPTs appear at the same time, or in a steady sequence, we sustain high rates of growth over a long period. But if there's a big gap between major innovations, economic growth will eventually peter out."[46]

The McKinsey Global Institute provides additional perspective:

> General-purpose technologies are . . . not only non-rival and long lasting, but their pervasiveness also makes them especially disruptive. . . . General-purpose technologies also tend to shift value to consumers, at least in the long run. This is because new technologies eventually give all players an opportunity to raise productivity, driving increased competition that leads to lower prices. General-purpose technologies can also enable—or spawn—more technologies. . . . General purpose technologies can take many forms—including materials, media, and new sources of energy—but they all share the ability to bring about transformative change.[47]

Josef Schumpeter's notion of "creative destruction," the ever-present churning of technologies and businesses, rested in large part on the displacement of traditional technologies by radically new ones. As we will see in a later section, GPTs have become an important underpinning for modern Schumpeterian (innovation-driven) growth theory.

In the table below, Lipsey, Carlaw, and Bekar identify 24 GPTs from the agricultural revolution forward. They note that newly emerging GPTs have not been "common in human experience, averaging between two and three per millennium over the last 10,000 years" and that the frequency of the emergence of GPTs has accelerated over time.[48] The more GPTs in existence, the faster new ones develop and diffuse.

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[45] Lipsey, Carlaw, and Bekar, Chapter 4: "Technology and Technological Change," *op.cit.*
[46] Brynjolfsson and McAfee, *op.cit.*, p. 78.
[47] Manyika et al., *op.cit*.
[48] Some economists think the pattern of recent GPT emergence is consistent with Kondratieff long wave theory—half-century periods of expansion, stagnation, and recession catalyzed by a critical mass of new technologies.

No.	GPT	Date[2]	Classification
1	Domestication of plants	9000–8000 BC	Pr
2	Domestication of animals	8500–7500 BC[3]	Pr
3	Smelting of ore	8000–7000 BC	Pr
4	Wheel	4000–3000 BC[4]	P
5	Writing	3400–3200 BC	Pr
6	Bronze	2800 BC	P
7	Iron	1200 BC	P
8	Waterwheel	Early medieval period	P
9	Three-masted sailing ship	15th century	P
10	Printing	16th century	Pr
11	Steam engine	Late 18th to early 19th century	P
12	Factory system	Late 18th to early 19th century	O
13	Railway	Mid 19th century	P
14	Iron steamship	Mid 19th century	P
15	Internal combustion engine	Late 19th century	P
16	Electricity	Late 19th century	P
17	Motor vehicle	20th century	P
18	Airplane	20th century	P
19	Mass production, continuous process, factory[5]	20th century	O
20	Computer	20th century	P
21	Lean production	20th century	O
22	Internet	20th century	P
23	Biotechnology	20th century	Pr
24	Nanotechnology[6]	Sometime in the 21st century	Pr

Note: P, product; Pr, process; O, organizational.

In a 2014 article, Bresnahan thinks that the definition of GPT should be broadened considerably beyond a few key historic instances to include those that are industry-wide but not economy-wide.[49] One implication of this view, he says, is the importance of mechanisms for coordinating between the GPT-generating firm and those firms in "application sectors" adapting the GPT for specific purposes. The social returns of invention, he says, depend on the flow of information from one to the other and back, which could be through licensing or other means. Gambardella and McGahan suggest that since the 1990s, a new business model has emerged in a number of industries in which firms intentionally develop a GPT that is made available for licensing to "downstream specialists" in applications sectors.[50]

[49] Timothy Bresnahan, "Chapter 18: General Purpose Technologies," in Bronwyn H. Hall and Nathan Rosenberg, eds., *Handbook of the Economics of Innovation, Volume 2*, Elsevier, 2014.
[50] Alfonso Gambardella and Anita M. McGahan, "Business-Model Innovation" General Purpose Technologies and their Implications for Industry Structure," *Long Range Planning*, No. 43, 2010, pp. 262-271.

Regarding the present, Brynjolfsson and McAfee deem digital technologies "the most general purpose of all" because of their application in every facet of human endeavor.[51]

<u>The Dynamics of Innovation</u>

This section explores economic historians' views of the factors that have enabled invention-driven economic growth.

Cardwell says that technology development progresses in the presence of five institutional factors:

- Beliefs and psychology that allow people to be receptive to new ideas and inventions.
- A modicum of individual freedom—to travel, learn, experiment, change jobs, and invent.
- Economic and social incentives to invent.
- A supply of skilled technicians and assistants and "suitable systems of education and training."
- Systematic experimental and development methods and close association between science and technology fields.[52]

Others add that economic and social incentives to invent require:

- the presence of intellectual property law, a trustworthy court system, and functional capital markets;
- the absence of punishment for inventions that government and religious authorities might find threatening; and
- the absence of "rent-seekers," elites who focus on extracting the value generated by others.[53]

As a corollary, Aghion et al. indicate, radical inventions and GPTs tend to develop in response to the market incentives in nations on the technological frontier.[54]

The development of the First and Second Industrial Revolutions are consistent with these views. In addition to the historical and cultural factors noted earlier, the First Industrial Revolution began in Britain in response to high wages, cheap energy, sizable markets, and attractive rates of return on investing in new technologies. Similarly, technology leadership moved to the U.S. in the late 19th century as a result of that country's market size, land

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[51] Brynjolfsson and McAfee, *op.cit.*, p. 79.
[52] Donald Cardwell, *Wheels, Clocks, and Rockets*, New York: W.W. Norton & Co., 1995.
[53] Daron Acemoglu and James A. Robinson, *Why Nations Fail: The Origins of Power, Prosperity, and Poverty*, New York: Crown Business, 2012.
[54] Aghion, Akcigit, and Howitt, *op.cit.*

abundance, natural resource wealth, high wages, cheap energy, flexible labor markets, and, again, very attractive rates of return on investing in R&D and new technologies.

In a complementary analysis, Steven Johnson distills the results of an extensive review of historical, sociological, and biological literature into patterns that encourage innovative thinking, "where good ideas come from."[55] He says that invention is not a linear, formulaic process of isolated actors but rather a messy, chaotic, and uncertain one of substantial interactions. His overarching thesis is this:

> If there is a single maxim that runs through this book's arguments, it is that we are often better served by *connecting* ideas than we are by protecting them. Like the free market itself, the case for restricting the flow of innovation has long been buttressed by appeals to the "natural" order of things. But the truth is, when one looks at innovation in nature and in culture, environments that build walls around good ideas tend to be less innovative in the long run than more open-ended environments. Good ideas may not want to be free, but they do want to connect, fuse, recombine. They want to reinvent themselves by crossing conceptual borders. They want to complete each other as much as they want to compete.[56]

In looking at history, Johnson identifies seven patterns that serve as the basis for a healthy innovation ecosystem:

- <u>The Adjacent Possible</u> – Innovation builds on available material from surroundings. Good ideas emerge through novel recombinations and adaptations of "the parts and skills around them. . . . The adjacent possible is a kind of shadow future . . . a map of all the ways in which the present can reinvent itself. . . . The . . . truth about the adjacent possible is that its boundaries grow as you explore those boundaries. Each new combination ushers new combinations into the adjacent possible."
- <u>Liquid Networks</u> – Good ideas are more likely to emerge out of networks that are densely populated (e.g., cities, industry clusters) and are plastic or liquid, that is, "capable of adopting new configurations." "[H]igh-density liquid networks make it easier for innovation to happen, but they also serve the essential function of *storing* those innovations." A market-based economy is more innovative than a centrally-managed one because it "distributes decision-making authority across a much larger network of individual minds. . . . [I]ndividuals get smarter because they are connected to a network." Networks need to "strike the right balance between order and chaos." In 17th and 18th century England, coffeehouses and the Royal Society of London for Improving Natural Knowledge played very important roles in hosting

[55] Steven Johnson, *Where Good Ideas Come From: The Natural History of Innovation*, New York: Riverhead, 2010.
[56] A number of observers have noted that the State of California's ban on a non-compete clause in employment agreements has greatly facilitated the flow of knowledge between firms, resulting in innovation that all benefit from. See, for instance, Sharon Weinbar, "The Power of a Fluid Market: Employee Mobility Makes Silicon Valley Flow: The role of a non-compete in building a business," Scale Venture Partners website, March 19, 2013.

liquid networks that spawned a myriad of innovations, including Newton's *Principia.* In Britain and the U.S., a multitude of industry-specific agglomerations arose to provide the liquid local networks that facilitated innovation. (See box for further discussion.)

Historical Views on the Roles of Networks in Invention

For some time, it has been well understood that geographic agglomerations of industry enable the liquid networks necessary for innovation. Alfred Marshall's *Principles of Economics* (1890) and the Census Bureau's *1900 Census of Manufactures* are quite clear on the matter. More recently, emphasis on the importance of industry clusters was renewed by Michael Porter and Annalee Saxenian in the 1990s. Since then, a substantial amount of literature has appeared on the subject.[57]

University of Montreal Professor Leonard Dudley shows the historical importance of local networks in the following map. According to Dudley, a regional intercity network in each of three nations (Britain, France, and the U.S.) accounted for 74 percent of the 117 recognized technological innovations developed between 1700 and 1849.[58]

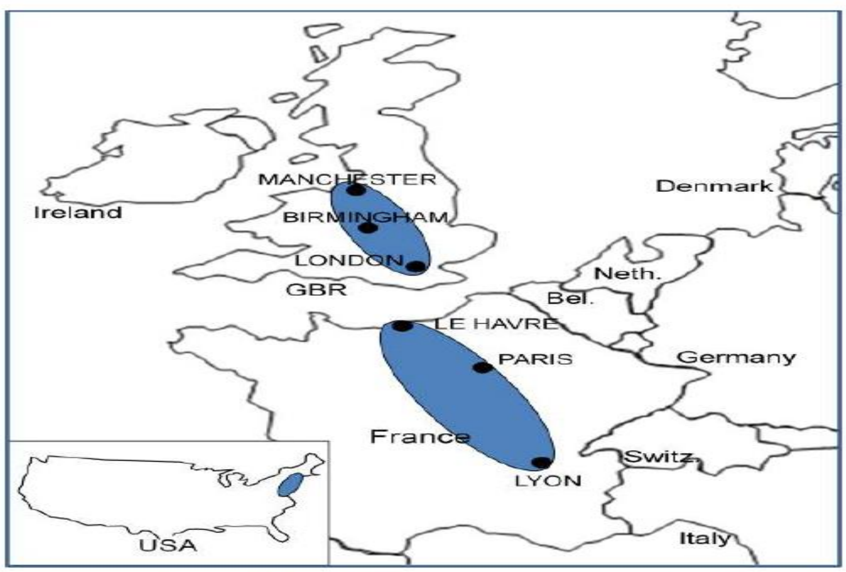


Figure 2. Areas of high innovation density, 1700-1849

[57] Hal Wolman and Diana Hincapie, "Clusters and Cluster-Based Development: A Literature Review and Policy Discussion," working paper, George Washington University, December 2010. Rainer von Hofe and Ke Chen, "Whither or Not Industrial Cluster: Conclusions or Confusions?," *The Industrial Geographer*, Volume 4, issue 1, 2006, p. 2-28. Joseph Cortright, "Making Sense of Clusters: Regional Competitiveness and Economic Development," Brookings Institution Metropolitan Policy Program, March 2006.

