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Design Rules, Volume 2: How Technology Shapes Organizations

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

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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 an individual 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 in order to convert stocks of material, energy and information into products and services of value to human beings. Technology is the guide, organizations are the means, value is the goal.

The purpose of this chapter is to build a robust and versatile language that is capable of representing the *value structure* of 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 networks, thus it is capable of hiding details. However, the language also makes it possible to "trace back" from each named functional component to a technical recipe and a corresponding task network. Finally, although the language itself is non-mathematical, the value structure it reveals can be used to specify equations and prove mathematical propositions about the value of technical systems.

The plan of the chapter as follows. I first explain why it is difficult to value technologies using standard economic methods based prices, quanities and probabilities. I then describe a methodology that shows how functional components are combined through technology to create a particular artifact or technical system. The methodology uses symbolic notation to clarify relationships between and among functional components. I illustrate these relationships using an ancient technology—the technology for making a garment from pieces of cloth. I go on to describe commonly observed patterns within technical systems, including optional features; composite functions; and platforms.

Introduction

In Chapters 2-5, I developed a theory of the economy as a vast network of technologically determined tasks and transfers of material, energy and information. In this network, technology (a technical recipe) specifies what needs to happen within and across organizations to convert primitive resources into complex artifacts and systems.

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. Modern societies have constructed huge edifices of technologies and organizations, so that designed artifacts and organizations form a large part of our day-to-day experience.

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 is a reason for action.

Organizations are formed in a free economy because an individual or group perceives value in carrying out a technical recipe that is beyond the capacity of a single person.[1] Because the agents are free, the search for value is decentralized and frequently uncoordinated. As Richard Heilbroner observed, decentralized value-seeking by many independent agents causes the process of technical and organizational change to appear impersonal: "a diffuse 'force' bearing on social and economic life." [2]

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[1] Puranam, Alexey, Reitzig (2014); Puranam (2018).

[2] Heilbroner (1967) p. 344.

then describe a methodology that shows how functional components are combined through technology to create a particular artifact or technical system. The methodology uses symbolic notation to clarify relationships between and among functional components. I illustrate these relationships using an ancient technology—the technology for making a garment from pieces of cloth. I go on to describe commonly observed patterns within technical systems, including optional features; composite functions; and platforms.

In the next chapter, I will 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 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 estimation process. They are, first, the presence of "radical" uncertainty; second, the challenge of complexity and complementarity; and last, the need to set priorities among a large set of competing problems. I discuss each of these difficulties in subsections below.

The First Difficulty—"Radical Uncertainty"

The first and most important difficulty is the presence of "radical uncertainty." According to Mervyn King, radical uncertainty is "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 assume 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.[4]

When faced with decisions involving radical uncertainty, the standard approach is to guess the expected value of future cash flows, and turn the crank of net present value. A number of heuristic tools can be used to structure the forecasts and turn them into estimates. 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

[3] King (2016), Ch 4; Kay and King (2020).

[4] Brealey, Myers and Allen (2019).

confidence. 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.

Throughout the 20th century and into the 21st, most economists embraced methods of valuation based on prices, quantities, and probabilities.[5] However, a few argued that these methods did not work in cases of critical importance. An early dissenter was Frank Knight of the University of Chicago. Knight drew a distinction between "risk" and "uncertainty." "Risky" gambles, he asserted, are based on known probabilities, obtained by measuring the frequency repeated events. In cases involving "uncertainty," however, it is impossible to identify and classify all future possible "states of nature." Without knowing what states might occur, it is impossible to assign a meaningful probability to any one.[6]

New technology is precisely the type of setting in which probabilistic estimates fail. The failure is captured in a quote by Andy Grove. When asked by a shareholder in 1996 about the return on investment from his firm's Internet ventures, he responded, "What's my ROI on e-commerce? Are you crazy? This is Columbus in the New World. What was his ROI?" [7]

In 1998, Nathan Rosenberg explained in detail why it is impossible to estimate values and probabilities for technological outcomes. Technological uncertainty, he argued, has many dimensions. First, one does not know ex ante if a "primitive" technology can be refined to the point of becoming economically viable. Second, most technologies do not function alone, but are nested in larger systems of complements. Third, until individuals have direct experience with a new technology, they cannot imagine how they might use it.

