Guiding the Emergence of Excellent Large Digital Systems

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*Abstract*

*In their early years many major technologies have failed to create the huge productivity gains they would eventually deliver. Today, many emergent and large-scale digital systems display weaknesses parallel to immature systems of the past. System builders need to learn from campaigns that created productivity-driving systems in the past and in recent years and build highly effective large systems for our future. Insights into the opportunities are presented in this article.*

**Introduction**

Many major technologies have frustrated the first generations to use them. Big new technologies – the kind that will transform society – have “bugs” when they are first introduced. While they may provide amazing new benefits, their most important contributions will require decades of work fixing the bugs, making complementary innovations, and re-structuring how society works (Lipsey, Carlaw & Bekar, 2005).

Take steam power. The first British steam engine was patented in 1698. Steam does not seem to have contributed to higher wages until after 1830 (Williamson, 1990).

Interchangeable-parts manufacturing is another example. The French general Jean-Baptiste de Gribeauval developed the idea of manufacturing with interchangeable parts in the 1760s. Thomas Jefferson, U.S. minister to France, recommended Americans adopt it. And they did. Yet despite clocks, locks, and guns made with interchangeable parts in the first half of the 19th Century, it was 1870 before the effort could be said to be increasing growth as economists would measure it. It was 1910 before interchangeable parts products – including mass-produced automobiles – truly transformed life. Table 1 summarizes the major milestones before the technology was fully integrated.

Though interchangeable parts technology took 140 years to deliver its largest contributions, products made with interchangeable parts surround us everywhere today. Many of the most successful businesses of the 20th Century, from Ford Motor to IKEA, were built on advancement of de Gribeauval’s innovation.

(See Table 1 at the end of the article)

This history suggests an enormous challenge for technologists today. We are 73 years from completion of ENIAC, the first large all-electronic computer. Computing inventions are impressive. Yet digital technology still frustrates users. It has yet to create the widespread prosperity that previous technologies produced (see Gordon, 2016 for further insight). Technologists need to identify what it will take for large digital systems to operate with comprehensive usefulness and consistent, crisp reliability like interchangeable parts manufacturing, for instance, finally delivered after 1920.

Today we lack comprehensive understanding of this evolution in innovation. An illustration of our limited knowledge on this issue is the conflicting viewpoints espoused in the premier professional business journals – the Harvard Business Review and the M.I.T. Sloan Management Review.

Carr’s claim in Harvard Business Review that “IT Doesn’t Matter” (Carr, 2003) continues to challenge information technologists. Carr argued that new IT – information technology – systems were unlikely to be powerful enough to be strategically important. They were becoming “commodity factors of production” (p. 42). An important principle of future IT management would be, “Follow, don’t lead.” He wrote that “Waiting will decrease your risk of buying something technologically flawed or doomed to rapid obsolescence” (p.48).

In contrast, the M.I.T. Sloan Management Review argues information technology delivers valuable transformations. In health care, for instance, it contends a hospital’s system makes care “safer, faster and cheaper” (Kane, 2015). Data in the journal suggests the best large systems contribute powerfully. Kane argues that companies need to do strategic technology planning with a ten or twenty-year time horizon – while he acknowledges this is counter-intuitive given technology’s unpredictability (Kane, 2016). However, no detailed picture of how to create powerful systems has been provided.

This paper seeks to show that IT *can* matter and to explore what we know about how to make it matter. It summarizes how powerful large technological systems have been built and presents fivepreliminary principles for creating productivity-driving large digital systems. The processes described require difficult long-term effort. However, they have proved worthwhile for some and there is reason to believe they can help many others.

# **Powerfully Productive Technology Systems and their Emergence**

David (1990) called attention to big technologies’ failure to increase productivity in early decades by showing that the first electric motors in factories did little to increase productivity. He noted that in the early 1900s, electric motors worked well and demonstrated more flexibility and efficiency than water or steam power. However, they did not much improve output before the mid 1920s.

Nineteenth Century factories had been built several stories tall because large water and steam power plants were much more efficient than smaller ones. Belts brought power from central sources to many machines. Moving materials and parts around in such factories was difficult. Significant changes required shutting everything off. When electricity reached such factories and engineers added electric motors, they did not reduce the difficulties of getting things done.