[58] Leonard Dudley, "Necessity's Children?: The Inventions of the Industrial Revolution," presented at the annual meeting of the Economic History Association, Washington, DC, September 30, 2013.

- The Slow Hunch – Typically, good ideas start out in a "partial, incomplete form. They have the seeds of something profound, but they lack a key element that can turn the hunch into something truly powerful. And more often than not, that missing element is somewhere else, living as another hunch in another person's head." A productive innovation ecosystem provides the space, patience, and opportunity for initial hunches to come to fruition. "Liquid networks create an environment where those partial ideas can connect; they provide a kind of dating service for promising hunches. They make it easier to disseminate good ideas, of course, but they also do something more sublime: they help *complete* ideas."
- Serendipity – "The hunch requires an environment where surprising new connections can be forged . . . . The challenge, of course, is how to create environments that foster these serendipitous connections, on all appropriate scales: in the private space of your own mind; within larger institutions; and across the information networks of society itself. . . . [S]ecrecy . . . comes at great cost. Protecting ideas from copycats and competitors also protects them from other ideas that might improve them, might transform them from hints and hunches to true innovations." Johnson notes that the "Web is an unrivaled medium for serendipity if you are actively seeking it out."
- Error – "[G]ood ideas are more likely to emerge in environments that contain a certain amount of noise and error. . . . [N]oise-free environments end up being too sterile and predictable in their output." The opportunity to make mistakes increases the likelihood of innovation. Mistakes can help creators complete slow hunches. The quantity of experimentation leads to quality. "Error often creates a path that leads you out of your comfortable assumptions. . . . Being wrong forces you to explore."
- Exaptation – Exaptation is "*borrowing* a mature technology from an entirely different field, and putting it to work to solve an unrelated problem." The printing press, computer punch cards, and the guitar amplifier are examples of innovative exaptations. The opportunity to borrow a technology for a new purpose is very much a function of the thickness and diversity of networks.
  - Cities, with their mixture of industries and disciplines, have shown themselves to be fertile ground for exaptation.
  - A Stanford Business School study determined that the technological innovativeness of the school's graduates was highly correlated with their social networks: "[T]he most creative individuals . . . consistently had broad social networks that extended outside their organization and involved people from diverse fields of expertise. Diverse, horizontal social networks . . . were *three times* more innovative than uniform, vertical networks. In groups united by shared values and long-term familiarity, conformity and convention tended to dampen any potential creative sparks. . . . [E]ntrepreneurs who built bridges

outside their "islands" . . . were able to borrow or co-opt new ideas from these external environments and put them to use in a new context. . . ."

  - "Many of history's great innovators managed to build a cross-disciplinary coffeehouse environment within their own private work routines. . . . Chance favors the connected mind."[59]

- Platforms – Platforms contribute to innovative activity in three senses. One is providing a physical or electronic place for people to meet, such as a coffeehouse, a cafeteria, a business incubator, or an online discussion room. Second is cultural, technical, or electronic framework for further action, such as a musical genre, a scientific paradigm, or an application programming interface (API). Third is previous innovations like the invention of the trumpet (if one is Miles Davis) or the HTTP protocol (if one is building a website).

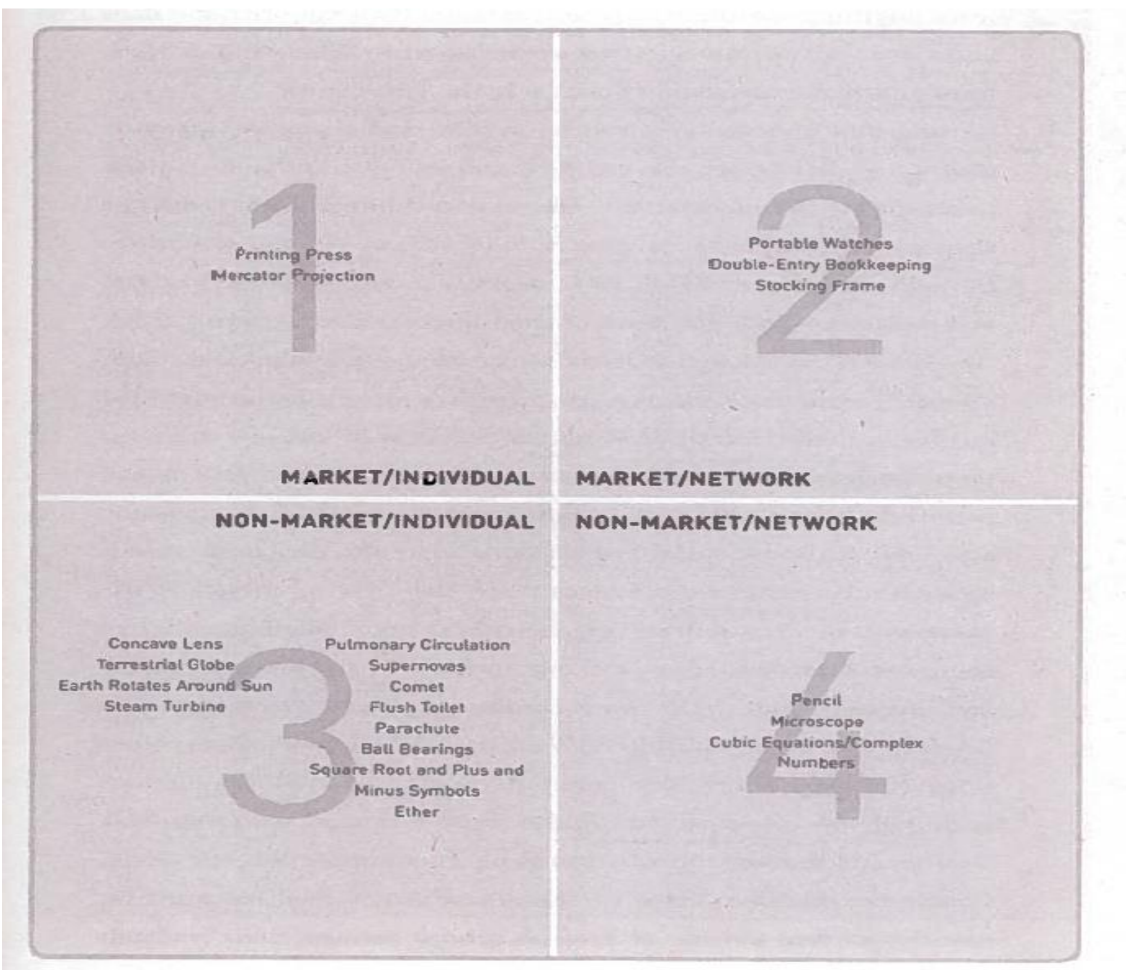
Seeking to visually see the patterns by which innovations have emerged historically, Johnson classifies each major innovation between 1400 and the present in terms of development by an individual or network and the role of the profit motive, as so:

[59] Brynjolfsson and McAfee cite research that says problem-solving is facilitated by the involvement of "people whose expertise was far away from the apparent domain of the problem . . . . [I]t actually seemed to help a solver to be 'marginal'—to have education, training, and experience that were not obviously relevant to the problem." *Ibid.*, p. 84.

Definitions:

- Individual: "[I]nnovations that involved a small, coordinated team within an organization" or a single inventor.
- Networked: "all innovations that evolved through collective, distributive processes, with a large number of groups working on the same problem.
- Market: "Inventors who planned to capitalize directly from the sale or licensing of their invention . . . ."
- Non-market: "[t]hose who wished their ideas to flow freely into the infosphere."
- Quadrant 1: "the private corporation or solo entrepreneur"
- Quadrant 2: "a marketplace where multiple private firms interact"
- Quadrant 3: "the amateur scientist or hobbyist who shares his or her ideas freely"
- Quadrant 4: "open-source or academic environments, where ideas can be built upon and reimagined in large, collaborative networks.

