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Design Rules, Volume 2: How Technology Shapes Organizations

Chapter 7 The Value Structure of Technologies, Part 2: Technical and Strategic Bottlenecks as Guides for Action

Carliss Y. Baldwin

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Harvard Business School

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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

The purpose of this chapter is to present analytic tools based on functional maps that can be used to identify investment opportunities and to formulate strategy in large, evolving technical systems. I argue that the points of value creation and value capture in a technical system are the system's bottlenecks. Bottlenecks arise first as important technical problems to be solved. Once the problem is solved, the solution in combination module boundaries and property rights can be used to capture a stream of rents.

In this chapter I extend the functional mapping techniques developed in the last chapter to locate technical and strategic bottlenecks, modules, and property rights. I then show how these analytic tools can be used to construct narratives explaining the dynamics of three nascent technical systems: early aircraft, high-speed steel in machine tools, and container shipping.

Introduction

Descriptive functional analysis as set forth in the previous chapter decomposes a technical system into elementary functional components and identifies components as essential or optional. Strategic functional analysis seeks to identify the most likely arenas of technical change, the most attractive investments, and the technical and strategic bottlenecks that are points of potential holdup and value capture.

The purpose of this chapter is to present analytic tools based on functional maps that can be used to formulate strategy in large, evolving technical systems. I argue that the points of value creation and value capture in a technical system are the system's bottlenecks. Bottlenecks arise first as important technical problems to be solved. Once the problem is solved, the solution in combination module boundaries and property rights can be used to capture a stream of rents. Thus value-enhancing technical change arises through the effective management of bottlenecks in conjunction with module boundaries and property rights.

To support the strategic analysis of large systems, I extend the notation of the previous chapter to provide descriptors indicating time, (non)existence, uniqueness, and ownership of a given functional component, as well as modular groupings of components. With this extended notation, technology strategists can look at an existing of planned technical system at the level of its embedded functional components and quickly determine:

- where new technical recipes must be created for the technical system to work;
- which components, if any, are points of leverage by virtue of being essential *and* controlled by a profit-seeking agent; and
- which technological investments can be isolated within modules, and which require redesign of large parts of the system.

These inferences can be obtained from the functional map alone, and do not require forecasting numerical values prices or units sold. In effect, the analyst must make a subjective judgment (or rough estimate) of the value of the final system, but can then look to the functional map to reveal technological opportunities and strategic threats.

I then show how these analytic tools can be used to construct narratives explaining the dynamics of three nascent technical systems: early aircraft, high-speed steel in machine tools, and container shipping. The narratives are based on the *value structure of the technical system as revealed by functional analysis*. However, consistent with the constraints of radical uncertainty, it is not necessary to estimate prices or quantities or assign formal probabilities to events. Despite their lack of numerical content, the narratives can nonetheless serve as guides for action and the basis for predicting the trajectory of the technical system as a whole.

7.1 Bottlenecks Defined

In prior work, many scholars have argued that "bottlenecks" are key to understanding the direction and pace of technological change and to capturing value in large, 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.[1] On the other hand, firms wishing to *capture* value are advised to control bottlenecks, become a bottleneck, and beware of bottlenecks controlled by others.[2]

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

[1] Rosenberg 1963, 1969, 1982; Hughes 1987; Langlois and Robertson, 1992; Ethiraj 2007; Arthur 2009; Adner and Kapoor 2010, 2016. Hughes 1987 used the military term "reverse salient" to mean something very similar to a bottleneck.

[2] Teece,1986; Langlois, 2002; Jacobides, Knudsen and Augier, 2006; Pisano and Teece, 2007; Jacobides, MacDuffie and Tae, 2012; Jacobides and Tae, 2016; Henkel and Hoffmann, 2014.

pass, and that part of the system is a source of congestion, then it is a bottleneck. More generally, a bottleneck is any component in a complex system whose performance significantly limits the performance of the system as a whole.

