Algorithms and the Changing Frontier[*]

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Abstract: We first summarize the dominant interpretations of the "frontier" in the United States and predecessor colonies over the past 400 years: agricultural (1610s-1880s), industrial (1890s-1930s), scientific (1940s-1980s), and algorithmic (1990s-present). We describe the difference between the algorithmic frontier and the scientific frontier, and then propose that the recent phenomenon referred to as "globalization" is actually better understood as the progression of the algorithmic frontier, as enabled by standards that in turn have facilitated the interoperability of firm-level production algorithms. We employ data on the adoption of management standards published by the International Standards Organization to map the evolution of today's algorithmic frontier and test the correlation of globalization with standardization.

Keywords: algorithms, globalization, interoperability, information and communications technology/ICT, International Standards Organization/ISO, production recipes, supply chains, standards

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> Everywhere, economic activity is turning outward by embracing shared business and technology standards that let businesses plug into truly global systems of production.
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> — Sam Palmisano, former CEO of IBM (2006, p. 130)

I. Introduction

"What is the frontier?" Frederick Jackson Turner asked in his seminal work, *The Frontier in American History* (1893). "In the census reports it is treated as the margin of that settlement which has a density of two or more to the square mile." When Turner wrote of the closing of the American frontier, he was referring to the end of an interval that lasted over three hundred years, as the first European settlements in the North American continent grew and expanded westward. The frontier was viewed as a place, bounded on one side by the easternmost fields cleared for agriculture and on the other by the westernmost wilderness. In between, Turner argued, was a marginal space in which necessity was, even more than elsewhere, the mother of invention.

By the time Franklin Delano Roosevelt wrote to Vannevar Bush in November 1944 to request the report celebrated in this research volume, the frontier itself had changed. "New frontiers of the mind are before us," Roosevelt wrote, "and if they are pioneered with the same vision, boldness, and drive with which we have waged this war we can create a fuller and more fruitful employment and a fuller and more fruitful life." Much as Thomas Jefferson had charged Meriwether Lewis and William Clark to survey the previously unexplored domains of the West in 1803, so Roosevelt tasked Bush to survey previously unexplored domains of human inquiry. The desired endpoint of the undertaking was the same in both cases: to improve lives and increase prosperity.

The title of the report Bush produced, *Science the Endless Frontier,* succinctly expressed how societal progress was defined by the middle of the twentieth century. Released in July 1945, a month after the Allied victory in Europe and a year before George Doriot created the world's first publicly owned venture capital firm, Bush's report was about how best to maintain in peacetime a rate of scientific progress that had been unprecedented when driven by the necessities of war.

The frontier of scientific knowledge has advanced at least as dramatically in the nearly seventy years since 1945 as the frontier of the American West advanced in the seventy years after 1803.

In both cases, the advancement was part of "the changing frontier" that has been a central feature of American economic history, which in turn is the title of this volume. The real change related to the evolution of the frontier itself.

It is significant that America's first World's Fair opened in Philadelphia exactly seventy years after Lewis and Clark returned to St. Louis at the end of their two-year expedition. The International Exhibition of Arts, Manufacturers, and Products of the Soil and Mine, as it was officially called, was a sort of museum in reverse in which inventions that signaled the creation of major new industries were first exhibited to the general public. These included Alexander Graham Bell's telephone (communications technology), the Remington typewriter (office services), the Wallace-Farmer Electric Dynamo (electric power), and Heinz Ketchup (food processing). Indeed, there is considerable poetic significance in the fact that Frederick Jackson Turner first presented his renowned paper on "The Significance of the Frontier in American History" before the American Historical Society at a subsequent World's Fair—the 1893 World's Columbian Exposition in Chicago.

What of today? Where is the changing frontier of societal advance situated in 2013, both in the United States and globally? Is that frontier expanding or closing? These are the questions we seek to answer in this paper. We do so first by summarizing different dominant interpretations of the frontier over the past four hundred years: agricultural (1610s-1880s), industrial (1890s-1930s), scientific (1940s-1980s), and algorithmic (1990s-present). We then employ data from the International Standards Organization (ISO) to map the evolution of today's algorithmic frontier. We close by conjecturing about the future evolution of the changing frontier.

II. Changing Frontiers in the United States

Historical Context

The first American frontier requires little description. The map in Figure 1 illustrates the movement of the frontier westward from 1803 through the nineteenth century. The social complexity of the process of westward movement—a subject of active scholarly inquiry in the century since Turner presented his paper—yields to remarkable simplicity when looked at from a cartographic perspective. Inexorably, the frontier moved westward until European settlements covered a continent. The economy of the United States during this lengthy interval was defined by two industries: agriculture and the extraction of natural resources. Accordingly, we refer to this first, most famous frontier in American history as the agricultural frontier.

[Insert Figure 1 Here]

The second American frontier was not the scientific one that formed the subject of the Bush report but its industrial precursor. The World's Fair was to the era of the industrial frontier what the earliest precursors of the rodeo were to the era of the agricultural frontier: places where successful experimentation could be recognized and rewarded. The inventive wave that had been building since the 1870s continued to gain force. In the 1900s alone the Wright brothers flew the first plane at Kitty Hawk, Henry Ford sold his first Model A, Samuel Insull merged Commonwealth Electric with Chicago Edison to create Commonwealth Edison—the world's first large-scale electric utility—and major breakthroughs were made in the development of the radio.

The frontier for the United States in the first third of its history was thus about realizing economies of scale afforded by the combination of new technologies and new modes of social organizations. The era from the 1890s to the 1930s (in particular from roughly 1910 to the start of World War II) was the one in which the basic infrastructure of the modern United States was developed. The high-level industrial classifications that experienced the greatest growth during this interval include utilities, electric equipment and supplies, rubber and plastic products, petroleum and coal products, and printing and publishing.[1] The inventions listed above were among the sparks that ignited the industrial engine of the early twentieth century.

Bibliometric analysis provides a particularly vivid lens through which to view the changing industrial frontier. Figure 2 presents data on word frequencies created using Google Ngram, which is based on a digital database of more than 5.2 million books published worldwide between 1500 and 2008 and comprises more than 500 billion words. Around that database Google created an interface they call the Ngram Viewer, which enables users to plot the frequency with which words and phrases appear in this dataset over time.[2] The Ngram tool can be used to get a sense of the intensity of interest in particular technologies over time—put simply,

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[1] Data from the Historical Statistics of the United States and the Census of Manufacturers.

[2] See http://books.google.com/ngrams.

the relative frequency with which particular words appear in published works of any type, for every year since 1500. Figure 2 presents a sample plot using the words "carriage, automobile, airplane, and rocket." The pattern shown for each of these words is consistent with the "hype cycle" hypothesized by Gartner Consulting, illustrated in Figure 3. In the Gartner model, societal interest (which we conjecture is correlated with word frequencies in the Ngram database) in a technology grows rapidly after its first introduction. Interest soon reaches a peak, after which an era of disillusionment sets in. Interest falls off, usually just as the foundation for widespread societal adoption is setting in. By the time a technology is ubiquitous, its everyday usage is roughly constant; economic stability is reflected by this bibliometric stability.[3]

[Insert Figures 2 and 3 Here]

Although the plot in Figure 2 is a simple representation of word frequency over time, it has some interesting characteristics. First, from 1900 to 1940, use of the word "carriage" decreases at just about the same rate that use of the word "automobile" increases; this is consistent with our intuition about the introduction of a more powerful substitute technology. Second, consistent with the Gartner hypothesis, the peak of relative intensity of usage comes well before technological maturity and market ubiquity. Finally, for these two, words at least, the "hype cycle" seems to become increasingly compressed over time. This is consistent with considerable data that documents the increasing rates of adoption of new technologies and shorter product life cycles over time.

The inventions that defined the industrial frontier from 1890 through the 1930s represented major advances not just for the United States but for humanity on a global scale. However, these inventions were the outcome not of scientific research but of systematic tinkering. In the middle of the twentieth century the nature of invention began to change; invention became more scientific, with scientific research playing an increasing role in motivating major advances.[4]

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[3] For more on the Gartner hype cycle see http://www.gartner.com/technology/research/methodologies/hype-cycle.jsp.

[4] Joseph Schumpeter wrote of the innovation as early as 1928 that within the emerging "trustified" capitalism "innovation is no longer . . . embodied typically in new firms, but goes on, within the big units now existing . . . Progress becomes 'automatised,' increasingly impersonal and decreasingly a matter of leadership and individual initiative." By 1959, John Jewkes, David Sawers, and Richard Stillerman wrote:

Again, simple word-frequency plots help illustrate. Figure 4, also created with Google's Ngram tool, illustrates the intensity of usage of the words "research" and "technology" from 1800 to 2000. Rarely used before 1900, "research" begins to gain currency only in the 1920s, rises steadily, and then levels off starting in the 1980s. Technology follows a similar trend, but the period of rapid rise begins in the 1960s.

[Insert Figure 4 Here]

Figure 5 illustrates the system of science-based innovation that came into being following World War II. Advances in fundamental knowledge—the basic science column on the left-hand side—undergird the system of science-based innovation in a modern economy. Of course, advances in basic science will have no impact on economic growth or human well-being if they do not translate first into technologies, and ultimately into goods and services. The core technologies represented in the second column are the direct translation of science into a capability for innovation. Core technologies may be developed within the university, in an entrepreneurial startup, or, most commonly, in the existing corporation. Core technologies typically are combined to create new goods and services. Industry production networks organized around existing goods and services are represented in the third column from the left. Industry production networks, or industry "clusters" when localized, are defined in terms of goods and services, not in terms of technologies. On the far right-hand side are the product markets themselves, where consumers and workers are situated. Innovations that renew or re-create existing industries not

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> In the twentieth century . . . the individual inventor is becoming rare; men with the power of originating are largely absorbed into research institutions of one kind or another, where they must have expensive equipment for their work. Useful invention is to an ever-increasing degree issuing from the research laboratories of large firms which alone can afford to operate on an appropriate scale . . . Invention has become more automatic, less the result of intuition or genius and more a matter of deliberate design.

