# Design Rules, Volume 2: How Technology Shapes Organizations

## Chapter 7 The Value Structure of Technologies, Part 2: Strategy without Numbers

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## Chapter 7 The Value Structure of Technologies, Part 2: Strategy without Numbers

**By Carliss Y. Baldwin**

**Note to Readers:** This is a draft of Chapter 7 of *Design Rules, Volume 2: How Technology Shapes Organizations*. It builds on prior chapters, but I believe it is possible to read this chapter on a stand-alone basis. The chapter may be cited as:

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I would be most grateful for your comments on any aspect of this chapter! Thank you in advance, Carliss.

## Abstract

Functional analysis as set forth in the last chapter decomposes a technical system into functional components that *do things* to advance the system's purpose and the goals of its designers. Functional analysis in turn can be used to construct value structure maps of technical systems. Such maps reveal targets of potential action and investment in the technical system where value may be created and captured. Value structure maps can be constructed without using numerical estimates based on prices, quanities and probabilities, thus they are an appropriate means of analyzing technical systems subject to radical uncertainty, complexity, and complementarity.

The purpose of this chapter is to illustrate how value structure mapping combined with narratives can be applied to problems of strategy in large technical systems. I first argue that the salient points of value creation and value capture in a large technical system are the system's *bottlenecks*. I then use value-mapping methodology to trace the evoluion of bottlenecks of three large technical systems: early aircraft; high-speed machine tools; and container shipping. Finally, I distill the lessons of the case studies into four principles for creating and capturing value in large, evolving technical systems.

## Introduction

Functional analysis as set forth in the last chapter decomposes a technical system into functional components that *do things* to advance the system's purpose and the goals of its designers. Functional analysis in turn can be used to construct value structure maps of technical systems. Such maps reveal targets of potential action and investment in the technical systemwhere value may be created and captured. Value structure maps can be constructed without using numerical estimates based on prices, quanities and probabilities, thus they are an appropriate means of analyzing technical systems subject to radical uncertainty, complexity, and complementarity.

The purpose of this chapter is to illustrate how value structure mapping combined with narratives can be applied to problems of strategy in large technical systems. I first argue that the salient points of value creation and value capture in a large technical system are the system's bottlenecks. *Technical bottlenecks* are places where new technical recipes must be created for the system to work (or work better). *Strategic bottlenecks* are components (including technical recipes) that are essential, unique, *and* controlled by a profit-seeking agent.

I then use value-mapping methodology based on functional analysis to construct narratives explaining the dynamics of three large technical systems: early aircraft; high-speed machine tools; and container shipping. Specifically, I trace the evolution of bottlenecks in all three systems, showing how technical bottlenecks may give rise to strategic bottlenecks and how strategic bottlenecks depend on property rights. Although they are not based on numerical estimates or probabilities, the narratives provide a basis for understanding the competitive dynamics of each system and predicting long-term outcomes.

In the conclusion to this chapter, I distill the lessons of the case studies into four principles for creating and capturing value in large, evolving technical systems. The principles will serve as guideposts though the rest of this book.

## 7.1 Bottlenecks Defined

Many scholars have argued that "bottlenecks" are key to understanding the direction and pace of technological change and to capturing value in complex technical systems. On the one hand, firms and individuals seeking to *create* value through technology are said to look for and resolve the technology's bottlenecks. On the other hand, firms wishing to *capture* value are advised to control bottlenecks and beware of bottlenecks controlled by others.

But what is a bottleneck?

In common usage, a bottleneck is a narrow place that obstructs a flow of water or traffic, for example. Thus in a road system, if all routes pass over a bridge or a mountain pass, and that part of the system is a source of congestion, then it is a bottleneck. More generally, a bottleneck is "someone or something that retards or halts free movement and progress.[1]

In this book, I define a bottleneck as a functional component of a technical system that has no — or very poor — alternatives at the present time. A bottleneck is both *essential* to the functioning of the whole and *unique* in that it has no substitutes. A bottleneck component is thus a strong functional and economic complement of all other components of the system. To know that something is a bottleneck, an observer must see it in relation to a larger system, know what constitutes good system-level performance,

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[1] Merriam-Webster Online Dictionary.

and understand how the bottleneck constricts that performance.

In technical systems, there are two types of bottlenecks, technical and strategic. With a *technical bottleneck*, the hindrance to performance derives from physical properties of the system. For example, in a railroad system, if there is no bridge over a river and goods must be taken onto barges and reloaded on the other side, then the river constitutes a technical bottleneck. It impedes the performance of the whole system and there is no good way around it.

