Design Rules, Volume 2: How Technology Shapes Organizations

Chapter 6 The Value Structure of Technologies, Part 1: Mapping Functional Relationships

Carliss Y. Baldwin

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By Carliss Y. Baldwin

Note to Readers: This is a draft of Chapter 6 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

Organizations are formed in a free economy because a person or group perceives value in carrying out a technical recipe that is beyond the capacity of a single person. Technology specifies what must be done, what resources must be assembled, what actions taken, what transfers made in order to convert stocks of material, energy and information into products of value to someone.

The purpose of this chapter to build a robust and versatile language that is capable of representing large technical systems. The language is based on elements I have labeled *functional components*. The language is more abstract than the language of technical recipes and task structures, thus it is capable of hiding details that may be distracting. However, the language also makes it possible to "track back" from each named functional component to a technical recipe (or the lack of one).

Introduction

In Chapters 2-4, I developed the concept of the economy as a vast network of technologically determined tasks and transfers of material, energy and information. On this view, transactions are but a small subset of all technologically required transfers. Moreover, in some parts of the network, transfers are too dense and complex for transactions to be cost effective. These areas become transaction free zones.

Technology (a technical recipe) specifies what needs to happen within and across transaction free zones to convert primitive resources into complex artifacts and systems. Modern societies have constructed huge edifices of technologies, so that designed artifacts and systems form a large part of our day-to-day experience. Performing the tasks and transfers specified by different technical recipes requires both people and assets (physical equipment, intellectual property, knowledge). The transfers are facilitated by organizational ties, including collocation, communication links, employment relations, social bonds, and processes for making decisions and resolving conflicts.

Technology shapes both technical dependencies and organizational ties. The structure of these two related networks is partly determined by the laws of nature (e.g., operations A, B, C, D, E must happen in a strict sequence) and partly by the preferences of the actors (e.g., the committee meets every Tuesday). Through engineering and organizational design, tasks can be grouped or separated and transfers can be added or removed. Crossing points can be made thinner (to facilitate transactions) or thicker (to foster ongoing interdependency and the transmission of knowledge). Complementary assets and activities can be brought under the purview of a single firm (unified governance) or allocated to different members of an ecosystem (distributed goverance).

Technology—the recipe for what needs to be done—lies at the center of this view of the economy. The fundamental premise of this book is that technology shapes organizations by influencing the search for value in an economy made up of free agents. Value is something that someone perceives as a good, and thus a reason for action. (In *Design Rules, Volume 1*, this idea was captured in the axiom "Designers see and seek value.").[1]

Organizations are formed in a free economy because a person or group perceives value in carrying out a technical recipe that is beyond the capacity of a single person.[2] Organizations continue in existence if and only if they can capture more value for their members than they dissipate. An organization with a value deficit, whose obligations exceed expected inflows, will be dissolved or reorganized. Technology specifies what must be done, what resources must be assembled, what actions taken, what transfers made in order to convert stocks of material, energy and information into products of value to someone. Technoogy is the means, value is the goal.

The purpose of this chapter to build a robust and versatile language that is capable of representing large technical systems. The language is based on elements I have labeled *functional components*. The language is more abstract than the language of technical recipes and task structures, thus it is capable of hiding details that may be distracting. However, the language also makes it possible to "track back" from each named functional component to a technical recipe (or the lack of one).

In the next chapter, I use the language of functional components to develop a theory of value based on the existence and location of "bottlenecks" in a technical system. Understanding bottlenecks requires a good "map" of the technical system, but does not require any quantification of benefits or costs associated with individual

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[1] Because agents are free, the search for value is decentralized and to some extent uncoordinated. As Richard Heilbroner observed, decentralized value-seeking by many agents causes the process of technical and organizational change to appear impersonal: "a diffuse 'force' bearing on social and economic life." Heilbroner (1967) p. 344.

[2] Puranam, Alexey, Reitzig (2014); Puranam (forthcoming).

components or the system as a whole.

6.1 Why it is Difficult to Value Technologies

In economics and finance, value is determined by an individual or group's willingness to pay for a good or service. The payment may be in the form of money, other goods, or effort. In principle, it would seem to be a simple thing to count every member of society's willingness to pay for a product or service and subtract the cost of all inputs to see if the technology's net value is positive. However, three difficulties arise that impede this value estimation process.

The First Difficulty—Complexity

The first difficulty is that technologies can be combined and recombined in many ways. As a result, technical architectures—descriptions of technical systems—are very complex. In practice we can chain technical recipes together end to end: A is an input to B, which is an input to C. Or we can stack them in parallel: A, B, and C are all inputs to D. But individual recipes are generally not things we can value easily, since their value lies in their relationship to other recipes, ie., in their complementarities.

To get even a hint of value, we need a unit of analysis—something that "carries" value—and a way to describe relationships that affect the apportionment of value among those units. Previous chapters took steps in that direction by defining task structure, transactions, transaction-free zones and various types of complementarity. But we still lack a robust and general way to go from technical recipes (our analytic raw material) to reasons for action and investment.

The Second Difficulty—"Radical" Uncertainty

The second difficulty is the problem of "radical" uncertainty. According to Mervyn King, radical uncertainty "refers to uncertainty so profound that it is impossible to represent the future in terms of a knowable and exhaustive list of outcomes to which we can attach probability."[3]

Virtually all theories of value and investment in economics and finance take for granted the fact that outcomes can be specified in terms of prices and quantities and associated with probabilities. The probability-weighted outcomes are summed to form an "expected value," which is then discounted for time and risk. The present values of benefits and costs are then summed to obtain a "net present value" or NPV.