This world of systematic innovation—if not based on science, per se, then on research more generally understood—represents the frontier that Vannevar Bush described, and sought to advance, in *Science the Endless Frontier.*

infrequently originate with workers near a production process, or with consumers of a product or service, rather than in a lab or university.

[Insert Figure 5 Here]

As Bush foresaw, this system has yielded significant dividends for American society. Tremendous scientific advances were made at Bell Telephone Laboratories, DuPont, General Electric, RCA Laboratories, the IBM T. J. Watson Research Center, the Xerox Palo Alto Research Center, together defining a Golden Age of corporate research and development (R&D) in the United States (Auerswald & Branscomb, 2005). It was the work that took place in these laboratories—arguably at least as much as that in universities, which was more distant from market applications—that defined the scientific frontier that drove the advance of the U.S. economy in the post-World War II era (Trajtenberg et al., 1992).

Coming fifty years after the publication of Turner's classic work on the closing of the western frontier, the title of the Bush report was significantly expansive: *Science the Endless Frontier* pointed to a dimension of human attainment that would not be subject to limitation, as the prior era had been. In the case of the westward expansion, an insurmountable obstacle ultimately was reached: the Pacific Ocean. To Bush and those of his generation, no such obstacle was foreseeable when it came to the scientific frontier. An end to science-based innovation was essentially inconceivable. Yet by the 1970s, fewer private firms—regardless of their size—found it to be in their interest to invest in the sort of basic research that the Bush report had championed. One-by-one, the great corporate laboratories either closed or sharply narrowed their focus.

Macroeconomic data also suggests that a significant structural shift took place in the economic frontier in the 1970s. Using a methodology developed by the Bureau of Economic Analysis (BEA), Lee and Schmidt (2010) calculate the changes to GDP that result from treating R&D as an investment rather than as an expense (Table 1). They find that recategorizing R&D in this manner adds 0.13 percent to GDP growth rates from 1959 to 1973. However, from 1973 to 1994, the impact vanishes. This coincides with the much-discussed productivity slowdown, as well as the "conglomerate" discount experienced by the largest and most diversified U.S. corporations starting in the late 1960s.

[Insert Table 1 Here]

In the BEA analysis, the recategorization of R&D as investment once again begins to change the calculation of GDP growth rates appreciably from 1995 to 2007. As Jorgenson and Stiroh (2000) have documented, the primary vehicle by which R&D was contributing to GDP growth in the late 1990s and 2000s was via innovations in information and communications technology (ICT). The new frontier was, and is, algorithmic rather than research-based.

This is not to say that the system of science-based innovation described in Figure 3 has vanished. Far from it: it is larger and more robust than ever. As in prior eras, the infrastructure developed during the advance of one frontier remains fundamental to society as the next develops. Agriculture output increased for decades after the agricultural frontier was overtaken by the industrial frontier. Manufacturing output increased for decades after the industrial frontier was overtaken by the scientific frontier. Similarly, the output of science-based innovation has continued to increase even as that frontier has been overtaken by the algorithmic frontier.

Theoretical Context

We can readily describe the difference between agricultural, industrial, scientific, and algorithmic frontiers using standard production theory. Each of the first three frontiers has an associated branch of economics. The economics of the agricultural frontier were Malthusian; the economics of the industrial frontier were those of classical growth theory; and the economics of science based-innovation are those of new growth theory. In this section, we argue that the algorithmic frontier requires different economics.

In a Malthusian world, land is the fundamental fixed factor, whereas populations are variable. Accordingly, rents accrue to land, and an interval of growth (though ephemeral) can be realized only through geographical expansion. Long-term growth is infeasible.

In an industrial model, capital replaces land. Investment can increase the capital-to-labor ratio. This increases the marginal product of labor, and thus the wage rate. Both the rate of population growth and the rate of technical change are exogenous. Growth is a matter of reaching the steady state level of per-capita consumption, which in turn is limited by the rate of technological advance. This, writ large, is the familiar world of the neoclassical growth model.

In the science-based model, technical change is the result of active investment. Knowledge is non-rival and non-excludable, so the outcomes of R&D investments spill over to the economy as a whole.[5] Achieving economic equilibrium in the presence of aggregate increasing returns to knowledge is feasible so long as the research technology exhibits locally decreasing returns. Long-term growth rates can be increased by subsidizing research or the accumulation of human capital. This, writ large, is the familiar new growth model.

How does the algorithmic model differ from the science-based model? Where the science-based model (like the Bush report) is built on the assumption that the transmission of economic knowledge is (or at least can be) costless and error free, the algorithmic model takes the costly process by which ideas are created, stored, shared, combined, and, of course, connected to economic exchange as the central problem of economic life. As Herbert Simon wrote in his prescient paper titled "Programs as Factors of Production," published in 1967, "If computers, regarded as factors of production, are to be classified with capital, they are capital with a difference."

Figure 6, drawn from Auerswald et al. (2000), illustrates this point.[6] A neoclassical production plan is a particular input-output relationship. In its simplest rendition, it is a point (x, y) where $x \geq 0$ is the quantity of the input and where $y \geq 0$ is the quantity of the output. Figure 1 shows the production possibilities of the firm, the shaded area **T**, and three specific possible production plans labeled **A**, **B**, and **C**. The production function in this figure exhibits constant returns to scale, such that the best a firm can do is

$$y = \theta x$$

where θ is a positive scalar that can be thought of as the organizational capital of the most productively efficient firm. The production function is comprised of the set of input-output pairs that lie on the boundary of the production possibilities set.

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[5] This notion is associated with the work of Romer (1986, 1990), although obviously present elsewhere. "non-rival" means that one person's use of an idea does not keep another person from using the idea; "non-excludable" means that it is impossible to keep a person from using an idea once it is "out in the open"; and "knowledge spillovers" refers to the costless transmission of ideas that are non-rival and non-excludable. Romer (1996) also employs the term "recipes" to refer production algorithms, following both Simon (1967) and Winter (1968).

[6] The description of Figure 6 that follows in the next three pages is drawn from Auerswald (2009) and Auerswald and Branscomb (2005).

[Insert Figure 6 Here]

All of this is just a restatement of standard theory. Now, however, assume further that the approach utilized by the firm to convert inputs to outputs is encoded as a program. This program runs inside the "black box" of the standard production function to convert inputs to outputs. As Sidney Winter noted in another significant paper, published in 1968, "'Knowing how to bake a cake' is clearly not the same thing as 'knowing how to bring together all of the ingredients for a cake.' Knowing how to bake a cake is knowing how to execute the sequence of operations that are specified, more or less closely, in a cake recipe." In the algorithmic model, this distinction takes on first-order importance: knowing how to bake a cake is different from knowing how to bring together all of the ingredients for a cake.

For the sake of illustration, let us say that a given production process is comprised of three operations, each of which can be conducted in one of just two ways. We can exhaustively enumerate all possible production recipes as the set of eight binary strings {000, 001, 010, 100, 011, 101, 110, 111}. Each of these recipes will be associated with its own scalar measure of effectiveness. Let us refer to the level of effectiveness as the "organizational capital" associated with the recipe. For example, recipe 010 might be associated with organizational capital θ, and recipe 101 might be associated with organizational capital θ'. Let us arbitrarily say that recipe 010 is the best of the bunch, so its associated level of organizational capital is greater than the organizational capital associated with any of the other recipes.

Referring back to Figure 6, input-output pair **A,** which lies on the boundary line as defined by $y = \theta x$, clearly "dominates" input-output pair **B;** the firm using recipe 010 produces more output with less input than the firm using recipe 101. For all firms to operate on the production possibilities frontier requires (1) that all firms have knowledge of the elements of the set of potentially usable recipes; (2) that all firms are aware of the effectiveness of each recipe in actual production. Under such conditions, all firms in this example would use production recipe 010.

Figure 6 also allows us to clearly see the difference between economic distance and technological distance. From an economic standpoint, input-output pair **A** is close to input-output pair **B** but distant from input-output pair **C**. However, from the standpoint of technology, pairs **A** and **C** are the same, as they are produced with the same recipe (010); input-output pair **B** is maximally different from both **A** and **C**, in that the recipe used to produce **B** differs in every operation from that used to produce pairs **A** and **C**. Taking one operation at a time, $0 \neq 1$; $1 \neq 0$; $0 \neq 1$. Since there are three operations in all and the two recipes differ in every operation, the technological distance between the two recipes is 3.

The complexity of a production recipe can be represented either in terms of both the number of "operations" or distinct units involved in the production process or (critically) the extent of the interdependence between those units.[7] The greater the complexity of technology as defined in terms of interdependence, the lower the correlation between the effectiveness of the original production recipes (i.e., the leader's method) and that of the same recipe altered slightly (i.e., an imperfect imitation).[8]

In the science-based (aka New Growth) model, technological distance does not exist; newly discovered recipes add to aggregate knowledge as soon as they are put into practice. In the algorithmic model, search for better recipes is constrained both by technological distance and by the complexity of the production process. Newly discovered recipes that are not easily imitated are the essence of economic differentiation and the basis for above-normal profits; the interoperability of recipes is essential to the functioning of complex supply chains.

