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Design Rules, Volume 2: How Technology Shapes Organizations

Chapter 5 Ecosystems and Complementarities

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By Carliss Y. Baldwin

Note to Readers: This is a draft of Chapter 5 of *Design Rules, Volume 2: How Technology Shapes Organizations*. It is replaces my previous working paper "Complementarity" dated October (2018). This chapter builds on prior chapters, but I believe it is possible to read it on a stand-alone basis. The chapter may be cited as:

Baldwin, C. Y. (2020) "Ecosystems and Complementarity" Harvard Business School Working Paper (August 2020).

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

Abstract

The purpose of this chapter is to introduce two new building blocks to the theory of how technology shapes organizations. The first is a new layer of organization structure: a business "ecosystem." The second is the economic concept of "complementarity." Ecosystems are groups of autonomous firms and individuals whose actions and investments create joint value. Ecosystems are defined by economic complementarities among their members: the value they create acting together is greater than the value they can create acting separately. The modern theory of complementarity thus helps to explain when and why ecosystems survive in the greater economy.

In the first half of this chapter, I define business ecosystems and show how they are related to task networks, transactions, transaction free zones, and corporations. I then describe the methods by which ecosystems are coordinated. The second half of the chapter investigates how economic complementarities influence ecosystems. Within ecosystems, centripetal forces "pull" firms together giving them incentives to combine. Conversely, centrifugal forces "push" firms apart providing incentives to remain separate. The continued existence of an ecosystem requires a balance of these forces, so that the system neither collapses into several large firms nor dissipates into a group of unrelated firms. In the final sections of the chapter, I identify necessary mathematical conditions for an ecosystem to survive as a dynamic equilibrium in the larger economy.

Introduction

In the last three decades of the 20th century, a number of technological innovations in the design of computers led companies in that industry to experiment with new forms of organization. First, based on the seminal work of Gordon Bell and Alan Newell, computer designers learned to modularize hardware systems and segregate

hardware from software.[1] Software developers also learned how to hide information behind stable interfaces; create powerful computer languages; and separate system software from applications using application programmer interfaces (APIs).[2] High rates of technical change in the industry, made possible by the physics of integrated circuits also rewarded the creation of modular systems that could be upgraded piecemeal.[3]

Following the success of System 360, the first modular computer system, modularity became a fundamental principle of computer design. Modularization in turn increased the number of thin crossing points in the underlying task networks. As we saw in Chapter 2, thin crossing points have correspondingly low transaction costs, making it relatively easy for third parties to compete by offering compatible modules instead of whole systems.

Throughout the computer industry, clusters of firms making modules soon became competitive with vertically integrated firms making whole systems.[4] Vertically integrated incumbents faced an unwelcome choice: Make their systems unassailable by giving up the benefits of modularity (including flexibility, scalability, and piecemeal upgrades) or tolerate the presence of specialist firms offering modules.

By 1995, specialist firms had essentially replaced vertically integrated firms. The power of modularity was thus one of the economic forces underlying the "vertical-to-horizontal" transition in the computer industry. The transition was an example of new technologies—integrated circuits and modular systems—shaping organizations in new ways.[5]

The purpose of this chapter is to introduce two new building blocks to the theory of how technology shapes organizations. The first is a new layer of organization structure: a business "ecosystem." The second is the economic concept of "complementarity." Ecosystems are groups of autonomous firms and individuals whose actions and investments create joint value.[6] Ecosystems are defined by economic complementarities among their members: the value they create acting together is greater than the value they can create acting separately. The modern theory of complementarity thus helps to explain when and why ecosystems survive in the greater economy.

In the first half of this chapter, I define business ecosystems and show how they are related to task networks, transactions, transaction free zones, and corporations. I then describe the methods by which ecosystems are coordinated. The second half of the chapter investigates how economic complementarities influence ecosystems. Within

[1] Bell and Newell (1971)

[2] Parnas (1972a; 1972b; 1979); Richie and Thompson (1974).

[3] Moore (1965); Mead and Conway (1980); Garud and Kumaraswamy (1993).

[4] Baldwin and Clark (2000) Ch. 14.

[5] Grove (1996); Moore (1996). See Chapter 1.

[6] Bogers, Sims and West (2019).

ecosystems, centripetal forces "pull" firms together giving them incentives to combine. Conversely, centrifugal forces "push" firms apart providing incentives to remain separate. The continued existence of an ecosystem requires a balance of these forces, so that the system neither collapses into several large firms nor dissipates into a group of unrelated firms. In the final sections of the chapter, I identify necessary mathematical conditions for an ecosystem to survive as a dynamic equilibrium in the larger economy.

5.1 Ecosystems in Relation to the Task Network, Transactions, and Transaction Free Zones

In prior chapters, I built up a picture of the economy as a network of tasks and transfers arranged according to the specifications of underlying technologies. Actors, including people and machines, perform the tasks and make the transfers, turning technical recipes into real goods and services. The tasks and transfers in turn may be grouped into "near-decomposable" modules that are "tightly connected within each module and only loosely connected to other modules."[7]

Transactions are transfers that are defined, measured and paid for. They carry an extra burden of cost relative to simple transfers. Modules are separated by thin crossing points in the task network where transaction costs are low. In contrast, areas in the task network that are densely interconnected (ie lie within a module) can be organized as "transaction free zones." Inside transaction free zones, the transfers of material, energy and information mandated by the underlying technical recipe take place freely. The absence of transactions makes the technical processes within the zone more efficient. Organizational ties in the form of common employment, collocation, and communication links exist within and across transaction free zones.

Transactions, transaction free zones, and organizational ties are social relationships that overlay the underlying task and transfer network. They partition the network into organizations, including firms, designed to achieve specific goals.[8] The organizations and individuals in the task network are connected by transactions and other uncompensated transfers. However, uncompensated transfers are more likely to arise within transaction free zones than across them.

A "Martian's View" of the Economy

In a famous passage written in 1991, Herbert Simon described the economy as it might appear to a "visitor from Mars:"

> Suppose that [a mythical visitor from Mars] approaches the Earth from space, equipped with a telescope that reveals social structures. The firms reveal themselves, say, as solid green areas with faint interior contours marking out

[7] Simon, (1962; 1981; 2002); Baldwin and Clark (2000) Ch. 3.

[8] Puranam, Alexy, Reitzig (2014); Puranam (2018).

> divisions and departments. Market transactions show as red lines connecting firms, forming a network in the spaces between them. …
>
> Organizations would be the dominant feature of the landscape. A message sent back home, describing the scene, would speak of "large green areas interconnected by red lines." It would not likely speak of "a network of red lines connecting green spots."[9]

Simon was challenging the view then common among economists that transactions were the fundamental units of economic analysis, and firms nothing more than a nexus of contracts (see Chapter 3). He insisted that important activities and relationships arose within firms that were outside the purview of market exchanges. In fact, he contended, organizations dominated transactions in terms of their contribution to productive work. In every modern society, whether capitalist or communist, "the greater part of the [economic system] would be within green areas, for almost all of the inhabitants would be employees, hence inside the firm boundaries."[10]

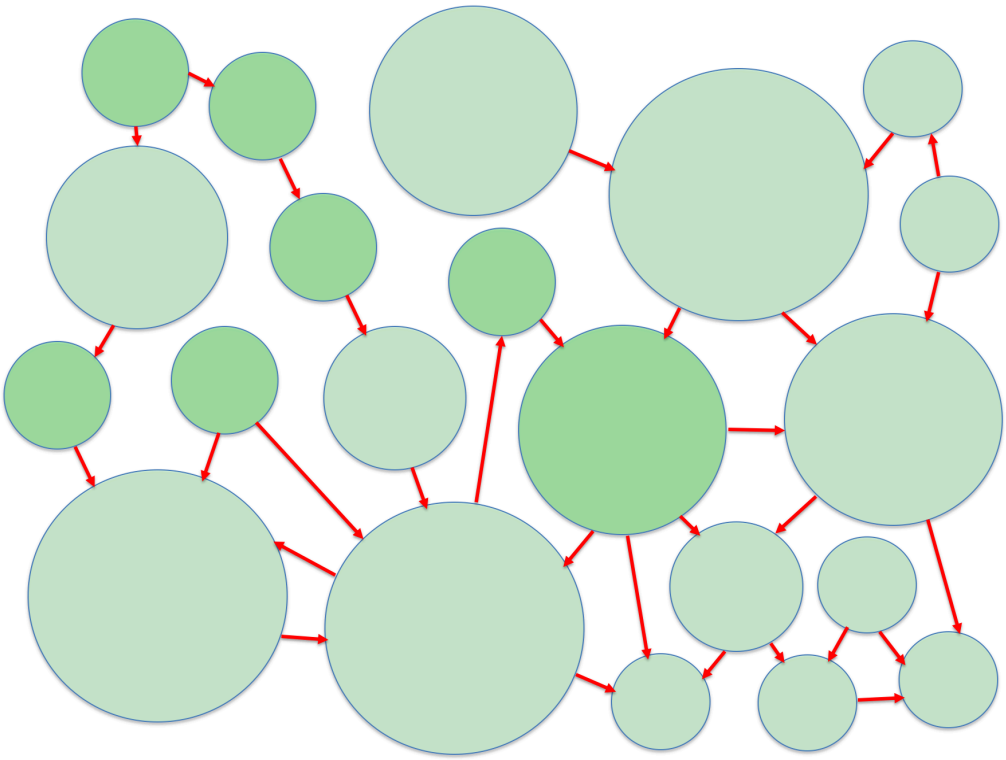
Plate 5-1 shows a "Martian's view" of the economy—a network of green circles connected by red lines. The green circles—firms—are by definition transaction free zones, since, according to Simon, no market transactions take place within them.