New technology is precisely the type of phenomenon for which this standard approach to valuation does not work. This problem is captured in a quote attributed to Andy Grove. When asked, what was the return on investment to Internet commerce, he

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[3] King (2016), Chapter 4. Radical uncertainty essentially the same as "Knightian uncertainty." (Knight, 1921). King's contribution is to point out the usefulness of narratives in structuring analysis and decisions in the presence of radical uncertainty: "The narrative is a story that integrates the most important pieces of information in order to provide a basis for … a decision." (p. 136).

replied, “This is Columbus in the New World. What was his return on investment?”[4]

It’s not that the standard methodology is impossible to apply. Many people can be taught to make up numbers that purport to quantify costs and benefits. But in cases involving new products, new markets and new technologies, the evaluator often does not have enough knowledge to set up the calculations with any confidence that they reflect an underlying reality. When lack of confidence about the estimates is taken into account, the quantitative results end up so imprecise as to be useless as a guide for action.

King argues that humans can act reasonably in the presence of radical uncertainty by constructing a “narrative”— “a story that integrates the most important pieces of information” in order to form the basis for choosing a course of action.[5] Humans have the capacity to judge stories, placing them on a spectrum from “true” to “plausible;” “possible;” “unlikely;” and finally “impossible.” Outcomes can be tested according to their consistency with the prevailing narrative and the story adapted to take account of new information.

The Third Difficulty— Priorities

The third difficulty that arises in valuing technology is that we lack a theory of priorities. Technologies are generally complex, embedding many interacting technical recipes. Where among the recipes should we focus our attention, activities, investments? In the presence of radical uncertainty, there is no hope of calculating a meaningful rate of return on any effort or investment. Nevertheless, given the sheer number of recipes embedded in even very small systems, we need some way to separate the wheat from the chaff—the salient problems from the distractions. Otherwise we risk being overwhelmed.

Notice that by identifying what in a technical system is more or less important, we thereby change the narrative surrounding the technology. Changing the narrative changes the reasons for action, which then affects actions taken, hence the future path of the system. Cause and effect are unavoidably circular.

However, the narrative is in fact a means of entering into a dialogue with reality. Before the technical recipe can give rise to a new artifact, material reality must confirm that the “story told” was basically true. And before value can be realized and captured (by the inventor and others), free agents must concur that the new artifact makes their lives better in some ways. In these interactions between technology and reality, there is room for positive and negative surprises. These in turn lead to new conjectures, new narratives, and new value-seeking actions and investments. And so technology evolves.[6]

It is worth noting that human beings are no strangers to radical uncertainty or the need to prioritize problems and actions. These factors form the context of our daily lives. Thus to build a theory of technical value and value-seeking that is true to these

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[4] As reported by Arthur (2009) p. 170.

[5] *Ibid.* p.134.

[6] See Baldwin and Clark (2000) Chapter 9.

circumstances, we can begin with traditional ways people perceive and describe technologies plus our own ability to construct narratives and set priorities. That is my plan in this chapter and the next.

6.2 Functions are Carriers of Value in a Technical System

Every technical system has both a structure and one or more functions. The system's structure includes the causal dependencies among individual tasks and decisions. As discussed above, technological structure can be represented as a network of directed dependencies and visualized in the form of a design or task structure matrix and a corresponding network of organizational ties.

In contrast, functional analysis does not reveal the task structure of a given technology. Rather it tells us why particular groups of tasks are present in the task network, how they aggregate to serve a human purpose, and whether a subset of tasks is essential or optional.

Within technologies, functions are carriers of value. The presence of a function brings the system closer to fulfilling the purpose envisioned by its creators. Conversely, the absence of a function subtracts value from the system and may cause it to fail altogether. The development of technology thus amounts to a search for technical recipes that provide new functions or fulfill old functions in new and better ways.

Organizations in turn provide products and services that fulfill functions required by an underlying technology. These products and services are the functional components of a particular technical system. If the technical system as a whole has value, the functional components have value, and organizations that supply those components may capture enough value to survive.

In the rest of this chapter, I describe a methodology that exposes how functional components may be combined through technology to create a particular artifact or technical system. The method uses symbolic notation to clarify relationships between and among functions. I illustrate these relationships using an ancient technology—the technology for making a garment from pieces of cloth sewn together. I go on to describe commonly observed patterns within technologies, including composite functions; a platform system; and convergent platforms.

We begin with a primitive unit of analysis: the component.

6.3 Functional Components are the Units of Analysis

"Technologies consist of parts." Brian Arthur[7]

Scholars who have studied technology universally observe that complex technologies and artifacts are made up of simpler technologies and artifacts often called

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[7] Arthur (2009) p. 33.

components.

The idea of a component is multi-faceted. A component can be a chunk of knowledge, for example: “If you whip egg whites, they will turn into a soft foam.” It can be part of a technical recipe: “Whip four egg whites until they form soft peaks.” Or it can be a materal object: the beaten egg whites ready to be incorporated into a souffle.

The if-then statement is a component of a system of knowledge relevant to cooking and chemistry. The instruction is a component of a specific recipe. The beaten egg whites are a component of the end product—the souffle ready to be eaten. Following common practice, I am going to use the single term “component” to mean all three things. Note that they are closely related: the knowledge is the basis of the recipe, and the recipe is the route to the material artifact.[8] Technology operates on all three levels.