Consistent with common usage, in what follows, I define a bottleneck as a critical part of a technical system that has no — or very poor — alternatives at the present time. There may be one or many bottlenecks in a given system but each has the dual properties that (1) it is necessary to the functioning of the whole; and (2) there is no good way around it. Thus to know that something is a bottleneck, the observer must see it in relation to a larger system, know what constitutes good system-level performance, 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 problem of technical performance, but the owner of the bridge can charge 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, hence travellers and shippers have no good alternative except to use the bridge and pay the toll.[3]

7.2 Technical Bottlenecks

There are three basic sub-types of technical bottlenecks in man-made systems. First, as we saw in the previous chapter, a complex technical system can generally be broken down into functional component, each of which is necessary to the performance of the whole. Each component in turn represents a problem to be solved by the designer(s) of the system. Brian Arthur describes the invention of novel technologies as a process of linking solutions “until each problem and subproblem resolves itself into one that can be physically dealt with.”[4]

The unsolved problems Arthur refers to are the *functional bottlenecks* standing in the way of the creation of a new technical artifact or system. When the last or most difficult subproblem is solved, this is generally recognized as a breakthough, and the event becomes part of the lore of the technology. For example, as discussed later in this chapter, the Wright brothers solved the critical subproblem of lateral control of a flying machine, and are credited with the invention of the first successful airplane.

Second, many complex systems involve flows. The flows may be water through an irrigation system, trains through a railroad, goods through a factory, electrons through

[3] This assumes that no one builds a second bridge. However, if traffic only warrants one bridge, the owner of the first bridge can either set the toll or credibly threaten to lower the toll so as to make a second bridge unprofitable.

[4] Arthur 2009, p. 110.

a computer, messages through a communication network, customers through a store, patients through an emergency room, or laws through Congress.

In flow systems, the capacity of the slowest segment constrains the capacity of the system as a whole. Call this a *flow bottleneck*. All systems involving flow are subject to capacity contraints. And all capacity constraints take the form of a “minimum” function in the value structure of the system. Furthermore, improving the capacity of any other segment has no effect on the capacity of the system as a whole. Only the flow bottleneck matters.

Third, many systems require parts that match or fit together, 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.

Constraints on “matching” or “fit” are the third source of technical bottlenecks in man-made systems. Call this a *matching bottleneck*. 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.[5]

I will discuss this example in greater detail later in this chapter.

Functional and flow bottlenecks both involve a mismatch of elements. In a functional bottleneck, the mismatch is the non-existence of a critical solution to a subproblem. A technical recipe for one or more functional components is missing. In 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 sub-types have generally have different implications for managerial action, thus it is useful to distinguish between them.

Technical bottlenecks are theoretically distinct from modules. Technical bottlenecks are problems that exist whether the designer wants them or not. They are uncovered by identifying functional relationships between the characteristics of components (their capacity, size, strength, shape, etc.) and the performance of the system (good or bad).

In contrast, a module is a group of tasks and decisions that are tightly connected to each other, but only loosely connected with the rest of the system.[6] Modular structure

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

[6] Baldwin and Clark, 2000, Chapter 3.

is revealed by tracking dependencies of the form "if Task A changes, Task B may have to change as well." By definition, a change within one module cannot be made without triggering changes in the others.

In a particular system at a particular time, the boundaries of modules may or may not correspond to location and extent of bottlenecks. However, modular structure is at least partly under the control of system designers and thus module boundaries can be drawn or redrawn to suit the designers' purposes. By definition, each component in a module is co-specialized to every other, thus in effect, components within modules are subject to very strong matching requirements. The operative question for designers is, where should these strong matching requirements be placed? As we shall see in subsequent chapters, a firm's strategy toward technical and strategic bottlenecks informs its choices about module boundaries and the resulting technical architecture.

7.3 Strategic Bottlenecks and Property Rights

Strategic bottlenecks are points of value capture and thus a source of rent in a technical system. A strategic bottleneck needs two things: (1) a *unique solution* to an underlying technical bottleneck; plus (2) *control over access* to the solution. In the railroad 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 a bridge (the solution) and then prevent others from using the bridge unless they pay a toll (control).