Productivity rose only after system builders greatly improved electric power systems and extended them to much of the United States. Owners now built entirely new factories running exclusively on electricity, with many motors and no belts. They were usually on one level – a whole new system. Rapid productivity growth began in the 1920s and continued for decades.

This illustrates the fact that when big technologies emerge there are usually barriers that prevent them from making maximum contribution. Sometimes aspects of the technology do not perform well enough for it to achieve its potential. For example, 18th Century metallurgy made it dangerous for steam engines to operate at high pressures, so engines could not generate the power they later would (Dickinson, 1938/1963). On the other hand, when technologies do work well, often the business world needs reorganization to take advantage.

David referred to the technologies he discussed as “general purpose engines,” which he defined as “key functional components embodied in hardware that can be applied as elements … for a wide variety of specific operations” (David, 1990; p. 355). The term “general purpose engines” turned out to be misleading. Not all technologies that have followed the pattern function as modular units (Field, 2011). However, research shows that many technologies we take for granted went through long periods when they did not work well enough or fit into systems well enough to contribute as they eventually would. A big new technology can achieve its potential only if both technology and systems in which it is embedded mature in three ways:

* They must work very well.
* Many complementary innovations must have been made to enable the technology to relate to people’s lives and tools.
* The innovations must be fairly widely diffused.

Researchers on electric power and other large systems that emerged prior to the 21st Century show that both orchestration of complementary innovations and reorganization of business depended on the work of leaders they call “system builders.” Key system builders in emergence of electrical systems were Edison, Westinghouse, and Siemens, for example. There are few documented examples of highly effective large technological systems emerging without leadership of an individual or very small group (Hughes, 1987).

Perhaps a major reason why computing is not yet driving economic takeoff is that today’s system builders have produced few major systems that meet the above criteria for achieving their potential. Few work very well and fit well into larger systems created through well-developed complementary innovation. Producing such systems could be a source of sustained advantage for technology leaders and their firms.

# **Highly Effective Large Digital Systems Today**

Today our technical abilities vastly exceed those of earlier eras and continue to improve rapidly. However, technical sophistication has not reliably predicted business success or national prosperity. Some digital systems have significantly increased productivity – for instance see Banker, Chang and Kao (2002) on accounting systems. In many ways, however, large digital systems today have much in common with systems from early days of steam, interchangeable parts, or electricity. In education, for example, computers have increased overhead costs without evidence of increasing productivity or performance (Gordon, 2017). In most of health care, gains have been elusive (Mead, 2006).

Even in offices, people spend much time struggling to understand databases, to get software programs to talk to another, and to address computer security. Production in early 20th Century factories was slowed by difficulties of transition from old power drivers to electricity and by the continuing complexities of running factories set up for water power or steam. Productivity today is slowed by continuing difficulties of shifting from paper to digital systems and by difficulties of creating truly efficient, flexible digital ways of working.

A few large digital systems today do work well and benefit from sufficient complementary innovations. Amazon.com is one example. It rarely creates the difficulties common to other technological systems. Through customer-focused processes, Amazon has produced many innovations complementing its core electronic commerce functionality: well-developed recommendation engines, efficient connection to sellers of lower-priced used items, and remarkable logistics systems (Stone, 2013). Amazon’s systems are economically mature in the sense that past systems were mature when they made their greatest contributions to economic growth.

Big-Box brick-and-mortar retail systems also deliver excellent efficiency. A study by the Federal Reserve Bank of Chicago (2004) found emergence of highly effective systems in brick-and-mortar retail accounted for three-quarters of the acceleration in U.S. total factor productivity growth in America’s last highly prosperous period, the second half of the 1990s. The systems derived from systems Walmart developed under Sam Walton from the 1960s to his death in 1992. Walmart created technology that smoothly managed products from factory to checkout and supported customer-oriented management of individual stores. A Harvard case showed Walmart’s systems saved it the equivalent of 3.1% of sales just from reductions in in-bound logistics spending and regional offices – and these were by no means their only benefits (Foley, Bradley & Ghemawat, 1994). The systems produced vast value for customers and investors. Soon competitors learned from Walmart, and retailing as a whole grew rapidly more efficient.

## **IT Does Matter**

This evidence shows Carr is not entirely correct. Information technology sometimes matters tremendously. Today Walton heirs are Nos. 10, 11, and 12 on *Forbes’* list of richest Americans (Forbes 400, 2019). Bezos of Amazon is No. 1. Amazon was a mid-sized firm in 2003 when Carr published, with survival by no means assured. Today, however, there is no greater strategic success.