According to the theory laid out in Chapters 2 and 3, if we looked inside the green circles, we would see different tasks and transfers performed by actors coordinated through unified goverance, hierarchy and the exercise of direct authority. The task networks of the smithy and the kitchen as well as the disk drive and laptop makers in Chapter 2 would be contained within their respective green circles. Plate 5-2 depicts the greater task network, made up of tasks and transfers within firms and transactions between them.

[9] Simon (1991) p. 27.

[10] Ibid.

Plate 5-1 A "Martian's View" of the Economy Containing Firms (Green Circles) and Transactions (Red Lines)



Definition of a Business Ecosystem

In this volume, I define a business ecosystem as follows:

A business ecosystem is a group of autonomous firms and individuals whose actions, decisions, and investments are complementary in the sense that their value as a system is greater than the sum of the values of the separate parts.[11]

This definition is consistent with my earlier definition in 2012: "Ecosystems… encompass numerous corporations, individuals, and communities that might be individually autonomous but [are] related through their connection with an underlying, evolving technical system."[12] It is also consistent with the definition recently proposed by Marcel Bogers, Jonathan Sims and Joel West (2019) based on their comprehensive

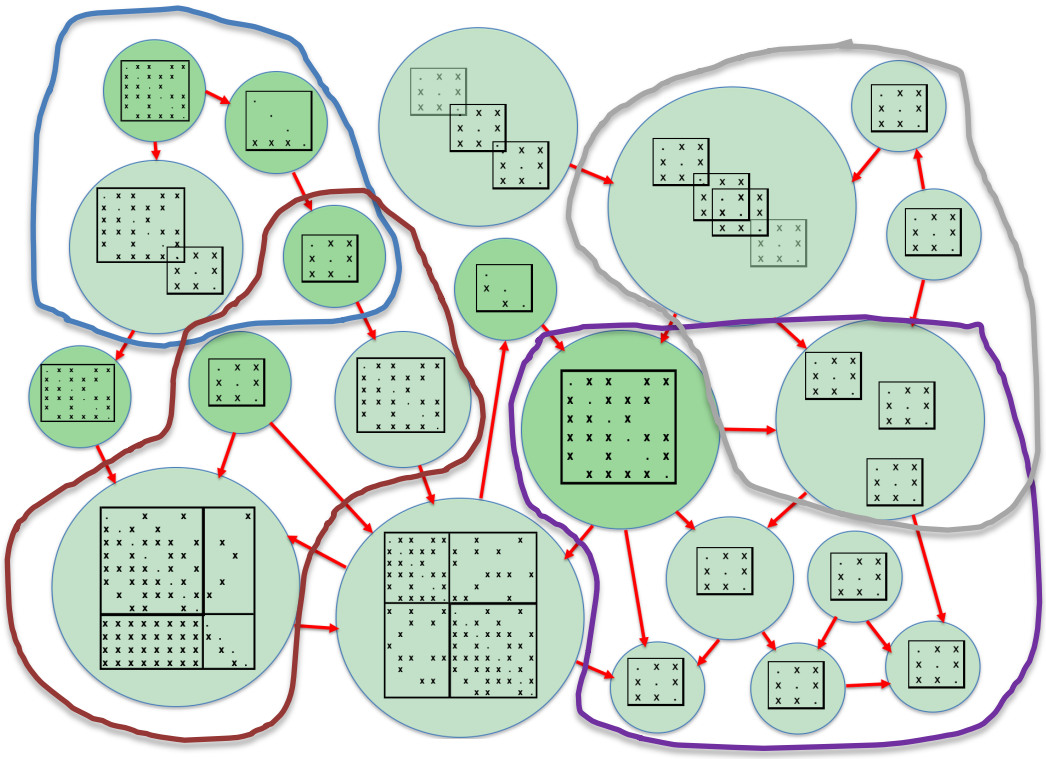
[11] The term "ecosystem" was first used in a business strategy setting by J.F. Moore (1996) and Iansiti and Levien (2004). The concept was further developed by Adner (2006); Adner and Kapoor (2010); Baldwin (2012); and Williamson and De Meyer (2012).

[12] Baldwin (2012) p. 20.

review of the literature: "An ecosystem is an interdependent network of self-interested actors jointly creating value."[13]

Ecosystems are "meta-organizations" that provide another level of structure above Simon's firms and transactions.[14] If firms are viewed as circles around transaction-free zones, then an ecosystem can be seen as a "circle around circles." Four overlapping ecosystems are shown in Plate 5-2.

Plate 5-2 Martian's View Showing Tasks and Transfers within Firms and Ecosystems



As indicated in the figure, there may be transactions within ecosystems: indeed there must be transactions because each firm must meet a test of financial sufficiency in order to survive in the economy. Their cash inflows from product sales and capital transactions must exceed their cash outlays, or they face dissolution.

It is also common for ecosystems to overlap: a single firm or individual may belong to several ecosystems at once. Finally, although they are not shown in the figure, individuals can be members of ecosystems, functioning as both producers and consumers.

[13] Bogers, Sims and West (2019) p. 2.

[14] Gulati, Puranam, and Tushman (2012).

5.2 Methods of Coordinating Ecosystems

Technologies are complex systems and thus never reach an optimal configuration by pure chance.[15] As a result, the ecosystems that implement complex technical recipes require coordination to reach and maintain high levels of functionality.[16] At the same time, ecosystems are comprised of autonomous organizations and individuals, thus coordination via unified governance, hierarchical management and direct authority is not possible. In this section I review the principal methods of coordination employed in ecosystems, including the price system; bilateral negotiations and contracts; multilateral agreements and systems integration; and platforms. Each method is discussed in a separate subsection below.

The Price System

Adam Smith set forth in some detail how prices work in a competitive market to *direct effort* to the production of the goods most desired by members of society.[17] Given competition in goods markets, producers acting in their own self-interest will voluntarily make the goods that others want and sell them at reasonable prices. According to Smith, the market price of a good in relation to its cost is *all* that producers need to know to achieve this happy outcome. Producers whose costs are higher than the market price will fail to make a profit and channel their efforts toward other goals.

Almost 200 years later, Friedrich Hayek spelled out in detail how the price system operates to collect widely dispersed knowledge and transmit it to those able to take action:

> In a system where the knowledge of relevant facts is dispersed among many people, the price system can act to coordinate the separate actions of different people. …
>
> The most significant fact about this system is … how little the individual participants need to know in order to be able to take the right action. … Only the most essential information is passed on, and passed on only to those concerned.
>
> The marvel is that in a case like that of a scarcity of one raw material, without an order being issued, without more than perhaps a handful of people knowing the cause, tens of thousands of people whose identity could not be ascertained by months of investigation, are made to use the material or its products more sparingly; i.e., they move in the right direction.[18]

[15] Simon (1981); Arthur (2009).

[16] Adner (2003; 2017); Adner and Kapoor (2010).

[17] Smith (1776) Book I.

[18] Hayek (1945) pp. 526-527.

Given common knowledge of the definition of each good, prices alone are theoretically sufficient to coordinate all actors in a very large economic system. Moreover, according to Hayek, prices are marvelously efficient in comparison with bureaucratic central planning based on authority.