In economics, the ability to exclude others from using a given resource is the classic definition of a property right.[7] Property rights in turn can be *de facto* based on power (my army controls the bridge; the chemical formula is a secret) or *de jure* based on the law (I own the bridge and police will arrest any trespassers; the chemical formula is patented and courts will punish infringers). Property rights over the solutions to technical bottlenecks, whether *de facto* or *de jure*, form the basis of strategic bottlenecks. Property rights establish boundaries, hence they are part of the contract structure of firms.

David Teece called the state of property rights, particularly intellectual property rights (IP), the "appropriability regime" pertaining to a resource, and noted that the regime might be weak or strong.[8] In strong appropriability regimes, it is easy to exclude others from using a particular resource. In weak appropriability regimes, it is hard.

Property rights—the ability to determine who has access to superior solutions to technical bottlenecks—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

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[7] In law and philosophy, "rights" refer to entitlements conferred by the state and/or natural rights recognized under some ethical system. In contrast, economic usage of the term "property right" focuses on the ability to exclude and the locus of effective control. See, for example, Alchian, A. A., *Concise Encyclopedia of Economics*, http://www.econlib.org/library/Enc/PropertyRights.html: "A property right is the exclusive authority to determine how a resource is used." Whether control over the resource derives from power, community norms, or a legal system is secondary to the fact of control.

[8] Teece, 1986.

control through a combination of physical control, secrecy, contracts, patents and copyrights. The components it controls by these means are deemed to be within its zone of authority.

In general, a firm's zone of authority coincides with its organizational boundaries. Within the boundaries established by asset ownership and employment contracts, a firm's and board of directors can set policies, establish procedures, and delegate authority as they see fit (see Chapter 2). Both the technical architecture and the contract structure of the firm lie within their purview. In contrast, a firm may influence, but does not control what happens outside its zone of authority.

Some firms have a narrow zone of authority. Such firms perform few tasks inhouse, have few organization-specific skills or secrets, and little or no formal IP. Others have a wide zone of authority. They perform many tasks, have many organization-specific skills and secrets, and large IP portfolios.

Zones of authority thus constitute a third dimension of architecture after bottlenecks and modules. Technical bottlenecks and modules are aspects of a system's technical architecture. In contrast, strategic bottlenecks and zones of authority, which reflect organizational boundaries and property rights, are key aspects of the contract structure of organizations and the resulting industry architecture.

To create and hold a strategic bottleneck, a firm must understand the system's architecture at several levels—legal and organizational as well as technical. First, what is the solution to the technical bottleneck? Second, what property rights to solutions does the legal system grant, and how can these be secured? Third, how should an organization be formed to deliver the solution, protect it, and obtain payment for it?

Bottlenecks, modules, and zones of authority are not cast in stone. Technical bottlenecks can be solved, strategic bottlenecks can be seized, property rights can be transferred, contracts can be revised, and module boundaries can be redrawn. In the next section, I extend the functional notation developed in the previous chapter to show the presence of both types of bottlenecks as well as modules and zones of authority.

7.4 Extending Functional Analysis

In the last chapter, we saw that, with only two operators (☐ and +), we can represent a large set of technical systems in terms of their underlying functional components and relationships. These representations identify what is essential and what is optional in any given technical system, and show how new functions can be created by combining existing ones.

This analysis is useful because functions are what connects technical recipes to value. Value-seeking by free agents in turn influences the direction of effort and investment in a given technical system. Effort and investment interacting with physical laws causes the system to change and evolve along a specific trajectory.[9]

Let f_i be a generic functional component contributing to a given technical architecture as described in the previous chapter. I will use the following notation to indicate the status of the functional component (and its underlying technical recipe) at one or more points in time.

In a given system:

f_{it} - a second subscript on a function indicates time ($t = 0, 1, \ldots$).

f_{it}^{o} - a superscript "o" indicates that at time *t*, no acceptable technical recipe for the functional component yet exists, i.e., 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.

f_{it}^{*} - a superscript "*" indicates that at time *t*, *only one* acceptable technical recipe for the functional component exists.

f_{it}^{*X} - a superscript "**X*" indicates that at time *t*, only one acceptable technical recipe exists, and *it is in the zone of authority of agent X*.[10] A superscript "**XY*" indicates that agents *X* and *Y* both claim to have authority over the recipe. Effectively both have veto power over its use.