Rosenberg went on to argue "if uncertainty exists along more than one dimension, and the decisionmaker does not have information about the joint distribution…, then we have little reason to believe that a 'rational' decision is possible, or that well-defined 'optimal'… strategy will be found."[8]

These rare dissenting voices criticized the standard method but stopped short of suggesting other ways to deal rationally with radical uncertainty. Knight believed that business men used "judgment" to make decisions, but did not ask how they formed such judgments or differentiated between good and bad judgment. Rosenberg trusted private firms to place their own bets and believed the market would terminate bad bets "quickly

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[5] Foss and Klein (2015) speak of "the gradual 'hardening' of economic theory in the 20th century, with the gradual emphasis on mathematical modeling of equilibrium states." Kay and King (2020) Chs. 5-7 trace evolution of probabilistic thinking and mathematical models of decision-making in economics during the 20th century.

[6] Knight (1921); Langlois and Cosgel (1993).

[7] Grove as reported by C. Anderson (1997) "In Search of the Perfect Market," *The Economist* (May 8, 1997) https://www.economist.com/special-report/1997/05/08/in-search-of-the-perfect-market (viewed 8/27/20), quoted by Arthur (2009) p. 170.

[8] Rosenberg (1998) pp 96-97.

and unsentimentally." [9]

In contrast, during the course of the 20th century, the proponents of quantification developed an entire toolbox of new methods of quantitative decision making: statistical forecasting, macroeconomic modeling, subjective probabilities, decision trees, simulation, stress testing (for banks), risk modeling (for securities), etc. Each tool had its own group of expert practitioners and devotees.

As Governor of the Bank of England in 2007, Mervyn King was familiar with most of these methodologies and relied on them. However, as the world plunged into the financial crisis of 2007-2008, he found that the models were useless in dealing with unfolding events. Observing what he and others actually did during the crisis, King and his coauthor John Kay proposed a new method of decision-making under so-called radical uncertainty.[10]

King and Kay argued that humans can act rationally 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.[11] 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.

There are in fact degrees of radical uncertainty. In cases involving technology, for example, the structure of a technical system—its parts and their relationships—may be known even if its behavior and future states cannot be predicted. In these cases, narratives can be clarified by describing the *value structure* of the technical system. This formal description in turn can be used to specify equations and derive mathematical propositions that do not depend on estimating prices, quantities or probability distributions.

The Second Difficulty—Complexity and Complementarity

Even with the help of narratives, it is difficult to make reasoned decisions about technologies. The second difficulty is that technologies have parts that can be combined and recombined in many ways. As a result, technical architectures—descriptions of technical systems—are very complex. There are often thousands of recipes describing millions of tasks and transfers. We need a way to hide this complexity and suppress unimportant details.

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[9] *Ibid.* p.109. During the 21st century, Knightian uncertainty and business judgment experienced a revival in the field of entrepreneurship. However, like Knight, these scholars were more interested in judgment as a function delegated to business managers and owners than in the means by which humans arrive at reasoned judgments. Tools and methods for arriving at judgments have not been explored in this literature. Bhide (2010); Foss and Klein (2012, 2015); Hallsberg (2015); Foss, Klein and Bjornskov (2019);

[10] King (2016); Kay and King (2020).

[11] King (2016) p.134.

The different parts of a technical system are also complementary. As we saw in Chapter 5, complementary goods are more valuable when used together (as a system) than when used separately. This property in turn makes it impossible to assign a unique value to any specific part. Its economic value depends on the value of the system(s) it is used in and the number of substitutes.

To understand the value structure of a technical system, we need a unit of analysis—something that "carries" value—and a way of describing the relationships among the various parts of a complex system. At this point, we lack a robust and general method for translating the parts of a technical recipe (our raw material) into a comprehensible narrative that provides reasons for particular actions and investments.

The Third Difficulty— Priorities

The third difficulty that arises in valuing technologies is that we lack a theory of priorities. As indicated technical systems embed many interacting technical recipes. Where among the recipes should we focus our attention, activities, investments? In the presence of radical uncertainty, complexity, and complementarity, there is no hope of calculating a meaningful rate of return on any specific effort or investment. Nevertheless, given the sheer number of recipes found in even very small systems, we need some way to separate the salient problems from the distractions.

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

Although this may seem to be a disadvantage, it turns out it isn't. 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.

