Exploring the Mechanisms that Drive Improvements in Cost and Performance

by

Jeffrey L. Funk

Associate Professor

National University of Singapore

Division of Engineering and Technology Management

9 Engineering Drive 1, Singapore 117576: EA-5-34

etmfjl@nus.edu.sg

Christopher L. Magee

Professor of the Practice, Engineering Systems Division

Massachusetts Institute of Technology

N52-395, 77 Massachusetts Avenue, Cambridge, MA

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Abstract

Understanding the mechanisms that drive improvements in cost and performance is essential for understanding broader issues such as technological diffusion, the appropriate policies to promote diffusion, when new technologies and industries become economically feasible, when firms should introduce products or processes based on new technologies, and what drives productivity growth. This paper argues that understanding these mechanisms requires us to investigate rates of improvement and specific technologies at a deeper level than just cumulative production and learning curves. This is done for 33 different technologies and 52 dimensions of performance/cost and finds that the improvements in cost and performance can be categorized as being predominantly driven by two different mechanisms - creation of new materials and geometric scale effects.

1. Introduction

Understanding the diffusion of new technologies has been an important issue in economics and management for many years. Management scholars would like to understand when new technologies and industries become economically feasible (McGahan, 2004; Balconi et al, 2010) and thus when firms should introduce products and processes that are based on new technologies (Tushman and Anderson, 1986; Wheelwright and Clark, 1992). Economic scholars would like to understand the effectiveness of policies that promote diffusion of new technologies, which Nobel Laureate Robert Solow (1956) concluded have a large impact on productivity growth.

A key factor identified in studies of diffusion is the profitability of a technology for users (Griliches, 1957; Mansfield, 1968). Greater profitability leads to faster rates of diffusion and the first users tend to be those with the greatest profitability. This suggests that levels of performance and cost of a new technology impact on diffusion since they directly impact the profitability for users, consistent with theories of supply and demand. In turn, this suggests that the rates of improvement in a technology's performance and cost also impact on diffusion, productivity growth and when firms should introduce new products and processes that are based on new technologies.

But what drives improvements in a technology's cost and performance? An important current view is that changes in product design lead to increases in performance and changes in process design lead to reductions in cost (Utterback 1994; Adner and Levinthal 2001). For performance, novel combinations of components lead to improved performance (Basalla 1988; Iansiti 1995). For cost, the predominant view – consistent with process design effects - is that costs fall as a function of cumulative production in a learning or experience curve. According to such curves, product costs drop a certain percentage each time cumulative production doubles (Wright 1936; Arrow 1962; Argote and Epple 1990; Ayres 1992). One suggested mechanism is that automated manufacturing equipment is introduced, incrementally modified, and organized into flow lines as cumulative production accumulates (Utterback 1994). Importantly, the concept of the learning curve has a strong impact on government policies. For example, clean energy policies focus on demand-based subsidies (Pontin, 2010; Lomborg, 2012) partly because many believe this is the surest way to reduce cost and so achieve subsidy-free diffusion sooner.

Another existing but less discussed view from the management and economic literatures focuses on physical dimensions or what this paper calls "geometric scaling." Building from various engineering literatures, Gold (1974 1981), Lipsey, Carlaw, and Bekar (2005), and Winter (2008) argue that changes in physical scale are important mechanisms for improvements in some technologies. Gold (1981) has argued that this phenomenon is overlooked when cumulative production and thus learning curves are emphasized; we treat this as a more detailed explanation for learning. Lipsey et al (2005) focus on the theoretical reasons for the benefits from increases in scale, as does Winter (2008); but Winter also discuses technologies that benefit from reductions in scale such as integrated circuits (ICs) and membranes. Winter calls for a better understanding of scaling, its impact on production functions, and thus the drivers of cost and performance improvements.

Extending this conceptual framework, this paper examines a wide array of performance and cost changes over time, or what Dosi (1982) calls trajectories, in order to better understand the technical basis for the improvements and how best to characterize and categorize them. It performs this analysis from a hierarchical perspective. High-level *drivers* include government policies that promote innovation, competition (Rosenberg 1994; Klevorick et al 1995), R&D spending, experience in production, or increases in demand (Schmookler 1966; Christensen 1997). The technically based *mechanisms* might include specific (kinds of) inventions, slight modification of production equipment, new production processes and equipment, new or improved components and other technical changes made by production workers, engineers and scientists. Our goal is to identify a set of technical mechanisms that better inform government policies and management strategies.

We investigate these mechanisms by gathering data on cost and performance in a wide variety of technologies and by examining the technical literature's analysis of these improvements. Beginning with the concept of geometric scaling, which we differentiate from the more well-known concept of "economies of scale", the literature review develops a more fine-grained understanding of the possible mechanisms in order to guide the data collection and analysis aspect of the research. In section 3, the paper describes the methods that were used to gather and interpret data on cost and performance including data on rapid rates of improvement. Section 4 reports on this data along with findings from the technical literature suggesting probable mechanisms for the improvements. Section 5 discusses the implications for theory, policy and strategy.

2. Literature Review

Economy of scale is a key issue in economic and managerial theories, particularly for production-related technologies (Porter 1980; McGahan 2004). Production-related technologies that benefit from economies of scale have a greater potential for reductions in cost (Smith 1776; Marshal 1920; Haldi and Whitcomb 1967; Levin 1977) and experience a different set of competitive dynamics than do other technologies (Porter 1980; McGahan 2004). But why do some production technologies have a greater potential for economies of scale than do others? One step in answering this was given by Chandler (1994) who noted that continuous flow (e.g., chemical) manufacturing benefits more from economies of scale than does discrete-parts manufacturing (e.g., apparel, machinery), a conclusion that others had reached previously (Pratten 1971).