Building a bridge can solve the technical problem, creating value in the form of cost savings to users. However, the owner of the bridge can capture part of the value created by charging users a toll. The bridge plus the ability to control it then constitutes a *strategic bottleneck*. The former system of boats and barges is far less efficient, thus unless someone builds a second bridge, travellers and shippers have no good alternative except to use the bridge and pay the toll.

In the next two sections, I expand on the basic definitions of technical and strategic bottlenecks.

## 7.2 Technical Bottlenecks

Technical bottlenecks are unsolved problems in a technical system that cause the system to fail or otherwise limit its performance.[2] There are three basic sub-types of technical bottleneck: functional bottlenecks, flow bottlenecks, and matching bottlenecks.

*Functional bottlenecks* are essential functional components that do not have proven technical recipes. As we saw in the previous chapter, a functional component *does something* that contributes to the purpose of system as a whole. In the case of new technologies, however, technical recipes for some components may not exist.

Brian Arthur has described the invention of novel technologies as a process of solving individual problems "until each problem and subproblem resolves itself into one that can be physically dealt with."[3] When the most difficult subproblem is solved, this is generally recognized as a breakthough, and becomes part of the lore of the technology. For example, in their experiments at Kitty Hawk, the Wright brothers solved the critical subproblem of lateral control of a flying machine. Thus they are credited with the invention of the first successful airplane. (We will look at this example again later in the chapter.)

Second, many complex technical systems involve flows. The flows may be water through an irrigation system, trains through a railroad network, goods through a factory, electrons through a computer, messages through a communication network, customers

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[2] Scholars who have written about technical bottlenecks include Rosenberg (1963, 1969, 1982); Langlois and Robertson (1992); Ethiraj (2007); Arthur (2009); Adner and Kapoor (2010, 2016); and Baldwin (2018). Hughes (1987) preferred to use the military term "reverse salient," but was essentially describing technical bottlenecks.

[3] Arthur 2009, p. 110.

through a store, patients through an emergency room, or laws through Congress.

All systems involving flow are subject to capacity contraints. In a system of one-directional flow, the capacity of the slowest segment constrains the capacity of the system as a whole. This a *flow bottleneck*. If the flow involves the movement of goods through a production process, the flow bottleneck is know as a *production bottleneck*. Production bottlenecks are of critical importance in high-volume mass production systems. We shall look in detail at production bottlenecks and their organizational implications in Chapters 8-10 below.

Third, many systems require parts that match or fit together. In these cases, the performance of the system as a whole will be constrained by mismatched components. For example, the power of the engine in an automobile must be matched by the power of its brakes. The strength of materials in a jet engine must match the force of the jets.

*Matching bottlenecks* are caused by mismatched components.Nathan Rosenberg describes a matching bottleneck caused by the introduction of high-speed steel alloys in the late 19th century.

> It was impossible to take advantage of higher cutting speeds with machine tools designed for the older carbon steel cutting tools because they could not withstand the stresses and strains … . As a result, the availability of high-speed steel for the cutting tool quickly generated a complete redesign in machine tool components—the structural, transmission, and control elements.[4]

We will look at this example in greater detail later in this chapter.

Functional and flow bottlenecks both involve a mismatch of elements. For a functional bottleneck, the mismatch is the absence of a solution to a critical subproblem. For a flow bottleneck, the mismatch is in flow capacity. Hence these types of bottlenecks can be viewed as special types of matching bottlenecks. However the three types of technical bottlenecks may shape organizations in different ways thus it is useful to distinguish between them.

*Technical bottlenecks are distinct from modules*. In general, technical bottlenecks are problems that exist whether the designer wants them or not. In contrast, modules are groups of tasks and related decisions that are tightly connected within a module, but only loosely connected with other modules.[5] In a given system, the boundaries of modules do not necessarily correspond to the locations of functional components or bottlenecks. A single function may be spread across several task modules. Conversely a single task module may serve several functions with the larger system.[6]

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[4] Rosenberg 1969, pp. 7-8.

[5] Baldwin and Clark (2000) Ch. 3.