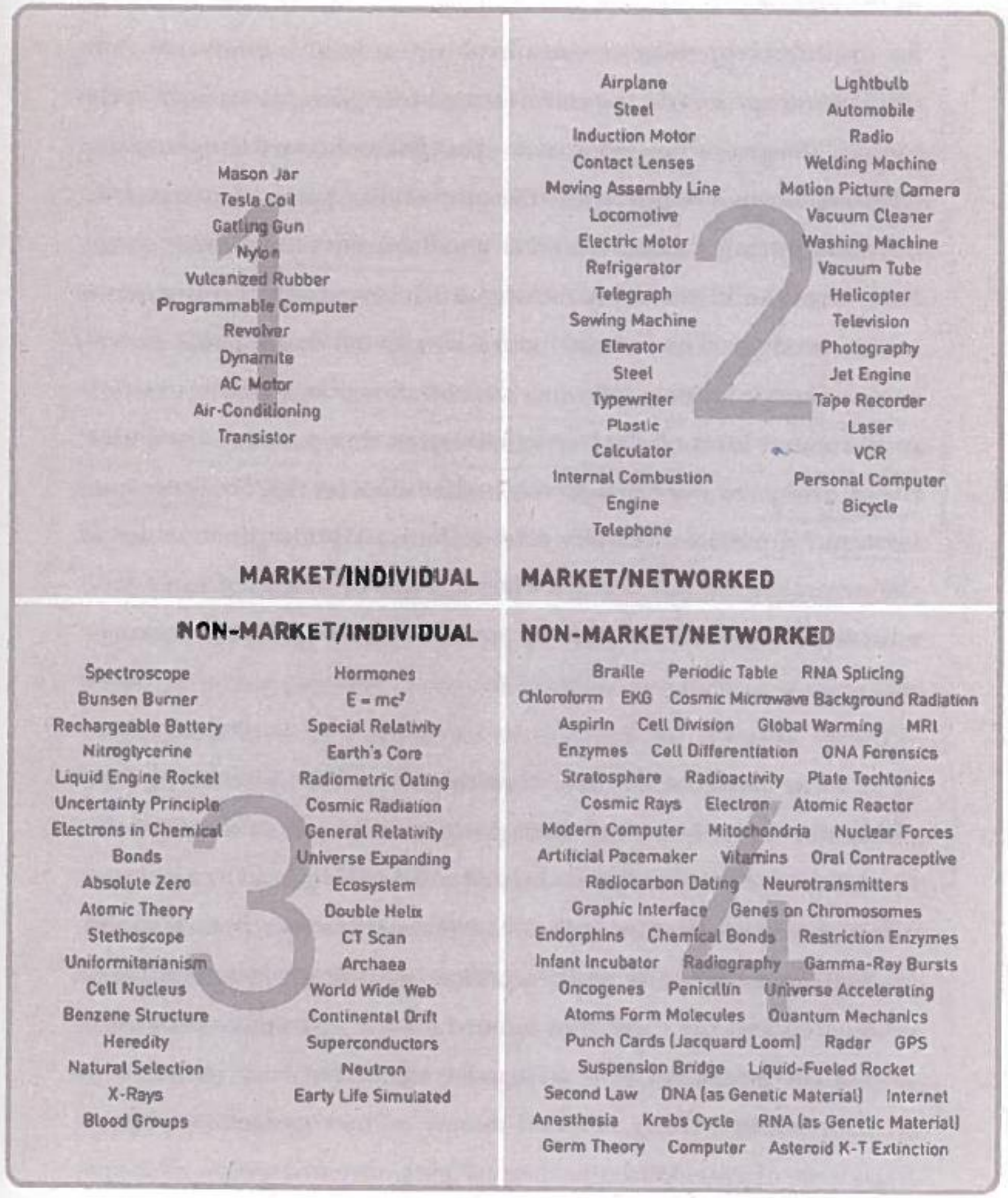
Johnson's findings for three two-hundred year periods are as follows:



1400–1600


1
Pressure Cooker
Manned Hot Air Balloon
Lithography
2
Chronometer
Balance Spring Watches
Steam Engine
Steamboat
Spinning Jenny
Power Loom
Cotton Gin
MARKET/INDIVIDUAL
MARKET/NETWORKED
NON-MARKET/INDIVIDUAL
NON-MARKET/NETWORKED
3
Magnetism (Planetary)
Speed of Light
Piano
Tuning Fork
Mercury Thermometer
Octant
Carbonated Water
Hooke's Law
Law of Falling Bodies
Elliptical Orbits of Planets
Moons of Jupiter
Microorganisms
Laws of Motion
Comet Orbits
Lightning Rods
Bifocal Lenses
Plant Respiration
Logarithms
Blood Circulation
Vernier Scale
Analytic Geometry
4
Vacuum Pump
Pendulum Clock
Boyle's Law
Light Spectrum
Calculus
Universal Gravitation
Flintlock
Telescope
Linnaean Taxonomy
Discovery of Oxygen
Photosynthesis
Milky Way
Hot Air Balloon
Smallpox Vaccine
Sunspots
Slide Rule
Mechanical Calculator
Ocean Tides
Barometer

1600–1800



1800–present

We can see several patterns from these diagrams.

- First, as we know, the number of innovations has grown dramatically with time.
- Second, the emphasis has shifted from innovations developed by individuals to those created through networks.
- Third, the majority of innovations have developed apart from the marketplace.

Johnson believes that a healthy innovation ecosystem requires a vibrant fourth quadrant:

> All of the patterns of innovation we observed . . . do best in open environments where ideas flow in unregulated channels. In more controlled environments, where the natural movement of ideas is tightly restrained, they suffocate. . . . All other things being equal, financial incentives indeed will spur innovation. The problem is, all other things are *never* equal. When you introduce financial rewards into a system, barricades and secrecy emerge, making it harder for the open patterns of innovation to work their magic. So the question is: What is the right balance? . . .
>
> [M]ost of the paradigmatic ideas in science and technology that arose during the past century have roots in academic research. . . . [O]pen networks of academic researchers often create emergent platforms where commercial development becomes possible. . . . [F]ourth-quadrant innovation creates a new open platform that commercial entities can then build upon, either by repackaging and refining the original breakthrough, or by developing emergent innovations on top of the underlying platform.

On the other side of invention, Brynjolfsson and McAfee note, consistent with the GPT framework, that there can be a significant time lag between an invention's development and the realization of its benefits to society. They extend that framework by indicating that in many instances, impact depends on changes in business practices and organizational structures.

> GPTs always need complements. Coming up with those can take years, or even decades, and this creates lags between the introduction of a technology and the productivity benefits. We've clearly seen this with both electricity and computerization. Perhaps the most important complementary innovations are the business process changes and organizational coinventions that new technologies make possible.[60]

Their examples include:

- Once electricity replaced steam power, it took 30 years for factory layouts to be redesigned to take full advantage of the "natural workflow of materials." Afterwards, "[p]roductivity didn't merely inch upward on the resulting assembly lines; it doubled or even tripled."[61]
- "[T]he large enterprise-wide IT systems that companies rolled out in the 1990s [made] possible a wave of business process redesign. . . . The real key was the introduction of complementary process innovations like vendor managed inventory, cross-docking, and efficient consumer response . . . . They . . . helped drive dramatic increases in the entire retailing and distribution industries, accounting for much of the additional productivity growth during this period."[62]

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[60] *Ibid.*, p. 102.
[61] *Ibid.*, p. 103.
[62] *Ibid.*

The Spread of the Bounty of Invention – Once Wide, Now Less So

Historically, the economic benefits of the First and Second Industrial Revolutions were widely spread. While some inventions, particularly in agriculture, led to substantial displacement, others created large-scale employment opportunities in manufacturing that more than compensated. The majority of workers were able to reap the benefits of greater productivity and living standards rose dramatically.

As the graphs in the front of this section suggest, it appears that the distribution in the U.S. of the economic bounty of the second machine age is different—the owners of capital and unique skills are accruing the large majority of benefits. Because of innovation, opportunities for others to maintain their income, let alone increase it, has declined. Inequality has grown significantly. According to Brynjolfsson and McAfee:

> [T]he data are quite clear that many people in the United States and elsewhere are losing ground over time, not just relative to others but in absolute terms. In America, the income of the median worker is lower in real dollars than it was in 1999 and the story largely repeats itself when we look at households instead of individual workers, or total wealth instead of annual income. Many people are falling behind as technology races ahead."[63]

The authors note that a good argument can be made that the average person has gained substantial benefits from invention, particularly in the realms of information, communication, media, and computation, which are not easily reflected in income or wealth. At the same time, the costs of housing, health care, and postsecondary education have gone up significantly. The availability of well-paying jobs for those without unique skills has declined as technology has enabled the movement of jobs off-shore as well as replaced workers with machines. With workers facing a weaker job market, employers have dramatically changed their policies with regard to job tenure, full-time work, pensions, and health care coverage.

Ironically, they note, greater inequality decreases the likelihood of invention and widespread benefits. Fewer workers with valued skills means fewer potential inventors. And fewer households with decent incomes means that markets for many newly invented goods and services are circumscribed.

Recent history suggests, then, that it is a mistake to assume that invention automatically leads to a better society for the large majority even as it might raise GDP. While the connection was largely true in the past, it has not been so of late and may not necessarily be so in the future. The outcomes depend very much on the policy choices made by our governing institutions, which are determined in large part in a democracy by public sentiment. In other words, we need institutional inventions that improve the odds the majority of households can reap the benefits of invention.

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[63] *Ibid.*, p. 168.

III. Innovation Accounting

Introduction

The National Economic Accounts were first developed during the Great Depression as a means of collecting, organizing, and analyzing data that represent the comprehensive operation of the nation's total economy. Based on these accounts, Gross National Product, an estimate of the nation's economic activity, was invented in 1942.

Economic accounting practice has traditionally linked inputs of capital and labor to the output of consumption, investment, net exports, and government output in the context of the circular flow of products and payments. No explicit account was taken of the innovations in technology and the organization of production that led either to a greater quantity of output from a given base of inputs or improvements in the quality of the inputs and outputs.[64]

Although economic accounting was not designed to determine the origins of growth, in the 1950s economist Robert Solow developed a methodology for growth accounting, "to measure the contribution of different factors to economic growth and to indirectly compute the rate of technological progress, measured as a residual, in an economy."[65] This residual was termed "total factor productivity" (TFP). "The problem with this approach to innovation accounting is that TFP is typically measured as a residual, a fact that has earned it the name 'the measure of our ignorance.' Moreover, because TFP is a partial indicator of innovation outcomes, it is not a complete basis for innovation accounting itself. . . ."[66]

Recent Progress in Including Innovation in National Economic Accounts

In 2008, the U.S. Bureau of Economic Analysis decided to include certain types of R&D expenditures in the national accounts, a useful but insufficient step forward for understanding the sources of economic growth. In the last few years, several economists, particularly Carol Corrado and Charles Hulten, have sought to devise an alternative approach that more fully identifies all major sources of growth. In 2012 (revised in 2013), Corrado and Hulten published a paper that "describes some of the steps involved in building a more comprehensive national innovation account as a satellite to the main national accounting framework." A comprehensive innovation account would cover investment ("capital deepening") in knowledge-based capital, including computerized information (software, databases), innovative property (such as R&D, mineral exploration, and artistic originals), and economic competencies (brand equity, worker training, organizational structure).

> The reallocation of resources between efficient and inefficient firms is also a source of aggregate efficiency gain . . . . Empirical research has shown that this is an

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[64] Carol A. Corrado and Charles R. Hulten, "Innovation Accounting," July 25, 2012 (revised August 1, 2013), pp. 2-3.
[65] "Growth Accounting," Wikipedia, accessed December 29, 2013.
[66] Corrado and Hulten *op.cit.*

important effect (Foster et. al. (2001)), particularly when the reallocation is due to young rapidly growing innovators displacing incumbent firms. Reallocation also has an important international dimension, and innovators in the U.S. and Europe outsource the production segment of the international value chain to foreign countries. A complete innovation [accounting] would thus involve both a domestic industry and firm level of detail, as well as a global dimension.

Currently available data are not sufficient for constructing a complete, accurate innovation account. On the basis of available statistics, Corrado and Hulten produced the following table to show the best understanding of the sources of economic growth.