These achievements suggest other digital systems could work far better than currently and that creating such high functioning systems can produce remarkable profits and competitive advantage. Thus, an important challenge, 70 years after ENIAC, is to enable other technology to work with this kind of maturity.

# **How Older Large Technological Systems Were Built**

To understand how such systems emerge, it helps to examine literature on pre-21st Century large technological systems. Only a few generalizations are possible because of the diversity of such systems. Systems especially from the Second Industrial Revolution (1880-1940) provide insights on four aspects of past system development which are relevant (Hughes, 1987):

* **A system builder or small group of system builders.** One or more key individuals led the development of each powerful Second Industrial Revolution system. There are few examples – perhaps none – of powerful, effective large technological systems emerging from interplay of market forces or from workings of a bureaucracy. Systems were generally built with widely available technical knowledge, and successful system builders usually faced significant competition. But when an effective system was constructed, an individual or small group could be identified as builder.
* **Long-term process**. Second Industrial Revolution system builders worked for decades on their creations to achieve their goals.
* **Rough vision driving many complementary innovations.** To describe large systems’ evolution, Hughes uses a military analogy. Generals know what they want to conquer. They seek to advance across a whole front, seizing many types of countryside. Similarly, system builders must make many types of technical advances and structural changes to realize their visions. Often armies fail to advance along a part of a front. The general must then focus resources there. Similarly, technological systems may fail to advance in key areas and system builders must focus innovation on them.
* **Innovation that involves changing the nature of organizational forms societal institutions.** Since existing social arrangements are usually inappropriate for society to gain full benefits of the new technology, system builders must create new ones – for instance, electrical manufacturing factories and utility holding companies.

Each of these has parallels in processes by which Walton created his retail systems and Bezos created online systems. We can hypothesize that each will have analogues in other successful large digital systems.

**Principles for Building Effective Large Digital Systems**

Based on how successful existing large technological systems emerged, five tentative principles seem appropriate. Four correspond to aspects of Second Industrial Revolution large technological system development. The fifth derives from aspects of Walmart and Amazon development that differ from earlier processes. Table 2 shows past process elements and the proposed principles.

(See Table 2 at the end of the text)

The principles are:

**1. A dedicated system builder or small group is essential to creating highly effective large digital systems.** Both Second Industrial Revolution experience and Amazon and Walmart’s show strong system builders are essential. Neither competition in an ecosystem nor bureaucracies have created many high-quality systems. The system builder is more than a system architect. Since society is not normally organized to take full advantage of the technology, they have to work in the larger society for change. Edison worked on new elements of the U.S. financial system. Walton had to build relationships that enabled Walmart systems to reach deeper into suppliers than computing had previously.

**2. Creating highly effective large digital systems requires very long-term pursuit of a vision.** The large systems Hughes studied and Walmart and Amazon systems all emerged from decades of work. History shows what technology planning with a 20-year or longer horizon means. Successful system builders have a rough vision. As they work, they confront technology that can do some of what they want well, some poorly, and some not at all. They quickly introduce systems to address challenges that current technology handles. They seek solutions other challenges in a long campaign.

This differs sharply from conventional management – only 2% of firms address technology with a ten- to 20-year time horizon and only 10% think five years or more ahead (Kane, 2016).

**3. Creating a highly effective large digital system means carrying out many projects that are highly complex themselves. System builders must ensure every product development process operates well and each is coordinated with the evolving vision.** Many of the innovations that form parts of large digital systems are themselves complex product systems – systems that involve many interacting disciplines and subsystems. Amazon’s warehouse systems, for instance, are complex product systems. Complex product system design is inherently challenging because numerous individuals and teams must coordinate (Yassine, 2018). But many such systems, together with innumerable smaller projects, must work together in a truly large digital system. System builders must ensure not only that each development process operates well but that each evolves to contribute to the whole.

**4. Creating highly effective large digital systems requires a community of managers and technologists** **dedicated to improvement and reinvention toward the vision.** Both Walton’s Walmart and Bezos’ Amazon built communities that saw constant improvement and reinvention as central. Walton recruited retail executives, especially top managers, who were passionate about technology and put them in positions that did not obviously call for tech – such as a supervisor of store openings – in an era when other retailers found putting tech people in such positions inconceivable.