[6] In a seminal paper on modularity, Ulrich (1995) defined a "modular product architecture" as having "a one-to-one mapping from functional elements … to physical components" (p. 422). However, after looking

### 7.3 Strategic Bottlenecks and Property Rights

A strategic bottleneck needs two things: (1) a *unique solution* to an underlying technical bottleneck; plus (2) *control over access* to the solution. Strategic bottlenecks are points of value capture and thus a potential source of economic rent in a technical system.[7] In the bridge example discussed above, if a river is a technical bottleneck in a rail network, a firm seeking to capture a strategic bottleneck must first build the bridge (the solution) and then prevent travellers from using the bridge unless they pay a toll (control). (The firm must also prevent investors from building a second bridge.)

In economics, a property right "is the exclusive authority to determine how a resource is used." [8] Users of the resource must obtain permission of the owner. Property rights in turn can be *de facto* based on power (my army controls the bridge) or *de jure* based on the law (I own the bridge and police will arrest any trespassers). David Teece called the state of property rights pertaining to a resource the "appropriability regime." and noted that the regime might be weak or strong. In strong appropriability regimes, it is easy to exclude others from using a particular resource. In weak appropriability regimes, it is hard.[9]

Property rights—the ability to determine who has access to a resource—are thus critical to protecting a strategic bottleneck and claiming the associated rents. I define the *zone of authority* of a given firm to be the totality of its property rights over the components of a technical architecture. A firm can exercise control through a combination of ownership, physical control, secrecy, contracts, patents and copyrights. The components it controls by these means are within its zone of authority.

Bottlenecks, modules, and zones of authority are not cast in stone. Technical bottlenecks can be solved and strategic bottlenecks can be seized. Module boundaries can be redrawn and property rights can be transferred. These actions and events will necessarily change narratives about technical systems and their associated organizations. To allow for such changes, I must extend value structure analysis can take account of technical and strategic bottlenecks and zones of authority.

### 7.4 Extending Value Structure Analysis

In the last chapter, with only two operators (☐ and +), we were able to represent a large set of technical systems in terms of their underlying functional components and relationships. Using value structure maps based on functional analysis, we were able to

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at a wide range of modular systems, Kim Clark and I adopted a definition of module and modularity that was based on structural linkages alone. The problem is that functions lie in the eye of the beholder and depend on specific use cases. In contrast structures and structural relationships are generally unambiguous.

[7] Strategic bottlenecks are discussed in Teece (198); Langlois (2002); Jacobides, Knudsen and Augier, (2006); Pisano and Teece (2007); Jacobides, MacDuffie and Tae (2012); Jacobides and Tae (2016); Henkel and Hoffmann (2014); and Baldwin (2018).

[8] Alchian, A. (undated) "Property Rights," *Encyclopedia of The Library of Economics and Liberty*: https://www.econlib.org/library/Enc/PropertyRights.html (viewed August 31, 2020).

[9] Teece (1986).

recognize which components were essential and which were optional in a particular technical system, and to show how new functions can be created by combining existing ones. We also were able to indicate module boundaries by drawing borders around modules. At this point, we need to denote the presence or absence of bottlenecks in the value structure map of a technical system.

Let "*name*" denote a particular functional component (equivalently its technical recipe) in a given technical system at a point in time.

As before, a border — $\boxed{name}$ — indicates that the component is a module. If there are multiple functional components within a module, the tasks needed to provide them are by definition interdependent. This means that if the technical recipe for one functional component in a module changes, the technical recipes for all other functional components in that module must be revisited.

A superscript "o" — $name^{o}$ — indicates that at the time of the observation, no workable technical recipe for the functional component yet exists. In this case, the function cannot be performed. If the function is essential (not optional), then the system as a whole is not functional. If the function is optional, then the option is not available.

A superscript "*" — $name^{*}$ —indicates that *only one* workable technical recipe for the component exists.

A superscript "*X*" — $name^{*X}$—indicates that only one workable technical recipe exists, and *it is in the zone of authority of agent X.*[10] The component can then be the basis of a strategic bottleneck benefiting *X*.

In the next three sections, I use cases from history to show how the identification and exploitation of bottlenecks can guide the search for new technical recipes, and indicate likely points of value capture within a large technical system. The case studies involve (1) early aircraft; (2) high-speed machine tools; and (3) container shipping.

## 7.5 Early Aircraft Design

As indicated in Chapter 6, a basic flying machine must have components to provide thrust (the engines); lift (the wings); a central framework (the fuselage); lateral and vertical stability (elevators, ailerons, rudder); a steering mechanism (same); and the ability to land (flaps, wheels, brakes). If one of these functional components is missing, the flying machine is unreliable at best, and dangerous at worst. Each functional component is *essential* for the functioning the system.