The actions of buyers and sellers in the economy are complementary. The seller has a good the buyer can use; the buyer has a need for the good and is willing to pay for it. Through the division of labor and specialization of knowledge, all members of society can be made better off. The "invisible hand of the market" operates to bring buyers and sellers into alignment while economizing on costly transfers of skills and knowledge.[19]

However, prices alone cannot convey the complex facts or detailed techical knowledge needed to carry out many production processes. As a result, there are areas in the task network where *prices are not an efficient way of communicating relevant information*. In Chapter 2, we saw that transactions with prices are best placed at the "thin crossing points" of the task network, where the transfers required by the underlying technology are few and simple. In parts of the network where the transfers are dense and complex, attempting to record and price each one will place an intolerable burden on productivity. Complex transfers should thus be placed within transaction free zones where transfers can take place freely without turning each one into a formal transaction. (See Chapter 3.)

Corporations are transaction free zones endowed by law with the ability to own assets, employ people, and buy and sell goods. Coordination within corporations does not take place via prices. Disputes are settled by appeal to a single governing body, the board of directors. Managers coordinate disparate activities by creating internal communication channels and hierarchies and by giving direct orders to employees.

The combination of corporations and transactions is sufficient to account for the "visitor from Mars" economic system depicted in Plate 5-1. However, these two institutions alone cannot address all complementarities present in the economic system. Coordination *between* corporations that goes beyond the price system is often desirable to achieve high levels of technological efficiency. Thus, in addition to formal transactions at market prices, members of ecosystems also use bilateral negotiations and contracts, multilateral negotiations and systems integration, and platforms to coordinate their joint efforts.

Bilateral Negotiations and Contracts

As described in Chapter 2, it is sometimes desirable to place transactions at thick crossing points in the task network. We saw this in the case of the disk drive maker and

[19] The phrase "invisible hand of the market" is generally attributed to Smith, although he used it in an entirely different context (Grampp, 2000.) The term became associated with Smith only after Paul Samuelson used it (and attributed it to Smith), in the first edition of his *Economics* textbook (Samuelson, 1948).

the laptop maker: their designs were interdependent but their manufacturing processes were independent. To make a functional laptop, the two companies did not have to merge but they did have work together to create a tighter complementary relationship.

In cases like this, the simplicity of market prices, which Hayek so admired, quickly disappears. To satify the needs of their joint undertaking, the two firms needed to set up a long-lasting formal and relational contract. Such contracts require agreement on more than just prices and quantities. Formal contracts contain long lists of specifications and tests of the quality of the transacted items. Relational contracts are based on long-term commitments by both parties, plus investments to enhance mutual understanding and trust. The terms of these contracts are complex, multidimensional, and often unstated.[20]

Under the definition given above, a buyer-supplier pair constitutes an ecosystem, albeit a small one. Buyers and suppliers generally do not exist in a vacuum, however. They almost always participate in a supply chain or network. *The chain or network is also an ecosystem coordinated by prices, bilateral contracts, multilateral negotiations and platforms.* Buyers and suppliers may also come together in a centralized marketplace that functions as a platform for trade. *The platform and its users are also an ecosystem, coordinated by prices, bilateral contracts, multilateral negotiations, and platform regulations.*[21]

Multilateral Negotiations and System Integration

When three or more parties are mutually complementary, bilateral contracting can lead to costly cycling. For example two parties may fail to reach a deal, because of doubts about the willingness of a third to contribute. Alternatively, the last party to sign up may demand a disproportionate share of the surplus value created because the other participants' costs are sunk.

Such cases can be addressed in two ways: (1) via simultaneous, multilateral negotiations involving all interested parties; and (2) through coordination by systems integrators capable of lining up all relevant actors.

Standards-setting organizations are an example of an *institution* that facilitates multilateral negotiations.[22] As we saw in Chapter 2, system-wide standards reduce the cost of negotiating bilateral contracts.[23] The standards and associated compliance tests

[20] Macneil (1985); Baker, Gibbons and Murphy (1999); Gibbons (2003).

[21] Some scholars, such as Adner (2017) and Jacobides et al. (2018) have argued that groups of autonomous firms and individuals that are coordinated only by prices, bilateral contracts, or platform markets are not ecosystems. However, attempts to define ecosystems more narrowly immediately run into difficulties in distinguishing between "true" and "false" ecosystems. I concur with Bogers et al. (2019) that a broader, more inclusive definition of ecosystem is preferable.

[22] Aoki (2001); Nelson and Sampat (2001).

[23] As a secondary benefit, standards also reduce case-to-case variation in products, paving the way for

serve as design rules which, if followed, cause the modules of a complex technical system to function together *as a system*.[24] Such modules are by definition complements, since each contributes additional value to a larger technical system.

As discussed in Chapter 3, standard-setting organizations create transaction free zones for the purpose of proposing, negotiating, and deciding on standards. The standards themselves may be owned by specific firms, but the standard-setting organization is usually subject to distributed governance. The organization acts for the good of all members not any single member. The ecosystem of the standard consists of the standard-setting organization and all users of the standard.[25]

Standardization is not feasible in all settings, however. Construction projects, movies and TV shows, toys, and fashion-dependent products require customization and/or thrive on novelty. In such cases, the agents contributing to the final product may be brought together through the efforts of a systems integrator.[26]

Systems integrators are responsible for making sure the whole system works. To be effective, they must understand all parts of a complex process in enough detail to address defects, shortfalls and delays wherever they arise. In other words, "they [must] know more than they make."[27] Systems integrators specialize in multilateral coordination. Their role is to induce many independent agents to act in ways that move the overall project forward without becoming enmired in disputes and bickering.

The ecosystem of a transient project includes the systems integrator and all participants in the project. In industries where transient projects are the norm, the members of each project ecosystem are generally drawn from a larger pool of firms and individuals with specific skills and resources. The larger pool is also an ecosystem, although it is often called an "industry." Examples include the construction industy, the apparel industry, and the movie industry.

Platforms

The final way of coordinating members of an ecosystem is through platforms. In this book, I define a "platform system" as:

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economies of scale and mass production.

[24] Baldwin and Clark (2000) Ch 3; Baldwin (2012).

[25] West (2007); Simcoe (2014).

[26] Brusoni, Prencipe and Pavitt (2001); Sturgeon (2002); Prencipe, Davies and Hobday (2004); Precipe (2004); Brusoni (2005); Brady, Davies and Gann (2005). According to Sapolsky (2004) the term "systems integrator" originated in the defense sector shortly after World War II. In construction, systems integrators are called general contractors. In movies and TV, they are called producers. In modern supply chains, they are called "sourcing agents."

[27] Brusoni, Prencipe and Pavitt (2001).

> a technical system comprising a core set of essential functional elements (the platform) plus a set of optional complements. The optional complements may be products, processes, transactions or messages. The platform has no value except in conjunction with the options.

Platforms are technologies whose purpose is to provide options—the ability to make a specific choice (or series of choices) in the future.[28] Because there are many different types of options in the world, there are also many different types of platforms.

Platform systems may be closed or open. In a *closed platform system*, the options are exercised by a single firm. Examples include Toyota's assembly lines, which can turn out a wide variety of customized vehicles, as well as railroads and communication networks, which can send trains or messages to many places over many different routes.

In an *open platform system*, options are exercised by external agents not under the control of the platform sponsor. The sponsor and users of an open platform constitute its ecosystem. Platforms divide the underlying technical system into core functions and complementary options. The platform sponsor attends to the core functions and leaves the options to members of the ecosystem. A platform system thus represents a clever compromise between centralized control and decentralized choice.

Inset Box 5-1 describes four types of open platforms with ecosystems. Each type provides members of its ecosystem with a different set of options.

Inset Box 5-1 Open Platforms with Ecosystems

Open platforms can be divided into four sub-types: standards-based platforms; logistics or supply chain platforms; transaction platforms; and communication platforms.

Standards-based platforms set standards that allow the complementary goods to interoperate with the platform and with each other. Examples include a computer operating system and applications, video game consoles and games, a microprocessor and compatible hardware, and TV sets and TV shows.[29] The ecosystem of a standards-based platform includes all parties that use the standard, including the makers of complements, systems integrators, and end users of the products created. Standards-based platforms and their ecosystems are analyzed in detail in Chapters 16 and 17.