Artifacts, designs and knowledge also have *functions*. Brian Arthur argues that the defining property of a technology is that it “captures a phenomenon,” that is, it has some fairly predictable and reliable effect on the material world.[9] Simple technologies capture simple phenomena: a hammer applies concentrated force to a given area. A needle draws thread through material and can be used to fasten things together. These are phenomena. When the phenomenon serves some human purpose—when applying force or fastening things together gets someone closer to her goal—then the phenomenon becomes a functional component.

Functional components can be combined and recombined in various ways. The combinations can exhibit new behaviors that are functions in their own right. For example, the beaten egg whites have as component technologies: (1) the eggs; (2) a bowl; and (3) a whisk or mixer. Each of these components has a function in the context of egg beating. But the beaten eggs are a phenomenon in their own right. They in turn can be combined with other ingredients, serving the function of providing a light and airy texture to a souffle (whose function is to be eaten with pleasure).

Functional components are mental constructs: they are perceived by designers as the building blocks of designs and may be combined and recombined in various ways. Functional combinations are unconstrained in the imagination: it is easy to imagine a horse with wings. (See Inset Box 6-1 on mental recombinations.)

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[8] On the interplay between propositional knowledge and the prescriptive knowledge found in a recipe or set of instructions, see Mokyr (2002) Chapter 1.

[9] Arthur (2009) pp. 50-54.

Inset Box 6-1 Mental Recombinations

There are essentially no constraints on the recombination of components in one's imagination. Since prehistoric times, humans have had the demonstrable capacity to mentally deconstruct objects and recombine their components in ways that do not arise naturally. We know this because of art. For example, one of the earliest figurative sculptures, the *Lion Man of Hohlenstein Stadel*, dated to 38,000 BCE, is an ivory carving with the body of a man and the head of a lion.[10]

As another example, consider the chimera of Arezzo, a bronze Etruscan statue dating to 400 BCE, shown in Plate 6-1. A chimera is a mythical beast with the head and body of a lion; the head of a goat on its torso; and a tail that is the head and body of a snake. The beast as portrayed in the statue is strikingly lifelike.

In human imagination, it is but a small step recombine functions and say: "I would like to have that beast, but it should be alive." Here, however, the world fights back against imagination. There is no way to transform the bronze statue into a flesh-and-blood creature. Living things come into being via a different process—a different recipe— involving sexual reproduction, the inheritance of traits, and evolution through artificial or natural selection. Many diverse forms are obtainable through this process, but no one has ever bred the chimera of Arezzo.

In earlier times, this recombination of functions—turning an inanimate form into a living being—might have seemed easier. If the theory of life posits the existence of a "life force" then one can imagine making the figure as shown and then "breathing life" into it. Legends of golems and the story of Frankenstein reflect this way of thinking. Today we have a much more detailed and complex understanding of "life" and the technological challenge appears much greater.

A mental recombination of functional components is the starting point of all technological search. But technologies—knowledge, designs, and artifacts—must operate in the real world. Many combinations like the flesh-and-blood chimera are easy to imagine but impossible to make.

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[10] http://www.visual-arts-cork.com/prehistoric/lion-man-hohlenstein-stadel.htm, viewed 9/23/15.

Plate 6-1 The Chimera of Arezzo

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However, functional combinations that become actual technologies are constrained by the laws of nature. *Functional components can be traced back to actual technical recipes*—instructions on how to manipulate material objects in a structured way in order to achieve some desired effect. The function *is* the desired effect for which the recipe exists.

It is the property of "tracking back" that distinguishes representations based on functional components from the categorizations of technology found in economics and management theories. Categorical theories of technology are based on constructs such as "general purpose technology;" "increasing returns technology;" "digital technology;" "network technology;" "disruptive technology;" etc. These descriptors refer to facts about technologies that affect their impact, hence their value. But none of these categorical descriptions can be traced back to any specific technical recipes.

As we shall see below, complex functions may be attained by combining simpler functions in various ways. Thus behind every complex function lie long strings of instructions describing actions performed to achieve subsidiary functions, which in turn rest on prior strings of instructions.

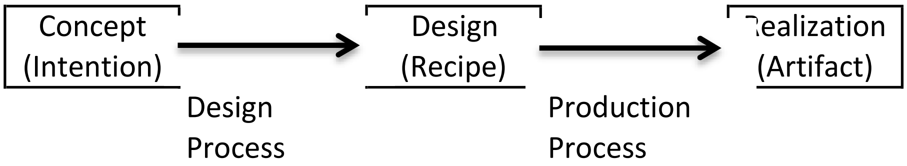
Knowledge about complex functions and their associated technical recipes may be distributed across different actors. Functions are a cognitive device that permits the division of knowledge and labor in a complex system. The person or team at the last stage of functional assembly does not have to know all the technical recipes for all the inputs to her own recipe. But she must understand the functions of each input, the new function to which her effort is directed, and a particular technical recipe that gets from the one to the other.

6.4 Technological Search

Technological search is essentially a search for new combinations of functional components that capture new phenomena, serve new functions, or serve old functions in better ways. The search begins as a mental process of combining images and symbols and predicting effects.[11] The predictions have two dimensions: physical and social. Physical predictions hypothesize that the laws of nature as they relate to the artifact work in a particular way. Social predictions hypothesize that humans interacting with the artifact will find it useful and desirable.

A complementary set of predictions about the physical world and human desires is the starting point of a design process aimed at developing a new technical recipe. The nascent design then passes through a series of "generate-test cycles" where the initial predictions are tested, modified and tested again.[12] As predictions are refuted, the underlying recipe is revised to address the differences between hope and reality. At the end of the day, the entire design may work to serve a human purpose, or it may not. When the recipe works, a useful new artifact has been created, knowledge advances, and the human repertory of technologies is enlarged.