**5. Creating highly effective large digital systems calls for deep focus on very long-term customer needs.** One difference between reports of Second Industrial Revolution system builders and stories of Walmart and Amazon is deep long-term customer focus in the newer firms. Getting early 20th Century technologies to function required extensive, difficult metal-working – an overwhelmingly technical challenge. But flexibility and low cost of digital technologies allows easy construction of initial versions of big innovations. Many online bookstores appeared rapidly when the Internet emerged in the 1990s, for example. Making online systems work well then called for understanding customer wants and fulfilling them over years.

Figure 1 diagrams the multi-decade process of creating effective large digital systems following the above principles.

# **Conclusion: Highly Effective Large Digital Systems**

Creating large systems that fully leverage today’s incredibly powerful technologies turns out to be even more difficult than we usually recognize. The biggest challenge may be recognizing just how powerfully today’s technology can improve our lives and our customers’ lives. And then once the potential is realized, the big challenge will be organizing over the long term to deliver what is possible.

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Table 1

**Emergence of Interchangeable Parts as Driver of Economic Development**

|  |  |  |
| --- | --- | --- |
|  | **Ideas and Capabilities** | **Impact on Society and Economy** |
| *1765* | French General de Gribeauval seeks to rationalize military procurement by insisting on (hand-made) interchangeable parts | Benefits including lower cost and easier battlefield repair are sought; they are hard to realize |
| *1785* | French officers and Thomas Jefferson, U.S. minister to France, recommend the system to Americans |  |
| *1790s-early 1800s* | U.S. Army and manufacturers attempt to apply French principles | “Uniformity” seen as central to military discipline, efficiency. Only partially achieved. |
| *1815-1850* | Mechanics develop machines to make the parts; U.S. armories achieve interchangeability at high cost. | Private firms learn machine practice from armories, but do not deliver interchangeability |
| *1851* | U.S. gunmaker Robbins & Lawrence demonstrates true interchangeability of gun parts in London | British see U.S. tech as superior. But most manufactured parts still not interchangeable |
| *1850s* | Browne & Sharpe carefully creates system for making sewing machines with interchangeable parts | Singer Co., with old-style craft manufacturing, has costs just as low |
| *1861-65* | Civil War – North makes guns with the new system | South is able to import and make guns competitively |
| *1870-1900* | Interchangeable parts production costs fall; Singer adopts the system. Bicycle introduced as interchangeable parts product | Interchangeable parts now a better system for high-volume products, but these are not a large share of output |
| *Early 1900s* | Meat-packing, flour-milling, brewing industries have large, repetitive processes. Ford draws on their experiences to make Model T. | Mass-produced products begin to be central to middle class life |
| *1920s* | Other car makers follow Ford; electrical appliances, other new products made with interchangeable parts | Interchangeable parts are a major driver of prosperity. |

Source: Hounshell (1984)

Table 2

**Key Elements in Emergence of Highly Effective Large Technological Systems   
and Preliminary Principles for Driving and Guiding Them**

|  |  |  |
| --- | --- | --- |
| **Second Industrial Revolution Systems** | **Big Box Retail and Online Retail** | **Preliminary Principles** |
| System builders such as Edison, Westinghouse drive emergence and development of systems. | Sam Walton and Jeff Bezos drove system building. | 1. A system builder or small group of system builders is central. |
| Systems such as the electric power network emerged over multiple decades. | Walmart and Amazon systems took decades to become major drivers of profit. | 2. Creating highly effective large digital systems is a very long-term process. |
| Creating the electric power network involved creation of multiple systems such as local power networks, repeatedly requiring new technical solutions. | Walmart and Amazon systems were built through numerous complex product system projects. | 3. Creating a highly effective large digital system requires many large innovation projects that are highly complex themselves. System builders must coordinate each with evolving vision. |
| System builders created not only new technologies but new organizational forms and societal institutions. | Extent of institutional change involved not studied yet, but both Walmart and Amazon built substantial communities of people dedicated to improvement. | 4. Creating highly effective large digital systems requires building community of managers and technologists dedicated to improvement and reinvention. |
| *Little evidence of customer focus in development of Second Industrial Revolution systems* | Walton and Bezos focused on creating what customers would want over very long term. | 5. Creating highly effective large digital technology systems calls for deep focus on customer’s very long-term needs. |

Figure 1

**The Process of Creating a Highly Effective Large Digital System**