$\boxed{f_{1t} \square f_{2t} \square f_{3t}} \; \square \; \boxed{f_4} \; \square \; \boxed{f_5} \; \square \; \boxed{f_6} = G$ - a box (not brackets) around a group of functions indicates that they are part of the same module. Functional components within a module 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 functions in that module will have to be revisited. Thus the technical recipes for functions 1-3 must change as a group, whereas the technical recipes for functions 4-6 can each be changed separately. All functions must still be present for the system as a whole to achieve its function *G*.

Finally, I note the locus of authority for each component or group by placing the name of the authority below the functions. Cases in which no well-defined entity controls a function or group receive the label "*N*" for "numerous." Components with numerous providers and cannot be strategic bottlenecks.

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

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[9] Dosi (1982).

[10] It would be simpler to say the component *is owned by* Agent X. 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.

involve (1) early aircraft design; (2) high-speed steel in 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. The Wright brothers directed their efforts towards solving this problem, initiating a series of experiments with gliders at Kitty Hawk, NC. 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 experiments with glider designs. Through their experiments, they were able to understand the deeper mechanics of airflow. 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.[11]

The Wrights were granted a patent (# 821,393) 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."[12] They defended their patent vigorously in a long, drawn-out litigation with Herring-Curtiss Co. Glenn Curtiss, CEO of Herring-Curtis claimed that his design for ailerons was not derived from the Wright's patent.[13] The litigation continued until, in 1917, the US War Department pressured most of the makers of airplanes into a patent pool with unlimited cross-licensing and capped license

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

[12] *Ibid.* "We wish it to be understood, however, that our invention is not limited to this particular construction, since any construction whereby the angular relations of the lateral margins of aeroplanes may be varied in opposite directions with respect to the normal planes fo said aeroplanes comes within the scope of our invention."

[13] Judge's Decree, WRIGHT CO. v. HERRING-CURTISS CO. et al. (District Court, W. D. New York. February 21, 1913.) in *The Federal Reporter* Volume 204, p. 597.

fees on the Wright's fundamental patent.[14]

We can map the early evolution of aircraft designs in terms of functions in the following way. Let $(a_1,...,a_6)$ denote the afore-mentioned functional components that when combined can be transformed into a flying machine. In 1901 (*t =0*), as the Wrights were beginning their experiments at Kitty Hawk, the state of the technology was as follows:

$$\boxed{\underset{N}{a_{10}} \square \underset{N}{a_{20}} \square \underset{N}{a_{30}} \square \underset{N}{a^{o}_{40}} \square \underset{N}{a_{50}}} = A^{o} \quad . \qquad (1)$$

thrust ☐ lift ☐ frame ☐ control ☐ landing => Flying Machine

At this time, 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.

This state of affairs was well-understood by aviators at the time. In a speech in 1897, Oliver Chanute, one of the most respected men in the field, 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."[15] In essence, his statement was a verbal functional analysis of the state of aircraft technology, which equation (1) captures in a compact, generalizable way.

Functional analysis, whether verbal as in Chanute's statement or formal as in equation (1), serves to identify targets of investment in technical systems without having to identify specific markets, estimate revenues, or assess cash flows.

A successful flying machine was an artifact subject to radical uncertainty. In 1901, there were no "business models" for flying machines. Direct sources of revenue for aviators were limited to prizes and gate receipts at flying shows (which sustained the Wright brothers though most of their early years).[16] 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 a business model for flying machines did not exist, the *functional architecture* of a flying machine was understood by most aviators and engineers. Moreover the control function was acknowledged to be the most difficult problem remaining to be solved. The control function was essential: unless it was solved there could be no reliable or safe flying machines.

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[14] "End Patent War of Aircraft Makers" *New York Times* August 8, 1917, retrieved 3/17/2016; Katznelson and Howells (2015).

[15] As noted in the Judge's Decree, WRIGHT CO. v. HERRING-CURTISS CO. et al. p. 601.