Thus a new technology generally progresses through three states as shown below. First there is a *concept*, then a *design*, then a *realization*. Going from concept to design means forming a preliminary intention and then coming up with a recipe for making the intended artifact. Going from design to realization means performing the steps in the recipe to bring the design into the material world. At the end of this three-stage process, one has an artifact which can be combined with other artifacts to make up a larger system. Both the tasks of design and the tasks of realization (production) are part of the greater task network.



Of course, the general process is not linear as shown in the picture. There will be feedback from realization to design. Concepts may be modified based on what turns out to be feasible in the real world. The process may start with the realization of a phenomenon for which a concept does not yet exist. Concepts, designs, and realizations

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[11] Bucciarelli (1994).

[12] Simon (1981) pp. 149-150.

inform each other and become co-adapted over time. The desired end result is is a congruent triad: a concept (intention) with a corresponding design (recipe) that can be realized. Eric von Hippel and Georg von Krogh call these combinations "need-solution pairs."[13]

Also, in the eyes of their creators, new technologies must be cost-effective in expectation. The expectations are usually *not* formal expectations based on probability. Simply, viewed *ex ante*, the anticipated cost of going from concept to artifact must be less than the anticipated value of the artifact itself. The value and cost may be measured in terms of prices of goods obtained in markets or in terms of the private utilities of key resource providers. The estimates do not have to be precise. They may subject to behavioral biases. They might turn out to be wrong.

The fact that new designs and artifacts have both market value and private value means that there are two routes by which new technologies and new artifacts may be created: a market route where R&D and new product development are funded by corporations or the government, i.e. people are paid to innovate; and a private route where users pursue innovations that improve their own circumstances or to make their visions real.[14]

6.5 Combining Functions

Simpler technologies can be combined in structured ways to make something more complex. Thus a needle, thread, scissors, and cloth can be combined with a pattern and the techniques of stitching to make a garment. The needle, thread, scissors, cloth, pattern and stitching process all contribute to the creation of the garment.

Interestingly, the functions of a garment are very different from the functions of its contributing components. The functions of a garment are arguably threefold: to provide warmth, to satisfy modesty, and to signal status or style. These are the human purposes served by the garment. A needle is necessary to fashion a garment, but a needle cannot provide warmth, satisfy modesty, or signal status. Similarly, the functional components needed to beat egg whites cannot supply a soft foamy substance except according to the instructions of the technical recipe.

The ability to see how various functional components can be combined to create something with entirely different functions is a complex and mysterious human ability. In Volume 1, Kim Clark and I took it as axiomatic: "designers see and seek value." Value however depends on functions: what you will pay for a garment or the time you will spend making it depends on how well it performs its functions and the value you place on each one.

Functional decomposition and assembly can be applied to services as well as to

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[13] Von Hippel and von Krogh (2015).

[14] Von Hippel (2016). On the prevalence of user innovation in different countries, see von Hippel, de Jong and Flowers (2012) and De Jong et al. (2015).

physical artifacts. For example, to provide the service of movie watching, one needs content (the movie), a method of storing and transferring the content, a way to play the content, and a venue. Traditionally *movies* were stored and transferred as *film reels*, *projected* onto a canvas *screen*, in a *theatre*. Now Netflix provides *movies* stored as *files*, transferred via the *Internet*, played by a *computer* on an electronic *display*, at *home*. Each functional component contributes to the experience of movie watching, and a technical recipe lies behind each one. But the functions of movie watching are different from the functions of any of the contributing components.

Sometimes the performance of specific functions can be traced back to one or a few of the constitutive components. Back tracking to underlying causes is another human ability, different from being able to envision novel combinations of functions. Back tracking can assist in the process of improving or customizing the design and ultimate artifact. For example, in the case of a garment, if one wants to increase warmth, it makes sense to focus on changing the cloth. If more modesty or more style is your objective, best start with the pattern.

Modularity in various stages of design, production and use also supports the process of improvement. Most garments are almost completely modular in design: at the design stage, patterns, cloth, thread and stitching techniques can be mixed and matched in many different ways. Garments are also quite modular in production: the same stitcher can work on a wide range of cloths, threads and patterns. Thus it is relatively easy to experiment and innovate on garment designs.

Modularity in use, however, varies by garment type. Sportwear garments can be mixed and matched to different occasions and upgraded piecemeal.[15] A dress, by contrast, is not modular in use and a man's suit loses all status and style (but not warmth or modesty) if disparate pieces are worn together.

6.6 Functional Complementarity

In the context of making a garment, the functions of the needle, thread, scissors, cloth, pattern and stitching are complementary. *One needs all of them to make a garment.* One can design a garment in one's head, but absent any one of the functional components, one cannot make a proper garment (although with cloth alone, one can have a sarong or a sari).