We can understand the greater benefits of economies of scale for continuous flow than for discrete parts manufacturing with the concept of geometric scaling (Gold 1981; Rosenberg 1994; Freeman and Soete 1997; Lipsey, Carlaw, and Bekar 2005; Winter 2008). Geometric scaling refers to the relationship between the technology's core concepts (Dosi, 1982), physical laws and dimensions (scale), and effectiveness. Or as others describe it: the "scale effects are permanently embedded in the geometry and the physical nature of the world in which we live (Lipsey, Carlaw, and Bekar 2005). Geometric scaling is more important to continuous flow than to other types of manufacturing because of differences in the geometry of their relevant equipment. Continuous flow manufacturing plants consist of pipes and reaction vessels that are used to process chemicals and other materials, paints, and pharmaceuticals. The cost of pipes varies approximately with radius (which determines the surface area of a pipe) whereas their output varies as a function of radius squared (the square of the radius determines the volume of flow). Similarly, the costs of reaction vessels vary as radius squared (which determines the surface area of a sphere) whereas their output varies as radius cubed (which determines the volume of the sphere) This means that output rises faster than does equipment cost as dimensions increase and empirical analyses have confirmed the cost advantages of large scale equipment: the capital costs of continuous-flow factories are a function of plant size to the *n*th power, where *n* is typically between 0.6 and 0.7 (Axelrod, Caze, and Wickham 1968; Mannan 2005).

Similar arguments are made by some for furnaces and smelters, which occupy an intermediate position between continuous-flow and discrete-parts production in terms of the benefits from increases in scale. Furnaces and smelters are used to process metals, ceramics, and other materials and benefits from larger dimensions exist in their construction and operation. As with chemical plants, it is because of geometric ratios. The cost of constructing a cylindrical blast furnace is largely a function of surface area while the output is a function of volume. Construction costs include both material and processing, where, for example, the cost of welding together a heating furnace is proportional to the length of the seams while capacity is a function of the furnace volume. Similarly, the heat loss from a blast furnace or smelter is proportional to the area of its surface while the amount of metal that can be smelted is again proportional to the volume (Lipsey, Carlaw and Bekar 2005). These benefits from geometric scaling have resulted in dramatic increases in dimensional scale and dramatic reductions in costs for many furnaces and smelters such as those for steel making (Gold 1974; Smil 2010).

The potential benefits from increasing the geometric scale of production equipment in discrete-parts production/assembly are apparently much smaller than they are from increasing the scale of furnaces, smelters, or continuous-flow manufacturing plants basically because of the unchanged dimensions of the discrete parts as opposed to larger "batches" in continuous or near-continuous processing. The cutting speeds of lathes and boring machines have been increased (primarily through larger motors and frames) so that these machines can produce more parts per unit time and per capital cost than do smaller and slower machines (Ayres and Weaver 1998). However, the challenges with moving individual parts within and between machines (Rosenberg, 1969) makes it more difficult to benefit from these increases in cutting speed than it is to realize benefits from increasing the dimensions of pipes and reaction vessels. Thus, discrete-parts manufacturing mechanical products such as automobiles, appliances, and bicycles benefit less from increases in scale than do continuous-flow factories (Pratten 1971; Chandler 1994).

Other research indicates that the benefits from increasing the geometric scale of systems should exist outside of production equipment, but empirical work has not been done. Although these increases in scale might be considered similar to economy of scale, it is both the inherent geometry associated with the technology and the specific physical laws that determine the existence and degree of benefits from increases in geometric scale. Thus we would expect each of the technologies to benefit differently from increases in scale because there are different forms of geometry and physical laws for each of them. For example, the largest steam engines are now thousands of times larger than they were 300 years ago (Smil 2010) and the theory of geometric scaling suggests that their output per cost should be many times larger than are smaller engines. This is because for steam and internal combustion engines, the output from a cylinder and a piston is roughly a function of volume, i.e., cylinder diameter squared, while costs are roughly a function of the external surface areas of the piston and cylinder, i.e., diameter. Steam engines probably also benefit from increases in the scale of the boiler; as the diameter of the boiler is increased, the output of the engine increases as a function of diameter cubed, while costs tend to rise only as a function of diameter squared. These increases in geometric scale also facilitated higher temperatures and pressures, due to heat losses being through surfaces but combustion occurring throughout the volume (Lipsey, Carlaw, and Bekar 2005), all of which contributes towards improvements in thermal efficiency (Smil 2010).

Similarly, scaling theory suggests that the carrying capacity of ships, buses, trucks, and aircraft rises roughly with volume (i.e., cube of a dimension) while cost tends to rise with surface area (i.e., square of a dimension) (Lipsey, Carlaw, and Bekar 2005). The surface area could be that of a ship's hull, a bus' body, a truck's rear bed, or an airplane's fuselage, where each is similar to the shape of a rather elongated sphere, even though aircraft have wings and truck beds are more like cubes than spheres. Furthermore, the speed of transportation equipment is also a function of size, partly because the engines benefit from increases in dimensions and partly because the aerodynamic lift and drag ratios improve as size increases.

Geometric scaling can also help explain why some technologies such as integrated circuits (ICs) benefit from reductions in scale where this phenomenon has no relationship with economy of scale. Although Winter (2008) is one of the few business or social science scholars to mention reductions in scale, engineers and scientists regularly discuss the importance of this mechanism for ICs and magnetic storage (Moore, 2006 Daniel et al 1999; Orton 2009; Kurzweil 2005; ICKnowledge 2009). Furthermore, some social scientists have recognized that improvements in ICs have had a large impact on the cost and performance of computers, other electronic systems and essentially mechanical artifacts such as vehicles and manufacturing equipment (Bresnahan and Trajtenberg 1995). Still others have defined computers as a general purpose technology (Lipsey et al 2005) in which their improvements have had a large impact on the performance and cost of still higher-order systems such as retail and logistics (Cortada 2003). These arguments help us better understand the drivers of performance and cost for complex systems and they are more explicit than general arguments that technologies are composed of a "nested hierarchy of subsystems" (Tushman and Rosenkopf 1992; Tushman and Murmann 1998).

In summary, some of the economics and management literature suggests that geometric scaling is an important mechanism for improvements in cost and performance for production and other technologies. Some of this literature also suggests that some technologies directly experience improvements through geometric scaling while those consisting of higher-level "systems" indirectly experience them through improvements in specific "components." This paper tests these arguments by examining specific cases in greater depth. Although we find that geometric scaling is an important driver of improvements, it cannot explain many of the improvements that were found for some technologies. In a sense this is not surprising since the discussion of drivers of performance/cost improvement in the management literature is relatively silent on the role of invention and science. This oversight may result from only looking at the top of the hierarchy and neglecting the technical aspects but in this work we go deeper convinced that such deeper understanding is also needed for policy and strategy guidance. Thus, we looked for other drivers of these improvements: our method of finding these drivers is outlined in the next section.