[16] McCullough (2015).

Understanding the functional architecture 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 it.[17]

Furthermore, early airplanes were integral systems, as noted by the box around all five functions. To test any theory about control, an aviator needed to build a whole plane. All parts were specialized to all other parts.[18]

In 1906 (*t=1*), after the Wright brothers had solved the control problem and been granted their patent, the state of the system's technology changed to:

$$\begin{array}{l} \boxed{a_{11} \square a_{21} \square a_{31} \square a_{41}^{*W} \square a_{51}} = A \quad . \\ \;N \quad\; N \quad\; N \quad\; W \quad\; N \end{array} \tag{2}$$

thrust □ lift □ frame □ control □ landing => Flying Machine

Now there was an adequate technical recipe that solved the problem of control. *Furthermore, it was unique and patented by the Wright brothers.* Solving the problem of control filled out the set of complementary functions needed to make a flying machine, Safe, reliable flying machines were now feasible.

However, as indicated by the supersrcript "**W*" on the control function in equation (2), one functional component had a unique solution, which was owned by the Wrights. In principle, anyone wanting to build a flying machine for any purpose, had to seek a license from them. Thus the control function changed from being a technical bottleneck to a *strategic bottleneck*.

Consistent with the predictions of the property rights literature, the Wrights and their successors[19] could and did demand a cut of all revenue streams related to flying machines that used their system of control. Furthermore, in terms of transaction cost economics, every company that obtained revenue from flying machines had assets that were specific to the Wrights' patent. Thus each was vulnerable to hold-up, should the Wrights change their license terms.

The strategic bottleneck would cease to exist and associated license fees could be avoided if another method of control, *that was not derived from the Wrights'*, could be found. Thus strategic bottlenecks are also a target of investment in a technical system: if a second way to fulfill the function can be found, the power of the first owner to capture

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

[18] One can argue that engines (providing thrust) were a possible exception. However even if they purchased an engine from a third party, aviators would have to modify it substantially in work with the rest of their design. The Wright brothers made their own engines. McCullough (2015).

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

value is reduced dramatically.

Glenn Curtiss of Herring-Curtiss Co. understood this principle very well. In many 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 designs. [20]

For some amount of time, aircraft continued to be integral systems. Each aviator designed his own and built it himself or contracted to have it built. However, companies were founded and began to compete in to manufacture aircraft for commercial and military markets. By 1917, at least 47 aviation companies were involved in aircraft manufacture.[21] At this point a new modular structure and related industry architecture began to emerge.

Specifically engines, providing thrust, became a separable module constrained mainly by power and weight. Thus very early in aviation history, 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. The rest of the functional components, however, remained highly interdependent: redesigning the basic wings, for example, meant redesigning ailerons and the fuselage. The wheels were also initially a separable module, however, as the demand for speed increased, concerns about drag led to the development of retractable landing gear that were incorporated into the the airplane itself.[22]

Equation (3) shows the industry architecture of aircraft design and production that prevailed through most of the 20th Century. The Wright patent expired in 1922; even before then, with the government-sponsored formation of an industry-wide patent pool in 1917, it 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.

$$\underbrace{\boxed{a_{12}}}_{\textit{RR, P\&W}} \qquad \underbrace{\boxed{a_{22} \quad a_{32} \quad a_{42} \quad a_{52}}}_{\textit{Aircraft Manufacturers}} \tag{3}$$

thrust ☐ lift ☐ frame ☐ control ☐ landing => Flying Machine

Interdependency among techical components is a choice, but, as Daniel Whitney has observed, it is a choice constrained by physics.[23] 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.

[20] In 1917, under pressure from the US government, 47 aviation companies formed a patent pool. As part of the settlement, the Wrights' case against Herring-Curtiss was dismissed. Kaztnelson and Howells (2015).

[21] *Ibid.*

[22] Vincenti (1994).

[23] Whitney, D. E. (1996, 2004).

As the machine is flying, there are *many* automated transfers of material, energy and information taking place within the aircraft itself in real time.