We can represent this functional complementarity in the following way. Let $f_1, f_2, \ldots f_6$ denote each of the six functional components needed to make a garment. Set $f_i = 1$, if the function is present and $f_i = 0$ if it is absent. Let $G = 1$ if the garment's function is present and $G = 0$ if it is absent. The complementarity of the underlying functional components can then be expressed as follows:

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[15] Sportwear: "clothing consisting of separate pieces as jackets, trousers, sweaters, skirts and shirts, that are casually styled and can be worn singly or in various combinations." http://dictionary.reference.com/browse/sportswear, viewed 2/3/16.

$$f_1 \square f_2 \square f_3 \square f_4 \square f_5 \square f_6 = G \qquad (1)$$

needle ☐ thread ☐ scissors ☐ cloth ☐ pattern ☐ stitching => Garment

Here ☐ denotes a complementary combination of *essential functions* via some technological recipe. If any member of the combination is absent, the recipe will fail, and the joint function will be absent and worthless.[16]

In this case, the component functions of the needle, thread, etc. have no value except as they are combined together to make a garment. *As functional components, they are strong complements* with respect to the making of a garment.

Although each function is essential, there may several different ways to accomplish each. First, there may several possible technical recipes. For example, cloth may be wool, cotton, silk or synthetic, thin or thick, knitted or woven, patterned or plain. Each recipe in turn may have many realizations, e.g., many bolts of cloth. *Thus strong functional complementarity does not imply that the goods and services supplying those functions are strong economic complements as defined in the previous chapter.*

In the case of a garment, there are many sheep farms and textile mills, scissors makers, needle makers, and steel mills. There are also many designers, pattern makers, clothing factories, and stores. Thus each functional component contributing to a garment has many potential suppliers. Different methods of fulfilling each function can be mixed and matched at will. The goods and services performing the required functions are thus weak complements, not strong complements. Such goods and services are not subject to the risk of holdup, thus do not have to be contained within a single firm under unified governance.[17]

6.7 Functional Hierarchy

Behind each functional component lies a technology: knowledge of a procedure that captures the functional phenomenon. Behind needles and scissors, there are technologies of metal working; behind thread, there is agriculture, animal husbandry and spinning. Behind cloth lies thread, looms and the techniques of weaving. Behind patterns lie multiple methods of recording and transferring designs. And behind stitching, lies thousands of years of experimentation, leading to a set of basic stitch patterns.[18] The recipes and realizations behind each function in turn can be decomposed into subsidiary

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[16] In value terms, a series of ☐s indicates a multivariate mathematical function defined on the domain $x = (0, 1)$ with the property that if any argument is zero, the value of the function is also zero. Otherwise the value of the function is one:

$$x_1 \square \ldots \square x_N \equiv F(x_1, \ldots, x_N) \text{ such that } F = 0 \text{ iff } (x_1 \vee \ldots \vee x_N) = 0, \text{ and } F = 1 \text{ otherwise .}$$

[17] Strong functional complementarity is necessary but not sufficient for strong economic complementarity.

[18] Vasbinder, N. (2014).

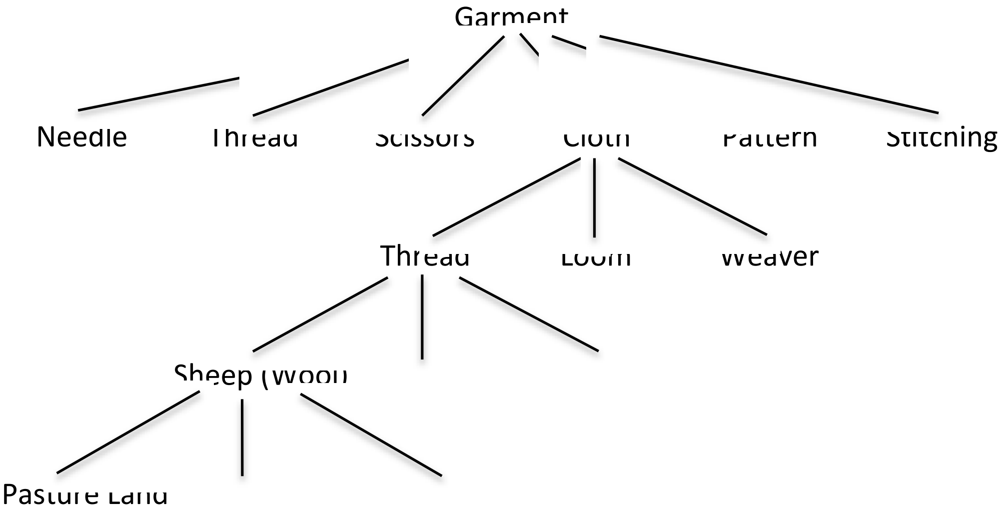
functions, each of which also has a design and corresponding realization.

The whole system forms a hierarchy as defined by Herbert Simon: the system is “composed of subsystems that in turn have their own subsystems” until one reaches the lowest level of elementary components.[19] In this case, the “lowest level” is the natural world. *A series of technologies—intermediate recipes and realizations—must bridge the gap from the natural world to the final useful good.*

Figure 6-1 traces out one branch of the functional hierarchy for a garment made of woolen cloth. Cloth needs thread, thread needs wool, which comes from sheep (and other mammals), sheep need pastures, and pastures need land, fences and grass. With land and grass, we arrive at the natural world. Each subordinate good performs a function that contributes to the making of the superior good. Each subordinate function in turn is implemented by means of a technical design—a recipe—that requires tasks and transfers.

In principle, one could zoom in on the functional hierarchy and arrive at the task network. The functional hierarchy offers a macroscopic view of the system suppressing many details, while the task network offers a more microscopic view. (Note that the functional hierarchy depicted in the figure is not an organizational hierarchy. Activities may be distributed across many independent organizations with transfers taking place via transactions.)