In the very early 20th Century, technical recipes existed for all of the functional components of an aircraft except stability and steering. This state of affairs was well-

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[10] It would be simpler to say the component *is owned by* Agent X and I will sometimes use that language as a shortcut. However, some technical recipes, such as the knowledge in the head of a trained employee, cannot be owned. However, by virtue of the employment contract, such knowledge can still be in the zone of authority of the employer.

understood by the aviation engineers and aviators of the time. In published speech in 1897, Octave Chanute, a respected French-American engineer, indicated that “the use of a horse power motor … was a minor detail and not a serious problem, [but] the maintenance of equilibrium was the most important problem in connection with aerial navigation.”[11] His statement was in essence a narrative about the state of aircraft technology at that time, which declared the “maintenance of equilibrium” to be the most difficult remaining technical bottleneck.

In 1901 “flying machines” were a technology subject to radical uncertainty. There were no “business models” for aviation. The main sources of revenue for aviators were prizes and gate receipts at flying shows (which sustained the Wright brothers though most of their early years).[12] People could speculate about the possibilities of air mail and military applications but these markets did not exist. Commercial aviation lay in the far distant future.

However, even though aviation was not yet a business, the technical architecture of flying machines was understood by most aviators and engineers. We can thus map the value structure of an early flying machine in the following way:

**1901:**

$$\boxed{\textit{thrust} \ \square \ \textit{lift} \ \square \ \textit{frame} \ \square \ \textit{control}^{o} \ \square \ \textit{landing}} \rightarrow \textbf{\textit{Flying Machine}}$$

In 1901, there were adequate solutions (technical recipes) for many of the functional subproblems, but no solution to the problem of control, which included vertical and lateral stability and steering. For want of this essential function, the system-as-a-whole was not viable. There were no safe aircraft.

Early aircraft were also integral (non-modular) technical systems, as indicated by the box around all five functional components. To test any theory about control, an aviator needed to build a whole plane. All parts were specialized to all other parts.[13]

Understanding the technical architecture and value structure in this way, the Wright brothers focused their attention on the control problem and pursued it tenaciously until they had solved it. The special nature of the control function—its status as a *technical bottleneck*—is indicated by the superscript “o” on the function in equation (1). Numerous companies and individuals, not only the Wrights, were trying to solve this

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[11] As noted in the Judge’s Decree, WRIGHT CO. v. HERRING-CURTISS CO. et al.*The Federal Reporter, Volume 204* p. 601. https://books.google.com/books/reader?id=ZDaTAAAAIAAJ&num=11&printsec=frontcover&output=reader&pg=GBS.PA597#v=onepage&q&f=false (viewed August 31, 2020).

[12] McCullough (2015).

[13] One might argue that engines (providing thrust) were an exception. However, even if they purchased an engine from a third party, aviators still had to modify it substantially in work in their designs. The Wright brothers made their own engines. McCullough (2015).

problem.[14]

In the spring of 1901, the Wrights initiated a series of experiments with gliders at Kitty Hawk, NC. Over the next two years, they devised a method of three-axis control based on a technique called “wing-warping” and a movable, vertical rudder. Adding an engine to their glider, they are credited with achieving the first, controlled, powered, sustained heavier-than-air flight on December 17, 1903.

Interestingly, in surface vehicles, the functions of stability and steering are separable, while in a flying machine the two functions are interdependent. Wings are used to turn and a rudder functions as a stabilizer. The Wright brothers discovered these non-obvious principles through their experiments with glider designs. As a result of this knowledge, they were able to frame their patent claims very broadly, stating that wing-warping (their specific solution) was only one way to achieve three-axis control of a flying machine.[15]

In 1906, after the Wright brothers had solved the control problem, they were granted a patent for “a means for maintaining or restoring the equilibrium or lateral balance of the apparatus, to provide means for guiding the machine both vertically and horizontally, and to provide a structure combining lightness, strength, convenience of construction.”[16]

The value structure of the technical system became:

**1906**

$\boxed{\textit{thrust} \square \textit{lift} \square \textit{frame} \square \textit{control}^{*W} \square \textit{landing}}$ ➔ ***Flying Machine***

Now there was an adequate technical recipe that solved the problem of control. *It was unique and controlled by the Wright brothers.* Solving the problem of control completed the list of essential functions needed to make a flying machine, Safe, reliable flying machines could now be built.