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). As John Paul MacDuffie has shown, for a physically interdependent system such as an aircraft or an automobile, the process of modularization will be long and difficult, hence continued interdependency may be a more cost-effective choice.[24]

In 2003, Boeing Corporation attempted to modularize the production and design 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.[25] One hundred years after the Wright brothers' first flight, it was still difficult to split up the design and production of aircraft into a series of modules separated by thin crossing points.[26] Physics pushed 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 functional analysis guided investments in new technical recipes 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 and direct the transmission components as needed.[27]

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 greatly increased the hardness of steel when heated to high temperatures. The impact of these new products was to greatly 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 significantly by a factor of 4 or 5.

In 1907, Taylor and White obtained patents for the treatment process (#668,369, #668,290), which they assigned to Bethlehem Steel.[28] However, the patents did not last

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[24] MacDuffie (2013).

[25] Hart-Smith (2001); Hiltzik, M. (2011); Denning (2013).

[26] Allworth, J. (2013).

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

[28] Judge's Decree, Bethlehem Steel Company v. Niles-Bement-Pond Company as reported in *Electromechanical and Metallurgical Industry*, 7(3):105-107. https://books.google.com/books?id=d5TmAAAAMAAJ&lpg=PA106&dq=taylor%20white%20process%2C%20patent&pg=PA106#v=onepage&q=taylor%20white%20process,%20patent&f=false (accessed

long: they were struck down in 1909 when the judge ruled that the so-called "treatment" amounted to little more than heating the tool to a very high temperature, as was standard practice among toolmakers. At that point, techniques for making high-speed cutting tools were effectively in the public domain.

However, the new steel cutting tools could not achieve their full potential with the frames, transmission and control systems that had been developed for low-speed carbon steel. Thus mechanical engineers went to work on the other parts of the system. As Guy Hubbard reported in a retrospective article published in 1930:

> 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.[29]

We can map the early evolution high speed steel machine tools in terms of functions in the following way. Let (s_1, s_2) denote the high-speed steel alloy (as it comes out of the steel mill) and the Taylor-White steel treatment process. These two functional components were necessary to create the steel cutting tool. Let (m_1, m_2, m_3) denote the other functional components of a machine tool: frame, transmission, controls. The state of the system in 1900 (*t=0*) was as follows:[30]

$$\underset{N}{s_{10}} \square \underset{B}{s_{20}^{*B}} \square \underset{N}{m_{10}^{o}} \square \underset{N}{m_{20}^{o}} \square \underset{N}{m_{30}^{o}} \quad = M^{o} \tag{4}$$

alloy ☐ treatment ☐ frame ☐ transmission ☐ control => 0

The steel alloys existed, but they were not unique and not subject to patenting. The Taylor-White treatment process existed: Bethlehem Steel claimed that the process was a unique and had applied for several patents. However, at this time, frames, transmissions and control systems that could handle a high-speed cutting process did not exist.[31]

In the absence of these functional complements, the system-as-a-whole would not function. Attention was therefore directed to redesigning frames, transmissions, and

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February 11, 2016).

[29] Hubbard, G. (1930) "Metal-Working Plants," *Mechanical Engineering*, 52:411 as quoted by Rosenberg (1963).

[30] In 1900, Link-Belt Engineering Co. became the first machine tool company to license the Taylor-White process, paying Bethlehem $3000 for working drawings plus the shop right to use all patents pending on the process. Dodge, J. M. (1915).

[31] Bethlehem had created tools for demonstration purposes, but apparently their designs were not immediately transferrable to the shops of the tool makers. Module boundaries among the functional components were not yet determined. Dodge, J.M. (1915).

controls. These were technical bottlenecks in the larger system, whereas the patent on the Taylor-White treatment process was a strategic bottleneck.

In 1910, the situation had changed. The technical bottlenecks blocking the use of high-speed steel had been remedied. The Taylor-White patent had been declared invalid, and new alloys were available in the market. Thus the state of the system was as follows:

$$\underset{N}{\boxed{s_{11} \square s_{21}}} \; \square \; \underset{N}{\boxed{m_{11} \square m_{21} \square m_{31}}} = M \tag{5}$$

alloy ☐ treatment ☐ frame ☐ transmission ☐ control => High-speed Machine Tool

All technical bottlenecks had been eliminated thus the system was fully functional. Furthermore, with the invalidation of the Taylor-White patent, there were no strategic bottlenecks. No functional component was unique and thus no agent could capture value via threat of holdup.