Table 3. Sources of Growth in U.S. Private Industry Output per Hour, Including Intangibles, 1980 to 2011

	1980-2011 (1)	1980-1990 (2)	1990-2001 (3)	2001-2007 (4)	2007-2011 (5)
1. Output per hour	2.25	2.20	2.58	2.24	1.44
Contribution of:					
2. Capital deepening	1.18	.96	1.38	1.13	1.27
3. Tangible[1]	.53	.40	.70	.45	.49
4. Intangible	.66	.56	.69	.68	.77
a. Computerized information	.17	.12	.23	.15	.16
b. Innovative property	.25	.26	.19	.25	.42
c. Economic competencies	.23	.18	.26	.27	.19
5. Labor composition	.29	.31	.32	.19	.34
6. TFP	.77	.94	.88	.92	-.16
Memos—Percent of Line 1 explained by:					
7. Intangible capital deepening	27.0[2]	25.5	26.6	30.3	---
8. Total capital deepening	49.5[2]	43.6	53.6	50.7	---
9. TFP	38.5[2]	42.5	34.1	41.0	---
10. Total capital deepening *without* new intangibles[3]	36.7[2]	30.8	41.8	35.1	---
11. TFP *without* new intangibles	49.8[2]	53.3	44.6	55.3	---

Notes—Private industry excludes education, health, and real estate. Figures are annualized percent change calculated from natural log differences. Contributions are in percentage points and independently rounded. Column 2, 3, and 4 periods are between years with business cycle peaks as defined by the NBER.

Source—Elaboration of output, hours, and fixed asset data from BEA; labor composition index is from BLS. Estimates of intangibles not capitalized in the U.S. national accounts as of May 2013 are based on data from BEA (R&D and entertainment and artistic originals) and INTAN-Invest (2012).

1. Excludes land (but includes inventories).

2. Calculated from 1980 to 2007.

The table indicates that:

- about half of average annual growth in U.S. output per hour between 1980 and 2007 was due to capital deepening, that is, investment in tangible (e.g., equipment) and intangible capital;
- about 39 percent (the residual, TFP) can be attributed to the direct impacts of product and process innovation; and
- the remainder is due to improvement in labor composition, that is, increases in skills, education, and experience.

Each of these sources of growth can be attributed, directly or indirectly, to innovation. Between 1980 and 2007, annual average growth in private industry output per hour was 2.25 percent, of which 1.18 percent is attributable to capital deepening, 0.77 percent to TFP, and 0.29 percent to improvements in labor composition.

In their various works, Corrado and Hulten say that substantial improvements in economic data collection will be required to obtain a more complete and accurate accounting of the sources of economic growth. Of particular interest are improved data on investment in intangibles, the output or benefits of knowledge-based capital investments, and prices adjusted for changes in quality due to innovation. While much progress has been made in estimating additions to GDP due to improved quality, it is a highly inexact science.

Towards A New Measure of the Role of Invention in Economic Growth

In fact, the second machine age increasingly is generating economic activity and growth in dimensions that not readily captured by traditional GDP or the Corrado-Hulten innovation account. In essence, the problem is that while GDP measures the market value of produced goods and services, more and more goods and services have value to consumers far and above the value assigned by market price. Examples include:

- The explosion of free products—such as Wikipedia, Craigslist, Skype, and Google—improve the consumer experience, but reduce GDP by replacing paid products.
- The personal value derived by consumers from spending millions of hours on zero-wage, zero-price activities such as using Facebook and social media.
- Increased buying choices, e.g., instant access to millions of distinct goods on Amazon.
- Reduced search and transaction costs for goods and services.
- Greater consumer satisfaction due to improved decision-making based on crowd-sourced ratings of specific goods and services.
- User-generated content, e.g., the 43,200 hours of videos uploaded to YouTube and the 250 million photographs uploaded to Facebook every day.[67]

[67] Brynjolfsson and McAfee, *op.cit.*, pp. 111-120.

To this list, Joseph Stiglitz adds:

> Any good measure of how well we are doing must also take account of sustainability. Just as a firm needs to measure the depreciation of its capital, so, too, our national accounts need to reflect the depletion of natural resources and the degradation of our environment. . . .
>
> Recent methodological advances have enabled us to assess better what contributes to citizens' sense of well-being, and to gather the data needed to make such assessments on a regular basis. These studies, for instance, verify and quantify what should be obvious: the loss of a job has a greater impact than can be accounted for just by the loss of income. They also demonstrate the importance of social connectedness.[68]

As noted in this paper's introduction, Hanauer and Beinhocker have proposed a definition of economic prosperity as "the accumulation of solutions to human problems." Based on this perspective, the authors call for a new approach to tracking economic growth, one based on measuring a "basket of solutions" to human problems rather than the value of economic production. Such an approach cover the no-cost activities list above.

> If the true measure of the prosperity of a society is the availability of solutions to human problems, then growth cannot simply be measured by changes in GDP. Rather, *growth must be a measure of the rate at which new solutions to human problems become available*. Additionally, since problems differ in importance, a new view of growth also must take this into account; finding a universal flu vaccine is more important than creating a crunchier potato chip. But in general, economic growth is the actual experience of having one's life improved. . . . .
>
> This all implies that we must find new ways to measure progress. In the same way that no good doctor would measure the health of a person by just one factor—her temperature, say—the economy shouldn't be measured with just GDP. No single metric such as GDP can capture the way in which economic activity is actually improving the lives of most citizens and the overall health of the economy.
>
> It is not immediately obvious how the rate at which a society solves people's problems might be directly measured. However, there might be ways to do it indirectly. For example, we measure inflation by tracking the price of a basket of goods. What about measuring access to a "basket of solutions" to human problems? How many people have access to good nutrition, health care, education, housing, transportation, a clean environment, information, communications, and other things that make a tangible impact on the quality of life? We could also ask how the basket itself is changing over time as innovation yields new solutions—for example, solving the problem of getting information has dramatically improved with the development

[68] Joseph Stiglitz, "GDP Fetishism," *Project Syndicate* website, September 7, 2009.

> of the Web and smartphones. Growth and prosperity could then be measured as a combination of access to existing solutions and the addition of new solutions through innovations.[69]

While the Hanauer-Beinhocker measure is not currently available, Brynjolfsson and McAfee suggest that "the biggest opportunity [in creating new metrics of economic growth] is in using the tools of the second machine age itself: the extraordinary volume, variety, and timeliness of the data available digitally."[70] Economist Joseph Stiglitz adds:

> The fact that GDP may be a poor measure of well-being, or even of market activity, has, of course, long been recognized. But changes in society and the economy may have heightened the problems, at the same time that advances in economics and statistical techniques may have provided opportunities to improve our metrics. . . .[71]

[69] Hanauer and Beinhocker, *op.cit.*, pp. 35-36.
[70] Brynjolfsson and McAfee, op.cit., p. 123.
[71] Stiglitz, *op.cit.*

IV. Macroeconometric Analysis: Effect of R&D Expenditures on Growth

In 2012, Italian economist Mario Coccia carried out a thorough review of academic literature regarding the statistical correlation between R&D expenditures and various manifestations of economic growth, including GDP, total factor productivity (TFP), and labor productivity.[72] He then followed up with additional statistical analysis. His findings can be summarized as follows:

- For advanced nations, the literature consistently shows a positive correlation between R&D intensity (usually measured as a percent of GDP or R&D per capita) and various measures of economic growth, including GDP, TFP, and labor productivity. Coccia notes that a recent analysis of 65 countries over the 1965-2005 period indicates that "a 10% increase in R&D per capita generates an average increase of about 1.6% in the long-run TFP." In summary, he says: "Trends of these [advanced] countries show the strategic role of R&D intensity that is considered as one of the most important determinants for supporting long-term economic growth, well- being and welfare of nations."
- Coccia then says that "The level of R&D intensity is a necessary but not sufficient condition to support patterns of economic growth." Also important is the allocation of R&D resources between the public and the private sectors. Specifically:
    - The level of private R&D expenditures has a stronger impact on economic growth than does the level of public R&D expenditures. In advanced countries, the level of private R&D expenditures can explain 63 percent of trends in labor productivity. "[T]he empirical evidence shows, at spatial and temporal levels, that R&D intensity should be driven mainly by the business enterprise sector in order to spur labor productivity growth . . . ."
    - At the same time, the level of private R&D expenditures is very much positively influenced by the level of public R&D expenditure. The correlation between public R&D and private R&D is 77 percent. "Results suggest that current market forces in efficient national systems of innovation, governed by fruitful university, industry and government linkages (Triple Helix), should support R&D intensity by business enterprise sector and, as a consequence, labor productivity growth."
    - He provides a diagram that seems to suggest that the desirable ratio between public and private R&D expenditures is 1:2.

Coccia's finding of the positive impact of public R&D on private R&D is consistent with Steven Johnson's emphasis on the importance of the "fourth quadrant."

Charts on advanced nation R&D intensity and labor productivity are provided below. Note the relative positive position of the U.S. According to the National Science Foundation, in 2012 industry accounted for 63 percent of U.S. R&D expenditures and the federal and other

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[72] Mario Coccia, "Political economy of R&D to support the modern competitiveness of nations and determinants of economic optimization and inertia," *Technovation* 32(6): 370-379, June 2012.

governments and nonprofits accounted for 37 percent. These numbers are in line with Coccia's ratio.

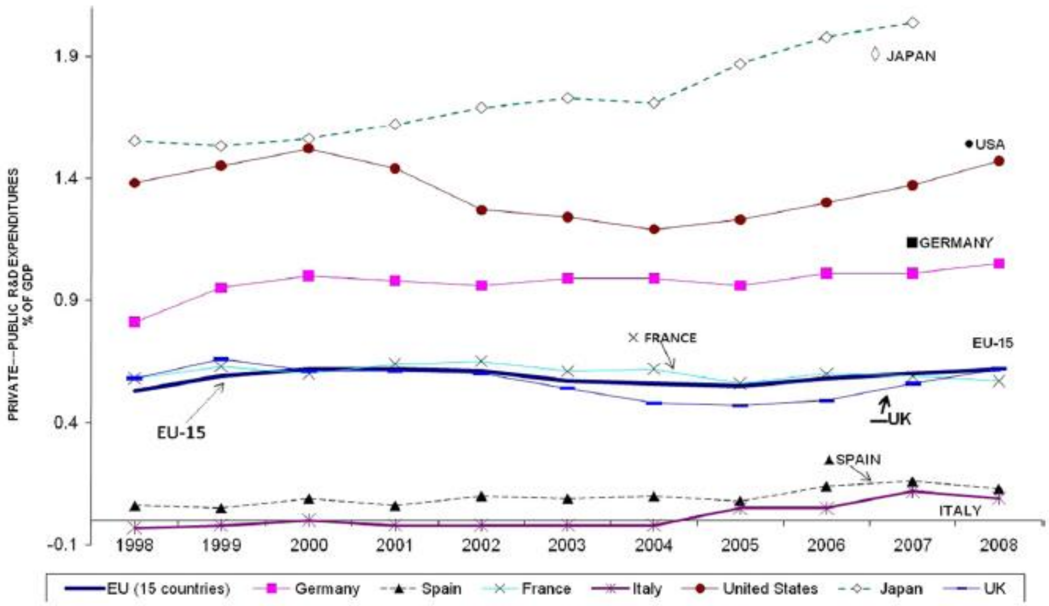

Fig. 1. Private minus public R&D expenditures over time per country.