However, as indicated by the supersrcript “_*W_” on the control function, one essential functional component had a unique solution owned by the Wrights. Anyone wanting to build a flying machine for any purpose had to seek a license from them. Thus the control function evolved from being a technical bottleneck into a *strategic bottleneck*.

The Wrights and their successors[17] thus controlled access to a unique and essential functional component in a flying machine system. Consistent with the predictions of the property rights literature, they could and did demand a cut of all

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[14] Judge’s Decree, WRIGHT CO. v. HERRING-CURTISS CO. et al. *op. cit.*

[15] Wright, O., & Wright, W. (1906). *U.S. Patent No. 821,393*. Washington, DC: U.S. Patent and Trademark Office.

[16] *Ibid.*

[17] Wilbur Wright died in 1912 and Orville Wright sold his stake in the company in 1915.

revenues related to flying machines that used their system of control. Furthermore, every company that obtained revenue from flying machines was vulnerable to hold-up, should the Wrights change their license terms.

The strategic bottleneck and the associated threat of hold-up would cease to exist if another method of control, *that was not derived from the Wrights'*, could be found. Thus do strategic bottlenecks become targets of investment in technical systems: if a second way to fulfill the function can be found, the power of the first owner to capture value is reduced dramatically.

Glenn Curtiss of Herring-Curtiss Co. understood this. In several rounds of litigation lasting over a decade, he tried to establish his ailerons as an alternative, independent solution to the control problem. However he was not successful in proving the independence of his design from the Wrights' original design.[18]

For the first two decades of the 20th century, airplanes continued to be integral (non-modular) technical systems.[19] Each aviator designed his own and built it himself or contracted to have it built.

However as airplane designs improved and more uses for air transportation were discovered, a number of companies (including Wright and Herring-Curtiss) began to make airplanes for commercial and military markets. By 1917, at least 47 aviation companies were involved in aircraft manufacture.[20] At this point a new technical architecture with related organizational and industry architecture became dominant.

Specifically engines, providing thrust, became a separate module defined mainly by power and weight. Thus engine design and production were separated from the rest of the aircraft, and specialist firms like Rolls-Royce and Pratt & Whitney began supplying engines to the aircraft manufacturers. (Aircraft engines were far from typical modules, however. Engine and aircraft designers worked closely on each new product line to adapt the engine and planes to one another. Like the laptop and disk drive companies discussed in Chapter 2, they used formal and relational contracts to support transactions at thick crossing points in the task network.)

Except for the engines, the rest of the functional components remained highly interdependent: redesigning the basic wings, for example, meant redesigning ailerons and the fuselage. Early in aviation history, wheels were a separate module. However, as aircraft speeds increased, concerns about drag led to the development of retractable landing gear, which folded the wheels into the fuselage during flight.[21]

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[18] Katznelson and Howells (2015).

[19] In American English the word "airplane" became common after 1907. It replaced "aeroplane," which continued to be used in the United Kingdom and Canada..

[20] Katznelson and Howells (2015).

[21] Vincenti (1994). The earliest airplanes did not have wheels, but landed on skids attached to the fuselage and the wings.

In 1917, as it prepared entered World War I, the U.S. government forced all aviation companies into an industry-wide patent pool. At that point the Wright patent ceased to be a strategic bottleneck. Engines were a separate module, but the myriad of technical interdependencies among the other components made it difficult to modularize the aircraft itself. The value structure of modern airplanes, which prevailed through most of the 20th Century was as follows.

**1917-2020**

$\boxed{\textit{thrust}} \square \boxed{\textit{lift} \square \textit{frame} \square \textit{control} \square \textit{landing}}$ ➔ ***Modern Airplane***

In any technical system, the modularity of techical components is a choice. However, Daniel Whitney has shown that it is a choice moderated by the physics of the technology.[22] From a physical standpoint, an aircraft must have structural integrity and its total weight must be commensurate with its wingspan, propellers, the power of its engines, and the strength of its wheels and brakes.

Such physical dependencies, especially if they are not completely understood, create natural interdependencies in the underlying design and production processes. Modularizing the system requires understanding each of the dependencies *in detail* and then creating a design rule that spans the parts (see Chapter 2). John Paul MacDuffie has shown that, in physically interdependent systems such as aircraft or automobiles, the process of modularization will be long and difficult. Continued interdependency may be the better choice.[23]

In 2003, Boeing Corporation attempted to modularize the design and production of its new 787 Dreamliner. Because of unmapped physical dependencies among components, the first planes were delivered late and with technical defects, and the project ran significantly over budget.[24] One hundred years after the Wright brothers' first flight, it was still virtually impossible to split up the design and production of an airplane into a series of modules separated by thin crossing points.[25] Physics pushed the designs in the opposite direction.