3. Methodology

We looked for cost and performance data on a wide variety of technologies; for the most part, these technologies are defined in terms of a single concept/principle (Uttterback, 1994; Henderson and Clark, 1990) and thus the improvements occur within a fixed conceptual framework. In doing so we also looked for technologies that have experienced a wide range of improvement rates including those that have experienced rapid rates of improvement and/or those that are considered to be important technologies of the 19th, 20th and 21st centuries (Rosenberg 1994; Chandler 1994; Freeman and Soete 1997; Freeman and Louca 2002). For example, Kurzweil (2005) shows that ICs, magnetic storage, and systems composed of these "components" (e.g., computers, telecommunications) have experienced rapid improvements in cost and performance, e.g., doubling every few years and thus orders of magnitude improvements over decades (Kurzweil 2005).

Cost and performance improvement data was searched for in the economics and management literatures, general histories of technology (Cardwell 1995; Crump 2001; McClellan and Dorn 2006), histories of individual technologies, archival publications giving quantitative data over time for various technologies (Martino, 1971; Koh and Magee, 2006 and 2008), general web sites such as Wikipedia, Answers.com and howstuffworks.com, technical reports, and technology-specific web sites. Furthermore, terms such as cost, performance, trends, improvements, and specific technological terms were searched for in order to find data where the "images" function of Google facilitated a search for data presented in figures. Independent of the search procedure, we also tried to find multiple sources in order to enhance the reliability of the estimated rates of improvement.

The search and data analysis led to the creation of a relatively large set of information on technologies and their rates of improvement, which are summarized in Table 1. The technologies are placed into 9 categories, the first six of which are the transforming, storing, and transporting of energy, information, and living organisms, which is consistent with characterizations of engineering systems (de Weck et al 2011). In total, there are 33 individual technologies shown in Table 1; these are individually numbered for ease of later discussion. Since a variety of performance measures are often relevant for a specific technology, data was collected on multiple dimensions some of which are represented in performance of basic functions per unit cost while others are in performance of functions per mass or per volume totaling 52 metrics in the table.

In the analysis of this information, we maintained the hierarchical perspective discussed in Section 1 that differentiates high-level *drivers* from more specific technically distinct mechanisms. Identifying these technically-based *mechanisms* required us to look closely at the engineering and scientific literature to link data on improvements in performance and cost with the technical changes. Our initial literature base started with what was known to the authors. However, many of the analyzed papers were found using keyword searches on Google Scholar. Various search terms (such as battery technology overview, battery technology or more generic terms) were employed until some highly cited articles were found in the topic of interest. These papers were added to our analysis base.

Our initial analysis of the papers was aimed at understanding the composition of a technology's system because the performance (and cost) of some systems is largely dependent on the performance (and cost) of one or two types of components. All technologies can be characterized as a "nested hierarchy of subsystems" (Tushman and Rosenkopf 1992; Tushman and Murmann 1998; Malerba, et al 1999 and the articles and other material allowed us to arrive at such an understanding. This analysis was facilitated by the technical backgrounds of the two authors and by interviews with academic and practicing engineers both as part of this research and throughout our careers. This search was also facilitated by the technical backgrounds of the two authors and their conversations with academic and practicing engineers both as part of this research and throughout our careers.

Thus, the first mechanism identified was essentially to note component improvements that drive the higher-level system improvements (Funk, 2009). The mechanism we examined next was geometric scale changes since changes in scale have been identified as an important improvement mechanism by the management, economic, and engineering literatures. Eexamples of geometric scaling were searched for outside of chemical plants, furnaces, and smelters (since these have been empirically analyzed to some extent). Whenever a relevant discussion of geometric scaling was found in any literature, the original reference was obtained in order to access the relevant details adding to our literature for analysis. For each instance of geometric scaling, the type of geometrical scaling was identified and data on the changes in scale and on cost/price for various levels of scale were gathered. Thus, for component changes and scale effects, this paper only reports on those technologies for which we could identify the mechanisms with high reliability. As will be seen in the results section, this yet left us with a large number of technologies whose improvements were not well explained.

Our analysis of the technical literature found another prevalent mechanism which is consistent with the importance of science and invention in technical improvement; engineers and scientists create (or improve existing) materials to better exploit their underlying physical phenomena where creating these materials involved simultaneously creating new processes for producing them (Stobaugh 1988; Morris et al 1991; Olsen, 2000; Linton and Walsh 2008, Magee 2012). Examples of the scientific phenomena being better exploited will be more specifically discussed in the next section but include electroluminescence, electrochemical reactions, amplification and other phenomena in transistors, and photovoltaic effect where advances in science facilitate the creation of new materials and processes (Cardwell 1995; Crump 2001; McCllelan and Dorn 2006; Dosi and Nelson 2010). The word "create" is used because scientists and engineers often create materials that do not naturally exist (as opposed to finding them) and in doing so must also create the processes that enable these new materials and their superior performance to exist. Furthermore, these new materials often involve new "classes" of materials and not just modifications to existing materials. Thus, overall, we found two prevalent *technical* mechanisms that drive improvements in cost and performance: 1) creating materials to better exploit their physical phenomena; and 2) geometric scaling.

The data on cost and performance improvements was often found in the form of time series, while others were found for specific moments in time. Performance improvements from creating materials that exploit a physical phenomenon were almost always in the form of a time series graph that included the names of the materials that enabled the performance improvements. This substantially facilitated our task of identifying the new types of materials that enabled the improvements. For scaling, we looked for data for a single moment in time in order to isolate the impact of changes in scale, which was found for most technologies. However, for others, data for different levels of scale could only be found for different moments in time which might confound separating the impact of scaling from other technical changes

We used our analysis of this data to simply assign each technology to one of the two main direct mechanisms that enable improvements (and to identify important component technology changes), even though many benefited from both mechanisms. We also note that these two mechanisms are the authors' attempt at categorizing a complex set of technical changes and that each mechanism is by itself complex and in specific instances is enabled or accompanied by other technical knowledge. Nevertheless, we believe that our attempts to identify these technical mechanisms facilitate the identification of high-level drivers.