Human beings are no strangers to radical uncertainty, complexity, complementarity, or the need to set priorities. These conditions are the stuff of our daily lives. Thus to build a theory of technical value and value-seeking that takes these circumstances into account, we can begin with the traditional ways people perceive and describe technologies. Below I will describe a methodology for understanding the value structure of technologies that depends on the logic of narratives, and is independent of prices, quantities and formal probabilities.

In defining the value structure of technologies, I owe a great debt of gratitude to a number of 20th century historians who approached technologies as systems. These include Elizabeth Eisenstein, S. Colum Gilfillan, Abbott Payson Usher, Nathan

Rosenberg, Walter Vincenti, David Landes, Thomas Hughes and David Hounshell.[12] All provided careful descriptions of the technologies they studied in terms of the functions of different components: They translated specialized engineering knowledge and documents into language anyone could understand. All of them characterized technologies as systems of interacting components each with a function in the system. In constructing their historical narratives, they carefully distinguished between important and unimportant parts of the systems.

The similarities in their analysis led me to believe that their diverse approaches could be distilled into a single methodology that would be applicable to all technical systems. In this chapter, I describe a methodology, based on functional components, that reveals the *value structure* of technologies subject to radical uncertainty, complexity, complementarity, and the need to set priorities.

6.2 Functions 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 tasks and transfers and visualized in the form of a design structure matrix (DSM) and a corresponding network of organizational ties.[13]

Artifacts, designs and knowledge also have *functions*. Brian Arthur has argued that technology begins by "capturing a phenomenon." In other words, a prescribed set of actions has some fairly predictable and reliable effect on the material world.[14] Simple technologies capture simple phenomena: a hammer applies concentrated force to a small area. A needle can draw thread through material and thus can fasten different pieces together. These are phenomena. When a phenomenon serves some human purpose—when applying force or fastening things together gets someone closer to her goal—then the phenomenon gains a function and becomes a technology.[15]

Functional analysis does not reveal the task structure of a given technology. Rather it tells us (1) why particular groups of tasks are present in the task network (they have functions); (2) how they combine to serve a human purpose, and (3) whether a subset of tasks is essential or optional.

The next section looks at more closely at how components that deliver specific functions —like a hammer or a needle— may be combined to achieve new functions in larger technical systems.

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[12] Gilfillan (1935); Usher (1954); Rosenberg (1963, 1968); Landes (1983); Hounshell (1985); Hughes (1987, 1993); Vincenti (1990).

[13] See Ch. 4.

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

[15] As defined in Ch. 1: "A technology is a way of changing the material world that serves a human purpose." *Ibid.* p. 28; Dosi (1982) pp. 151-152; Dosi and Nelson (2010) p. 55.

6.3 Functional Components as Carriers of Value

"Technologies consist of parts." Brian Arthur[16]

I define a *functional component* as a part within a larger technical system that brings the system closer to fulfilling its ultimate purpose. A functional component does something: it has a demonstrable role within the system. Conversely, the absence of a functional component detracts from the system and may cause it to fail altogether.

Within technical systems, functional components are carriers of value. If the technical system as a whole has value, the functional components have value, and organizations that supply those components have value.

Just as the word "technology" has several meanings, the concept of a functional component is multi-faceted.[17] A functional component may be a chunk of knowledge, for example: "If you whip egg whites, they will turn into a soft foam." It may be part of a technical recipe: "Whip six egg whites until they form soft peaks." Or it may be a materal object: the beaten egg whites ready to be folded into a souffle.

The if-then statement is a component in a system of knowledge relevant to cooking and chemistry. The instruction is a component in 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 "functional 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. Technology encompasses all three levels.

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 dish.

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. There are essentially no constraints on the recombination of components in one's imagination. It is easy to imagine a horse with wings.

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

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[16] Arthur (2009) p. 33.

[17] See Ch. 1.

effect for which the recipe exists.

It is the property of "tracing back" that distinguishes my theory of technology from the categorical theories commonly found in economics and management. (See Chapter 1.) Categorical theories of technology are based on descriptors such as "general purpose technology;" "increasing returns technology;" "digital technology;" "network technology;" "disruptive technology;" etc. These terms refer to groupings of similar technologies. But none of the categorical descriptions can be traced back to specific technical recipes. *In contrast, every functional component in a real technical system is the product of a particular recipe.*

Functional components also permit knowledge and labor to be split among different agents contributing to a large technical system. A function is essentially a label or "tag" placed on a particular recipe or group of recipes. It is a summary of what the recipe does. Behind every functional component, there is a string of instructions describing actions performed on subsidiary components, which in turn rest on prior strings of instructions. The person or team at the last stage does not have to know the detailed recipes used in all previous stages. But they must understand the function of each input they use, the new functions to which their effort is directed, and the particular technical recipes that will convert the inputs into the desired output.