Logistical or supply chain platforms facilitate the movement of products through a modular production network. Examples include Apple's supply chain for manufacturing Iphones and Ipads, Flex.com's supply chain for consumer electronics manufacturing, and various apparel supply chains.[30] Their ecosystems generally include designers, manufacturers, transporters, wholesalers and retailers of the goods in question, as well as systems integrators providing

[28] Baldwin and Woodard (2009).

[29] Bresnahan and Greenstein (1998); Gawer and Cusumano (2002).

[30] Sturgeon (2002); Berger (2005).

coordination. Logistics platforms and their ecosystems are the focus of Chapters 18 and 19.

Transaction platforms facilitate transactions—legally recognized exchanges of property rights in return for payment.[31] Examples of transaction platforms include traditional marketplaces and bazaars, online retailers and marketplaces such as Amazon, Alibaba, and Ebay, travel brokers such as Expedia and AirBNB; and ride hailing services. The ecosystem of a transaction platform includes buyers and sellers, as well as providers of ancillary services including advertising, logistics, transportation and finance. The different groups are commonly called "sides." A transaction platform whose ecosystem contains only buyers and sellers is called a "two-sided market."

Communication platforms transfer messages. Traditional examples include relay beacons, mail and courier services, newspapers, telephone systems, radio and TV. Digital communication platforms include email, search engines, social media, data repositories, news aggregators, online newspapers, and rating and review sites.[32] The ecosystem of a communication platform consists of senders and recipients of messages, advertisers, data collectors, and other service providers. As with transaction platforms, it is customary to refer to the different categories of platform users and complementors as "sides." Platforms serving several distinct groups are known as "N-sided" or "multi-sided" markets.

Transaction and communication platforms are discussed in detail in Chapters 20-22.

Large technical systems are made up of many complementary functional components, that work together according to the dictates of a technological recipe.[33] Complementarity and the resulting need for coordination lie at the heart of all technical systems. Therefore to understand how technology shapes organizations, we must look more deeply into the economic theory of complementarity.

Michael Jacobides, Carmelo Cennamo and Annabelle Gawer were the first management scholars to apply the modern economic theory of complementarity to ecosystems.[34] Here I build upon their prior work.

In the rest of this chapter, I will use the mathematical theory of complementarity developed by Paul Milgrom, John Roberts and Donald Topkis to describe conditions under which an ecosystem can be in a dynamic equilibrium within the larger economy. The mathematical arguments require patience and attention from the reader, but in the end, they deliver a more complete and precise theory than purely verbal arguments can achieve.

[31] Rochet and Tirole (2003; 2006); Evans, Hagiu and Schmalensee (2008); Hagiu (2009); Hagiu and Wright (2015); Parker, Van Alstyne and Chouhury (2016).

[32] Ibid.

[33] Arthur (2009). In the next Chapter, I will propose a method of representing a technical system as an arrangement of functional components and complementary relationships.

[34] Jacobides, Cennamo and Gawer (2018).

5.3 Strong vs. Weak Complementarity

According to the Cambridge English Dictionary, two or more things are complementary when they are "different, but useful or attractive when used together." Complementary goods are enhanced when they are used together. Examples include right and left shoes; razors and blades; cake and icing; horses and carriages; cars and highways; TV sets and TV shows; computer hardware and software; and tea, hot water and a cup.

The value of a group of complements in joint use is *super-additive*, that is, the things together are more valuable (to someone) than the sum of their values in separate use. For example, to a tea drinker, the value of tea steeped in hot water and poured into a cup is worth more than the value of tea in a canister, hot water in a kettle, and a cup on the shelf:

$$V(\text{Tea, Hot Water, Cup}) > V(\text{Tea}) + V(\text{Hot Water}) + V(\text{Cup}) \quad . \qquad (1)$$

Goods are *strong complements* if they are unproductive unless used together. Strong complementarity applies to *specific and unique* goods that through some technological transformation have become inseparable. Examples are the windows of a house and the house itself, a lock and its key, the engine and chassis of a car, and the two ends of a pipeline. (Strong complements are also called "specific", "co-specialized", "perfect", "strict", and "unique" complements.[35])

Tea, hot water and a cup are not strong complements because one can drink tea from a glass, use hot water to make coffee, and serve other liquids in the cup. Furthermore, if there are several providers of each component, then each complement will retain its value even if a *specific* complement is withdrawn. If Twinings tea is not available, a tea drinker can use Lipton tea instead. For most tea drinkers, the value of the bundle is not (much) diminished by using a different brand of tea.

If there are substitutes for all components in a group of complements, withdrawal of one component does not destroy the value of the others. Such components are *weak complements*. (Weak complements are also called "imperfect" or "generic" complements.)

In some cases, one component in a group of complements may be unique while the other components have substitutes. In such cases, the withdrawal of the unique component will destroy the value of the system. Conversely, any of the non-unique components can be withdrawn without inflicting much harm.

The presence of both unique and non-unique complements in a technical system creates an asymmetric economic relationship. The non-unique components *will depend on* the unique ones for their value but the reverse is not true. The dependency is one-way.

[35] Williamson (1985); Teece (1986); Hart and Moore (1990); Jacobides, Cennamo, and Gawer (2018).

As a result, the owner of the unique component, by threatening to withdraw her component, can claim a greater share of the surplus value created by the system than the owners of non-unique components.

If there are several, separately owned unique complements in a technical system, each owner can independently destroy the value of the system by withdrawing their part of it. Each owner of a unique complement wields the same threat, thus has equal power in the group.

5.4 Supermodular Complementarity

Strong and weak complementarity are concepts that can be applied using intuition alone, without recourse to mathematics. However, qualitative definitions and reasoning can only take us so far toward a comprehensive theory of business ecosystems.

The concept of complementarity was given a formal mathematical definition by Francis Edgeworth in the 19th Century and (independently) Wilfredo Pareto in the early 20th century.[36] The concept was generalized and refined by Donald Topkis, Paul Milgrom, and John Roberts in the 1990s.[37] The modern concept goes by the impressive name "supermodularity on a sub-lattice."

Intuitively, two items are supermodular complements if *more of one makes more of the other more valuable in relation to some desirable end result*. Examples of supermodular complements include sunny days and sunscreen, free time and leisure activities, smart phones and apps, and cars and highways. So-called direct and indirect network effects are also forms of supermodular complementarity.

Formally, two input variables are supermodular complements if an increase in one increases the positive effect of the other. Thus let x and y be inputs to a technical system that creates value. Let $V(x, y)$ be an increasing function of each input variable.[38] Then x and y are supermodular complements if:

$$V(x + \Delta x, y + \Delta y) - V(x + \Delta x, y) > V(x, y + \Delta y) - V(x, y). \qquad (2)$$

Here, the impact of increasing y is greater if x is increased as well. This is known as the property of "increasing differences." In effect, x provides y with an "extra kick."[39]

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[36] Samuelson (1974).

[37] Milgrom and Roberts (1990; 1994;1995); Topkis (1998).

[38] Technically, supermodular functions can be decreasing in the input variables. Then the property of supermodularity implies that moving from low to mixed will destroy less value than moving from mixed to high. This reversal can be cured by redefining the input variables so that the value increments are positive.

[39] Supermodular complementarity is often defined using a weak inequality (≥) instead of a strong inequality (>). However, if the equality holds, the two inputs have additive value, not superadditive value. Although this generalizes the concept and the proofs, it makes the exposition more complex and the concept less intuitive. My arguments depend on the existence of superadditivity, thus I exclude the edge

The definition can be applied pairwise to any group of input variables. The variables x and y may be continuous variables, discrete variables, or binary (yes/no) variables.[40] Indeed, one of the strengths of supermodular theory is that many different kinds of variables, including material quantities, decisions, endogenous choices, and exogenous parameters, can be incorporated within a single mathematical framework.[41]

Supermodular value functions have the property of *monotone comparative statics*, meaning that the choice variables will be non-decreasing in the other choice variable and the environmental variables. In other words, each optimized choice will tend to move up or down systematically in line with increases or decreases in other choices and/or environmental parameters.[42]

5.5 Strong and Weak Complements are Supermodular Complements

Both strong and weak complements are perforce supermodular complements. To see this, we must apply the test of increasing differences to each type of complement and verify that the test is satisfied. Doing this is a way of building intuition as to what supermodular complementarity implies.

Strong Two-way Complements

Recall that strong, two-way complements are symmetrically unique so that withdrawing any one destroys the value of the entire system.