In this light, consider the notion, central to the science-based model, that both ideas are "non-rival" and "non-excludable," economically relevant innovations are characteristically subject to "knowledge spillovers." In the algorithmic model, the ideas that actually propel growth and development are overwhelmingly uncodified, context dependent, and transferable only at

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[7] Coase (1937, p. 390) argued that, in the presence of technological interdependencies, firms will expand to realize economies of scope. When firms do expand in such a manner to internalize the externalities, they create what Auerswald et al. (2000) term "intra-firm externalities." Indeed, if one particular unit of a firm is not linked to any other via such intra-firm externalities, then we reasonably wonder why that unit is part of the firm to begin with (rather than, for example, acting as an outside contractor). In this sense, a transactions cost theory of the firm predicts that, in industries where technological interdependencies abound, managers will typically be charged with solving complex coordination problems.

[8] See Auerswald (2009) and related prior work; also Rivkin (2000).

significant cost—which is to say that tacit knowledge dominates, information asymmetries are the norm, and transactions costs are significant.[9]

While knowledge spillovers of the type that are central to to the science-based model clearly exist, they are unlikely to be of significant relevance in the practical work of creating the new business entities that drive twenty-first-century global value chains.[10] The reason for this is that most productive knowledge is firm specific and producers far from dominant production clusters must learn to produce through a process of trial and error. Market-driven innovation involves the search for ideas that are rivalrous and excludable (at least temporarily), out of which ventures with proprietary value can be created. The impediments to innovation that matter most are not a lack of appropriability of returns but the everyday battles involved in communicating ideas, building trust, and making deals across geographically disparate regions and diverse economic units (Auerswald, 2008). To the extent that the public benefits not captured by the investing firm (resulting from knowledge spillovers or other mechanisms) are temporally far off or uncertain, it is unlikely that they will be of greater importance to innovation-related decision-making than will be the immediate, first-order challenges of organizing and financing the firm's operations (Bloom & Van Reenen, 2010).

Standards have become increasingly important in the era of the algorithmic frontier because they enable the interoperability of firm-level recipes. The existence of standards turns a firm-level recipe into a subroutine of a larger program comprising many different recipes. That larger program enumerates the full instructions for the operation of a supply chain. As Paul Agnew, an early proponent of international standards, pointed out, compatibility standards resolve the difficulties that arise "at the transition points—points at which the product passes from department to department within a company, or is sold by one company to another or to an

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[9] Important early work by Mansfield (1961, 1963) on the subject of technological change related to imitation by one firm of the production methods of another. This work advanced the studies by Griliches (1957) on technological adoption. Where Griliches had used published data to study the adoption of essentially modular agricultural technologies, Mansfield (1961) used questionnaires and interviews to study the adoption of new production techniques by large firms in four industries.

[10] We emphasize that the focus here is not on web pages and pirated music videos. These digitized products—even including patents—are not the same thing as production algorithms or recipes.

individual" (Agnew, quoted in Murphy & Yates, 2009, p. 7). Without standards, the interdependencies between the firm-level recipes comprising a supply chain would grow at a greater rate than the length of the chain, and the operation of the supply chain would be unmanageable.

Note that standardization to enable the interoperability of recipes as subroutines is different from the standardization of firm-level recipes themselves. In the food service industry, standardized recipes and production processes have famously been the success of franchise-based firms like McDonalds and KFC. Such firms have contributed to advancing the algorithmic frontier, but the particularly strict form of encoding that the franchise model represents is not the focus of this paper.

In the next section we continue this line of argument by proposing that the recent phenomenon referred to as "globalization" is actually better understood as the progression of the algorithmic frontier, enabled by standards that in turn facilitate interoperability.

III. Globalization Is Really Standardization

The emphasis of the science-based model on product innovation naturally leads to a view of the economic frontier in which technology adoption or transfer (largely based on technical standards) are the main conduits for global innovation and knowledge stocks are well represented by patents. The algorithmic model begins with the premise that product innovation is impossible without process innovation; the conversion of new or improved products, and the related technical standards, into commercial products of global value requires substantial innovation in production processes. Not all firms are at the boundaries of the production-possibilities frontier, and differences in the quality of operational processes could separate firms with largely similar technical capabilities. Symmetric access to product innovations does not suggest a convergence in productivity.

As indicated above, the algorithmic frontier originates with the modern revolution in ICT. Changes in ICT have, of course, increased the ease of and potential for global communication, yet such interconnection has proceeded unevenly. At the regional level, large cities like New York, which have always been connected to other large cities, are becoming even more tightly connected. A more recent trend is that smaller cities like Wilmington, DE, are also becoming globally connected. At the same time, many countries in the developing world are becoming connected through large urban centers, but these cities often end up more connected to global cities like New York or London than to smaller cities in their own country (Taylor & Lang, 2005). Industries in which production can be fragmented into interoperable subroutines tend to be distributed in places where production is cheap and efficient; industries in which interdependence between operations is more intensive and fragmentation is not possible—which is to say, knowledge intensive goods and services—tend to locate in cities (Clarke, 2009). As a result, the world has not become flatter in terms of the distribution of economic opportunities and outcomes, but the peaks have become more dispersed across the emerging world (Florida, 2005).

The recent wave of global integration termed "globalization" tends to be described in terms of the international integration of commodity, capital, and labor markets (Bordo et al., 2003). If this is what we mean by the term, however, then it is clear that our current period is not the first example of globalization. There have been two major periods of globalization (Baldwin & Martin, 1999) since the mid-nineteenth century. The first began in the mid-nineteenth century and ended with the onset of World War I. After an interlude between the wars that included the Great Depression, the second era of globalization began during the reconstruction after World War II. Growth in trade accelerated following the end of WWII, but in the past century we have seen trade flows of comparable magnitude to our current experience.[11] This type of global integration has actually been occurring for at least one thousand years, although the flow of information has not always been from the West to the East (Sen, 2002).[12]

What makes the current era unique and different from prior eras of globalization? Alternatively, what has been the driver of the shift from the scientific frontier to the algorithmic? The primary difference between the algorithmic frontier and the earlier era of the scientific frontier is the rise of distributed networks of production and innovation (Auerswald & Branscomb, 2008). In this view, globalization is really a process of interdependence and interconnectedness (Acs & Preston,

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[11] Foreign direct investment as a share of GDP, starting with the third wave of democracy in 1974, accelerated from 5.2% between 1950 and 1973 to 25.3% from 1974 to 2007 (WTO, 2008, p. 15).

[12] Sen (2002) cites as examples the transfer of knowledge of mathematics (decimal system) from India to the West, and of paper, gunpowder, and the printing press from China to Western Europe, among other technologies.

1997). The real driver expanding the algorithmic frontier is the increasing reach of collaborative networks of all kinds—particularly production, but also research.[13] As Branstetter, Li, and Veloso write in this volume, “The important role of multi-national corporations in the international invention explosions in China and India may help to explain why they are occurring at an early stage of economic development.” The production networks themselves are the direct result of standardization. For that reason, we assert that globalization is really standardization.

The transformation of IBM, which embodied the large-scale research-based firm of the scientific era, epitomizes the structural evolution that has taken place on a global scale.[14] Once the epitome of the industrial giant with an international reach driven by science-based innovation, IBM is today best “understood as global rather than multinational” (Palmisano, 2006, p. 127). The change involves sourcing production from a variety of firms in different countries, and marketing the resulting products globally as well. Palmisano describes the integration of China and India into the global economy as the “most visible signs of this change.” Between 2002 and 2003, he writes, foreign firms built sixty thousand manufacturing plants in China, many of them targeting global markets. Similar ties with firms in India are expanding the base from which global products and services are created.

Shared standards and business practices have been a precondition to this process of economic integration. In contrast with the traditional multinational assembly of subsidiaries, the global enterprise is a flexible assembly of firms around the world, with skills and capacity that can be drawn upon for the most efficient combination of business processes.

In our most recent period of globalization, the role of standards grew in importance as trade resumed in the post-WWII era. High transactions costs initially impeded trade, despite the emphasis on open markets and the resumption of (mostly) free trade through the Bretton Woods institutions. Some of the impediments stemmed from difficulties at the transition points of the global economy rather than tariff levels per se. The growth of supply chains and the role of standardization in facilitating efficient chains thus have been critical to the functioning of global

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[13] The resulting diversity of production levels is thus a result of the degree of incumbency and competition in an industry (Auerswald, 2012).

[14] At its peak in the 1960s-1970s, IBM was investing half of its net income on developing new products and spent more money on computing research than the federal government (Acs, 2013, p. 72.)

markets. Standardization of containerized shipping (Levinson, 2008) and pallets (Vanderbilt, 2012; Raballand & Aldaz-Carroll, 2007), two seemingly innocuous and generally unheralded developments, combined to transform global trading patterns. Entrepreneurs Malcolm Mclean in shipping and Norman Cahners in pallets, performing an essential operations research task, were responsible for these two transformations (Levinson, 2008; Vanderbilt, 2012). As a result of these standards, global shipping costs fell from over $5.86 per ton in the 1950s to about $0.16 dollars today (Murphy & Yates, 2009, p. 50).