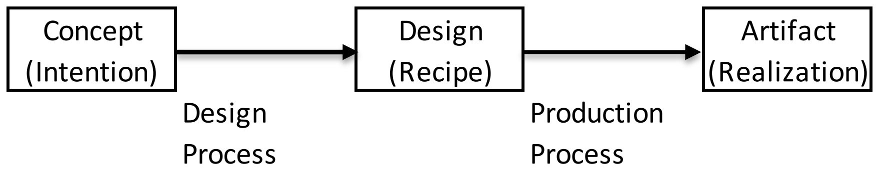
6.4 Technological Search

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.[18] The search begins as a mental process of combining images and symbols and predicting effects.[19] 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.

These predictions are the starting point of a design process aimed at developing a new technical recipe. The nascent design then progresses through three states. 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. Both the design process and the production process are parts of the greater task network.

[18] Schumpeter (1934).

[19] Bucciarelli (1994).



Of course, the three-stage process is not as linear as the diagram suggests.[20] The design under development must pass through a series of "generate-test cycles" where the initial predictions, each a narrative in its own right, are tested, modified and tested again.[21] As predictions are refuted, the underlying recipe must be revised to address the differences between hope and reality.

The desired end result is a congruent triad: a concept (intention) with a corresponding design (recipe) that can be realized. When the recipe works, a useful new artifact has been created. Knowledge advances, and the human repertory of technologies is enlarged.

To justify the effort involved in technological search, new technologies must be cost-effective in expectation. The expectations do not have to be precise or based on formal probabilities. They may be subject to bias. They might turn out to be wrong. However, *in the eyes of the would-be creators*, the anticipated cost of going from concept to artifact must be less than the anticipated value of the artifact itself.

6.5 Combining Functional Components

Simple 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.

The functions of a garment are very different from the functions of its contributing components. The functions of a garment are 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. Of all the functional components of a garment, only cloth can fulfill the same functions (though not as well). Similarly, the functional components needed to beat egg whites (eggs, bowl, whisk) cannot supply a soft foamy substance except by following the instructions of the technical recipe.

In this sense the technologies of garment-making and egg-beating are *transformativ*e—what comes out in the end is very different from what goes into the

[20] Godin (2006).

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

recipe.

Functional analysis can be applied to services as well as to 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, thus movies are another transformative technology.

The ability to see how various components can be combined to create something entirely different is a complex and mysterious human ability. It requires an understanding of cause and effect in the material world *and* the ability to imagine a state of the world that does not yet exist.[22]

Once a prototype exists, however, the performance of specific functions in the system can be traced back to one or more of the functional components. Working backward along a causal chain can lead to improvements in the artifact. For example, in the case of a garment, if you want to increase warmth, it makes sense to focus on the cloth. If more modesty or more style is your objective, best start with the pattern.

Modularity in design, production or use also supports the process of improvement.[23] Most garments are almost completely modular in design: at this 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. Modularity in use, however, varies by garment type. Sportwear garments can be mixed and matched to different occasions and upgraded piecemeal.[24] In contrast, once a dress has been sewn together, its parts cannot be separated.

6.6 Functional Complementarity

In making a garment, the functions of the needle, thread, scissors, cloth, pattern and stitching are all *essential.* 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).

The complementarity of the essential functional components can be represented as

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[22] The neuroscientist, Gerald Edelman calls this ability "higher-order consciousness." Edelman (1992).

[23] Baldwin and Clark (1997); Sako and Murray (2000).

[24] Sportwear is "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.

follows:

needle ☐ *thread* ☐ *scissors* ☐ *cloth* ☐ *pattern* ☐ *stitching* ➔ ***Garment***

Here, the linking symbol ☐ denotes a complementary combination of *essential functions* via some technical recipe. If any of the functional components is absent, the recipe will fail and the functions of the garment will not be achieved. A box around a word indicates that the component is a module.