4. Results

This section describes the evidence for the two key drivers of improvements and how they impact on many of the rates of improvement that are summarized in Table 1. These drivers are: 1) creating new materials (and often their associated processes) to better exploit their underlying physical phenomena; and 2) geometric scaling. Some technologies directly experience improvements through these two mechanisms while those consisting of higher-level "systems" indirectly experience them through improvements in specific "components." The first sub-section discusses the role of new materials and the subsequent two sub-sections are devoted to geometric scaling, one for technologies that benefit from reductions in scale and one for increases in scale. A fourth sub-section discusses the impact of components on systems, where the components experience improvements through the two mechanisms listed above and for most of the cases, one or two components have had a large impact on the performance and/or cost of a system.

4.1 Creating Materials that better Exploit Physical Phenomena

The technical literature clearly establishes that many of the technologies shown in Table 1 experience improvements through the creation of materials that better exploit physical phenomena where there is a tight linkage between creating materials and the processes for making them (Olsen, 2000) and where creating new classes of materials (See Table 2) are often more important than are small modifications to either existing materials or processes. For items 1, 2, and 3 in Table 1, (lighting, LEDs [light emitting diodes], and organic LEDs [OLEDs]), scientists and engineers improved the luminosity per Watt by finding materials that better exploit the phenomena of incandescence, fluorescence, and electroluminescence. Paraphrasing Azevedo et al (2009) (page 483) "In 1962, Holonyak, made a red emitting GaAsP inorganic LED….Changing materials (toAlGaAs/GaAs) and incorporating quantum wells, by 1980, the efficacy of his red LED had grown to 2 lm/W…. An output of 10 lm/W was achieved in 1990, and a red emitting light AllnGaP/GaP-based LED reached an output of 100 lm/W in 2000." Similar improvements in OLEDs were made by creating new organic materials such as nitrides and polymers (Sheats et al 1996; Lee 2005).

Creating new materials also lie behind much of the improvements shown in Table 1 for the performance and cost of GaAs lasers (item 4), photosensors (5), solar cells (6), energy storage devices (batteries [10], capacitors [11], flywheels [12]), organic transistors (20), crop yields (28), and load bearing (30) and magnetic materials (31). Thus, overall 14 of the 33 technology cases showed that the clearly dominant mechanism was materials/process creation and improvement.

For example, improvements in GaAs lasers (4) came from creating better materials for the laser package's lasing material, heat sink, solder, and mirror (Martinson, 2007; Danner, 2012). Improvements in photo sensors (5) came from creating better materials for the lens, electrode, filter and making changes in the processes (Suzuki, 2010). Similarly, scientists and engineers created new types of semiconducting (e.g., silicon, gallium arsenide, cadmium telluride) and non-semiconducting (e.g., organic ones) materials that more effectively translate photons into electrons for solar cells (6), which exploit the photovoltaic effect and depend on improvements in processes (Green, 2009, US DoE, 2010). Others benefited from the creation of: lead, nickel-metal hydride and lithium for batteries (item 10) (Tarascon 2009); of carbon, polymers, metal oxides, and ruthenium oxide for capacitors (11) (Naoi and Simon, 2008); of steel, glass, and carbon fiber for flywheels (12) (Bolund et al, 2007), of small molecules, polymers and phosphorescent materials for organic transistors (20) (Shaw and Seidler, 2001); of biological materials such as such as open pollinated, single cross, double cross, and biotech seeds for better crop yield (26) (Troyer, 2006); of composites and carbon fibers for load bearing materials (28), and of rare earths for magnetic materials (29) (NAS/NRC 1989).

Other technologies such as man-made fibers, ceramics, polymers, and other engineered materials also benefit from creating specific combinations of materials that better exploit physical phenomena. Data is not presented in Table 1 for these materials, however, because it is difficult to quantify the improvements as they occur over multiple dimensions of performance that are not all well documented. Although some materials are developed because they have excellent strength-to weight ratios or magnetic-related dimensions of performance as shown in Table 1, many materials-related technologies have multiple dimensions of performance and thus progress is often from finding materials that offer a new combination of performance attributes or even a new performance attribute in addition to materials which improve an existing dimension of performance. For example, dimensions of performance for man-made fibers include tensile strength, elastic recovery, modulus, and moisture regain where different dimensions of performance and different combinations of them are important for different applications (Ayres and Weaver 1998). Overall, even not being able to document these cases and not considering cases where materials creation/modification enables other changes, we still find 14 of 33 classes where this mechanism is clearly dominant.

4.2 Geometrical Scaling – reductions in scale

The technical literature clearly shows that several of the technologies listed in Table 1 have benefited from reductions in scale. ICs (item 14) contain multiple transistors, resistors and capacitors whose organization determines the functionality of the IC. ICs are used in computers and other electronic products to process data including text, audio and video. They are manufactured by depositing multiple layers of materials on a silicon substrate and by forming patterns in these layers with various types of equipment (Henderson 1995). For example, reducing the linear scale of features in these patterns on microprocessors from 10 microns to 0.045 microns (ICKnowledge, 2009; ITRS, 2012) led to increases in the number of transistors per microprocessor chip from 2300 to 2.6 billion (Wikipedia, 2013a) between 1971 and 2011. Reductions in these features also led to increases in speed and reductions in power consumption for transistors and memory cells. These features include the length and width of individual transistors, the width of the lines that connect transistors, and the thickness of individual material layers; completely new forms of manufacturing equipment and materials processes were needed to achieve these reductions in feature size (Henderson, 1995; ICKnowledge 2009).

Similar arguments apply for MEMS in inkjet printers (15), magnetic (21, 22) and optical (23) storage, and in genome sequencing (26). Reductions in the relevant feature sizes led to improvements in the drops per second and resolution of ink jet printers (Stasiak et al 2009), in the magnetic recording density of magnetic cores, drums, disks, and tape, to some extent in optical storage, and in the sequencing cost per genome over time. MEMS are fabricated using processes similar to those used to fabricate ICs and engineers reduced the feature size from 0.5 mm in 1967 to .005 mm in 2004 (Kurzweil 2005). For magnetic storage (21,22), smaller magnetic storage areas led to higher recording densities of magnetic cores, drums, disks, and tape (Daniel et al 1999); these smaller storage areas also required the creation of magnetic materials with higher coercivity (Hitachi 2012). For example, in their review of challenges for improving the density of magnetic storage, Eleser et al (1999) write that “These challenges include the superparamagnetic effect, the need for increasing read head sensitivity, the need to scale head-to-disk spacing with the linear density, the need to follow extremely narrow data tracks, and the need to switch magnetic materials at increasing speeds.” For optical discs, reductions in the wavelength of light emitted by semiconductor lasers are needed to reduce the size of storage cells where the physical limit for the wavelength of visible light reduces the opportunities for reductions scale (Esener et al 1999). For genome sequencing, the importance of scale can be seen in titles of highly cited papers such as “Genome sequencing in micro-fabricated high-density pico-liter reactors” (Margulies, 2005) and “Toward nano-scale genome sequencing” (Ryan et al, 2007). In all of these decreasing scale examples, totally new forms of equipment, processes and factories were required. Overall, 6 of the 33 cases show clear evidence in the technical literature for scale reductions being the strongest or dominant mechanism and it is interesting that all of these are cases of very rapid annual improvement (>20%).