Let $x = 1$ if complement x is present, and $x = 0$ if it is not present. Similarly let $y = 1$, if complement y is present, and $y = 0$ if it is not. From the definition, x and y are strong two-way complements if:

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case and will take the inequality as given.

[40] If $V(x, y)$ is a continuous function, then in the limit, equation (2) becomes $\frac{\partial V}{\partial x \partial y} > 0$. This is the classical Edgeworth-Pareto definition of complementarity. Samuelson (1974).

[41] However, the input variables must form a sub-lattice. On each input dimension of a sub-lattice, the quantity of the input can be measured and ranked. Furthermore, an increase in one variable never causes a decrease in another variable:

> Constraining the choice x to lie in a sublattice… says that increasing the value of some variables never prevents one from increasing others as well … and that decreasing some variables never prevents decreasing others. Milgrom and Roberts (1995) p. 182.

Variables that can be quantified (thus ranked) and chosen independently of one another form a sub-lattice. At the beginning of this chapter, I noted that tea, hot water and a cup are complements, but not strong complements because alternatives exist for each input variable. However, there is also no natural ordering relationship between a tea and coffee, hot water and other liquids, or a cup and a glass. Thus the input variables do not form a sub-lattice, and the function, although super-additive, is not supermodular.

[42] The test for supermodularity implies that the value function V cannot decline in any input variable. Thus any function with an interior maximum is not a supermodular function.

$$V(0,0) = V(1,0) = V(0,1) = 0 \quad \text{; and}$$

$$V(1,1) > 0 \quad .$$

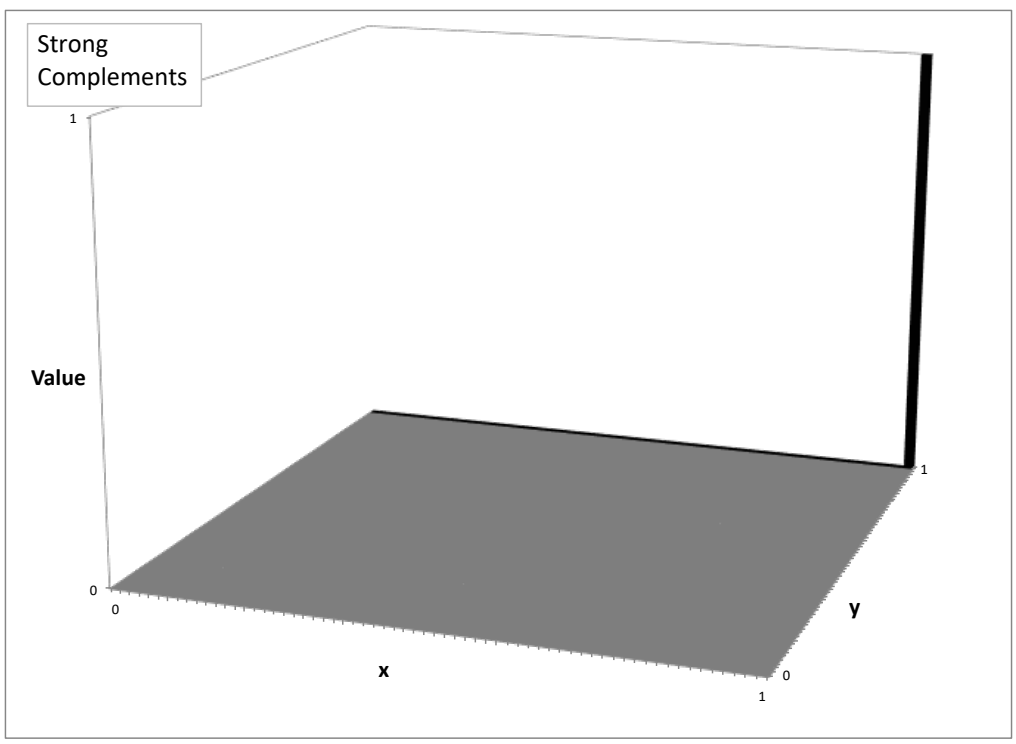
Substituting these values into equation (2) above we have the test:

$$V(1,1) - V(1,0) > V(0,1) - V(0,0)$$

All terms in the expression are zero except $V(1,1)$, which is greater than zero. Thus the test is satisfied and the strong two-way complements x and y are also supermodular complements.

Figure 5-1 presents a graph of a generic value function for strong two-way complements. The function has value if and only if both inputs are present, i.e., $x = 1$ and $y = 1$. Otherwise the system has no value. Obviously, this argument can be generalized to any number of complementary components.

Figure 5-1 Value Function for Strong Complements *x* and *y*



Weak Complements

In contrast, Figure 5-2 depicts a value function in which the input variables are weak complements. *Here each input, x and y, has separate, stand-alone value.* However,

the fact that they are complements means that the value realized when both are present is greater than the sum of the values of the separate parts:

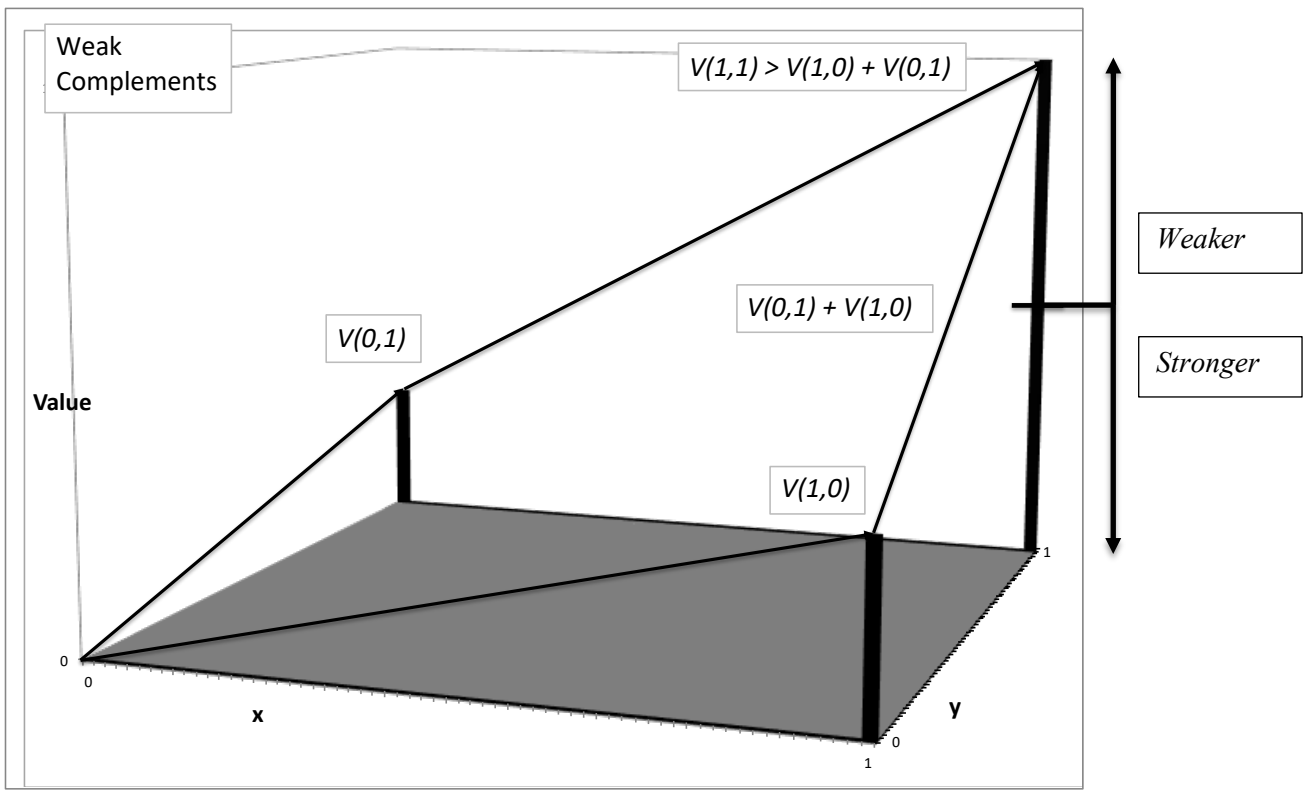
$$V(1,1) > V(1,0) + V(0,1) \quad .$$

After substituting for each term into Equation (2), noting that $V(0,0) = 0$, and rearranging terms, we obtain:

$$V(1,1) - V(1,0) > V(0,1) - V(0,0) \quad .$$

Again the test of increasing differences is satisfied. Weak complements are supermodular complements.