Figure 6-1 Part of the Functional Design Hierarchy for a Garment



Functional analysis does not require a precise characterization of how the system will work or who might be willing to pay for it. All that is needed to begin the process of

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[19] Simon (1981) pp. 195-200.

functional analysis is a set of conjectures, one material and one social: First, the envisioned artifact “might be created through this combination of functional components whose recipes do or do not yet exist”; and second “it might be perceived as useful or desirable by human beings.”

These dual conjectures provide the basis for a narrative that can guide action and investment in the presence of radical uncertainty. The narrative can be tested against reality and adapted through a process of trial and error. Importantly the narrative may be proven wrong. But at the first pass, the narrative must be *plausible* in order to garner resources for the search.

Functional narratives differ greatly in terms of their complexity and need for resources. Some are simple and require small expenditures: these can be investigated by individuals using their own skill sets and modest financial resources. Many “single user innovations” fall into this category.[20] Other narratives require organizations, that is cooperating groups of individuals usually interacting within a transaction free zone. The organizations in turn may be large or small.

6.8 A Threefold Pattern

The garment example displays a threefold pattern: (1) functional transformation (the functions of the complex artifact are different from the functions of the contributing components); (2) functional complementarity (the contributing components combine to make comething more valuable than the separate components); and (3) structural hierarchy and modularity (each component is a subsystem made up of simpler components and different components can be worked on separately and mixed and matched with others).

This pattern is extremely common in the realm of technology. It has two consequences. On the one hand, functional transformation and complementarity encourage the formation of complex designs and artifacts from simpler underlying components. Thus, through human ingenuity, technologies can evolve into ever-more-complex systems. On the other hand, structural hierarchy and modularity permit a division of knowledge and effort across different actors. One can appreciate the functioning of a needle, thread and cloth without necessarily knowing how to make any of them. There can be a high degree of information hiding across different components.

In essence, functional transformation and complementarity are testimony to human cognitive powers, especially our ability to see a possible new function, form a design and then systematically carry out the technical recipe. Structural hierarchy and modularity in contrast take account of our cognitive and physical limitations: the strict bounds on any single person’s ability to understand and to act.

The threefold pattern of technology creates both path dependency and an

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[20] Baldwin and von Hippel (2011); von Hippel (2016).

accumulation of recombinable designs.[21] What was invented in the past can be combined with other inventions and used as the basis for further inventions in the future. The pattern also rewards cooperative social groups that provide a division of labor, easy transfers of material goods, and the storage and cataloging of knowledge.

As social technologies were invented to support group coordination, knowledge accumulation, and the division of labor, complex societies formed that were capable of creating ever-more-complex edifices of technological recipes.[22] Furthermore, the "open edges" of these technological structures—where potential new functions can be perceived and developed—were dispersed and decentralized among many makers and users, like a tree with many branch tips all capable of growth. Thus in complex technical systems and in complex societies, innovation can take place (if allowed) without central direction or control.

However, the second of the three features—functional complementarity—can sometimes create opportunities for holdup which can bring innovation to a halt. If co-specialized inputs are controlled by different parties then, as we saw in Chapter 5, each is at risk of holdup by the others. Both property rights theory and transaction cost economics would then recommend placing the co-specialized inputs under unified governance.

When functional transformation takes place for the first time, a new type of artifact comes into being. This is the essence of technological novelty: the new phenomenon captured is not a simple extension or combination of prior phenomena.[23] Here radical uncertainty is at its height. It may be impossible to conceive of, much less associate prices, quantities and probabilities, with future consequences of the technology.

Once the novel artifact exists, however, designers can begin to study how it really works. Through back tracking of cause and effect (discussed above) the shortcomings of the system can often be mapped onto the designs of one or more functional subsystems. This in turn creates incentives to improve the performance of subsystems in ways that contribute to the whole.

For example, a flying machine must have functional components to provide lift (the wings); thrust (the engine); a central framework (the fuselage); lateral and vertical stability (elevators, ailerons, rudder); a steering mechanism (the same); and the ability to land (flaps, wheels).[24] These individual, contributory functions can be combined in a transformative way to make an airplane. But once there has been a proof of concept—a demonstration that the transformation is feasible in the material world—then designers

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[21] On path dependence in human societies, see Nelson and Winter (1982); David (1985); Arthur (1994); Margolis and Liebowitz (2000;) and Page (2006).

[22] On ancient civilizations and their technologies, see for example, Krantzberg and Gies (1975); Fukuyama (2011); Graeber (2011); and Scott (2017).

[23] Arthur, B. 2009, Chapter 6.

[24] Arthur (2009).

can go to work to improve the functioning of the whole by manipulating the underlying technical recipes. They may be able to do this in a modular fashion, varying each recipe independently. However, if the technology is truly novel and transformative, the causal links between functions will not be well understood. (If they were well understood, the recipe would have been invented earlier.)

Until the underlying dependencies are mapped out and calibrated, the structure of each new design will inevitably be interdependent. Changing one part will require changes in other parts. For example, in the case of an airplane, one cannot increase the size and weight of the fuselage without changing the lift capacity of the wings, the thrust of the engine, the stabilizers, the steering mechanism and the provisions for landing.

Eventually it may be possible to modularize the design of the artifact by the method of dependency elimination via design rules described in Chapter 2. But any modularization will take time. Furthermore, the laws of nature operating through the technology may make modularization easy or hard. For example, technologies, such as those used to make automobiles and aircraft, that involve high levels of energy exchange between components and/or three-dimensional fitted interfaces have defied most attempts at modularization.[25]

6.9 Features

Once the novel artifact exists, users will begin to integrate it into their lives and in so doing will perceive new uses and ways in which it could be better. As users interact with the concrete thing-in-reality (as opposed an abstract imaginary thing), they will develop new concepts that give rise to a demand for features. *Features are optional functions that add value to the core function.* For example, a garment may have a collar and/or sleeves, a jacket may have buttons, pants may have cuffs and belt loops. The main functions of the garment can be performed without these embellishments, hence they are optional. But once the extra functions have been envisioned and perceived as desirable, technical recipes for achieving them take on value and the concept-design-realization process will kick in.