The fact that each component is essential means that the technologies are *strong functional complements*. However, that fact that the different functions are modules means that there may be several different ways to accomplish each. For example, the cloth in the recipe may be wool, cotton, silk or synthetic, thin or thick, knitted or woven, patterned or plain. Each type of cloth may have many different suppliers competing with one another on the basis of price and quality. Similarly, there may be many suppliers of needles, thread, and scissors, many pattern templates and many stitches.

Thus strong *functional* complementarity does not necessarily imply that the goods and services supplying the functions are strong *economic* complements as defined in Chapter 5. Strong economic complements are both *essential* and *unique* with respect to each other. Strong functional complementarity is necessary but not sufficient for strong economic complementarity.

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, lie thousands of years of experimentation with basic stitch patterns.[25] The recipes and realizations behind each function in turn can be decomposed into subsidiary 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.[26] 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, wool comes from sheep, sheep need pastures, pastures need land, fences and grass. With land and grass, we arrive at the natural world. Each subordinate good provides a function that contributes to the making

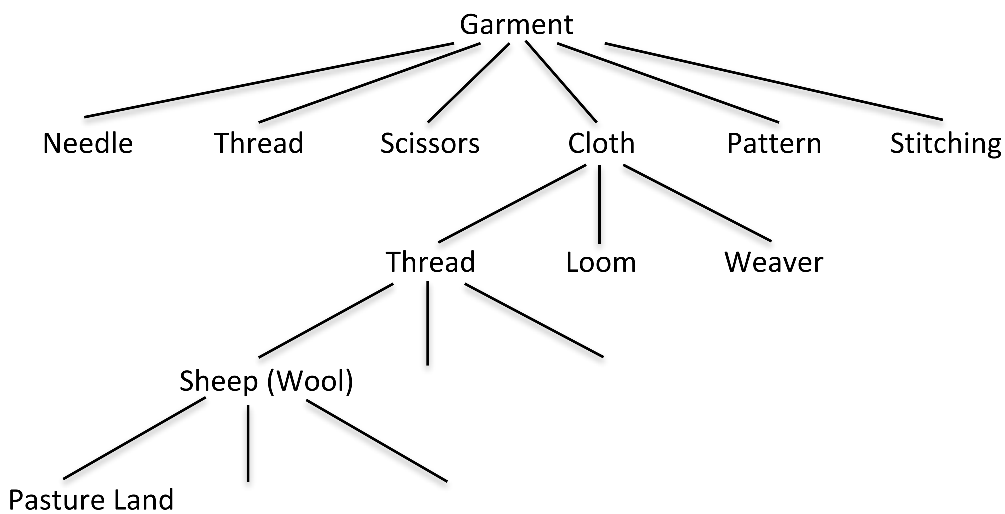
[25] Vasbinder, N. (2014).

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

of the superior good. Each subordinate function in turn is implemented by means of a technical recipe that requires specific tasks and transfers.[27]

Thus one can zoom in on the functional hierarchy and arrive at a task network. The functional hierarchy offers a macroscopic view of the system that suppresses many details, while the task network offers a more microscopic view.

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



6.8 The Role of Narratives

The identification of functional components 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 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 "as a product or service, the artifact might be useful or desirable to 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

[27] Note that the functional hierarchy depicted in the figure is not an organizational hierarchy. Activities may be distributed across many independent organizations (a business ecosystem) with transfers taking place via transactions.

individuals using their own skills and financial resources. Many "single user innovations" fall into this category.[28] Other narratives require organizations, that is, cooperating groups of individuals, or ecosystems of independent firms supplying complementary goods and services.

6.9 Technological Novelty

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.[29] Here radical uncertainty is at its height. At this point, it it is generally impossible to estimate future prices, quantities and probabilities for products based on the technology. On the first pass, the new technology may be of no use to anyone.[30]

Once the novel artifact exists, however, designers can begin to study how it really works. By tracing back cause and effect (discussed above), the shortcomings of the system can be mapped onto the performance of one or more functional components. This in turn creates incentives to modify the components in ways that contribute to the performance of 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).[31] 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 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, the technology 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 described in Chapter 2. But any modularization will take time. Furthermore, the laws of nature operating through the technology may make

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

[29] Arthur (2009) Ch. 6.

[30] Rosenberg (1998) p. 97-98.