Figure 5-2 Value Function for Weak Supermodular Complements *x* and *y*



The Milgrom-Roberts definition of supermodular complementarity invites us to think of complementarities arrayed on a continuum, ranging from very weak to super-strong. In Figure 5-2 the tickmark on the right-hand column indicates the value of the sum of the separate values of the two inputs: $V(1,0) + V(0,1)$.

Now imagine moving the tickmark up or down, while keeping $V(1,1)$ the same. (The separate values of the inputs must increase or decrease correspondingly.) The incremental "system value" resulting from the complementarity of the two inputs is measured by the distance from the tickmark to the top of the column.

As the sum of the separate values increases, the tickmark moves up the column and the degree of complementarity between the two inputs becomes weaker. Conversely, as the tick mark moves down the column, the extra value created by the two inputs together increases, and the degree of complementarity becomes stronger.

Strong One-way Complements

Strong one-way complementarity exists when one complement is unique, while the other(s) are not. The owner of the unique component can destroy the value of the system by preventing others from using or accessing his input. In contrast, withdrawal of inputs by other members of the ecosystem will not destroy the value of the system. (If the ecosystem is numerous the withdrawal of any one member will not hurt the system very much.)

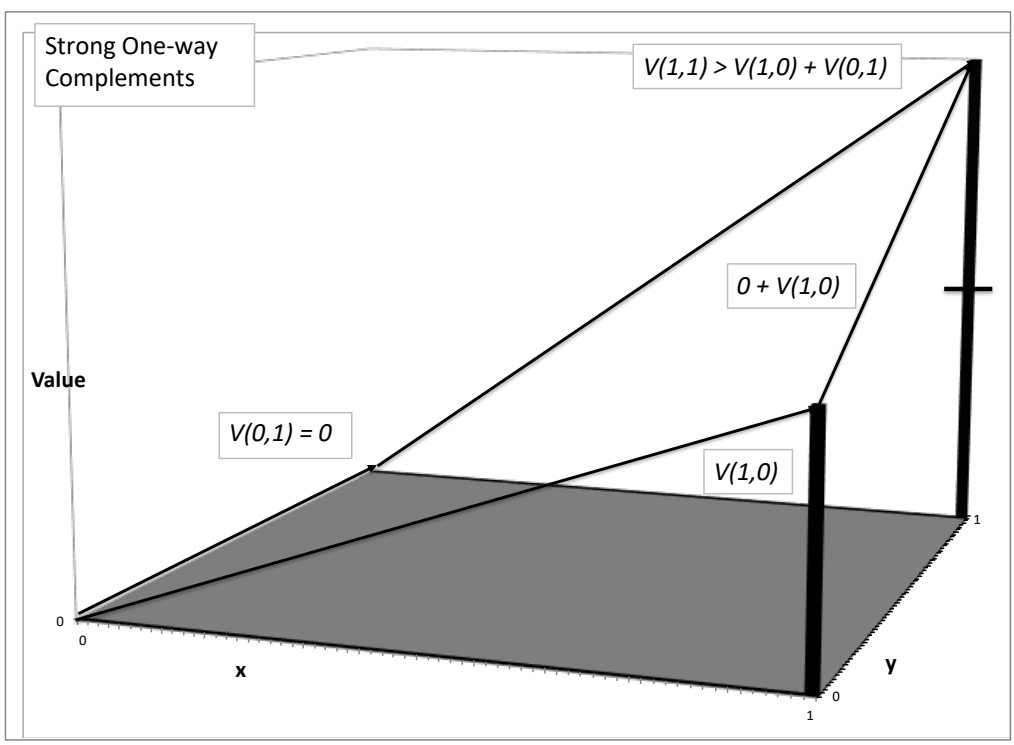
This form of complementarity is depicted in Figure 5-3. Here, I assume that y depends on x. Thus if x is present and y is not, the system has significant stand-alone value. In contrast, without x, y alone has no value.

Once again, we can substitute known values into the test of increasing differences, obtaining:

$$V(1,1) - V(1,0) \; > \; 0$$

Again the test is satisfied. Strong one-way complements are supermodular complements.

Figure 5-3 Value Function for Strong One-way Complements: y Depends on x



Strong one-way complementarity is typically found in platform systems. If the platform is unique and/or users have made "relationship specific" investments in using it, then the platform will be essential to its users, but no (single) user will be essential to the platform. This asymmetry of dependence generally allows the sponsor to claim a large share of the surplus created by the system as a whole.[43]

5.6 Strong Two-way Complements Should be Managed by a Single Firm

Two branches of organizational economics—transaction cost economics and property rights theory—define optimal firm boundaries on the basis of strong two-way complementarity. Although they are based on different assumptions, the theories arrive at the same conclusion: strong two-way complements, both assets and people, should ideally be placed within a single firm under unified governance. Inset Box 5-2 reviews these theories with the aim of highlighting their similarities.

The intuition behind the theories is immediately apparent from Figure 5-1. The owner of input x obtains no value unless the owner of y takes symmetric action. Input x may be a physical good, an asset, a skill, or a piece of knowledge, the result is the same. If the inputs are costly and moves are simultaneous, the agents face a classic Prisoners' Dilemma game. If the moves are sequential, the actors face a Trust game: by threatening to withold his input, the second mover can appropriate the entire reward. In either case, the equilibrium of the game is for both to do nothing.[44]

However, if x and y are owned and controlled by the same actor, he or she will have incentives to employ both inputs to obtain the joint surplus $V(1,1)$. Unified governance of resources resolves the prisoners' dilemma or the trust dilemma by placing all decisions under the control of a single agent. This result can be generalized to span any number of strong two-way complementary inputs.

Inset Box 5-2 Strong Complementarity and Economic Theories of the Firm

Transaction Cost Economics

In transaction costs economics, a market is an institution where bilateral exchanges (transactions) take place between autonomous agents. In contrast, firms are subject to unified governance: a single actor has the authority to make decisions for the entire enterprise.

The main problem with bilateral exchange is holdup, that is, the opportunistic withdrawal of a strongly complementary asset by a counterparty. Within a firm, holdup is controlled through the exercise of direct authority (fiat). It follows that, in a given technical system, a single firm should own (or otherwise control) all strong two-way complements.[45]

[43] Generally the platform sponsor must leave some of the surplus in the users' hands to provide incentives for future investments and follow-on effort. Empirically, the platform "cut" is often around 30% of the system's aggregate revenue.

[44] Given simultaneous moves, the equilibrium is a Nash equilibrium. Given sequential moves, it is a subgame perfect equilibrium. On trust games, see Berg, Dickhaut and McCabe (1995).

[45] Williamson (1985); Argyres and Zenger (2012).

Property Rights Theory

In property rights theory, a firm is viewed a coalition of suppliers, some of whom provide physical and intellectual capital (assets) and while others provide skills and effort (workers).[46]

Initially the actors form coalitions (firms) that include owners of assets and workers. There is no hierarchy or authority: all participants act in their own best interest. Once a coalition has formed, workers make relationship-specific investments in skills and other forms of human capital. These investments improve the productivity of the coalition, but are worthless outside it. Through these investments, *the assets and skills provided by different members become strong two-way complements*. Their joint value can only be realized if both are present.[47]

At the next stage, a specific product design is revealed.[48] Members of the coalition then bargain over how to split the surplus created by the assets and workers together. The ownership of assets affects the way the joint surplus is divided, because any owner can threaten to withdraw her asset, thus destroying the surplus.

Within this framework, it can be shown that all strong two-way complementary assets should be owned by a single agent in order to maximize the surplus created by the coalition.

The main problems arising in this context are under-investment in relationship-specific skills by workers and *ex ante* defensive investments by asset owners aimed at improving their *ex post* bargaining positions. Rather than maximizing the value of their joint output, workers and asset owners will instead invest to improve their outside options.

5.7 When are Ecosystems Sustainable?

If strong two-way complements should be controlled by a single agent or held within the boundaries of a single firm, what is the role of ecosystems? When is an ecosystem the best way to organize the tasks mandated by a complex technology? This section uses the theory of weak complements to begin to answer that question in a structured way.