Kim Clark described how consumer interactions with a novel artifact cause them to refine their perceptions and develop a new hierarchy of concepts:

> What the product is, how it meets needs, how it functions … is not defined in one fell swoop. … Understanding and insight develop over a period of time *as broad categorizations are broken down into related subcategories of concept and refined through experience*.[26] (Emphasis added.)

Clark presents evidence that early innovative effort in automobiles focused on engines, which provided a core function (motive power). Later, however, as comfort and ease of operation became more important to consumers, manufacturers paid more

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[25] MacDuffie (2013); Whitney (1996; 2004).

[26] Clark (1985), p. 245-246.

attention to optional features such as automatic transmissions. Thus the first automatic transmissions appeared in the 1930s even though the scientific and engineering knowledge needed to build them was in place by 1920. "The automatic shifting of gears was not a major item on the [original] technical agenda. … [However, in the 1930s, it] was the technical solution to a design problem whose time had come."[27]

The functional representation of an artifact with features starts with the core function and then adds the options. It can be written as follows:

$$G \square [1 + g_1 + g_2 + g_1 \square g_2 + g_1 \square [g_3 + g_4] + ...] = G' \tag{2}$$

The leading 1 in the brackets indicates that the core function has stand-alone value, even without any added features. In contrast, optional features, indicated by g_i, have value only in combination with the core. The features in turn may be valued independently ($g_1 + g_2$) or in combinations ($g_1 \square g_2$). There may also be sub-hierarchies of features: ($g_1 \square [g_3 + g_4]$). Again, behind each feature lies a technical recipe that delivers the feature in conjunction with the basic garment.

6.10 Composite Functions

In some cases, functions are complementary, but the combination is not transformative. Instead, the individual components continue to perform their original functions, but work together as a system. Consider, for example, a camera. The camera itself takes pictures, but simply having an image with no ability to store it or view it is not very valuable to most users. Thus one needs a camera plus a storage device and a viewing medium to make a useful system. In a classic camera, the storage device is film and the viewing medium is photos on paper. In a digital camera, the storage device is a digital disk or flash drive; the viewing medium is often the screen of phone or tablet. In either case, the three components together make up an economically viable system.

Composite combinations can be represented by accounting for the presence or absence of each component both separately and jointly. For example, let c_1, c_2, c_3 denote the three functional components of the camera system and let C denote the functions of the system. As before, we set c_i and C equal to 1 or 0 if the function is present or absent. The camera system's functional representation is then:

$$c_1 + c_2 + c_3 + c_1 \square c_2 \square c_3 = C \tag{3}$$

camera + storage + viewing + camera □ storage □ viewing => camera system

Thus we can see that the functions of the camera system can be decomposed into three stand-alone functions, plus the combination of functions.

Value can be associated with each term in the expression as long as the term is positive (= 1), i.e., as long as the function is present. In the case of a camera system, the

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[27] *Ibid.* p. 247.

value of the stand-alone functions to most users is small, perhaps zero. However, in other cases, contributing functions may retain considerable stand-alone value.

Consider for example the combination of a camera system like *C* above and a phone system. Like the camera, the phone also has many contributing functions and corresponding technologies, some of which are transformative and some of which are composite. (Specifically, a phone system needs a handset, a communication grid, and a switching mechanism. If any of these is missing, the value of the phone is essentially zero.)

Let us denote the camera system's functions as *C* and the telephone system's functions as *T*. Each has the formulaic structure of equation (3). Now consider a technology that combines a camera and phone into a larger system—a camera-telephone, whose functions are denoted *CT*. Again this is not a transformative change: the underlying functions are visible and separate within the combined system. The combined system then has a functional representation as follows:

$$C + T + C \square T = CT \qquad (4)$$

This is the same formulaic representation as in equation (3). But when we go to assign values, it is no longer the case that the stand-alone functions are close to worthless and the individual components strong complements. If the value of *C* is high, then its value inside the camera-phone will also be high. The same goes for the value of *T*. There may be incremental value in the combination $C \square T$ but it's also possible that the combination adds nothing.

The assignment of value to combinations of functional components is a form of judgment. Based on a narrative about how people will use the system, we can judge that a camera has little value in the absence of storage and viewing functions, while a camera system and a telephone system each have significant stand-alone value. These values do not have to be expressed in monetary units or even numbers. At this point, judgments may simply be "large", "negligible", or "negative'. These judgments then become part of the narrative surrounding each technical system.

However, we are starting to see a *value structure* emerge from the functional map. One can proceed from judgments about the desirability of different arrangements of functional components to a list of technical recipes that must be carried out to achieve the overall functional goal. Without estimating revenues or costs, we are beginning to associate value with technical recipes in an objective and systematic way.

6.11 Platforms Systems

Another pattern worth noting is that of a technical platform. In these systems there is a common core of functions (called the platform) and a set of complementary functions that have no value separate from the platform. Symmetrically, the platform generally has no value in the absence of the complementary functions.[28] This pattern may be found in video games (console = platform; games = complements) and other hardware-software combinations.