4.3. Geometrical Scaling: increases in scale

Many of the technologies shown in Table 1 experienced improvements through increases in scale. Since prior research has examined the benefits of increased scale for chemical plants, furnaces and smelters, this section focuses on scaling in other types of technologies including other types of production equipment where data was collected on the cost per output for different levels of scale. Two of the technologies in Table 1, wheat production (26) and liquid crystal displays (LCD)(17), involved increases in the scale of production equipment, Wheat harvesting benefited from the replacement of human labor with machines and subsequent increases in the scale of these machines throughout the late 19th century and 20th century (Spielmaker, 2006) where the increases in the scale of this equipment were supported by the benefits from increasing the scale of engines (see below).

For LCDs, increases in the scale of their equipment have been accompanied by increases in the size of LCD substrates where multiple LCD panels (e.g., ones for laptop computers) are processed on single substrates followed by the division of these substrates into individual LCD panels. As shown in Table 3, one analysis found that the cost per output for one type of manufacturing equipment was 88% cheaper for 2.7 than 0.17 square meter substrates (Keshner and Arya, 2004). A second analysis found that the cost per output for a complete production facility was 36% cheaper for 5.3 than 1.4 square meter substrates (Display Search, 2010). This is primarily because the loading time and the costs of the loading equipment do not increase much with increases in substrate size and because there are smaller "edge effects" with larger than smaller substrates. Edge effects refer to the fact that yields are lower near the edge of the substrates and to the fact that the equipment must be much larger than the substrates in order to have consistent conditions across the substrate. The latter means that the ratio of equipment-to-substrate size decreases as the substrate size as increased (Keshner and Arya 2004; Display Search 2010).

Table 3 also lists technologies other than production equipment that benefit from increases in scale. For the theoretical reasons given in the literature review, large steam and internal combustion engines were 2/3 (data is from 1800) and 74% (data is from 2010) cheaper than were small ones respectively. Furthermore, much larger engines have been installed and their implementation suggests that costs per horsepower continue to fall as scale is increased. For example, a 90,000 horsepower marine engine (Dorneanu, 2007) is used in ships and much larger versions of steam engines have been implemented, including their modern day version, the steam turbine (Smil, 2010). Although cost or price data for these engines are not available, if the same benefits from increases in scale were to exist in a change from 225 to 90,000 horsepower as found with a change from 2.3 to 225 horsepower, such an extrapolation would mean that the 90,000 horsepower engine would be about 1% the price per HP of the 2.3 engines; this is consistent with the constant rates of improvement for engines (including both internal combustion and jet engines) over many years shown in Table 1 (items 7 and 8).

Electricity generation and transmission also benefits from increases in scale. Steam turbines benefit from increases in scale for the same reasons that engines do, boilers benefit for the same reasons that reaction vessels in chemical plants do (discussed in literature review), and the cost of electricity transmission per distance falls as higher voltages are implemented (Koh and Magee 2008). In addition to the creation of better dielectric materials, the latter is because higher voltages require larger cables and energy loss is a function of the cable's surface area while transmission is a function of the cable's volume (AEP, 2008). Capital cost per electrical output fell by 59% between 1928 and 1958 as the size of the generation plants were increased by six times and the price per distance of transmission fell 2% a year as the scale of the transmission equipment (in volts) was increased by more than 10,000 times. The result is that the cost of energy transport fell 2% a year (item 13 in Table 1) and the price of electricity fell from $4.50 per kilowatt hour in 1892 to about $0.09 by 1969 in constant dollars (Hirsh 1989).

Many types of transportation equipment also benefit from increases in scale. The existing capital cost per capacity is 59%, 52%, and 14% lower for large oil tankers, freight vessels and aircraft than for small ones while large aircraft currently have 48% lower fuel consumption per capacity than do small aircraft. Furthermore, the advantages of scale become even more apparent when one considers that some of the first oil tankers were very small (e.g., 1807 tons in late 19th century) and the first commercial aircraft, the DC-1 (early 1930s), could only carry 12 passengers (Wikipedia, 2013b). Extrapolating to these extremes suggests that today's largest oil tanker (265,000 tons) is almost 1/20 the price per ton of an 1807-ton tanker and that the A380 (853 passengers in economy mode) has a price per passenger almost 1/2 that of the DC-1. This data is consistent with the falling cost of transport for both freight and humans that are shown in Table 1 (item 29); this falling cost is also driven by the falling cost of computers, which is discussed in the next subsection. Overall, increasing scale is important in 5 of the cases in Table 1 (items 7, 8, 9 17, and 29) which interestingly are among the cases showing the smallest annual rate of improvement.

4.4. Improvements in Components, Improvements in Systems

Many of the technologies in Table 1 experienced improvements in cost and performance because specific "components" have a large impact on their performance and cost and these components experienced rapid improvements in performance and cost. Rapid improvements in electronic components, in particular ICs, have led to rapid improvements in computers (item 16 in Table 1, Flamm 1988; Ceruzzi 1998) where the improvements in ICs are driven by reductions in scale. As one computer designer argued, by the late 1940s computer designers had recognized that "architectural tricks could not lower the cost of a basic computer; low cost computing had to wait for low cost logic" (Smith 1988), which mostly came in the form of better ICs. For example, an order of magnitude improvement in the numbers of transistors per chip about every seven years (See Table 1) led to similar levels of improvements in computations per second (Koh and Magee, 2006) and per kilowatt hour of computers (Koomey et al, 2011).