Looking back at Figure 5-2, let x and y represent two weakly complementary inputs to a technical system. The distance from the tickmark to the top of the righthand column denotes the value of the complementary relationship. This is the maximum amount that a rational actor or actors would pay to coordinate the two resource owners. As the distance decreases, the value of using the two inputs together becomes less and

[46] Holmstrom and Roberts (1998), p. 77 say that "a firm is exactly a collection of assets under common ownership." However, the assets must be used in conjunction with suppliers of human capital (workers) who in turn make relationship-specific investments. Thus the productive entity includes both the assets and the workers, working as a voluntary coalition.

[47] Grossman and Hart (1986); Hart and Moore (1990); Hart (1995).

[48] The *ex post* revelation of the design prevents the parties from reaching an *ex ante* contract specifying their separate roles. The work that will be done is "non-contractible."

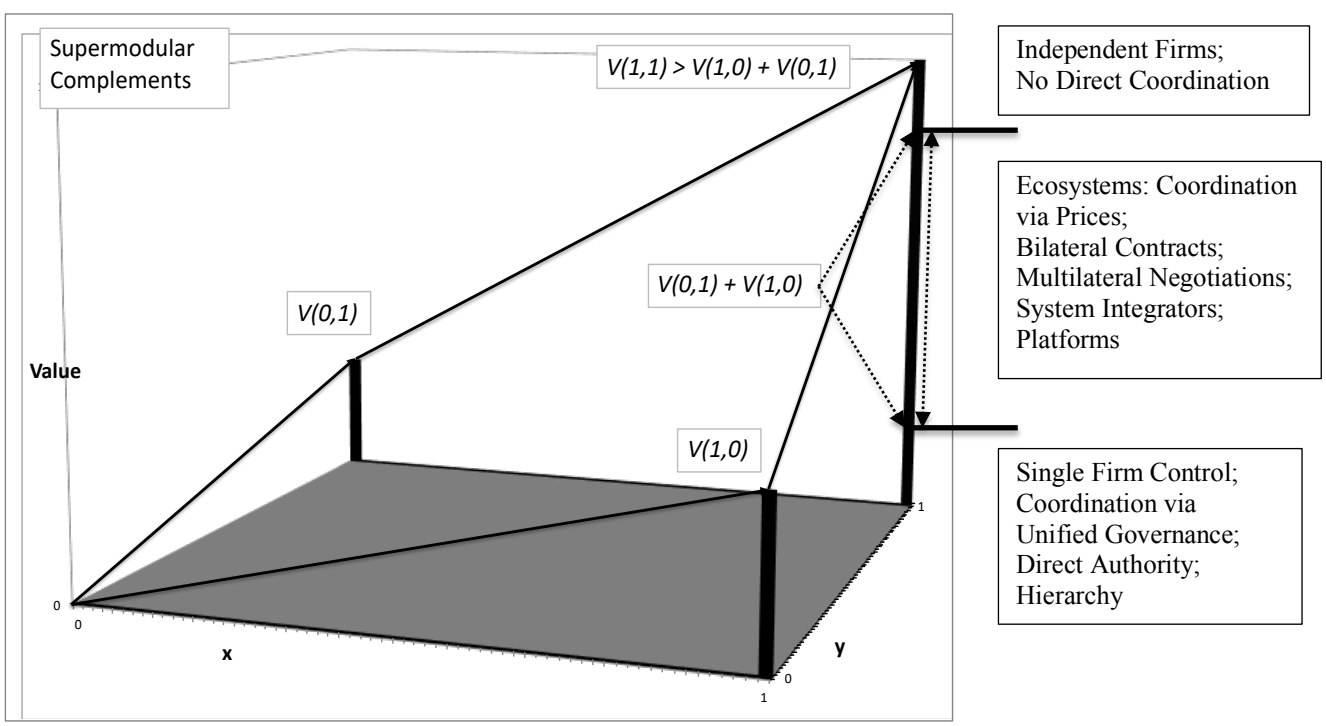
less, and the rewards to coordination decline. *If the distance is small, the owners of weak complements may rationally elect to ignore one another and act independently.*

Moving the tickmark in the other direction towards the base of the column increases the supermodular surplus and commensurately increases the amount X and Y (or a third party) should be willing spend on coordination. When the tickmark reaches the base of the column, x and y become strong complements. Neither is worth anything unless both are present. We are now in the world of transaction cost economics and property rights theory: to reduce the threat of holdup and the need for defensive investments, the two inputs should be controlled by single firm which can guarantee the presence of both and benefit from the value thus created.

In summary, near the base of the column, the value of coordination is very high: prudence in the face of the threat of holdup dictates placing all strong two-way complements within a single firm. Conversely, near the top of the column, the value of coordination is low. Resource owners can behave as if they were fully independent with little loss of value.

Ecosystems are best suited to the middle ground. (See Figure 5-4.) Here the benefits of consistent action are high enough so that fairly large investments in coordination are warranted. Prices, bilateral contracts, multilateral negotiations, systems integration, and platforms each have a role to play in promoting consistent behavior. However, there are also significant benefits to autonomy, which I will describe below.

Figure 5-4 When Are Ecosystems Sustainable?



In physics, centripetal forces pull objects towards a center; centrifugal forces drive objects away from the center. By analogy, in business ecosystems, some economic forces create incentives for organizations to combine, thus may be called centripetal forces. Other economic forces encourage organizations to remain separate, thus may be called centrifugal forces.[49]

A sustainable ecosystem (one that is not collapsing or exploding) requires centripetal and centrifugal forces to be roughly in balance. The complementarities that define the ecosystem cannot be too strong—otherwise it would collapse into a few large organizations. Nor can they be so weak that members can simply ignore one another.

In the next two sections, I describe the major centripetal and centrifugal forces at work in business ecosystems. Following that, I will derive necessary conditions for an ecosystem made up of autonomous firms and individuals to be sustainable over the long term.

5.8 Centripetal Forces in Ecosystems

Strong complementarity in the underlying technical system is the main source of centripetal forces in an ecosystem. Strong complementarity in turn may be caused by task interdependence, incomplete contracts and unobservable effort, or the need for long-lived, co-specialized investments. I discuss each of these antecedent causes below.

Task Interdependence

Tasks within a module by definition require many uncodified and contingent transfers of material, energy and information (see Chapter 2). As a result, a change in any task can have multiple effects on other tasks in the module. These effects in turn may require modification (adaptation) of the other tasks. Problem-solving within a module consists of tracing the cause-and-effect relationships among tasks and then modifying *specific* tasks and transfers to achieve a better outcome. Over time, the tasks and transfers become co-specialized through an ongoing process of mutual adaptation.

At the same time, the people performing tasks within a module will generate a pattern of organizational ties that works to solve frequently-arising problems (see Chapter 4). Assets will also be configured to support the most common work flows. Hence the assets and people tend to become co-specialized as well.[50]

Within a module, we have seen, there are no thin crossing points where transaction costs are low. It follows that all tasks, assets and people should be placed within a single transaction free zone. Placing the zone within a legally chartered

[49] Economic forces are factors in the larger economic system that create incentives for firms and individuals to adopt different strategies.

[50] This is equivalent to Hart and Moore's (1990) assumption that individuals make "relationship-specific investments" in their firms.

corporation brings other advantages including unified governance and the ability to use direct authority and hierarchy to make internal processes more efficient.

Centripetal forces favoring the co-specialization of assets and people in the task network are strongest when a specific technical recipe demands synchonization and tight scheduling of transfers. This is true of many of the technologies that undergird high-volume "mass" production. Such technologies include moving assembly lines as well as modern methods of producing steel, aluminum, chemicals, oil and semiconductor chips.[51]

In short, the technological theory of tasks and transfers presented in this volume leads to the same conclusions as transaction cost economics and property rights theory for much the same reasons. *Strong two-way complements* are most efficiently managed within a single firm.

Incomplete Contracts and Unobservable Effort

Incomplete contracts and unobservable effort are a second source of centripetal forces. For example, when a one-time transaction is based on quantity alone (*x* dollars per widget transferred), then agents have incentives to maximize their payoff by favoring quantity at the expense of quality. If both quality and quantity are easy to measure, then the principal can write a "complete contract" that sets the right price on each dimension. Agents can then maximize their payoffs under the contract, and the principal will be satisfied with both the quantity and quality of goods supplied. However, if one dimension is easy to measure and the other hard, then basing a contract on the measurable dimension alone will lead to a misallocation of effort.[52]

To address this problem, the principal can enter into a long-term relational contract with the agents, hiring them into an organization subject to hierarchy, close monitoring, and direct authority. Employees of the organization can be paid based on the principal's observation of their work and evaluation of their contributions to the enterprise.[53] Employers can also use the promise of long-term employment and promotions to elicit non-observable effort that is important to the company's long-term success.[54]

In general, when the underlying technology rests on non-contractible actions and unobservable effort, any incentive system that rewards short-term, contractible actions only will backfire. The imperfect solution to this problem is to replace short-term "spot" transactions with workers with longer-term "relational" contracts.[55] The relational

[51] These technologies are the focus of Chapters 8, 9, and 10 below.