The functional representation of this pattern is almost identical in form to the core + features representation shown above. The only difference is that, if the platform has no stand-alone value, the leading “1” inside the brackets disappears. Thus let *P* now denote the functions of the platform game console; $v_1, \ldots v_N$ denote the functions of different video games that can be played on the console; and *V* denote the functions of a complete system. The functional representation of the video game system is:

$$P\square[v_1 + ... + v_N] = V \qquad (5)$$

console ☐ [game 1 + … + game *N*] => video game system

In this expression, the console and games are strong functional complements,[29] but each game’s function is independent of the other games. A user can select anywhere from 1 to *N* games for his system, and the presence or absence of any one has no affect on the functioning of the others. (As always, there may be subsidiary functions and features in both the console and the individual games.)

6.12 Convergent Platforms

One final, quite complicated pattern is that of convergent platforms. In this case, two separate systems, which are platforms in their own right, are combined to create a new *larger* platform providing a base for complements that could not be supported on either of the original platforms. For example, with the advent of the Internet, personal computers and the phone system were combined into a new platform that supported a large number of new functions, such as shopping, email, social networking, weather and news reporting, etc. Though personal computers and the phone system both survived as separate platforms in their traditional uses, the functions that knit them together, including the Internet, the Worldwide Web, browser programs, routers, modems, Wifi, and search engines, were both complementary and transformative.

Let *PC* denote the functionality of a personal computer and *T* the functionality of the telephone system. Let $a_1, \ldots a_6$ denote the functions of the Internet protocols, the Worldwide Web, a browser, modem, router and a search engine. Let $b_1, \ldots , b_N$ denote various Internet applications such as shopping, advertising, news, email, social networking, online gaming, travel planning, blogging, etc. Let *I* denote the functions of an Internet-enabled home computer system. This functionality is represented as follows:

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[28] Baldwin and Woodard (2011).

[29] If the platform is unique, i.e., the games only work on a specific platform, then the platform will be a strong, one-way economic complement of the games. But, as indicated above, strong functional complementarity does not necessarily give rise to strong economic complementarity.

$$\left[PC \square T \square a_1 \square a_2 \square ... \square a_6\right] \square \left[b_1 + b_2 + ... + b_N\right] = I$$

[Internet Platform]□[Internet Applications] => Internet-enabled home computer

The platform is denoted by the first bracketed term. It is formed by a complementary combination of a PC and telephone system, plus Internet and WWW protocols, hardware, and software. The platform is essential, and every one of its contributory functions is needed to achieve a functional platform.

Applications are what make the platform valuable. However, no single application is essential and users can choose subsets that individually work for them. Also a given application can be a platform in its own right. For example, suppose b_j refers to the functionality of a social networking site such as Facebook. Facebook contains features and applications that support dating, advertising, news, shopping, archiving. Thus we can expand b_j to show Facebook's platform structure:

$$b_j = FB \square [c_1 + ... + c_n]$$

Note also that a personal computer (*PC*) and the telephone system (*T*) are each platforms in their own right, independent of the Internet. PCs are a platform for non-Internet applications and the telephone system is a platform for voice calls and text messaging.

6.11 Conclusion—How Technology Shapes Organizations

The fundamental premise of this book is that technology shapes organizations by channeling the search for value (in an economy of free agents) towards different organizational structures and forms. Thus to understand the organizations that will develop and implement particular technologies, we must first understand the technologies' "value structure."

However, three difficulties impede efforts to value technologies. First, technical systems are complex, comprising in some cases millions of technical recipes, involving billions or even trillions of tasks. Second, technologies, by definition, create new artifacts that are subject to "radical" uncertainty. Radical uncertainty is a state of knowledge in which it is impossible to enumerate (or even envision) all outcomes or associate outcomes with formal probabilities. Human beings can cope with radical uncertainty by constructing narratives and then refining them until they become true. Third, given complexity and radical uncertainty we lack ways of setting priorities for action and investment in technical systems. We don't know which problems to turn our attention to first.

This chapter begins to explore the value structure of technologies and its impact on organizations. In this chapter, I set forth a method of representing technologies in terms of logical relationships among *functional components*. Within a technical system, functional components *do something*: they fulfill a purpose, that furthers the purpose or goal of the system. Thus functional analysis tells us why particular tasks exist and how they aggregate to serve a human purpose or fulfill a need. It also indicates whether a subset of tasks is essential or optional.

Functional components must conform to the laws of nature. Each functional component in a working technical system will eventually have an corresponding technical recipe. However, functions can be perceived before the recipe itself exists.

All technical systems display generic patterns of functional complementarity that are described in this chapter. The most fundamental pattern is that of *essentiality*. The garment example in this chapter illustrated this pattern: if any of the listed functional components is absent, one cannot have a garment. Thus any technical system that creates garments must include all of these functional components. A second fundamental pattern is *hierarchy*. Functional components have corresponding recipes, which in turn have functional components. Backtracking the recipes must eventually lead back to the natural world, since technical recipes are what convert natural objects into manmade things.

Other relationships explored in this chapter include (1) the relationship of optional features to the "core" system and to each other; (2) composite functions that have stand-alone value and value in combination; (3) platform systems comprised of an essential core that does not have stand-alone value but has value in combination with optional complements; and (4) convergent platforms created via the combination of existing platforms with additional essential and optional components.

The next step in understanding the value structure of technologies is to show how functional analysis can serve as the starting point for the construction of a narrative that points out which components in a given technical system are particularly important, thus worthy of attention or investment. I turn to that task in the next chapter.

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