Similar arguments about the role of ICs can be made for other electronic products such as digital cameras (Preil, 2012), eBook readers, video games, high density television, set-top boxes, servers, and routers, and also for even higher level systems such as corporate information systems (Cortada, 2003). Not only do the cost of ICs and other electronic components make up more than 95% of the cost of many electronic products (iSuppli, 2013), the performance of these products is largely determined by the speed, functionality and power consumption of ICs. Furthermore, improvements in computers (along with better magnetic materials) have led to improvements in the performance and cost of medical equipment such as magnetic resonance imaging and computer tomography [items 18 and 19 in table 1). For example, Kalendar (2006) argues that "Computed tomography became feasible with the development of modern computer technology in the 1960s." Trajtenberg (1990) argues "it was not until the early seventies, coupled with significant advances in electro-optics and nuclear physics, that the revolution in imaging technologies started in earnest. Computed Tomography scanners came to epitomize this revolution and set the stage for subsequent innovations, such as……….and the wonder of the eighties, Magnetic Resonance Imaging."

Rapid improvements in electronic components such as vacuum tubes, ICs, lasers, and photo-sensors (See Table 1) also led to rapid improvements in data speeds and spectral efficiency of both wireline (MacKie-Mason and Varian 1994; Okin, 2005) and wireless telecommunication (items 24 and 25 in Table 1). Improvements in electronic components enabled faster data speeds and higher bandwidth for single cable, coaxial cable and more recently optical fiber (Koh and Magee 2006) where improvements in optical cable also required improvements in the purity of glass. Taking this one step further, increases in the bandwidth facilitated the emergence of music and video services, podcasts, 3D content, blogs, social networking services, mashups, and cloud computing (Okin 2005).

For wireless, although the introduction of cellular systems, smaller cells, and better protocols for these cellular systems were needed to achieve improvements in the data rates for wireless communication, rapid improvements in ICs enabled the implementation of these cellular systems, smaller cells, and better protocols (Subramanian 1999; Gonzalez 2010) and improvements in mobile phones. Cellular systems required faster switching speeds, which were enabled by the improvements in computers and ICs mentioned in the previous paragraphs (Garrard 1999). Similar arguments are made by the International Solid State Circuits Conference (ISSCC 2010) each year for Ethernet, USB (Universal Serial Bus), WLAN (wireless local area network), and WPAN (wireless personal area network), which are sub-technologies within the category of wireless transport in Table 1.

Finally, some mechanical systems such as electric motors, machine tools, and engines for cars and aircraft have also benefitted from improvements in components. Improvements in the power density of electric motors (item 9) primarily depended on improvements in the magnetic strength of magnetic materials, which depended on creating better magnetic materials. In addition to increases in scale, improvements in machine tools (item 32) and engines depended on stronger materials for cutting tools (American Machinist 1977; Ayres and Weaver 1998) and more heat resistant materials for engines (NAS/NRC, 1989). Improvements in engines also depended on improvements in electronic components for better control of combustion processes and improvements in the tolerances for pistons and cylinders that came from better machine tools (Cardwell 1995; Crump 2001; McClellan and Dorn 2006; Koh and Magee 2008). Overall, using the technical literature, we have identified at least 7 cases from Table 1 (9, 16, 18, 19, 24, 25, 32) where improved components play a very important role in performance improvement but since the mechanism is general, even more cases are assured. However, incorporating faster improving components in more slowly improving systems does not result in obvious automatic acceleration of performance improvement (for example, computers in engines).

Table 4 summarizes our findings for the mechanisms driving improvements in 33 different technologies. The mechanism appearing in the most cases is materials creation and improvement; its dominance in today's technologies is consistent with the strong role of science in improving these technologies. The mechanism with the second most entries is improvements in components. However, if drivers of the improvements in the components are identified, as also shown in Table 4, one can conclude that scale reductions appears in 11 cases as compared to 16 cases for creating materials and all cases of rapid improvements involve one of these two mechanisms. On the other hand, scale increases are the driver in only 5 cases and these are among the slower improving technologies in our information base. Nevertheless, scale increases are under reported in our analysis because we chose not to look at scale increases in production equipment for chemicals, furnaces, and smelters since others have done so.

5. Discussion

Using a relatively large data base on technologies and their rates of improvements, this paper found from an analysis of the technical literature that most of the observed improvement can be categorized into two mechanisms: 1) creating materials to better exploit their physical phenomena; and 2) geometric scaling. Some technologies directly realize improvements through these two mechanisms while those consisting of higher-level "systems" indirectly benefit from them through improvements in specific "components." Of the 33 different technologies and 52 dimensions of performance shown in Table 1, our analysis of the technical literature indicates that these mechanisms were able to explain the improvements for 31 of the technologies and 50 of the dimensions; the exceptions are laboratory concentration of penicillin and laboratory cooling. We thus do not argue that the two identified mechanisms explain all of technological improvement but there does seem to be strong evidence for their importance.

The first mechanism stressed in this paper, creating new materials that better exploit physical phenomena, leads to orders of magnitude improvements when scientists and engineers create new forms of materials and do this with new processes. While these new materials often involve modifications to existing ones, sometimes they involve new classes of materials and these new classes of materials may be needed to achieve the large improvements shown in Table 1. The technical literature we examined identifies new classes of materials for all of the "material creation" technologies except two of them (photosensors, lasers). We tentatively conclude that without these new classes of materials, the range of improvements might well be reduced below those achieved and documented in Table 1.

The second mechanism stressed in this paper, geometric scaling, impacts on some technologies through increases in scale and on other technologies through reductions in scale. In both cases, large changes in both product and process design were implemented over time with each increment requiring non-trivial redesigns. Reductions in scale are shown in the technical literature to provide a mechanism for rapid rates of improvements in ICs, magnetic storage, MEMS, and DNA sequencing equipment. Scientists and engineers reduced the sizes of the product features and did so by introducing better processes that often involved completely new forms of equipment as well as new controls on materials. This new equipment was usually developed in laboratories and often involved completely new technology such as lasers and new chemical/material creations. Furthermore, rapid improvements in many higher-level "systems" were achieved through the improvements in ICs and other components that benefit from reductions in scale.