## 7.6 High-speed Steel for Machine Tools

The case of high-speed steel for machine tools provides another example where value structure analysis can explain actions and investments within a system of complements. A machine tool for cutting metal, such as a lathe, has four basic functional components: (1) a cutting tool; (2) a frame, which carries or supports the tool and the work; (3) transmission components, which move the tool or the work or both in precise ways corresponding to the desired shape; (4) control components which adjust the frame

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[22] Whitney (1996, 2004).

[23] MacDuffie (2013).

[24] Hart-Smith (2001); Hiltzik, M. (2011); Denning (2013); Kotha and Srikanth (2013).

[25] Allworth, J. (2013).

and direct the transmission components as needed.[26]

In the early 20th Century, Frederick W. Taylor and Maunsel White at Bethlehem Steel Company introduced a set of steel alloys, and a process for tempering them, that increased the hardness of steel when heated to high temperatures. The impact of these new products was to increase the speed at which metal could be removed by a milling machine or a lathe. The potential efficiency of lathes and milling machines went up by a factor of 4 or 5. In 1907, Taylor and White obtained patents for the treatment process which they assigned to Bethlehem Steel.[27]

We can use value structure maps based on functional analysis to explain the evolution of high-speed machine tools. In 1900, Link-Belt Engineering Co. became the first machine tool company to license the Taylor-White process, paying Bethlehem $3000 for the right to use all patents pending on the process.[28] The cutting tool for the new machine tools required steel alloys treated according to the Taylor-White process. The steel alloys existed, but they could not be patented. The Taylor-White process existed: Bethlehem claimed the process was unique and had applied for several patents. However, frames, transmissions and control systems that could handle a high-speed cutting process did not exist.[29]

**1900**

*alloy* ☐ *treatment*$^{*B}$ ☐ *frame*$^{o}$ ☐ *transmission*$^{o}$ ☐ *control*$^{o}$ ➔ ***High-Speed Machine Tool***

The new steel cutting tools could not achieve their full potential with existing frames, transmission and control systems. These components were now technical bottlenecks in the larger system, while the Taylor-White treatment process was a strategic bottleneck. All parts were interdependent.

Thus mechanical engineers immediately went to work to solve the technical bottlenecks. According to Guy Hubbard:

> Beds and slides rapidly become heavier, feed works stronger, and the driving cones are designed for much wider belts than of old. The legs of big lathes grow shorter and shorter, and finally disappear as the beds grow down to the floor. On these big machines massive tool blocks take the place of tool posts, and multiple tooling comes into vogue.[30]

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[26] Einstein (1930) as reported by Rosenberg (1967).

[27] Judge's Decree, Bethlehem Steel Company v. Niles-Bement-Pond Company.

[28] Dodge (1915).

[29] Bethlehem had created tools for demonstration purposes, but their designs were not easily transferrable to the shops of the tool makers. Dodge (1915).

[30] Hubbard, G. (1930) as quoted by Rosenberg (1963).

By 1910, the technical bottlenecks in frames, transmissions and control systems had all been solved. The high-speed system was fully functional.

In addition, in 1909, the Taylor-White patents were struck down by a judge who ruled that the so-called treatment amounted to little more than heating the steel to a very high temperature, as was standard practice among toolmakers. At that point, techniques for making high-speed steel cutting tools were effectively in the public domain. No functional component was unique and thus no agent could capture value via threat of holdup.

The value structure map of the new system was as follows:

**1910 - 1990**

*alloy* ☐ *treatment* ☐ *frame* ☐ *transmission* ☐ *control* ➔ ***High-Speed Machine Tool***

Machine tools were manufactured in many different establishments, each of which would have had its own methods and designs. It is likely that in most shops, the cutting tool made of the treated alloy was separate from the frame, transmission, and control elements. The cutting tool was subject to wear and would need to be replaced fairly often. Separating the cutting tool from the rest of the system for purposes of easy replacement was a sensible design decision.

The other functional components remained interdependent until late in the 20th century. Control units were designed by the manufacturer and hard-wired into the system until personal computers became a cheap, modular alternative in the 1980s.[31] Modular transmission systems appeared shortly afterward.[32] Modular frames are an area of intense research and active patenting today.