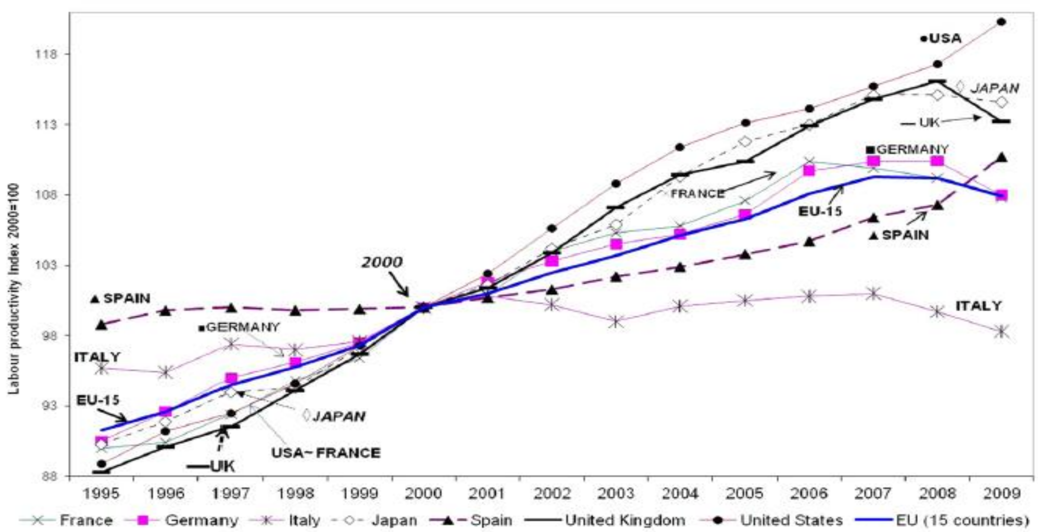

Fig. 2. Labor productivity index 2000 = 100 over time per country.
Source: OECD (2011b) *Labor Force Statistics and national sources*, OECD Productivity database; http://www.oecd.org/ (accessed November, 2011).

V. Microeconometric Analysis

In the last several decades, numerous studies have analyzed differences between high and low-technology-based firms in terms of firm size, firm survival, job multiplier effects, percentage change in average number of jobs, product introduction and innovation, and job type. In general, these studies find that high-tech firms (defined as ones that spend more on R&D) have more positive outcomes. For example:

- German high-tech firms were more likely to generate new products, an important dimension of economic growth.[73]
- U.S. and Swedish high-tech firms tended to have greater multiplier effects because they were more likely to hire workers with more skills and education, leading them to earn more.[74]
- German high-tech firms experienced a statistically significant greater change in average employment size in comparison to low-technology firms (10.5 percent vs. 8.4 percent over seven years) and were more likely to survive longer (14.0 percent remain vs. 12.4 percent).[75]

Among the literature reviewed, the most comprehensive and nuanced is an analysis by Italian economists Rinaldo Evangelista and Antonio Vezzani of firm-level data in the fourth EU Community innovation Survey (reference period 2002-2004).[76] Evangelista and Vezzani examine the effects of three types of innovation—product, process, and organizational—on firm outcomes. Their findings:

- "The evidence presented shows . . . that all types of innovation end up affecting employment in an indirect way, that is improving the competitive performance of firms (growth of sales), which in turn creates room for generating new jobs. The employment effects of innovation activities do differ according to the underlying strategy pursued by firms. . . .
- [I]nnovation strategies characterized by the combination of product, process and organizational innovations show the strongest employment impact, in both manufacturing and services industries. . . .

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[73] Eva Kirner, Steffen Kinkel, and Angela Jaeger, "Innovation paths and the innovation performance of low-technology firms- An empirical analysis of German industry," *Research Policy*, 38(3): 447-458, April 2009.

[74] John Abowd, John Haltiwanger, Julia Lane, Kevin McKinney, and Kristin Sandusky, "Technology and the demand for skill: An analysis of within and between firm differences," NBER Working paper: #13043, April 2007; and Enrico Moretti and Per Thulin, "Local multipliers and human capital in the United States and Sweden," *Industrial and Corporate Change*, 22(1): 339-362, February 2013.

[75] Matthias Almus and Eric A. Nerlinger, "Growth of new technology-based firms: Which factors matter?," *Small Business Economics*, 13(2): 141-154, September 1999.

[76] Rinaldo Evangelista and Antonio Vezzani, "The impact of technological and organizational innovations on employment in European firms," *Industrial and Corporate Change*, 21(4): 871–899, August 2012.

- [E]mployment growth is also associated . . . with the adoption of stand-alone organizational innovations. . . .
- [N]egative direct effects of process innovations have been found only in the manufacturing industry and only when process innovations are combined with organizational changes . . . .
- [J]ob losses are concentrated among noninnovating firms. This seems to be a reasonable hypothesis, taking into account that in sectors dominated by process oriented innovation strategies, competition and selection mechanisms are rather severe with noninnovating firms likely to pay a high price also in terms of employment growth (losses)."

Evangelista and Vezzani's findings about the value of the combination of types of innovations is consistent with the general tenor of Steven Johnson's observation that complex, nuanced sets of innovations are more likely to be productive than are stand-alone innovations developed in closed environments. Their findings also align with those of Brynjolfsson and McAfee regarding the need for complementary innovations in business processes and organizational structure to fully capture the revenue and profit benefits of technological innovations.

VI. Economic Theory and Models

Neoclassical economic theory and models traditionally have ignored technological change. This was initially so in part because the assumptions of the neoclassical model leave no room for invention—there is neither imperfect information nor uncertainty to act on.[77] In addition, economists did not have the necessary knowledge and techniques. . While in recent years neoclassical models have paid more attention to innovation, they continue to make it exogenous (that is, not explained by the model), underplay and simplify it, and instead focus on fiscal and monetary policy for business stability and the importance of free and lightly regulated markets for optimal economic outcomes.

At the same time, an increasingly sophisticated alternative approach has emerged, Schumpeterian growth theory. This theory is constructed around Schumpeter's famous observation about "creative destruction," innovation-driven industrial restructuring as the catalyst for economic growth.

Recently, economists Phillippe Aghion, Ufuk Akcigit, and Peter Howitt published the most comprehensive articulation and testing of Schumpeterian growth theory to date.[78] They begin by saying:

> This model is Schumpeterian in that: (i) it is about growth generated by innovations; (ii) innovations result from entrepreneurial investments that are themselves motivated by the prospects of monopoly rents; and (iii) new innovations replace old technologies: in other words, growth involves creative destruction.

Their key findings:

- Faster innovation-led growth is generally associated with higher turnover rates, i.e. higher rates of creation and destruction, of firms and jobs.
- "Innovation and productivity growth by incumbent firms appear to be stimulated by competition and entry" of new firms, particularly in sectors near the "technology frontier."
- "Patent protection complements product market competition in encouraging R&D investments and innovation."
- Liberalized trade stimulates innovation by promoting competition and by increasing the market for successful innovations.
- "[L]arge incumbents focus on improving the existing technologies whereas small new entrants focus on innovating with new radical products or technologies."
- Schumpeterian creative destruction is the basis for technological change and economic growth: "[T]he reallocation of resources among incumbents as well as from incumbents to new entrants are the major sources of productivity growth."

[77] Emil Malizia and Edward Feser, *Understanding Local Economic Development*, CUPR/Transaction, 1999.
[78] Aghion, Akcigit, and Howitt, *op.cit*.

- The economic growth in nations closer to the technology frontier is "driven by 'innovation-enhancing' rather than 'imitation-enhancing' policies or institutions."
- The closer a nation is to the technology frontier, the more its economic growth relies on research education.
- "GPTs are Schumpeterian in nature, as they typically lead to older technologies in all sectors of the economy to be abandoned as they diffuse to these sectors. . . . The diffusion of a new GPT is associated with an increase in the flow of firm entry and exit."
- The initial effect of the "positive technology shock" of a GPT may be to slow growth, not increase it. Also, "[T]he diffusion of a new GPT generates an increase in wage inequality both between and within educational groups."[79]
- Schumpeterian growth theory finds that public policies should "match the particular context of a country or region," not be the same everywhere.
- "'[E]xtractive economies' where creative destruction is deterred by political elites, are more likely to fall in low-growth traps."

Schumpeterian growth theory, we can see, integrates and is consistent with the findings of prior sections.

[79] These findings are consistent with those of Brynjolfsson and McAfee regarding the impacts of an introduction of a GPT on productivity and equality.