Quantifying the degree to which technologies benefit from changes in scale is highly context sensitive and complicated. Since the benefits depend on the physical laws that govern the technology, different technologies do not benefit to the same extent from changes in scale. For example, the degree to which vehicles and aircraft will benefit from increases in scale will clearly differ because different laws govern the operation of transportation equipment on land and in air. Similarly, the degree to which ICs and MEMS benefit from reductions in scale will also clearly differ. Important dimensions of performance for ICs are power consumption and speed and both benefit greatly from reductions in scale whereas the benefits for MEMS only involves improvements in resolution for printers. Thus, the benefits from reductions in scale are much larger for ICs than for MEMS in printers. Nevertheless, the fact that the most rapid rates of improvements in Table 1 are for technologies that benefit from reductions in scale suggests that this is an important issue for both researchers and practitioners and an important heuristic for finding technologies with large potential for high rates of improvement.

Overall, the results provide a deeper understanding of learning in a technological context than do current models and they provide new insights into technological diffusion (Griliches, 1957; Mansfield, 1968) and productivity growth (Solow, 1956, 1997). The technology diffusion and productivity growth literatures pay little attention to improvement rates but it seems apparent that rapid improvement rates lead to earlier economic feasibility and faster rates of diffusion and productivity growth. Thus, one aspect of this work is that more attention to improvement rates is required in research on technological change. The mechanisms identified in this work provide an initial operational explanation for why some technologies experience rapid rates of improvement over long periods of time that is superior to any explanation that might come from current theories such as the learning curve (Wright 1936; Arrow 1962; Argote and Epple 1990; Ayres 1992).

To put it simply, the incremental modification of equipment that is emphasized by the learning curve is one part of both mechanisms but it is not the most important part of the mechanisms. It is in the process side of creating materials and processes that better exploit phenomena, where many small improvements are made to the processes in order to both improve performance and reduce cost. It is also part of geometric scaling because reducing the scale of features on ICs involves improvements to processes and because increasing the scale of production equipment also involves improvements in processes. Nevertheless, incremental modifications of equipment cannot explain the many orders of magnitude improvements that many technologies experience in terms of output per cost, mass, or volume. In fact, learning from production cannot explain even small improvements in a per mass or volume basis since such improvements clearly involve something more basic about the artifact than just small changes in processes. Our work identifies the creation of new materials and large reductions in scale as the basic artifact changes responsible for the improvements in which they are a specific form of learning that requires R&D activities and not necessarily cumulative production.

In conclusion, we believe that this paper's analysis provides a first step towards a much better understanding of when new technologies become economically feasible, of technological diffusion (Griliches, 1957; Mansfield, 1968), and of productivity growth (Solow, 1956; Solow, 1997). Some research should further probe the technical mechanisms in more detail while other research should probe the implications of the mechanisms for policy or strategy. For example, with respect to the technical mechanisms, we believe that further research should attempt to understand the relative contributions of the two mechanisms and to further decompose them into more detailed mechanisms. With respect to policy and strategy, research should identify the implications of these technical mechanisms for policy and strategy. For example, as a start, we believe that this paper's analysis suggests that: 1) R& D subsidies are much superior to demand subsidies as policy instruments; 2) policies that support specific component technologies, or a better understanding of the relevant science, are superior to policies that merely support increases in cumulative production; and 3) policies that subsidize construction of large-scale factories in a hope to reduce costs are probably mistaken particularly when new materials or scale reduction are needed for the desired performance improvement. Further research is needed in these areas.

6. References

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Table 1. Annual Rates of Improvement for Specific Technologies

Technology Domain	Sub-Technology	Dimensions of measure	Time Period	Improvement Rate Per Year
Energy Trans-formation	1 Lighting	Light intensity per unit cost	1840-1985	4.5%
	2 LEDs	Luminosity per Watt	1965-2008	31%
	3 Organic LEDs	Luminosity per Watt	1987-2005	29%
	4 GaAs Lasers	Power/length-bar	1987-2007	30%
	5 Photosensors	Light sensitivity (mV/micrometer)	1986-2008	18%
	6 Solar Cells	Power output per unit cost	1957-2003	16%
	7 Aircraft engine	Gas pressure ratio achieved	1943-1972	7%
		Thrust per weight-fuel consumed	1943-1972	11%
		Power of aircraft engine	1927-1957	5%
	8 Piston engines	Energy transformed per unit mass	1896-1946	13%
	9 Electric Motors	Energy transformed per unit mass	1880-1993	3.5%
		Energy transformed per unit volume	1890-1997	2.1%
Energy storage	10 Batteries	Energy stored per unit volume	1882-2005	4%
		Energy stored per unit mass	1882-2005	4%
		Energy stored per unit cost	1950-2002	3.6%
	11 Capacitors	Energy stored per unit cost	1945-2004	4%
		Energy stored per unit mass	1962-2004	17%
	12 Flywheels	Energy stored per unit cost	1983-2004	18%
		Energy stored per unit mass	1975-2003	10%
13. Energy Transport		Energy transported times distance	1890-2003	10%
		Energy transported times distance per unit cost	1890-1990	2%
Infor-mation Trans-formation	14 ICs	Number of transistors per chip/die	1971-2011	38%
	15 MEMS Printing	Drops per second for ink jet printer	1985-2009	61%
	16 Computers	Instructions per unit time	1945-2008	40%
		Instructions per unit time and dollar	1945-2008	38%
	17 Liquid Crystal Displays	Square meters per dollar	2001-2011	11%
	18 MRI	1/Resolution x scan time	1949-2006	32%
	19 Computer tomography	1/Resolution x unit time	1971-2006	29%
	20 Organic	Mobility (cm^2/ Volt-seconds)	1994-2007	101%