The European adoption of the global system for mobile communications (GSM) standards is another example of the benefit of standards harmonization. While Europe achieved rapid advances in mobile technology, in the U.S. the FCC decided not to adopt an official cellular standard but to allow competition to select the optimal technology (Guasch et al., 2007). As a result, the market became segmented in the U.S., with different companies each lobbying for their proprietary standards. Adoption of cellular technology was slower in the U.S. as a result.[15]

More generally, the diffusion of mobile phones based on the two dominant standards (GSM and CDMA) is one of the most astounding cases of the expansion of the algorithmic frontier. In 2000 there were just fewer than 740 million mobile phone subscriptions, or roughly 16 per 100 inhabitants;[16] by 2012 there were more than 6.3 billion subscriptions (101 per 100 inhabitants). There is dispersed ownership across countries, but the uptake has been faster than anyone foresaw. The rapid diffusion was enabled by the adoption of technical standards that enable communications to occur over the network. Once the technology was standardized, it was comparatively easy for firms like Vodafone to move into untested markets. Rather than building extensive landline networks, developing countries built mobile towers and "leap-frogged" the older technology. The fastest growing mobile markets between 2002 and 2008 were in Africa, India, and China (Kalba, 2008; Sauter & Watson, 2008, p. 20). This is even true when we look at hostile, conflict-ridden environments such as Afghanistan and Pakistan (Auerswald, 2012). In

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[15] Over time this has been important, but because mobile standards are updated almost every ten years, the lock-in effect from settling on a potentially inferior standard is reduced; the U.S. appears to have become slightly more innovative recently (Dodd, 2012).

[16] Data from ITU (2013). Retrieved from http://www.itu.int/en/ITU-D/Statistics/Documents/statistics/2013/Mobile_cellular_2000-2012.xls.

Afghanistan, the number of subscriptions rose from under 30,000 in 2000 to more than 18 million in 2012. The case of Pakistan is even more remarkable: in 2000 the number of mobile subscriptions was 360,000; it rose to more than 120 million by 2012.

Despite the importance of standards, empirical research on standardization has made little progress since the late 1990s.[17] The adoption of reference technical standards, however, has proved difficult to measure. The empirical literature lacks natural and direct measures of the intensity of reference technical standardization (Clougherty & Grajek, 2012).

The rapid globalization and economic integration witnessed in recent years has created the need for standardization of a different type: that of management systems, which are essentially the interface layer between production subroutines. As Palmisano (2006, p. 130) states:

> [S]tarting in the early 1970s, the revolution in information technology (it) improved the quality and cut the cost of global communications and business operations by several orders of magnitude. Most important, it standardized technologies and business operations all over the world, interlinking and facilitating work both within and among companies. This combination of shared technologies and shared business standards, all built on top of a global it and communications infrastructure, changed the sorts of globalization that companies found possible.

With diverse productivity levels among firms, companies in “ascending markets” within the developing world have faced significant signaling challenges in the global marketplace. In addition, they must manage information and compliance costs and adopt a common language of exchange. The result has been a remarkable increase in certain standards, or norms, issued by international organizations.

Few cross-county measures exist that would even correlate with the growth of standards to enable interoperability. One exception is data on process certifications offered by the ISO.

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[17] Among the few firm-level studies of the decision to seek certification from global standards bodies are Chen et al. (2008) and Guasch et al. (2007).

Data from the International Standards Organization to Map the Movement of the Algorithmic Frontier

Just two years after Vannevar Bush published *Science the Endless Frontier* (1945), the United States, along with the other leading powers, created the International Organization for Standardization.[18] This complemented existing national standards bodies, such as the American National Standards Institute in the United States and the British Standards Institute in the United Kingdom, but it provided a wider forum for the agreement, adoption, and dissemination of standards.

According to ISO (2004), standards are a "document, established by consensus and approved by a recognized body, that provides, for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context." The term "optimum order" is significant. The standardization of interfaces allows for a system-wide optimization of the balance between order and flexibility in the supply chain (Auerswald, 2012).

Today the two most common ISO management standards are the ISO 9000 and 14000 series, which have been supplemented in recent years by standards for information security management, food security, and, most recently, social responsibility (ISO 26000), among others.[19] Our focus will be on the ISO 9000 series of quality management standards because, among the ISO standards, they are the most general standards related to management of integration with other subroutines within a global supply chain.

ISO 9000 addresses "quality management," which covers what an organization does to fulfill quality and regulatory requirements, enhance customer satisfaction, and achieve continual

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[18] According to the ISO, "because 'International Organization for Standardization' would have different acronyms in different languages ('IOS' in English, 'OIN' in French for *Organisation internationale de normalisation*), its founders decided to give it an all-purpose shortened name. They chose 'ISO,' derived from the Greek *isos,* meaning 'equal.' Whatever the country, whatever the language, the short form of the organization's name is always ISO." From http://www.iso.org/iso/about/discover-iso_isos-name.htm.

[19] Appendix I provides a concise description of the quality-management standards.

performance improvement.[20] ISO 9000 consists of internationally agreed to principles and requirements for managing an enterprise so as to earn the confidence of customers and markets (Furusten, 2002).

The main benefit of certification is the widening market opportunities rather than improvements in quality itself (Breka, 1994; Litsikas, 1997; Rao et al., 1997). Terlaak and King (2006), however, argue that there must be other tangible financial incentives to justify the outlay of substantial organizational resources to obtain certification.[21] We hypothesize that the process of seeking ISO certification provides at least three categories of benefits to firms.

First, evidence of having completed ISO certification eases entry into production and distribution networks on a global scale because it signals a willingness and a capability for low-transactions-cost integration into global production networks. Foreign agents have limited information about the capabilities of potential partners. While there are alternative mechanisms to assess and verify whether companies can deliver on their market commitments, certification with a globally recognized quality standard appear to be considered a positive signal. Theoretically, Terlaak and King (2006) suggest that certification with a management-quality standard may reduce information asymmetries in supply chains and bestow a competitive advantage on certified firms. The pursuit of certification alone may communicate unobservable desirable organizational attributes. Companies submitting to the scrutiny of the ISO certification process may reveal information about their characteristics (particularly cost profile) to potential transaction partners.

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[20] The immediate predecessor to ISO 9000 was BS 5750, a quality-management standard in Great Britain. Since its inception, ISO 9000 quality-management standards have transitioned beyond manufacturing and have become widespread across industries, including the service sector, as can be seen in Table 4. Despite the widespread adoption of these standards across industries, the existing literature has been concerned with the trade effects from the adoption of these standards in agriculture (Swann, 2009).

[21] The authors examined the effects of ISO 9000 certification on the competitive advantage of U.S. manufacturing firms. Using a panel of firms, they found that firms grew faster after ISO certification, but found no effect of operational improvements. Importantly, firms' growth effect was greater in situations where buyers faced greater difficulties in acquiring information about suppliers.

Second, it is at least possible (though not demonstrated) that the process of completing ISO certification serves as a learning tool that materially improves productive efficiency. Past studies have suggested that achieving ISO certification standards induces organizations to adopt practices that improve operational performance (Litsikas, 1997; Rao et al., 1997). The outstanding question is whether certification signals actual development of capabilities. Since the process requires companies to undergo extensive restructuring of their organization and operational processes, does it naturally lead to better capabilities? The process of certification may help enterprises extract optimal returns from their stocks of knowledge by improving organizational adaptability.

Third, along similar lines, it is possible that the process of obtaining ISO certification increases functional compatibility and interoperability according to global norms, and thus eases adoption of platform technologies, or general-purpose technologies.

The literature therefore suggests that ISO certification may be more effective in expanding markets than improving productivity. This is in line with our production recipes model, in which organizations pursue ISO certification primarily to facilitate or enhance their participation in global supply chains. Increasing sales and exporting activity are two possible benefits of certification. We believe that the certification process leads to the kind of organizational improvements required for participation in global markets. Whether financial benefits accompany this outcome is an empirical question.

The ISO 9000 series quality-management standards are diffused across more than 170 countries, but certification remains concentrated. Table 2 presents the top ten countries by certified firms, which account for more than two-thirds of the total certifications in 2011. There are two notable trends in these data. First, the new frontier in quality processes, or process design algorithms, has expanded globally through distributed networks of production. The fast growing BRICS constitute more than a third of total certifications, and three countries are in the top ten: Brazil (#9), Russia (#14), India (#7), China (#1), and South Africa (#39). South Korea, arguably one of the most impressive growth stories of the twentieth century, rounds out the top ten.

The change in the composition of the top ten countries between 1993, the first year for which data is available, and 2011 is striking. In 1993 the top ten countries were, in order, the United Kingdom, Australia, United States, France, Germany, Netherlands, South Africa, Ireland, Italy, and Denmark; South Africa was the only nondeveloped country included and one of only a few outside Western Europe. The wide acceptance and adoption of the ISO series expanded the algorithmic frontier and expanded the capabilities and opportunities in the developing world.

[Insert Table 2 here]

The distributed nature of production networks is clear from this data. More than one-quarter of firms with foreign ownership (the majority-owned foreign affiliates of parent companies) are ISO certified.[22] However, the ISO story is not limited to the case of the parent companies of multinationals in developed countries imposing quality standards on their foreign subsidiaries. Interestingly, the top-certified developing countries, or ascending markets, did not dominate firms by country in 2011. Instead, industrialized firms in Japan, Western Europe, and the United States (#11) also found benefits from adopting process standards, such as the ISO 9000 series. Firms seeking ISO certification in the developed world include those at the technological frontier, such as General Electric (in energy, health care, and related services) and Netgear (ICT), which proudly proclaim their ISO certifications on their websites. Even in cases where product quality is undisputed, managers find the process of codifying the production process to be a useful activity (Corbett & Luca, 2002).

Figure 7 graphs the adoption rates of a broader range of ISO quality-management standards. The data follow a similar pattern, with initial adoption in Western Europe followed by gradual adoption outside. This process appears to have accelerated following the successful implementation of the ISO 9001 set of standards.

[Insert Figure 7 here]

To understand these data further, the sections that follow present basic regression analyses to examine the correlates of the diffusion process.

[Insert table 3 here]

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[22] Authors' calculations from World Bank Enterprise Survey (enterprisesurveys.org); majority-owned foreign affiliates are defined as businesses in which an investor of another country holds at least 10% voting ownership (BEA, 2013).