VII. Future Scenarios

As noted earlier, Brynjolfsson and McAfee assert that we are in a second machine age, one based on advanced electronic technologies that will, sooner than we think, transform our economy in remarkable and unexpected ways. They observe:

> Progress on some of the oldest and toughest challenges associated with computers, robots, and other digital gear was gradual for a long time. Then in the past few years it became sudden; digital gear started racing ahead, accomplishing tasks it had always been lousy at and displaying skills it was not supposed to acquire anytime soon.[80]

The examples they offer to support their conclusion include autonomous cars (pattern recognition), instantaneous translation (complex communications), IBM's *Jeopardy* computer champion Watson (pattern recognition + complex communications), robots that are mobile and dexterous, the ever-increasing breadth of smartphone functions, computer-generated prose, and additive manufacturing (3D printing). The overall result, they say, is that:

> [W]e're at an inflection point—a bend in the curve where many technologies that used to be found only in science fiction are becoming everyday reality. . . . The digital progress we've seen recently is certainly impressive, but it's just a small indication of what's to come. It's the dawn of the second machine age.[81]

Brynjolfsson and McAfee say that the emergence of the second machine age is based on three characteristics:

- Exponential technological progress—Consistent with Moore's Law, "[i]t's clear that many of the critical building blocks of computing—microchip density, processing speed, storage capacity, energy efficiency, download speed, and so on—have been improving at exponential rates for a long time."[82] Additional areas of exponential technological improvements include sensors, cameras, machine vision. "[S]teady exponential improvement has brought us into . . . a time when what's come before is no longer a particularly reliable guide to what will happen next."[83]
- Digitization—"Digitization . . . is the work of turning all kinds of information and media—text, sounds, photos, video, data from instruments and sensors, and so on—into the ones and zeroes that are the native language of computers and their kin."[84] Because data cost so little to produce, we're experiencing a data explosion of exponential proportions. "This surge in digitization has had two profound

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[80] Brynjolfsson and McAfee, *op.cit.*, p.20.
[81] *Ibid.*, pp. 34 and 37.
[82] *Ibid.*, p. 49. In 1965, Gordon Moore observed that the capacities of integrated circuits was doubling every year and would continue to do so "for at least ten years."
[83] *Ibid.*, p. 55.
[84] *Ibid.*, p. 61.

consequences: new ways of acquiring knowledge (in other words, of doing science) and higher rates of innovation."[85]

- Recombination—Consistent with Johnson's notion of the adjacent possible, Brynjolfsson and McAfee say:

    > [T]he true work of innovation is not coming up with something big and new, but instead recombining things that already exist. . . .
    >
    > The GPT of ICT has given birth to radically new ways to combine and recombine ideas. Like language, printing, the library, or universal education, the global digital network fosters recombinant innovation. We can mix and remix ideas, both old and recent, in ways we never could before. . . .
    >
    > [D]igital innovation is recombinant innovation in its purest form. Each development becomes a building block for future innovations. Progress doesn't run out, it accumulates. . . . [T]he number of potentially valuable building blocks is exploding around the world, and the possibilities are multiplying as never before. We'll call this the 'innovation-as-building-block' view of the world . . . . [B]uilding blocks don't ever get eaten or otherwise used up. In fact, they increase the opportunities for future recombinations.[86]

They conclude:

> The advances we've seen in the past few years . . . are not the crowning achievements of the computer era. They're the warm-up acts. As we move deeper into the second machine age we'll see more and more such wonders, and they'll become more and more impressive.
>
> How can we be so sure? Because the exponential, digital, and recombinant powers of the second machine age have made it possible for humanity to create two of the most important one-time events in our history: the emergence of real, useful artificial intelligence (AI) and the connection of most of the people on the planet via a common digital framework.[87]

In May 2013, the McKinsey Global Institute (MGI) published "Disruptive technologies: Advances that will transform life, business, and the global economy." In this report, MGI sought to identify 12 rapidly advancing technologies with the potential to be disruptive (in the Christensen sense of the term) and have substantial economic impact.

> Today, we see many rapidly evolving, potentially transformative technologies on the horizon . . . . [W]e attempt to . . . identify the technologies that have the greatest

[85] *Ibid.*, pp. 62.
[86] *Ibid.*, pp. 78-81.
[87] *Ibid.*, p. 90.

potential to drive substantial economic impact and disruption by 2025 . . . . Important technologies can come in any field or emerge from any scientific discipline, but they share four characteristics: high rate of technology change, broad potential scope of impact, large economic value that could be affected, and substantial potential for disruptive economic impact.[88]

As can be seen from the list below, the first nine of the 12 are digital technologies and the development of the other three certainly depend on digital technologies.

Exhibit E1

Twelve potentially economically disruptive technologies

Mobile Internet	Increasingly inexpensive and capable mobile computing devices and Internet connectivity
Automation of knowledge work	Intelligent software systems that can perform knowledge work tasks involving unstructured commands and subtle judgments
The Internet of Things	Networks of low-cost sensors and actuators for data collection, monitoring, decision making, and process optimization
Cloud technology	Use of computer hardware and software resources delivered over a network or the Internet, often as a service
Advanced robotics	Increasingly capable robots with enhanced senses, dexterity, and intelligence used to automate tasks or augment humans
Autonomous and near-autonomous vehicles	Vehicles that can navigate and operate with reduced or no human intervention
Next-generation genomics	Fast, low-cost gene sequencing, advanced big data analytics, and synthetic biology ("writing" DNA)
Energy storage	Devices or systems that store energy for later use, including batteries
3D printing	Additive manufacturing techniques to create objects by printing layers of material based on digital models
Advanced materials	Materials designed to have superior characteristics (e.g., strength, weight, conductivity) or functionality
Advanced oil and gas exploration and recovery	Exploration and recovery techniques that make extraction of unconventional oil and gas economical
Renewable energy	Generation of electricity from renewable sources with reduced harmful climate impact

SOURCE: McKinsey Global Institute analysis

[88] Manyika et al., *op.cit*., p. 2.

The next chart summarizes each technology's exponential progress and potential impacts.

Exhibit E2

Speed, scope, and economic value at stake of 12 potentially economically disruptive technologies

Technology	Illustrative rates of technology improvement and diffusion	Illustrative groups, products, and resources that could be impacted[1]	Illustrative pools of economic value that could be impacted[1]
Mobile Internet	**$5 million vs. $400[2]** Price of the fastest supercomputer in 1975 vs. that of an iPhone 4 today, equal in performance (MFLOPS) **6x** Growth in sales of smartphones and tablets since launch of iPhone in 2007	**4.3 billion** People remaining to be connected to the Internet, potentially through mobile Internet **1 billion** Transaction and interaction workers, nearly 40% of global workforce	**$1.7 trillion** GDP related to the Internet **$25 trillion** Interaction and transaction worker employment costs, 70% of global employment costs
Automation of knowledge work	**100x** Increase in computing power from IBM's Deep Blue (chess champion in 1997) to Watson (Jeopardy winner in 2011) **400+ million** Increase in number of users of intelligent digital assistants like Siri and Google Now in past 5 years	**230+ million** Knowledge workers, 9% of global workforce **1.1 billion** Smartphone users, with potential to use automated digital assistance apps	**$9+ trillion** Knowledge worker employment costs, 27% of global employment costs
The Internet of Things	**300%** Increase in connected machine-to-machine devices over past 5 years **80–90%** Price decline in MEMS (microelectromechanical systems) sensors in past 5 years	**1 trillion** Things that could be connected to the Internet across industries such as manufacturing, health care, and mining **100 million** Global machine to machine (M2M) device connections across sectors like transportation, security, health care, and utilities	**$36 trillion** Operating costs of key affected industries (manufacturing, health care, and mining)
Cloud technology	**18 months** Time to double server performance per dollar **3x** Monthly cost of owning a server vs. renting in the cloud	**2 billion** Global users of cloud-based email services like Gmail, Yahoo, and Hotmail **80%** North American institutions hosting or planning to host critical applications on the cloud	**$1.7 trillion** GDP related to the Internet **$3 trillion** Enterprise IT spend
Advanced robotics	**75–85%** Lower price for Baxter[3] than a typical industrial robot **170%** Growth in sales of industrial robots, 2009–11	**320 million** Manufacturing workers, 12% of global workforce **250 million** Annual major surgeries	**$6 trillion** Manufacturing worker employment costs, 19% of global employment costs **$2–3 trillion** Cost of major surgeries
Autonomous and near-autonomous vehicles	**7** Miles driven by top-performing driverless car in 2004 DARPA Grand Challenge along a 150-mile route **1,540** Miles cumulatively driven by cars competing in 2005 Grand Challenge **300,000+** Miles driven by Google's autonomous cars with only 1 accident (which was human-caused)	**1 billion** Cars and trucks globally **450,000** Civilian, military, and general aviation aircraft in the world	**$4 trillion** Automobile industry revenue **$155 billion** Revenue from sales of civilian, military, and general aviation aircraft
Next-generation genomics	**10 months** Time to double sequencing speed per dollar **100x** Increase in acreage of genetically modified crops, 1996–2012	**26 million** Annual deaths from cancer, cardiovascular disease, or type 2 diabetes **2.5 billion** People employed in agriculture	**$6.5 trillion** Global health-care costs **$1.1 trillion** Global value of wheat, rice, maize, soy, and barley
Energy storage	**40%** Price decline for a lithium-ion battery pack in an electric vehicle since 2009	**1 billion** Cars and trucks globally **1.2 billion** People without access to electricity	**$2.5 trillion** Revenue from global consumption of gasoline and diesel **$100 billion** Estimated value of electricity for households currently without access
3D printing	**90%** Lower price for a home 3D printer vs. 4 years ago **4x** Increase in additive manufacturing revenue in past 10 years	**320 million** Manufacturing workers, 12% of global workforce **8 billion** Annual number of toys manufactured globally	**$11 trillion** Global manufacturing GDP **$85 billion** Revenue from global toy sales
Advanced materials	**$1,000 vs. $50** Difference in price of 1 gram of nanotubes over 10 years **115x** Strength-to-weight ratio of carbon nanotubes vs. steel	**7.6 million tons** Annual global silicon consumption **45,000 metric tons** Annual global carbon fiber consumption	**$1.2 trillion** Revenue from global semiconductor sales **$4 billion** Revenue from global carbon fiber sales
Advanced oil and gas exploration and recovery	**3x** Increase in efficiency of US gas wells, 2007–11 **2x** Increase in efficiency of US oil wells, 2007–11	**22 billion** Barrels of oil equivalent in natural gas produced globally **30 billion** Barrels of crude oil produced globally	**$800 billion** Revenue from global sales of natural gas **$3.4 trillion** Revenue from global sales of crude oil
Renewable energy	**85%** Lower price for a solar photovoltaic cell per watt since 2000 **19x** Growth in solar photovoltaic and wind generation capacity since 2000	**21,000 TWh** Annual global electricity consumption **13 billion tons** Annual CO_2 emissions from electricity generation, more than from all cars, trucks, and planes	**$3.5 trillion** Value of global electricity consumption **$80 billion** Value of global carbon market transactions

1 Not comprehensive; indicative groups, products, and resources only.
2 For CDC-7600, considered the world's fastest computer from 1969 to 1975; equivalent to $32 million in 2013 at an average inflation rate of 4.3% per year since launch in 1969.
3 Baxter is a general-purpose basic manufacturing robot developed by startup Rethink Robotics.
SOURCE: McKinsey Global Institute analysis

The following charts describe in more detail the various types of impacts each technology is expected to have by 2025.