[31] Arthur (2009).

modularization easy or hard. For example, technologies that involve high levels of energy exchange between components and/or three-dimensional fitted interfaces have defied most attempts at modularization.[32]

6.10 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*.[33] (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 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."[34]

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

Core Garment □ [1 + *collar* + *zipper* + *sleeves*□[*cuffs*+*buttons*]] ➔ ***Augmented Garment***

The leading "1" in the brackets indicates that the core garment has stand-alone value, even without any added features. In contrast, optional features inside the brackets

[32] Whitney (1996; 2004); MacDuffie (2013); Kotha and Srikanth (2013).

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

[34] *Ibid.* p. 247.

have value only in combination with the core. The features in turn may be valued independently (*collar, zipper, sleeves*) or in combinations (*sleeves, cuffs, buttons*). There may also be subhierarchies of features: (*sleeves* □ [*cuffs* + *buttons*]). Again, behind each feature lies a technical recipe that delivers the feature in conjunction with the basic garment.[35]

6.11 Composite Functions

In some cases, 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 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 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 functions can be represented by accounting for each functional component both separately and jointly. For example, the camera system can be represented as:

camera + *storage* + *viewing* + [*camera* □ *storage* □ *viewing*] ➔ ***Camera System***

The first three terms indicate the value of each stand-alone function; the terms within brackets indicate the *incremental value* of the combination of functions. (This decomposition is similar to the decomposition of supermodular value found in Chapter 5. The value of the bracketed term reflects the value of the "supermodular surplus," created by combining the three complementary components into a system.)

In developing a narrative about the value of the camera system, we would probably conjecture that the value of each stand-alone function *by itself* was small.[36] In contrast, the value of the combination might be very high.

In other cases, the contributing functions might have considerable stand-alone value relative to their combined value. Consider the case of a camera system combined with telephone. Like the camera, the phone has many contributing functional components with technical recipes and task networks. 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 *camera* and the telephone system's functions as *telephone*. Now consider a technology that combines a camera and

[35] I have not drawn boxes around the features because they may or may not be modules. In most cases, the zipper and buttons are modules that would be purchased from suppliers, while the collar, sleeves and cuffs would be cut and sewn in the same facility as the rest of the garment.

[36] Admittedly storage might have value as a stand-alone function.

phone into a larger system—a *Cameraphone*. The combined system then has a functional representation as follows:

camera + *telephone* + [*camera* □ *telephone*] ➔ ***Cameraphone***

This is the same basic structure as that of the *Camera System* (see above). The underlying functions are visible and separate within the combined system. But if we construct a narrative about the value of *this* combination, it is no longer the case that the stand-alone functions are close to worthless. If the value of the *camera* function is high, then its value inside the *Cameraphone* will also be high. The same goes for the value of the *telephone* function. There might be incremental value in the combination but it is also possible that combining the two functions adds no value, i.e., users would be just as happy with separate devices.

Thus from a narrative about how people will use the camera system, we can judge that a camera function alone has little value in the absence of the storage and viewing functions. In contrast 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, they may simply be "large", "negligible", or "negative'.

We are starting to see a *value structure* emerge from the analysis of functional components. Without estimating revenues, costs or probabilities, we can associate value with different combinations of technical recipes in an objective and systematic way. The conclusions about value can be appended to the other narratives surrounding a technical system. The narratives plus judgments about value can be the basis of reasoned discussion and can support decisions to invest in a new technology or not.

6.12 Platforms and Platform Hierarchies

In Chapter 5, I introduced platforms as one of the methods of coordinating ecosystems of complementary firms and individuals. In a platform system, there is a common core of functions (the platform) and a set of complementary options, which have no value separate from the platform. The platform generally has no value in the absence of the options, but its value does not depend on the presence of any one option.

The functional representation of all platform-based technologies is as follows:

platform □ [*option 1* + … + *option N*] ➔ ***Platform System***

The platform and the options are strong *functional* complements, but each option's contribution is independent of the other options. The "+" sign indicates that the presence or absence of any option has no effect on the others. If the platform is unique, the platform and options will be strong one-way *economic* complements with each option dependent on the platform, but the platform will not be dependent on any single option.

It is also possible to build a new platform "on top of" existing platforms thus creating a platform hierarchy. For example, with the advent of the Internet in 1995, personal computers and the phone system could be combined with the Internet and

Worldwide Web protocols to provide new functions, such as online shopping, email, social networking, weather and news reporting, etc. Although personal computers and the phone system survived as separate platforms in their traditional uses, the functional components that knit them together, including the Internet, the Worldwide Web, browser programs, routers, modems, and search engines, led to transformative new functions.