	Transistors			
Infor-mation Storage	21 Magnetic Tape	Bits per unit cost	1955-2004	40%
		Bits per unit volume	1955-2004	10%
	22 Magnetic Disk	Bits per unit cost	1957-2004	39%
		Bits per unit volume	1957-2004	33%
	23 Optical Disk	Bits per unit cost	1996-2004	40%
		Bits per unit volume	1996-2004	28%
Infor-mation Transport	24 Wireline Transport	Bits per unit time	1858-1927	35%
		Bits x distance per unit cost	1858-2005	35%
	25 Wireless Transport	Coverage density, bits per area	1901-2007	37%
		Spectral efficiency, bits per unit bandwidth	1901-2007	17%
		Bits per unit time	1895-2008	19%
Living Organisms	Biological transfor-mation	26 Genome sequencing per unit cost	1965-2005	35%
		27 Harvest concentration of penicillin	1945-1980	17%
		28a U.S. wheat productivity (per input)	1948-2009	1.3%
		28b US wheat production per area	1945-2005	0.9%
	29 Transport of humans/freight	Ratio of GDP to transport sector	1880-2005	0.46%
		Aircraft passengers times speed	1926-1975	13%
Materials	30 Load Bearing	Strength to weight ratio	1880-1980	1.6%
	31 Magnetic	Magnetic strength	1930-1980	6.1%
		Magnetic coercivity		8.1%
Other	32 Machine Tools	Accuracy	1775-1970	7.0%
		Machining speed	1900-1975	6.3%
	33 Laboratory Cooling	Lowest temperature achieved	1880-1950	28%

MEMS: micro-electronic mechanical systems; LEDs: Light Emitting Diodes; ICs: Integrated Circuits; Magnetic Resonant Imaging

Sources, from top to bottom: (Nordhaus,1997; Azevedo, 2009; Sheats et al, 1996; Lee, 2005; Martinson, 2007; Suzuki, 2010; Nemet, 2006; Alexander and Nelson, 1973; Sahal, 1985; Koh and Magee, 2008; Wikipedia, 2013; Stasiak et al, 2009, Koh and Magee, 2006; Koomey, 2010; Economist, 2012; Kurzweil, 2005; Kalender, 2006; Shaw and Seidler, 2001; Dong et al, 2010; Koh and Magee, 2006; Amaya and Magee, 2008; NHGRI, 2012; Seth, Hossler and Hu, 2006; U.S. Department of Agriculture, 2012, Glaeser and Kohlhase, 2004: Martino, 1971; NAS/NRC, 1989; Ayres and Weaver, 1998; American Machinist, 1977; Martino, 1971)

Table 2. Different Classes of Materials that were found for Each Technology

Technology Domain	Sub-Technology	Dimensions of measure	Different Classes of Materials
Energy Trans-formation	Lighting	Light intensity per unit cost	Candle wax, gas, carbon and tungsten filaments, semiconductor and organic materials for LEDs
	LEDs	Luminosity per Watt	Group III-V, IV-IV, and II-VI semiconductors
	Organic LEDs		Small molecules, polymers, and phosphorescent materials
	Solar Cells	Power output per unit cost	Silicon, Gallium Arsenide, Cadmium Telluride, Cadmium Indium Gallium Selenide, Dye-Sensitized, Organic
Energy storage	Batteries	Energy stored per unit volume, mass or cost	Lead acid, Nickel Cadmium, Nickel Metal Hydride, Lithium Polymer, Lithium-ion
	Capacitors		Carbons, polymers, metal oxides, ruthenium oxide, ionic liquids
	Flywheels		Stone, steel, glass, carbon fibers
Information Trans-formation	Organic Transistors	Mobility (cm^2/ Volt-seconds)	Polythiophenes, thiophene oligomers, polymers, hthalocyanines, heteroacenes, tetrathiafulvalenes, perylene diimides naphthalene diimides, acenes, C60
Living Organisms	Biological transfor-mation	U.S. corn output per area	Open pollinated, double cross, single cross, biotech GMO
Materials	Load Bearing	Strength to weight ratio	Iron, Steel, Composites, Carbon Fibers
	Magnetic	Strength	Steel/Alnico Alloys, Fine particles, Rare earths
		Coercivity	Steel/Alnico Alloys, SmCo, PtCo, MaBi, Ferrites,

Sources, from top to bottom: (Azevedo, 2009; Sheats et al, 1996; Lee, 2005; U.S. DOE, 2010; Tarascon 2009; Naoi and Simon, 2008; Bolund et al, 2007; Shaw and Seidler, 2001; Dong et al, 2010; Troyer, 2006: NAS/NRC, 1989;

Table 3. Improvements from Increases in "Geometric" Scale

Technology	Sub-Technology	Dimensions of Scale	Increases in Scale		Amount of Cost Reduction	
			Small	Large	Dimension	Amount
Production Equipment for Electronics	Liquid Crystal Displays	Substrate Size	$0.17\ m^2$ (1997)	$2.7\ m^2$ (2005)	Equipment* cost per area	88%
			$1.4\ m^2$ (2003)	$5.3m^2$ (2008)		36%
Engines	Steam Engine	Horse-power	10 (1800)	20 (1800)	Price per horsepower	2/3
	Marine Engine		2.3 (2010)	225 (2010)		74%
Electricity	Generation	1000s of Watts	100,000 (1928)	600,000 (1958)	Capital cost per Watt	59%
	Transmission	Voltage	10,000 Volts (1880)	790,000 Volts (1965)	Price per distance	2% per year or >99.9%
	Final cost of electricity	1000s of Watts	93 (1892)	1.4 million (1969)	Price per kilowatt hour	> 99.9%
Transportation Equipment	Oil Tankers	Capacity in 1000s of tons	38.5 (2010)	265 (2010)	Capital cost per ton	59%
	Freight Vessels		40 (2010)	170 (2010)		52%
	Aircraft	Number of Passengers	132 (2012)	853 (2012)	Capital cost per passenger	14%
			40 (2007)	220 (2007)	Fuel usage per passenger	48%

Sources (from top to bottom): (Keshner and Arya, 2004; DisplaySearch, 2010; von Tunzelman, 1978; Honda, 2010; Hirsh, 1989; Koh and Magee, 2008; UNCTD, 2006; Airbus 2012 List Prices; Wikipedia, 2012; Morrel, 2007)

Table 4: Summary of Mechanism findings for all cases in Table 1

Mechanism	Specific Technologies in Table 1 by Item Number	Number of Technologies
Creating Materials	1, 2, 3, 4, 5, 6, 10, 11, 12, 20, 28, 30, 31	14
Scale Reduction	14, 15, 21, 22, 23, 26	6
Scale Increase	7, 8, 13, 17, 29	4
Component improvement	9, 16, 18, 19, 24, 25, 32	7
Components benefit from creating materials	9, 32	2
Components benefit from reductions in scale	16, 18, 19, 24, 25	5
Components benefit from increases in scale		0
Other, Unknown	27, 33	2
Total		33