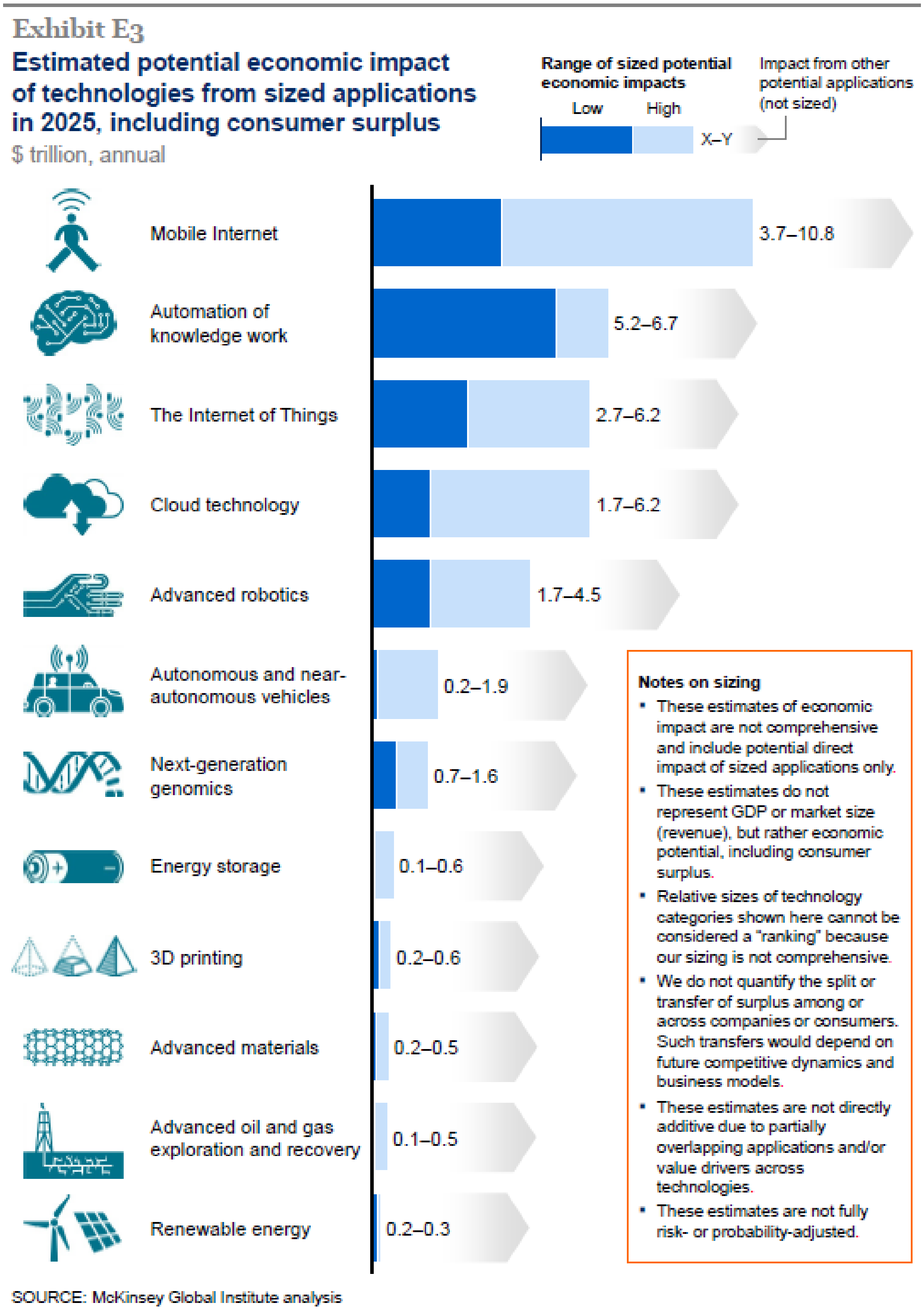


Exhibit E4

Estimated distribution of potential economic impact between developed and developing economies for sized applications

% of potential economic impact for sized applications

Impact on
- Developed economies
- Developing economies

Application	Developed economies	Developing economies	Developed	Developing
Mobile Internet	50	50	High-value applications, e.g., increasing worker productivity	Bulk of new mobile users
Automation of knowledge work	80	20	Higher impact of increasing labor productivity	Large number of knowledge workers
The Internet of Things	70	30	Major applications enabled by advanced technology infrastructure, e.g., advanced supply chain systems	Large applicable spend base, lower initial adoption
Cloud technology	30	70	Higher surplus per user	Majority of new adoption
Advanced robotics	80	20	Greater ability to pay for surgical robots and prosthetics; high savings from automation	Many manufacturing workers but lower savings from automation
Autonomous and near-autonomous vehicles	80	20	Early adoption in high-end vehicles	Many vehicles but smaller percentage of high-end vehicles and low cost of hiring drivers
Next-generation genomics	80	20	Greater early adoption of genomic technologies and treatments	Lower initial adoption, particularly for new treatments
Energy storage	60	40	Many new vehicles with potentially higher adoption of electric and hybrid models	Many vehicles but potentially smaller percentage of new electric and hybrid models
3D printing	60	40	Potential for earlier adoption in manufacturing and by consumers	Large manufacturing base and many consumers, but lower initial adoption
Advanced materials	90	10	Greater early adoption of new nano-based treatments due to more advanced health-care systems	Lower initial adoption for new nano-based treatments and substances
Advanced oil and gas exploration and recovery	80	20	North America leads in shale gas and light tight oil production	Significant investments being made but could require years to catch up
Renewable energy	20	80	Larger existing renewables base (especially wind) with moderate growth	Large renewables capacity development, e.g., in China

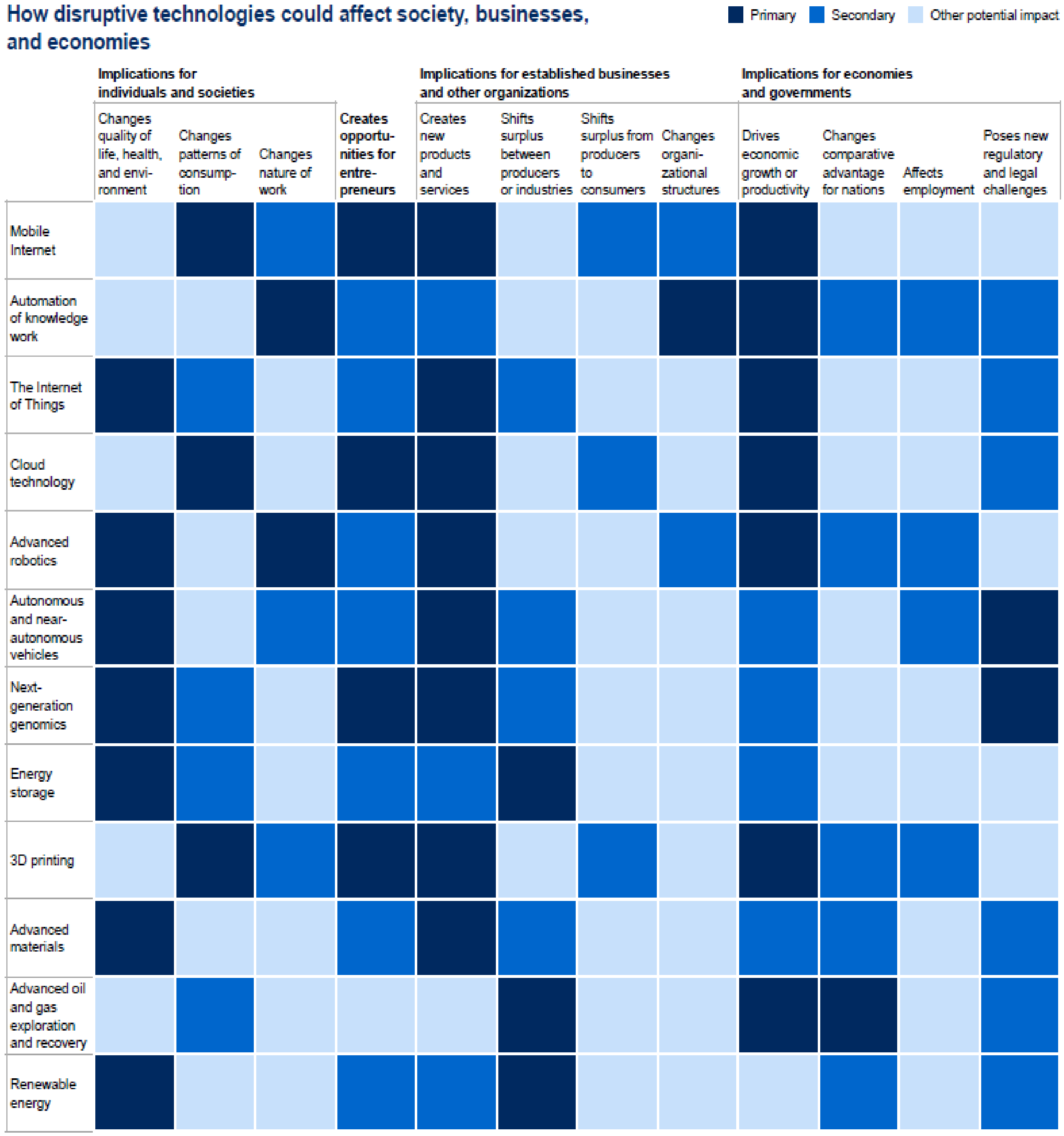
Notes on sizing

- These economic impact estimates are not comprehensive and include potential direct impact of sized applications only.
- These estimates do not represent GDP or market size (revenue), but rather economic potential, including consumer surplus.
- Relative sizes of technology categories shown here cannot be considered a "ranking" because our sizing is not comprehensive.
- We do not quantify the split or transfer of surplus among or across companies or consumers, as this would depend on emerging competitive dynamics and business models.
- These estimates are not directly additive due to partially overlapping applications and/or value drivers across technologies.
- These estimates are not fully risk- or probability-adjusted.