The functional components of an Internet-enabled personal computer can be represented as follows:

1995

[*computer* □ *telephone* □ *Internet* □ *Worldwide Web*

□ *modem* □ *browser* □ *search engine*]

□ [*shopping* + *social networking* + *news* + *email* + *games*

+ *other online activities…*] ➔ ***Internet-enabled personal computer***

The first two lines list the platform's essential functional components; the second two show a representative set of options. As before, modules in the system are indicated by borders.

Even though all functions within the platform were essential, only the Internet and Worldwide Web protocols were unique. Thus most of components in this technical system were *weak* economic complements, not strong ones. The fact that they and the options were modules also meant that users could mix and match different computers, telephones, modems, and optional applications. Hence the different components of this technical system could be produced by an ecosystem of independent firms.

This functional representation can be seen as a *value structure map* of the technical system. Each module was an independent locus of value creation and value capture subject to system-level design rules. Each could be the basis of a distinct narrative that justified action or investment. Cost-effective transactions could be located at module boundaries.

We arrived at this value structure map of the system using only information about the underlying technologies. We did not attempt to estimate prices, quantities or probabilities, nor did we calculate a return-on-investment for any component or the whole system. We merely identified the essential and optional components and drew module boundaries. From these data alone, we could predict that distributed modular complementarity (DMC) was likely to hold in this system, and thus an ecosystem might be a sustainable form of organization for implementing these technologies in the long run.

As a means of analysis, narratives have many limitations. Specifically, they lack the discipline and consistency of numerical estimates derived from real prices, quantities, and observed frequency distributions. Following the arrival of the Internet in the mid-1990s, thousands of startup were formed on the basis of plausible narratives about "first-mover advantage" and the need to "get big quick." Very few observers attempted to add up the stories to see if the overall narrative made sense. The ensuing Internet Bubble burst in March of 2000, and most of the new firms were wiped out.

However, recognizing the role narratives play in technological decision making, *and tying narratives to the value structure of the underlying technologies* gives us a different way of understanding how value might be created and captured in a complex and evolving technical system. I will use this methodology (with extensions) in the next chapter and throughout the rest of this book.

6.13 Conclusion—How Technology Shapes Organizations

The fundamental premise of this book is that, in an economy made up of free agents, technology shapes organizations by rewarding organizations that meet the requirements of the technology and implement its recipes effectively. Thus to understand which forms of organization are best suited to specific technologies, we must first understand how technologies allow organizations to create and capture value.

However, three common characteristics of technologies make it difficult to assess their value using standard methods found in economics and finance. First, technologies are subject to so-called radical uncertainty: it is impossible to envision all likely outcomes much less associate outcomes with prices, quantities or probabilities. Second, technical systems are complex and may included millions of technical recipes and billions of tasks. The recipes and tasks are also complementary: they create more value when combined that when deployed separately. Third, given radical uncertainty, complexity and complementarity, we lack ways of setting priorities for actions and investments in technical systems.

To address these difficulties, in this chapter I described a method of representing technologies in terms of logical relationships among *functional components*. Within a technical system, functional components *do something*: they fulfill a role that furthers the goals of the system. Thus functional components are carriers of value in a technical system. Functional analysis—breaking the system up into functional components linked by logical relationships—tells us why particular tasks exist and how they aggregate into larger systems.

All technical systems display fundamental patterns of functional association. The most fundamental pattern is *essentiality*. The garment example illustrates this pattern: if any of the listed functional components is absent, one cannot make a garment. A second fundamental pattern is *hierarchy.* Functional components have corresponding recipes, which in turn have their own functional components. Tracing the chain of recipes must eventually lead back to the natural world, since technologies are what convert natural objects into manmade things.

Other functional patterns explored in this chapter include (1) the relationship of optional features to a "core" artifact; (2) composite functions that have stand-alone value, but also value in combination; (3) platform systems comprised of an essential core and optional complements.

The next step in understanding how technology shapes organizations is to show how value structure maps of functional components can serve as the basis of a narrative that can inform strategy and decision-making in technical systems subject to radical uncertainty, complexity and complementarity. That is my goal in the next chapter.

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