Empirical Estimation of Cross-Country Adoption Processes

A credible certification process could facilitate entry into new markets or the expansion of existing ones. Our hypothesis is that this dynamic is more pertinent to companies in economies with limited alternative methods of signaling firm capability, specifically where national quality standards bodies and market institutions are weaker. Enterprises in economies with stronger and broadly recognized national standards institutions do not need external validation to conduct business. The availability and integrity of alternative standards systems is, in turn, positively associated with the level of institutional development.

Similarly, assuming that stylized facts from economic development literature are correct, the level of institutional development is positively correlated to the level of economic development (income). In the presence of institutional measures, however, the effect of income level on ISO standards adoption is ambiguous. Because the standards certification process involves substantial financial outlay, firms in richer countries wound find adoption more affordable than their counterparts in poorer countries. We expect this latter effect to overwhelm the institutional effect.

The quality of institutions should also correlate strongly with a country's proximity to global markets. The literature suggests that greater trade and foreign direct investment (FDI) activity is positively correlated with the adoption of ISO standards; that is, standards certifications follow FDI, specifically if the origin of the FDI is an ISO-rich country (Prakash & Potoski, 2007). The World Bank Enterprise Surveys data show a strong positive correlation between ISO certification and exporting activity. Eighty-eight percent of the time (significant at .01 level), regions with higher proportions of firms with standards certification also recorded greater exporting activity.[23]

In increasingly globalized supply chains, where market exchange occurs among actors from diverse institutional environments, participation in international trade and investment (trade openness) means that even countries with credible national standards alternatives would be compelled to adopt international standards. In such cases, the trade effect would likely overwhelm the institutional effect, and hence positive correlation with the adoption of ISO standards. Moreover, the substantial direct cost of attaining and maintaining certification makes

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[23] Authors' pairwise correlation analysis of data from the World Bank Enterprise Surveys, available at http://www.enterprisesurveys.org.

firm size an important factor in the decision to adopt ISO standards. Larger firms are more likely to invest in certification than smaller ones. Without firm-level panel data to test this hypothesis, a more useful approach is to examine the size distribution of a country's business sector. A rough indicator is the proportion of businesses classified as micro, small, and medium enterprises (MSMEs). It is natural that countries where the business sector is predominantly MSMEs would have fewer large firms and, hence, lower certification intensity than those with more large firms.

From the foregoing, the exact effect of the institutional and economic environment on ISO certification is not clear. We hypothesize that the global diffusion of certification is only weakly correlated to institutional quality. This effect is particularly confounded by the influence of income and trade. A priori, we expect certification to increase with increases in income and trade openness. Organizations in countries that are intensely engaged with global supply chains would most likely find international standardization unavoidable and, due to demonstration effect, would induce their domestic competitors to follow by pursuing certification. As shown by Prakash and Potoski (2007), the certification intensity of trading partners has a strong influence on adoption patterns. An analysis of the connection between bilateral trade-flow patterns and ISO certification is beyond the scope of this paper.

One way to examine cross-country variations in the adoption of standards certification is through regression analysis. We generate a cross-sectional time series (panel) data and specify a parsimonious regression model to evaluate our hypotheses. The basic equation is written as

$$y_{it} = x\beta_{it} + \varepsilon_{it}$$

where $i = 1,\ldots,m$ is the number of units (or panels); $t = 1,\ldots,T_i$; T_i is the number of periods in panel i; and ε_{it} is a disturbance that may be auto-correlated along t or contemporaneously correlated across i. We specify a generalized linear model of y_{it} with covariates x_{it} as

$$g\{E(y_{it})\} = x\beta_{it},\ y \sim F \text{ with parameters } \theta_{it}$$

for $i = 1,\ldots,m$ and $t = 1,\ldots,n_i$, with n_i observations for each group identifier i; $g(\bullet)$ is the link function and F is the distributional family. Substituting various definitions for $g(\bullet)$ and F results in a suite of models. For example, if y_{it} is distributed Gaussian (normal) and $g(\bullet)$ is the identity function, we have

$$E(y_{it})\} = x\beta_{it},\ y \sim N(\,),$$

which yields a linear, random-effects, or other regression-related models, depending on the correlation structure assumed.

Since our data consist of panels of ISO certification counts, the most appropriate specification of the generalized equation is the suite of count data regression models. Our preferred specification is the population-averaged panel-data negative binomial family that fits a generalized linear regression model and allows one to specify the within-group panel correlation structure. It is specified thus,

$$\begin{aligned}\ln iso_{it} = \alpha + \beta_1 \ln gdp_{it} + \beta_2 \ln pop_{it} + \beta_3 educ_{it} \\ + \beta_4 \ln inst_{it} + \beta_5 \ln tradop_{it} + region + \varepsilon_{it}\end{aligned}$$

where *iso* is the total number of ISO certifications, *gdp* is the real GDP per capita, *educ* is the average total years of education for males, *inst* is ICRG institutional quality indicator, *tradop* is PWT trade openness index, and *region* is the global subregion in which a country is located; *it* are country-year constants. We assume the within-group correlation parameter is common for all panels and hence specify the model with AR(1) correlation structure. We believe that this is a reasonable assumption, since the individual correlations are nearly equal and our time series is short (less than twenty years). This provides us with more information to produce a more reasonable estimate of the regression coefficients.

In total, our data consist of 144 countries over 18 years (1993-2010). Because of missing data on various key variables, the effective estimation sample used in most regressions is 126 countries over 18 years. The dependent variable is the count of ISO certifications per country per year. These data refer to the ISO 9000 series, the oldest and most widespread of all the ISO quality standards. Several covariates of ISO certification adoption, including country characteristics such as population, income, institutions, human capital, and industry and trade performance, are considered (see definitions in Table 4). Starting with measures of economic size, larger economies are assumed to generate more economic activity, hence more candidates for ISO certification. Real GDP per-capita and real GDP growth constitute our measures of economic size.

Innovation activity is associated with human capital capabilities that determine the absorptive capacity of potential adopters. Our preferred indicator of human capital is the average number of years of education for males. Countries with a more educated labor force would be more open to and more capable of implanting ISO certification. If our theoretical model is correct, then certification is closely linked to an economy's participation in global markets. International trade activity is one of the indicators of global market linkages. The PWT Trade Openness index, constructed as the ratio of the total of exports and imports to total nominal GDP, is the most common measure of global engagement.

[Insert Table 4 Here]

Other variables represent a country's quality of institutions. Institutions are key drivers of economic development and, specifically, innovation, whose performance is dependent on the quality of institutions governing knowledge exchange and information flow. Several measures of institutional quality have found extensive use in the literature. For this paper, the ICRG Quality of Governance Index is a widely accepted measure of institutions. Finally, following Comin and Hobijn (2004), we demean our measure of ISO adoption by controlling for the average regional adoption rate. A five-category indicator variable for global subregions captures regional differences in diffusion patterns. Apart from ISO counts, the rest of the data is extracted from the World Development Indicators and the Quality of Government (QoG) Dataset (Teorell et al., 2011).

Estimation Results

Summary statistics for variables used in estimating cross-country variations in ISO certification are contained in Table 5. It shows the mean, standard deviation, the minimum and maximum, and the number of observation.

[Insert Table 5 Here]

The regression estimation results are contained in Table 6. The first column is the base case with country size, education, and region variables. Column 2 introduces institutions, and column 3 is the full model with trade openness. The last column is the final model excluding institutions. The equation is estimated using individual years as the scale parameter, a measure of exposure.

[Insert Table 6 Here]

Estimation results suggest that our full models explain over 80 percent the variation in ISO certification across countries. Holding other variables constant, our results show that firms in Africa and West Asia, Latin America and the Caribbean, and the Far East are the leading adopters of ISO standards certification. Europe and North American firms are lagging, with North American firms the least likely to adopt ISO certification. We expected the availability of credible alternative national certification systems to increase with levels of institutional development, which would in turn diminish incentives for ISO certification. Assuming firms in Europe and North America operate under relatively strong standards institutions, our result appears to support this hypothesis. On closer scrutiny, however, the coefficient on the quality of institutions is negative and insignificant, suggesting that the level of institutional development is not the key correlate of adoption. Significant correlates of adoption include country size (per-capita real GDP and population), level of educational attainment, and openness to trade. As expected, the effects of income and trade openness are particularly strong. A 10% increase in per-capita GDP and trade openness is associated with 5.4% and 5.9% increases in the number of ISO certificates, respectively.

The result on the education variable confirms that standards adoption increases with a country's level of human capital. An additional year of average education is associated with between a 9 and 25 percentage point increase in certifications.[24] The significant effect of education is least surprising because the innovation literature is unanimous in finding that the quality of human capital is an important driver of innovation. Moreover, since our recipes model entails a high degree of tacit knowledge, it is natural that the ISO certification process would be knowledge intensive. This a phenomenon common to its predecessor models of innovation.

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[24] The table with 95% confidence intervals is not shown but is available upon request.

As countries participate more in global supply chains, they find international standardization more appealing. Globalization seems, indeed, to correlate with standardization.