SOURCE: McKinsey Global Institute analysis

Exhibit E6

How disruptive technologies could affect society, businesses, and economies



SOURCE: McKinsey Global Institute analysis

The MGI report ends with a discussion of the findings' implications, which are in turn positive, cautionary, and concerning. Selected quotes:

- [T]he future seems bright for entrepreneurs and innovators. . . .
- Many technologies . . . have real potential to drive tangible improvements in quality of life, health, and the environment. . . .
- Almost every technology on our list could change the game for businesses, creating entirely new products and services, as well as shifting pools of value between producers or from producers to consumers. . . .
- Each of these technologies has significant potential to drive economic growth and even change the sources of comparative advantages among nations. . . .
- Many of these technologies pose new regulatory and legal challenges. . . .
- Technologies such as advanced robots and knowledge work automation tools move companies further to a future of leaner, more productive operations, but also far more technologically advanced operations. The need for high-level technical skills will only grow, even on the assembly line. . . .[89]

Brynjolfsson and McAfee recognize that while the new technologies' potential bounty is clear, those technologies will have a tendency to exacerbate the spread between those more and less well off. They see three types of winners and losers in the second machine age:

- Those with significant quantities of non-human capital (equipment, structures, intellectual property, financial assets) will benefit from capital-biased technical change. The substitution of physical capital for labor will increase the share of income going to profits and reduce the share going to labor.
- Those with significant quantities of human capital (skills, experience, training, education) will benefit from skills-biased technical change. Relative demand for more workers with greater education and training will rise; it will fall for less educated workers who carry out routine cognitive and manual tasks, which are vulnerable to being replaced by machines.
- Those individuals with the greatest talent (or luck) will benefit from talent-biased technical change. "More often than not, when improvements in digital technologies make it more and more attractive to digitize something, superstars in various markets see a boost in their incomes while second-bests have a harder time competing." Relatively better performance can lead to absolute domination.

> Digitization creates winner-take-all markets because . . . with digital goods capacity constraints become increasingly irrelevant. A single producer with a

[89] *Ibid.*, pp. 19-21. Famed futurist Ray Kurzweil predicts that by 2029 "computers will be more intelligent than we are and will be able to understand what we say, learn from experience, make jokes, tell stories and even flirt." Source: Nadia Khomani, "2029: the year when robots will have the power to outsmart their makers," *The Guardian*, February 22, 2014.

website can, in principle, fill the demand from millions or even billions of customers

> [W]inner-take-all markets have also been boosted by technological improvements in telecommunications and transportation that also expand the market individuals and companies can reach.
>
> [T]he increased importance of networks (like the Internet or credit card networks) and interoperable products (like computer components) can also create winner-take-all markets. . . . If your friends keep in touch via Facebook, than makes Facebook more attractive to you, too.[90]

Brynjolfsson and McAfee also say that while the economics discipline is dominated by the belief "that automation and other forms of technological progress in aggregate create more jobs than they destroy," as evidenced by the last two centuries, that belief may not be correct in the second machine age. In addition to stagnant wages and rising inequality, they are quite concerned about the potential for technological unemployment, a term coined by John Maynard Keynes to mean "unemployment due to our discovery of means of economizing the use of labor outrunning the pace at which we can find new uses for labor."[91] Brynjolfsson and McAfee cite two major reasons that innovation will lead to technological unemployment:

- Friction in labor markets: "When technology eliminates one type of job, or even the need for a whole category of skills, those workers will have to develop new skills and find new jobs. Of course, that can take time, and in the meantime they may be unemployed. . . . Once one concedes that it takes time for workers and organizations to adjust to technical change, then it becomes apparent that accelerating technical change can lead to widening gaps and increasing possibilities for technological unemployment. Faster technological progress may ultimately bring greater wealth and longer lifespans, but it also requires faster adjustments by both people and institutions."[92]
- Lack of work that pays a living wage: If, due to the replacement of workers by machines, "neither the worker nor any entrepreneur can think of a profitable task that requires that worker's skills and capabilities, then that worker will go unemployed indefinitely. . . . [J]ust as technology can create inequality, it can also create unemployment. In theory, this can affect a large number of people, even a majority of the population, and even if the overall pie is growing.[93]

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[90] Brynjolfsson and McAfee, *op.cit.*, pp. 151 and 154-156.
[91] As quoted in *Ibid.*, p. 174.
[92] *Ibid.*, p. 178.
[93] *Ibid.*, p. 179.

MGI and Brynjolfsson and McAfee agree that national governments have the responsibility to provide a proper framework for disruptive technology development and deployment. The MGI report notes:

> The scope of impact of the technologies in this report makes clear that policy makers could benefit from an informed and comprehensive view of how they can help their economies benefit from new technologies. Policy makers can find ways to turn the disruptions into positive change; they can encourage development of the technologies that are most relevant to their economies. In many cases, such as in next-generation genomics or autonomous vehicles, the proper regulatory frameworks will need to be in place before those technologies can blossom fully. In other cases governments may need to be the standards setters or the funders of the research that helps move ideas from science labs into the economy. In still others, they will need to draw the lines between progress and personal rights.
>
> The challenge for policy makers—and for citizens—is enormous. It is a good time for policy makers to review how they address technology issues and develop a systematic approach; technology stops for no one, and governments cannot afford to be passive or reactive.[94]

Brynjolfsson and McAfee ask these questions:

> What should we do to encourage the bounty of the second machine age while working to reduce the spread, or at least mitigate its harmful effects? How can we best encourage technology to race ahead while ensuring that as few people as possible are left behind?[95]

They recognize that a good job helps people feel "fulfilled, content, and happy" and have a sense of self-worth. In the near term, they recommend these steps for promoting economic growth and individual opportunity:

- Increase educational attainment
- Promote entrepreneurship
- Use digital tools to promote more and better matches between employers and jobseekers
- Invest in research and development
- Upgrade infrastructure
- Encourage immigration, as many immigrants are educated and entrepreneurial
- Tax intelligently

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[94] *Ibid*., pp. 22-23.
[95] Brynjolfsson and McAfee, *op.cit.*, p. 206.

Longer-term, they suggest designing jobs that are "paired up to race *with* machines, instead of against them," taking advantage of the fact that a human-machine combination often outperforms a machine alone. They also suggest tax incentives that "encourage and reward work," such as an enhanced Earned Income Tax Credit or Milton Friedman's idea of a negative income tax.

To boost the bounty and reduce the spread, the federal government has a responsibility to create and implement an intelligent competitiveness policy, which it does not have at present. In global free markets, the geographic distribution of the benefits and costs of new technologies will not be even and is not preordained. Many other nations are strategically approaching the second machine age. The U.S. has large and unique advantages, but these can be eroded over time if not attended.

VIII. Conclusion

This paper's six sets of findings, grouped by perspective, reflect current thinking about technological invention and economic growth. Taken together, the findings can be organized in two categories—ways in which invention contributes to economic growth and the requisite conditions for invention and innovation to thrive.

Invention and Economic Growth

Each of the previous sections provides material that affirms the central role that technological invention plays in economic growth.

- In the introduction, the essential place of invention in economic well-being is expressed by Hanauer and Beinhocker: "Prosperity in a society *is the accumulation of solutions to human problems*."
- The economic history section describes the dramatic relationship between technological invention and economic growth, making clear that the latter could not happen without the former.
- The section on innovation accounting shows the paths by which invention has led to economic growth in the U.S. over the past quarter century--through product and process innovations, through investment in invention-enabled tangible and intangible capital, and through improvements in human capital, which are invention-enabled both in substance (i.e., what is taught) and process (how it is taught, e.g., through distance learning).
- The section on macroeconometric analysis indicates the strong, positive relationship between a nation's investment in R&D and its economic growth.
- The review of work on microeconomic analysis demonstrates that innovating firms create more jobs and growth than firms that do not innovate.
- Schumpeterian growth theory is rooted in the basic idea that economic growth stems from the "creative destruction" brought on by invention, innovation, and technological change.
- In the future scenarios section, Brynjolfsson and McAfee describe the bounty that awaits humans in the second machine age; MGI shows the extraordinary potential impacts of 12 transformative technologies on global and national economic growth in the years ahead.

At the same time, the literature provides several major cautions. With regard to economic growth, one should not confuse GDP, a dollar measure of economic production, with economic prosperity. The distribution of wealth and income is an important dimension of economic well-being that is not measured by GDP. Further, and very importantly, in coming years GDP-enhancing technological change will have a bias towards increasing inequality and technological unemployment.

While the causal connection between invention and economic growth is quite clear, understanding of that connection could be deepened. Further research is needed to find meaningful ways to measure aspects of economic well-being not encompassed in GDP and to better grasp the nature of the range of impacts of technological change on the workforce and labor markets.

Conditions Requisite for a Healthy Invention/Innovation Ecosystem

Collectively, the various sections identify the characteristics of a healthy ecosystem for technological invention and innovation:

- In the economic history section, Steven Johnson's work provides a cogent framework of seven key aspects of such an ecosystem: the adjacent possible, liquid networks, the slow hunch, serendipity, error, exaptation, and platforms. Within this framework, Johnson makes a strong history-based case for the foundational importance of nonmarket, cooperative invention. He also speaks to the need for balance between structure and flexibility.
- In the macroeconomics section, Coccia's work indicates that substantial investment in public R&D will catalyze private R&D, innovation, and growth.
- In the microeconomics section, findings by Evangelista and Vezzani imply that incentives encouraging firms to develop a mix of product, process, and organizational innovations leads to the highest rates of firm growth.
- In the economic theory and models section, Aghion, Akcigit, and Howitt indicate the importance to invention and innovation of:
    - Schumpeterian economic churning, which leads to a reallocation of resources among firms which in turn stimulates invention and productivity growth;
    - strong investment in research education; and
    - free trade.
- The scenarios section discusses the importance of a U.S. competitiveness policy to promote invention and innovation and widespread distribution of their benefits.
- Several chapters echo or complement each other regarding additional key prerequisites to invention and innovation, including:
    - a skilled workforce;
    - high rates of entrepreneurship;
    - patent and communications policies that properly balance intellectual property protection with the free flow of information;
    - organizations, such as industry and professional associations, that facilitate network development;
    - the availability of economic statistics that reliably measure patterns of invention, innovation, prosperity, R&D, investment in intangible capital, small business development, the economic benefits of digital technologies, and small business finance;

- an economy that is inclusive and seeks to improve living standards for all; and
- robust institutions of democracy, including freedom of expression, civility, and the opportunity to experiment in life without undue penalty.

These prerequisites for a healthy invention/innovation ecosystem suggest the value of a set of public policies that strategically encourage them. It is recognized that technological invention should be encouraged in combination with institutional invention by businesses, the government, and universities. As the literature shows, particularly from Brynjolfsson and McAfee, the impact of the technological invention on society is likely to be diminished without institutional invention.