## 7.7 Container Shipping

Until the middle of the 20th Century, the process of loading and unloading cargo ships was haphazard, labor-intensive, and above all, time-consuming. Cargo was carried on as loose items and stowed wherever it would fit. Theft was rampant. A study of a single voyage in 1954 of the ship *Warrior* from Brooklyn to Bremerhaven showed that she carried 194,582 separate items. Loading and unloading took 10 calendar days—as many days as the ship spent at sea.[33]

This labor-intensive technical system was revolutionized by containers. Large cargo ships carrying twenty times the tonnage of the *Warrior* can now be loaded and unloaded in a matter of hours. On board ship, the containers are stacked six or seven deep

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[31] Shibata, Yano and Kodama (2005).

[32] http://www.mmsonline.com/articles/five-key-concepts-of-modular-quick-change-tooling (accessed February 11, 2016).

[33] Levinson (2006), p. 33-34.

and locked together. In port, a crane moves them quickly from ship to truck and they are easily transferred to railcars for long-distance land shipment.

However, to handle containers, the technical system and task network of loading and unloading had to be completely redesigned and virtually every functional component—ships, cranes, ports, trucks and railcars—had to be changed.

The first proof-of-concept for containerized shipping was supplied by Malcolm McLean through his shipping line Pan-Atlantic on a run from Newark to Houston in 1956.[34] The system had a minimal set of functional components: 62 containers; a refitted ship; two large cranes; two ports each with reinforced piers; and trucks at both ends. The value structure was as follows:

**1956**

*containers*$^{P}$ □ *ship*$^{P}$* □ *cranes*$^{P}$ □ *trucks*
———————*Pan-Atlantic*———————

□ *Port of Newark**$^{Nwk}$ □ *Port of Houston**$^{Hou}$ ➔ ***Container Shipping***
——————*Local Authorities*——————

*All* of the listed functional components were required for system to have any value. The containers and the ship were unique, owned by Pan-Atlantic. The cranes and trucks were generic, but had to be able to handle the weight of the containers. Pan-Atlantic owned the cranes but not the trucks. The ports of Newark and Houston were unique and controlled by the local port authorities.

The system was highly modular: containers and the ship were strong complements, but each port was a separate module. The cranes and trucks were generic components that required very little customization to be functional in the new system.

The savings from this new system were immediately impressive. In 1956, the average cost of loading a medium-sized cargo ship was $5.83 per ton. McLean's first container voyage had a cost of loading and unloading of $0.158 per ton and the time needed to load and unload was greatly shortened as well.[35] (Less time for loading and unloading increases the number of days a ship can spend at sea with proportional impact on its revenue.)

A *97% reduction in unit cost* plus an increase in a ship's revenue-generating capacity justifies large capital investments. Indeed even before the trial ended, McLean had ordered more containers and new, larger ships. However, although the cost savings and ship-capacity increases were measurable, the new technology was still subject to radical uncertainty. In particular, it was impossible to know how shipping rates and demand would change, what profits would be obtained, and who would ultimately benefit

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[34] *Ibid.*; Cudahy (2006); Mayo and Nohria (2005).

[35] Levinson (2006) p. 52.

from this large technological shock.

Between 1956 and 1965, containers, container ships and container ports went through a rapid series of design changes. Containers and ships got bigger. Ports were designed specifically for container shipping with deeper channels, heavier piers, huge cranes, and wide access roads. The whole loading/unloading system was streamlined and automated. Railroads were brought to the docks and rail became the most common way to transport containers long distances over land.

The proliferation of designs for each functional component meant that Pan-Atlantic's system very quickly ceased to be unique. Just two years later, Matson Navigation of San Francisco designed its own system, *which had the same functional components, but differed in almost every particular from Pan-Atlantic's system*.

As it turned out, there was no difficult technical bottleneck, nor any sustainable strategic bottleneck in container shipping. Every functional component admitted several different solutions. As a result, there was active entry and much investment and innovation by shipping companies, ship builders, port authorities, crane makers, railroads, and trucking companies.

Until 1965, the many different container designs made transfers across different carriers difficult. That year the International Standards Organization (ISO) began sponsoring negotiations among the interested parties. An international container standard was published in 1970. As the ISO committees worked through the issues, non-standard containers disappeared from the global transportation network. By the early 1970s, only the two original pioneers—Pan-Atlantic (now Sea-Land) and Matson—used non-standard containers.[36]

In the end, container shipping had a huge positive impact on global trade flows.[37] However, because of the low barriers to entry and the absence of a strategic bottleneck, shipping companies and ship-builders were subject to the "Red Queen" effect: they had to run very fast to stay in the same place. In 1969, global overcapacity caused shipping rates to collapse, and many lines went bankrupt. The next two decades saw recurring boom-bust cycles and bankruptcies, even as global tonnage continued to grow.