Conclusion

Vannevar Bush is best known as the author of *Science and the Endless Frontier,* which provides the inspiration for this volume; for his work during World War II as director of the U.S. Office of Scientific Research and Development; and for his part in the development of analogue computers. However, one of Bush's most powerful and enduring contributions may have been that which he made via a July 1945, *Life* magazine article titled, "As We May Think," which was published just weeks before VJ Day. As he looked ahead to the frontier of societal advance in the postwar era, his emphasis was not on the products of publicly funded science but on the capacities of privately produced tools: "The world has arrived at an age of cheap complex devices of great reliability; and something is bound to come of it." In that essay, he envisions how existing low-cost technologies might be further advanced and networked into a system for the storage and retrieval of ideas, which he called the "memex": "Wholly new forms of encyclopedias will appear, ready made with a mesh of associative trails running through them, ready to be dropped into the memex and there amplified." The existence of this tool would allow for a continuation of the forward progress of human inquiry: "[Man] has built a civilization so complex that he needs to mechanize his records more fully if he is to push his experiment to its logical conclusion and not merely become bogged down part way there by overtaxing his limited memory."

Among those who read this essay in *Life* magazine was a 25-year-old aerospace engineer named Douglas Engelbart. Engelbart was so taken by the vision set forth in "As We May Think" that he redirected his career to making that vision a reality. In 1968, at the fall Joint Computer Conference (a semiannual meeting of the then-major computing societies held in San Francisco), Engelbart delivered to over a thousand participants a presentation that set forth for the first time the core elements of the user architecture that would define the information revolution in decades to come: the computer mouse, text editing, hypertext, windowing, and video conferencing.

This story of serendipitous inspiration and invention illustrates the fundamental link between the science-based frontier and the algorithmic frontier, as well as the differences between the two. Although Vannevar Bush conceived and led the most ambitious and large-scale R&D programs ever undertaken at that time (notably including the Manhattan Project), he was able to look ahead to an era where the greatest progress in science-based discovery would be enabled by lowering the cost of storing and sharing ideas horizontally among scientists. Douglas Engelbart further democratized that vision, prototyping an architecture of interaction through standardized interfaces that we have come to know simply as information and communications technology.

This anecdote also suggests that the legacy of Vannevar Bush is arguably not about the importance of science-based research per se, any more than it is about the creation of the National Science Foundation and the decades of discovery it has enabled. Rather, it is about the importance of understanding that, at any point in time, the frontier of social attainment is changing. When Bush led the committee that produced *Science the Endless Frontier* in 1945, the changing frontier consisted of the transition of an economy based on industrial growth through economies of scale to one based on improved goods and services through science-based innovation. Today, as we have sought to describe above, the frontier is changing again.

Just as the advent of science-based innovation motivated an earlier generation of economists to create new theoretical frameworks and analytic techniques to understand the rate and direction of technical change, so the advance of the algorithmic frontier is challenging the current generation of economists to respond in a like manner. The existence of this volume and the work it contains provide some evidence of the will that exists to meet that challenge.

APPENDIX 1: ISO Management Standards
(*Source:* ISO 2011)

ISO 9001:2008

ISO 9001:2008 gives the requirements for quality management systems. Certification to the standard is used in global supply chains to provide assurance about suppliers' ability to satisfy quality requirements and to enhance customer satisfaction in supplier-customer relationships.

Up to the end of December 2011, at least 1,111,698 certificates had been issued in 180 countries and economies, two more than in the previous year. The 2011 total represents a decrease of 1% (-6,812) over 2010.

The top three countries for the total number of certificates issued were China, Italy, and Japan, while the top three for growth in the number of certificates in 2011 were Italy, China, and Romania.

ISO 14001:2004

ISO 14001:2004, which gives the requirements for environmental management systems, retains its global relevance for organizations wishing to operate in an environmentally sustainable manner.

Up to the end of December 2011, at least 267,457 ISO 14001:2004 certificates had been issued, a growth of 6% (+15,909), in 158 countries, two more than in the previous year.

The top three countries for the total number of certificates were China, Japan, and Italy, while the top three for growth in the number of certificates in 2011 were China, Italy, and France.

ISO/TS 16949:2009

ISO/TS 16949:2009 gives the requirements for the application of ISO 9001:2008 by suppliers in the automotive sector. Up to the end of December 2011, at least 47,512 ISO/TS 16949:2009 certificates, a growth of 8% (+3,566), had been issued in 86 countries and economies, two more than in the previous year.

The top three countries for the total number of certificates were China, the Republic of Korea, and the U.S., while the top three for growth in the number of certificates in 2011 were China, India, and the Republic of Korea.

ISO 13485:2003

ISO 13485:2003 gives quality-management requirements for the medical device sector for regulatory purposes. Up to the end of December 2011, at least 20,034 ISO 13485:2003 certificates, growth of 6% (+1,200) had been issued in 95 countries and economies, two more than in the previous year.

The top three countries for the total number of certificates were the U.S., Germany, and the United Kingdom, while the top three for growth in the number of certificates in 2011 were the U.S., Israel, and Japan.

ISO/IEC 27001:2005

ISO/IEC 27001:2005 gives the requirements for information security-management systems. At the end of December 2011, at least 17,509 ISO/IEC 27001:2005 certificates, a growth of 12% (1,883) had been issued in one hundred countries and economies, eight less than in the previous year.

The top three countries for the total number of certificates were Japan, India, and the United Kingdom, while the top three for growth in the number of certificates in 2011 were Japan, Romania, and China.

ISO 22000:2005

ISO 22000:2005 gives the requirements for food-safety management systems. Up to the end of December 2011, at least 19,980 ISO 22000:2005 certificates, a growth of 8% (1,400) had been issued in 140 countries and economies, two more than in the previous year.

The top three countries for the total number of certificates were China, Greece, and Romania, while the top three for growth in the number of certificates in 2011 were China, Italy, and Romania.

ISO 50001:2011

ISO 50001:2011 gives the requirements for energy management systems. It was published in mid-June 2011. Up to the end of December 2011, at least 461 ISO 50001:2011 certificates had been issued in 32 countries and economies. The top three countries for the total number of certificates were Spain, Romania, and Sweden.

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Tables and Figures

Table 1: R&D and GDP

U.S. average annual real GDP growth rates, unadjusted and R&D adjusted: 1959–2007
(Percent)

Period	Unadjusted real GDP[a]	R&D-adjusted real GDP[b]	Difference
1959–2007	3.32	3.39	0.07
1959–73	4.20	4.33	0.13
1974–94	3.02	3.03	0.01
1995–2001	3.76	3.93	0.17
2002–07	2.75	2.87	0.12

Source: Lee & Schmidt (2010); Bureau of Economic Analysis; National Science Foundation Science and Engineering Indicators, 2012

Table 2: Top 10 Countries for ISO 9001 Certificates, 2011

Rank	Country	Number of certificates
1	China	328,213
2	Italy	171,947
3	Japan	56,912
4	Spain	53,057
5	Germany	49,450
6	United Kingdom	43,564
7	India	29,574
8	France	29,215
9	Brazil	28,325
10	Korea, Republic of	27,284
	Sum	817,631 (73.5%)
	All Others	294,067 (26.5%)
	Total	1,111,698

Source: ISO Survey 2011

Table 3: Top Five Industrial Sectors for ISO 9001 Certificates 2011

	Sector	Number of certificates
1	Services	203,970
2	Basic metal and fabricated metal products	101,848
3	Construction	83,864
4	Electrical and optical equipment	79,237
5	Machinery and equipment	58,427

Source: ISO Survey 2011

Table 4: Definition of Variables in Cross-Country Diffusion Analysis

Dependent variable:	
ISO certifications	Number of ISO certifications per country (log)
Independent variables:	
GDP per capita	Annual real GDP per capita, constant US$ (log)
GDP growth	Annual growth rate of total real GDP (%)
Population	Total population (log)
Trade Openness	PWT Trade Openness Index (log)
Human capital	Average years of education for males
Quality of institutions	The ICRG Quality of Government Index (log)

Table 5: Summary Statistics of Variables in Cross-Country ISO Certification Adoption

Variable		Mean	Std. Dev.	Min	Max	Obs
ISO certificates	Overall	3778.4	16430.51	0.5	328213.5	N = 2736
	Between		12305.33	0.71	107673.3	n = 144
	Within		10933.30	-103859.4	224318.6	T = 19
Real per-capita GDP	Overall	10664.8	12580.85	100.9	74163.57	N = 2590
	Between		12425.47	301.73	63493.78	n = 144
	Within		2189.35	-10475.97	22920.28	T = 18
Population	Overall	4.2E+07	1.42E+08	263725	1.34E+09	N = 2592
	Between		1.42E+08	288334.1	1.27E+09	n = 144
	Within		9276385	-1.08E+08	1.88E+08	T = 18
ICRG QoG Index	Overall	0.557	0.199	0.042	1	N = 2268
	Between		0.188	0.125	0.997	n = 126
	Within		0.066	0.286	0.846	T = 18
Years education of males	Overall	7.55	3.15	0.7	14.2	N = 2592
	Between		3.11	1.08	13.58	n = 144
	Within		0.57	5.97	8.94	T = 18
PWT trade openness index	Overall	84.17	45.79	14.78	456.56	N = 2592
	Between		43.00	22.88	376.87	n = 144
	Within		16.11	-1.319	199.89	T = 18