Machine tools were manufactured in many different establishments, each of which would have had its own methods and practices. It is likely that in most establishments, the cutting tool made of treated alloy would have been in a module separate from the frame, transmission, and control elements of the machine tool itself. The cutting tool was subject to wear and would need to be replaced from time to time. 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 generally designed by the manufacturer and hard-wired into the system until personal computers became a cheaper alternative in the 1980s.[32] Modular transmission systems appeared shortly thereafter.[33] 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 a haphazard, labor-intensive, and above all, time-consuming process. Cargo was carried on as loose items and stowed wherever it would fit. Theft was rampant. A study of a single voyage 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.[34]

The 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 and locked together. In port, a

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

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

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

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 component of the system—ships, cranes, ports, railcars, and trucks—had to be changed.

The first proof-of-concept for the system of containerized shipping was provided by Malcolm McLean through his shipping line Pan-Atlantic on a run from Newark, NJ to Houston, TX in 1956.[35] 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. The state of the system and its modular structure were as follows:

$$\boxed{c_{10}^{*P} \;\square\; c_{20}^{*P}} \;\square\; \boxed{c_{30}^{P}} \;\square\; \boxed{p_{10}^{*Nwk}} \;\square\; \boxed{p_{20}^{*Hou}} \;\square\; \boxed{t_{10}} = C \qquad (6)$$

———*Pan-Atlantic*——— —*Local Authorities*— *N*

containers □ ship □ cranes □ Port of Newark □ Port of Houston □ trucks => Container Shipping

All of the functional components were required for system to have any value. In addition, the containers and the ship were unique, co-specialized complements controlled by Pan-Atlantic. But even at the time of the trial, McLean had commissioned new larger containers and new ships. The cranes were generic, but had to be able to handle the weight of the containers. The ports of Newark and Houston were unique and controlled by the local port authorities. The trucks were generic.

The system was highly modular: containers and ships had to be co-designed, but the ports were separate modules. 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 as revealed by the trial were 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 of $0.158 per ton and time to load was greatly shortened as well.[36] These figures did not reflect the investments in capital equipment and retrofitting needed for container shipping, but a 97% reduction in variable cost pays for a lot of capital. Furthermore, shorter loading times meant that ships could spend more time at sea, an important increase in capacity and capital utilization.

Reflecting the modularity of the basic system, containers, container ships and container ports went through rapid design evolution in the fifteen years following the initial proof of concept. 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.

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

[36] Levinson, *op. cit.* p. 52.

The proliferation of designs for each functional component meant that Pan-Atlantic's system very quickly ceased to be unique. 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.*

Thus in contrast to the Wright brothers' method of control for airplanes, there was no *strategic bottleneck* in container shipping. Every functional component admitted several different potential solutions. As a result, there was active entry and lots of innovation by shipping lines, ship builders, port authorities, crane makers, railroads and trucking companies.

Until 1965, however, many different container designs were used, and transfers across different carriers were difficult. In that year, the International Standards Organization (ISO) began sponsoring negotiations among interested parties around the world. An international container standard was published in 1970. As the ISO committees worked through and resolved the issues, non-standard containers disappeared from the global transportation network. By the early 1970s, only the two companies that pioneered container shipping—Pan-Atlantic (renamed Sea-Land) and Matson—were still using non-standard containers.[37]

When Malcolm McLean sent the first retrofitted tanker as a container ship from Newark to Houston, it was impossible to know how the business of container shipping would evolve, what profits would be obtained, or who would ultimately benefit. In the end, containerization had a huge positive impact on global trade flows.[38] However, because of the low barriers to entry and the absence of a strategic bottleneck, the innovation may not have greatly benefited the shipping business. By 1969, a worldwide container shipbuilding boom resulted in global over capacity. Shipping rates collapsed, 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

What do these case studies reveal about how value is created and captured in large technical systems? The creators and sponsors of these systems must manage its modular structure (the technical architecture) in a way that solves two generic technical problems:

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

In addition, if the creator/sponsor of the system is a profit-seeking firm, it must manage its property rights to solve two generic strategic problems:

- Control and defend one or more strategic bottlenecks; and

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

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

- Prevent others from gaining control of any system-wide strategic bottleneck.