## 7.8 Conclusion—How Technology Shapes Organizations

This chapter has demonstrated the application of narratives based on functional analysis and value structure maps to three different historical technologies— early aircraft, high-speed machine tools, and container shipping. Each of these technologies, when first introduced, was subject to radical uncertainty, complexity, and complementarity. As a result, even if the tools of modern financial decision-making based on Net Present Value had existed when the technologies were introduced (the tools did not become widely available until the 1980s), numerical forecasts based on prices,

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[36] *Ibid.* p. 140-149.

[37] Bernhofer, El-Sahli, Kneller (2016).

quantities and probabilities would have had no credibility.

Yet, even before the first proofs of concept, *functional analysis of each technology could reveal its value structure including the location of functional and strategic bottlenecks*. Narratives based on value structure could be constructed and evaluated as to their plausibility by experts in each field. The narratives in turn could be used to establish priorities for action and investment in each competitive arena.

The historical record shows that the early inventors and investors in these and other technologies constructed narratives to justify their efforts. What this chapter demonstrates is that in cases involving technology, the narrative approach can be codified into a general methodology based on functional analysis, value structure maps, and tracking of technical and strategic bottlenecks. One methodology unifies all the cases.

*Value structure analysis can be applied to any technical system large or small.* I will use it throughout the rest of this book.

For purposes of formulating strategy, value structure analysis also highlights four basic principles, which can guide actions and investments in large technical systems.

First, to create value, the creators and sponsors of a technical system must:

- Provide all essential functional components; and
- Solve system-wide technical bottlenecks wherever they emerge.

No one can profit from a techical system unless all essential functional components are assembled into a working system. The Wrights needed to build a whole airplane to demonstrate that their method of control worked and gain their patent. Taylor and White had to test their high-speed steel in a specially-constructed machine toolbed. Malcolm McLean needed to retrofit a ship to carry containers, install cranes in Newark and Houston, hire trucks and obtain the cooperation of local port authorities before he could demonstrate the cost savings of container shipping.

Furthermore, technical systems are dynamic. As the technical system evolves, new technical bottlenecks will emerge in different parts of the system. All must be addressed in a timely way so that the system remains on an efficient trajectory of improvement. The importance of each new technical bottleneck can be assessed from its position in the value structure map. Technical bottlenecks in core functions or in a system-wide platform affect the entire technical system. Technical bottlenecks affecting features or options have less impact, hence lower priority.

Second, to capture value, the creators and sponsors of a technical system must:

- Control and defend one or more strategic bottleneck; and
- Prevent others from gaining control of any other system-wide strategic bottleneck.

A firm or individual that solves a system-wide technical bottleneck and can exclude others from using it can use this power to claim a share of the "supermodular" surplus generated by bringing the complementary components together. Such a firm has control of a strategic bottleneck.

The Wright brothers established a system-wide strategic bottleneck via their patent on flight control. Bethlehem Steel attempted to convert the Taylor-White process into a strategic bottleneck, but their patents were overturned. In contrast, the value structure of container shipping did not permit McLean or anyone else to control of a strategic bottleneck. The idea of a container was not patentable and each shipping line was free to design its own ships and containers. Although each port was unique, the ports had to vie against each other to host container ships.

A firm that controls a strategic bottleneck cannot expect its power to go unchallenged. Glenn Curtiss claimed that his ailerons were developed independently of the Wrights' wing-warping method of control, but his arguments were rejected by the court. In contrast, Bethlehem Steel's patents were overturned on grounds that the process was not sufficiently different from tool-makers' standard practices. Malcolm McLean had a "first-mover" advantage in container shipping, but was overtaken by a wave of ship-building that led to overcapacity and worldwide booms and busts.

In the rest of this book, I will explore how various firms solved (or failed to solve) these four generic problems by creating organizations that matched the requirements of the technologies they employed. We will see that in some cases, the most successful combination of technology and organization was an integrated technical architecture under the control of a single firm. In other cases, the most successful combination was a modular technical architecture in which knowledge and assets were widely distributed across an ecosystem of firms making complementary products. Explaining when and why each of these combinations is desirable is one of my key goals in the rest of this book.

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