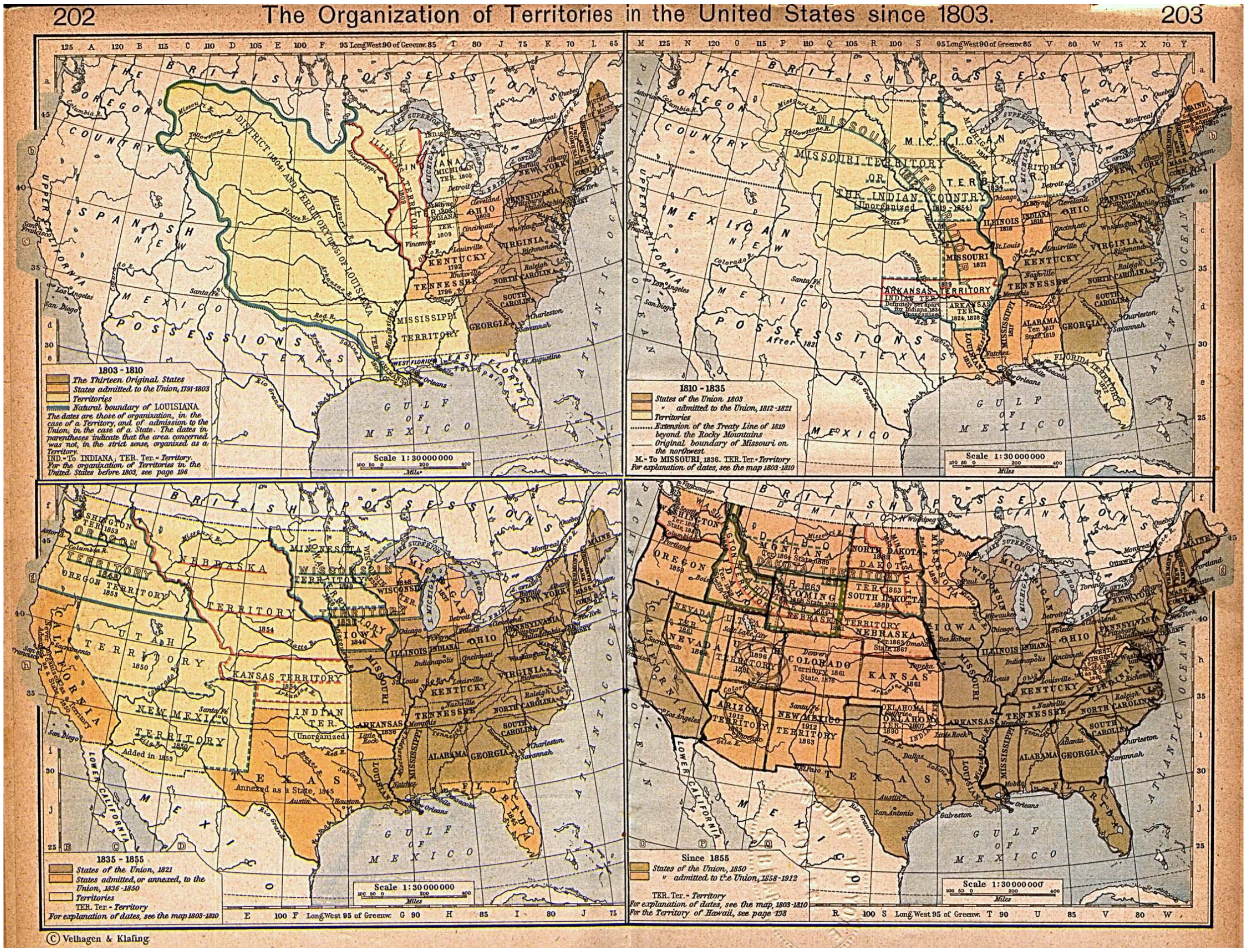
Source: Authors' own analysis of data

Table 6: GEE Model of Cross-Country ISO Certification Counts

	(1)	*(2)*	*(3)*	*(4)*
Real per-capita GDP (log)	0.557	0.543	0.530	0.544
	[0.068]**	[0.071]**	[0.064]**	[0.056]**
Population (log)	0.386	0.386	0.487	0.487
	[0.037]**	[0.047]**	[0.059]**	[0.051]**
Mean years education for males	0.222	0.235	0.191	0.169
	[0.045]**	[0.046]**	[0.044]**	[0.043]**
ICRG quality of governance index (log)		-0.175	-0.137	
		[0.148]	[0.143]	
PWT trade openness (log)			0.540	0.589
			[0.145]**	[0.144]**
Region (Base: Africa/West Asia):				
Latin America and the Caribbean	-0.088	-0.156	0.019	0.103
	[0.132]	[0.134]	[0.132]	[0.126]
North America	-1.371	-1.382	-1.138	-1.066
	[0.664]*	[0.661]*	[0.552]*	[0.520]*
Europe	-0.663	-0.698	-0.488	-0.417
	[0.239]**	[0.245]**	[0.224]*	[0.199]*
Far East	-0.100	-0.175	-0.461	-0.327
	[0.186]	[0.251]	[0.220]*	[0.190]+
Constant	-19.179	-19.235	-22.823	-22.942
	[0.945]**	[1.147]**	[1.623]**	[1.398]**
Wald chi2	257.80	194.04	259.89	340.99
Prob>chi2	0.00	0.00	0.00	0.00
N	2,590	2,267	2,267	2,590

+ $p<0.1$; * $p<0.05$; ** $p<0.01$
Bootsrap (300 reps) standard errors are in brackets.
Dependent variable = log ISO counts
Scale parameter (year)

Figure 1: Map of Movement of the Western Frontier. I (top left) 1803-1810; II (top right) 1810-1835; III (bottom left) 1835-1855; IV (bottom right) Since 1855.



Source: Shepherd (1923, p. 202)

Figure 2: Ngram, "Carriage, Automobile, Airplane, and Rocket"

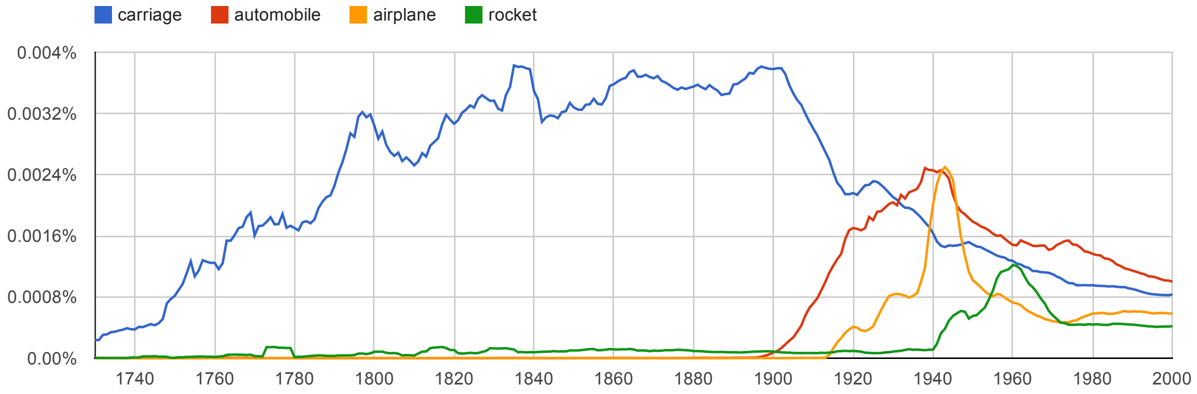
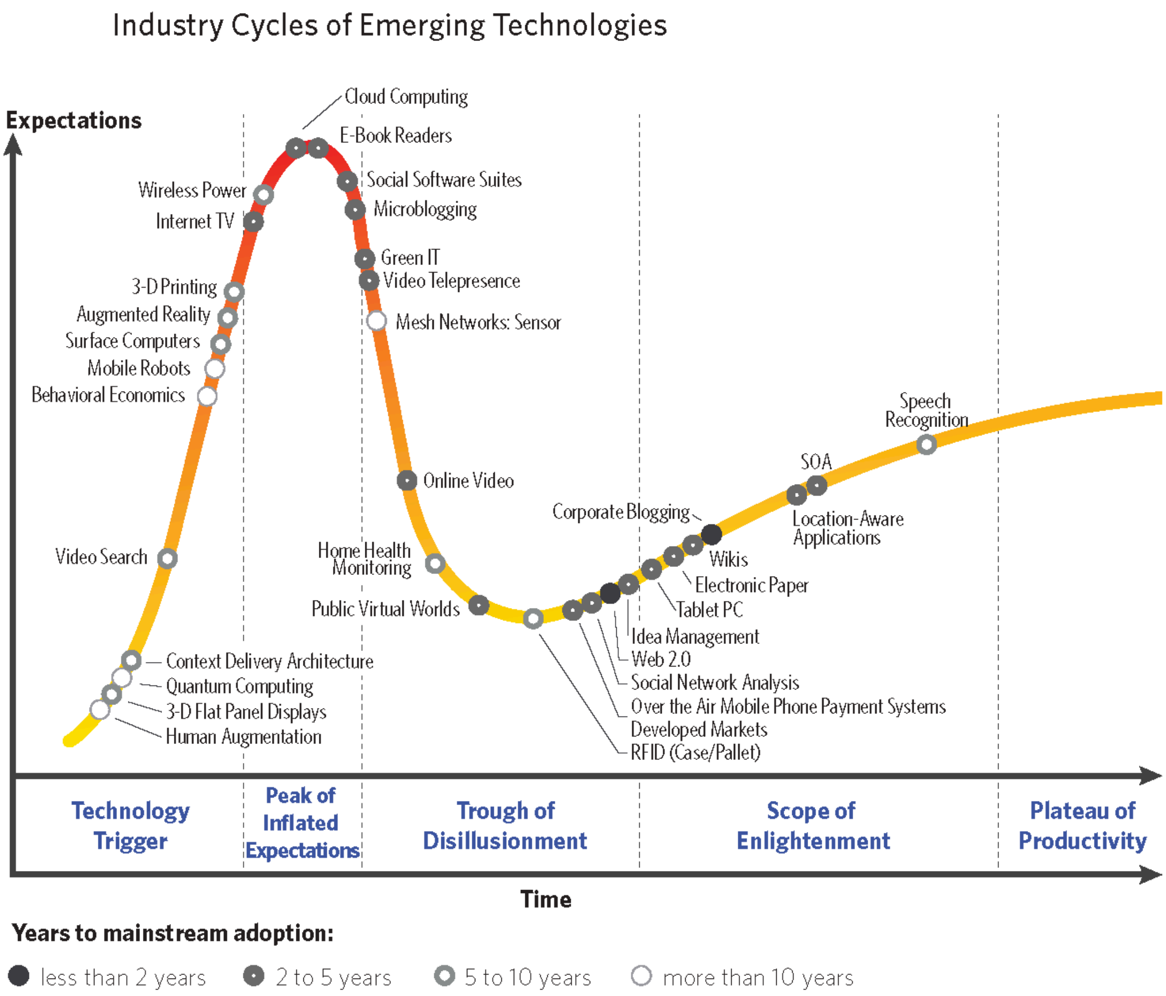