These four related problems can be solved using many different technical, organizational, and industry architectures. The technical system may be integrated with one or a few large modules. The modules in turn may be controlled by a single firm that is subject to unified governance. Alternatively, the technical architecture may be highly modular, with activities spread across many different organizations under distributed governance.

From the case studies, we can draw the following generalizations. First, 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 their proof of concept 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 containerized freight.

Even after the technical system has been shown to have value (relative to the next best alternative), an agent or agents must take responsibility for bringing the requisite functional components together. This is the job known as "system integration." The tasks of system integration are part of the task network, and we can think of them as an additional, implicit functional component. In the long run, system integration may turn into a strategic bottleneck or it may not. It was not a strategic bottleneck in any of our case studies. Although system integration is an essential part of providing any complex artifact or system, in these three cases, the recipes for system integration were not unique, and thus system integration services could be supplied by many different firms.

Second, as the technical system evolves, the underlying technical recipes change. 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, improving trajectory. The significance of each technical bottleneck in turn can be assessed from its position in the functional map. Technical bottlenecks in core functions or in a platform affect the entire technical system. Technical bottlenecks affecting features or options have lesser impact, hence lesser priority.

Third, a firm or individual that solves a system-wide technical bottleneck *and* can exclude others from using it can use its power of holdup to tax other participants in the system. Such a firm has control of a strategic bottleneck. The tax may take the form of a royalty or licensing fee or a product price well above cost.

A firm that controls a strategic bottleneck cannot expect its power to go unchallenged, but must protect its advantage. If two firms each control a strategic bottleneck and do not coordinate their actions, each will take a cut of the system surplus. This leaves less value for the other system participants, reducing their incentives to make system-specific investments. For this reason (as we saw in Chapter 5), Oliver Hart and

John Moore have argued that property rights to all essential and unique assets (in other words, all strategic bottlenecks) should be concentrated in the hands of a single owner.[39]

The Wright brothers established a system-wide strategic bottleneck via their patent on flight control. Control is an essential function, and, despite Curtiss's counterclaims, their solution as interpreted by the courts uniquely affected all subsequent solutions. Bethlehem Steel attempted to convert the Taylor-White process into a strategic bottleneck, but their patent was overturned.

The technical architecture of the container shipping system did not permit McLean or anyone else to gain 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 compatible containers. This situation in turn gave rise to a collective action problem, with a resulting loss of efficiency due to the lack of transferability of cargo from one line to another. This technical bottleneck was eventually resolved by creating a commons organization—a standard-setting committee under the aegis of the ISO. The committee developed and published a standard container design. The dimensions of the standard container were unique, however, they were not anyone's property, thus could not be the basis of a strategic bottleneck.

A single firm seeking to sponsor and profit from the evolution of a large, complex technical system must take measures to solve the four generic problems listed above. The sponsor does not have to bring all functional components within its own span of control, but it must ensure that all essential functional components can be obtained efficiently and that system-wide technical bottlenecks are addressed wherever they arise. To profit from the system, the sponsor must control and protect at least one strategic bottleneck and prevent other strategic bottlenecks from emerging. (Unique and essential components can be placed in the hands of collective organizations or in the public domain, without harm to the sponsor.)

In the rest of this book, I will explore how various firms solved (or failed to solve) these four generic problems. We will see that in some cases, the most effective structure turned out to be an integrated technical architecture under the control of a single firm. Such technologies gave rise to vertically integrated firms and industries. In other cases, the most effective structure turned out to be a modular technical architecture under the control of many firms, with different degrees of power over the system as a whole.

[39] Hart and Moore, 1990.

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