Figure 3: Gartner "Hype Cycle"



Note: For more on hype cycles, see http://www.gartner.com/technology/research/methodologies/hype-cycle.jsp

Figure 4: Ngram, “Research, Technology”

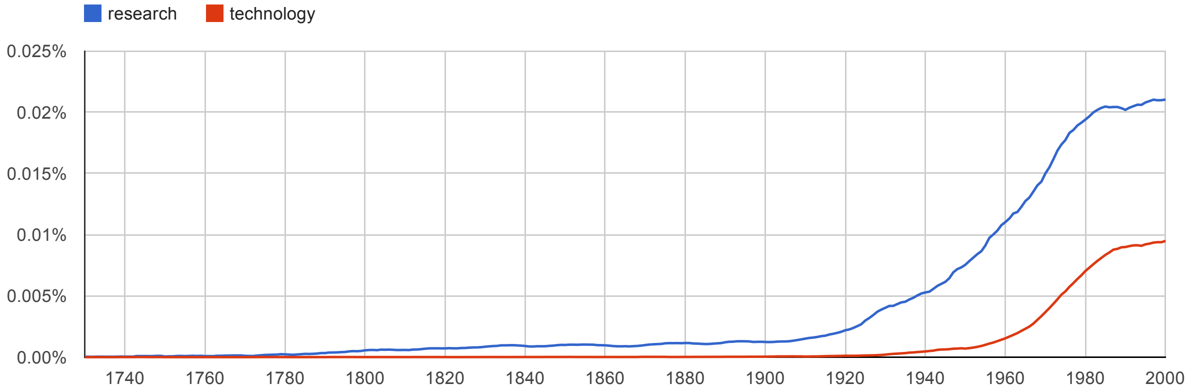


Figure 5: Post-WWII System of Science-Based Innovation

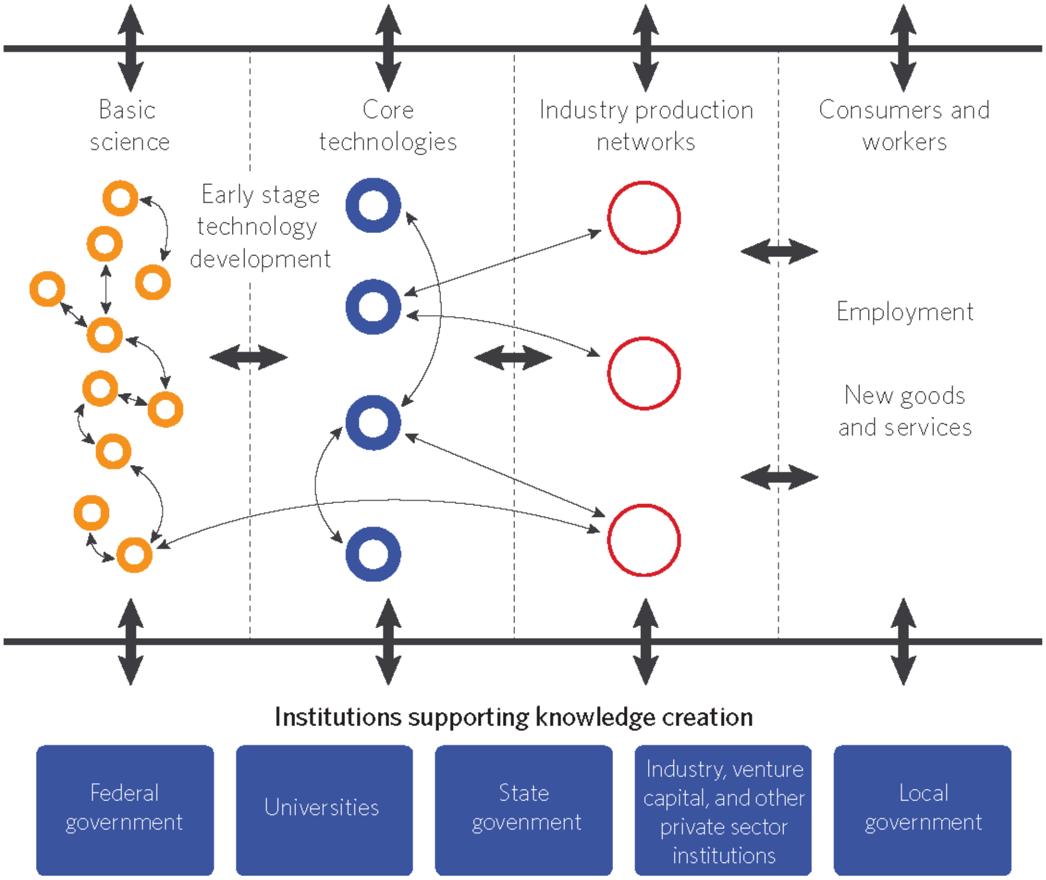
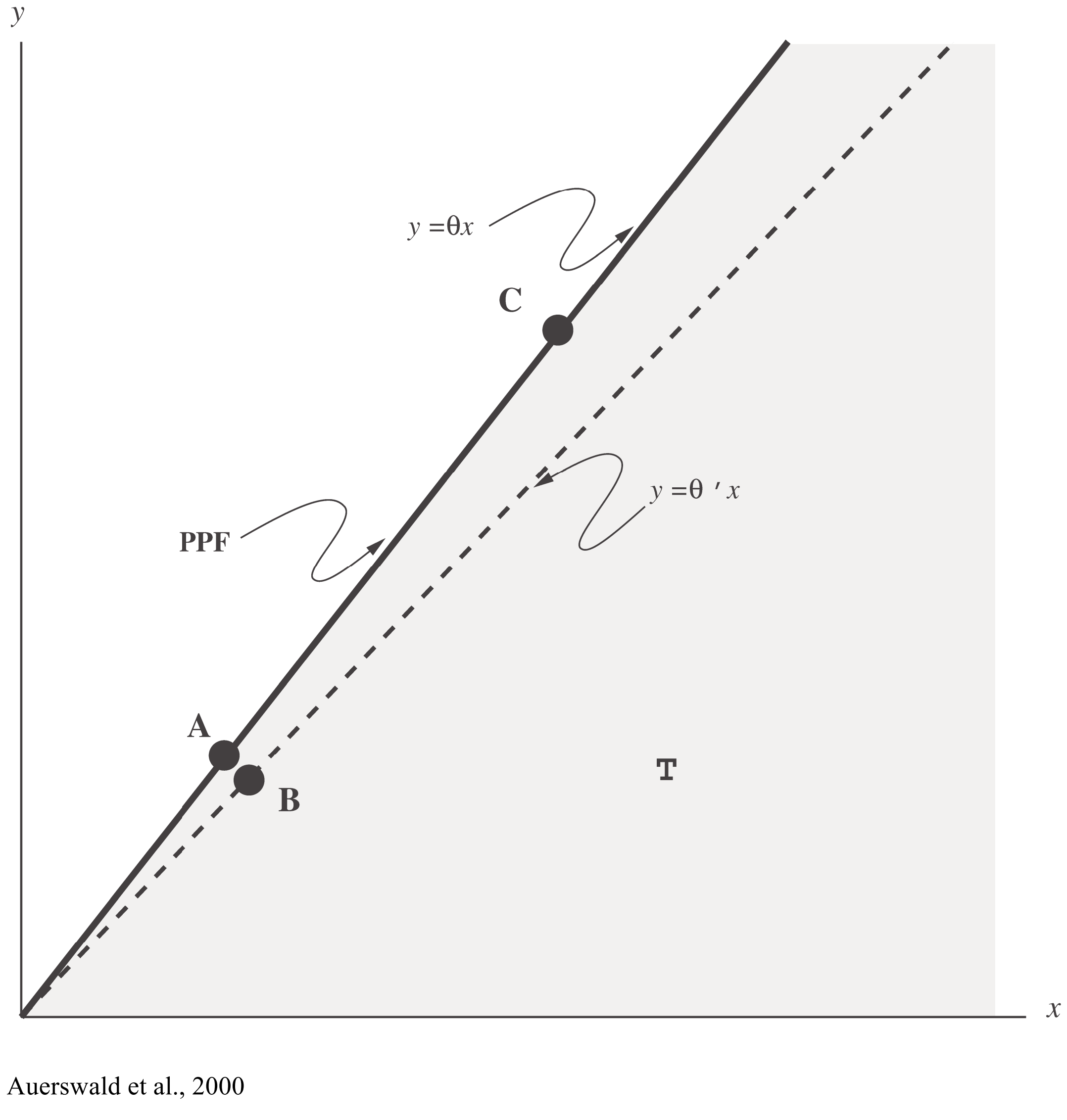


Figure 6: Production Possibilities Frontier

$$y = \theta x \qquad (1)$$



Source: Auerswald et al., 2000

Figure 7: Adoption Path of ISO Quality Management Standards