[52] Kerr (1975); Holmstrom and Milgrom (1991); Baker, Gibbons and Murphy (2002).

[53] Alchian and Demsetz (1972).

[54] Jensen and Meckling (1976); Aoki (1988); Milgrom and Roberts (1994); Prendergast (1999).

[55] Baker, Gibbons, Murphy (2002). Long-term relational contracts using subjective measures of individual performance have their own problems, but may be better than short-term transactional

contracts can be set up in ways that de-emphasize short-term results and allow agents to share in the organization's long-run success. Within the organization, the employer may also use monitoring and internal sanctions to discourage free-riding.[56]

Long-lived Co-specialized Investments

The third source of centripetal force is the need (dictated by technology) to make co-specialized long-lived capital investments.[57] Margaret Blair describes a very pure example of such a case. In 1793, a group of promoters saw an opportunity to transport coal from the Lehigh Valley to Philadelphia.[58] The project required three separate capital investments: (1) a coal mine; (2) roads from the mine to the river; (3) a series of dams and walls in the river to prevent boats from running aground.

From the perspective of task interdependence, each investment was module quite separate from the other two. Once the assets were in place, transfers of coal from one stage to the next could easily be converted into transactions. Managers of each stage could independently deal with problems of incomplete contracts and unobservable effort within their modules.

However, *at the time the investments were needed*, there were no other suppliers or customers for the separate services. Each stage, if built, would be a unique and essential step in the process of getting coal to Philadelphia. Thus from the standpoint of the investors, the three parts of the project were strong two-way complements.

The organizers of the project initially attempted to finance the three stages as separate ventures, but could find no backers. After nearly thirty years of failure, all three parts of the enterprise were assigned to single, specially chartered corporation, and the corporation raised the funds it needed to proceed.[59]

5.9 Centrifugal Forces in Ecosystems

Dispersed knowledge, modularity and network effects are the main sources of centrifugal forces in an ecosystem. These technological factors reward autonomy and high-powered incentives and encourage organizations to remain independent or break apart.

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arrangements.

[56] Alchian and Demsetz (1972); Jensen and Meckling (1976).

[57] Williamson (1985) labeled this factor "asset specificity."

[58] Blair (2003).

[59] Ibid.

Dispersed Knowledge and Diverse Talent

In large technical systems, the knowledge needed to solve problems may be dispersed among many different individuals scattered around the globe. At the same time creative problem solvers are very diverse in their habits of thought and action. Thus an organization that supports one person's excellence will frustrate others.[60] This fact was famously captured by Bill Joy, a co-founder of Sun Microsystems:

> Most of the bright people don't work for you – no matter who you are. [So] you need a strategy that allows for innovation occurring elsewhere." [61]

Ten years later, Joy expanded on his original observation:

> It's better to create an *ecology* that gets all the world's smartest people toiling in your garden for your goals. If you rely solely on your own employees, you'll never solve all your customers' needs.[62]

For "ecology", today we may substitute the word "ecosystem." Joy clearly envisioned a farflung group of autonomous "smart people" pursuing independent goals while at the same time providing complementary knowledge and effort to a larger system.

In short, no single setting can attract all types of creative people with relevant knowledge and skills. Individuals working in different firms (or as independent contractors) within an ecosystem do not have a share a common organizational environment. Choosing to work for different firms, they can exercise autonomy in problem selection and a degree of control over their creations that is impossible to achieve within a large corporation. The ecosystem provides a "big tent" that can encompass many different types of contributors working in a complementary fashion, where the whole is greater than the sum of its parts.

Modularity

Modularization splits the task network into near-decomposable modules with few or no lateral dependencies. Then through standard interfaces, modularization creates numerous thin crossing points, where transaction costs are low. The thin crossing points offer points of entry for would-be entrants who produce and sell modules rather than whole systems. The entrants in turn provide users with more and better options and put downward pressure on prices. As a result, an ecosystem of autonomous firms making

[60] Baldwin (2012).

[61] Joy as quoted by Surowiecki (1997).

[62] Karlgaard, R. (2007) Emphasis in original.

specialized modules will survive in competition against integrated firms making whole systems.[63]

As the number of participants in an ecosystem increases, there is a greater need for transactions and transfers of information between ecosystem members. Thus modularity not only provides opportunities for external parties to supply modules to the system: it also increases the demand for transactions and communication platforms with their own ecosystems.

Modularity makes dispersed knowledge more valuable because the knowledge can be used to change modules piecemeal rather than the whole system at once. Conversely, the presence of dispersed knowledge increases incentives to modularize. Each factor reinforces the other.

Network Effects

Network effects are the third source of centrifugal forces in ecosystems. Network effects arise when additional users increase the number or value of options available to other users.[64] For example, more buyers may attract more sellers to a transaction platform and vice versa. Message senders prefer to reach more recipients and message recipients prefer more senders. If members attempt to substitute internal transactions and internal communication for platforms open to all, they reduce their ability to trade and restrict their access to information, thus losing options.

Network effects explain why strong *one-way* (as opposed to two-way) complementarity does not necessarily lead to the collapse of an ecosystem into one big firm. Even though all users of the platform depend on the platform, the different *independent* users value the options provided by *other independent* users.

The platform sponsor in turn is rewarded for recruiting and retaining complementary independent users. If the platform sponsor attempts to exploit the members dependence by claiming too much of their joint surplus, members will defect.[65] The platform system will fly apart via a cascade of defections, and the sponsor will be left with nothing.

The options associated with dispersed knowledge, modularity, and network effects are most valuable when the underlying technologies and/or user preferences are changing rapidly. In the fashion and entertainment industries, users have a preference for novelty. Similarly, in the computer and communication industries, the rapid pace of technical change puts a premium on modular products where components can be mixed and matched and systems upgraded piecemeal.[66] Not surprisingly, these industries are

[63] Baldwin (2012).

[64] Arthur (1989); Church and Gandal (1992; 1993).

[65] Zhu and Iansiti (2012).

[66] Langlois and Robertson (1992); Garud and Kumaraswamy (1993); Baldwin and Clark (2000).

dominated by modular projects and production networks, which can be reconfigured rapidly to create new products.

5.10 A Balance of Forces—Distributed Modular Complementarity

Business ecosystems made up of autonomous firms and individuals persist when there is a dynamic balance of centripetal and centrifugal forces. Firms can change their boundaries and can also choose whether to integrate or modularize their product designs and internal processes. Individuals can choose to work in large corporations or small enterprises. Buyers and sellers can choose whether to transact directly or via a platform marketplace. Information producers and consumers can choose to communicate directly or via a central platform hub.

These choices in total affect the size of organizations, the volume of transactions and the flow of communications within an ecosystem. But even though ecosystems are always changing, if centripetal and centrifugal forces are in balance, the "Martian's view" will not change very much. Some members of an ecosystem will prosper and grow while others split apart or disappear. But the number, size and average growth rate of organizations will be stable, and entries and exits will be approximately equal.

Simon himself was conscious of the existence of a dynamic equilibrium between markets and organizations in the economy: "What mechanism maintains the highly fluid equilibrium between [markets and organizations]?[67] My answer is that equilibrium is maintained by a balance of centripetal and centifugal forces.

I label this balance of forces within an ecosystem as *distributed modular complementarity* or DMC for short. Each word in the phrase is significant. "Distributed" indicates that governance of the system is not unified, but spread across many independent, self-interested agents. "Modular" indicates that the underlying technical system is made up of near-decomposable modules. The modules, by definition, have few lateral dependencies and are separated by thin crossing points. Finally, mutual "complementarity" holds the system together, making the whole worth more than the separate parts.

When DMC holds, complementary assets and activities need not be owned or controlled by a single firm or agent. Each member of the ecosystem can act independently and each will benefit from the actions of the others.

Distributed modular complementarity places mathematical constraints on supermodular value functions beyond the test of increasing differences. Not all supermodular value functions support consistent action by *independent* actors. For example, the value function for strong complements fails this test (see Figure 5-1).

Reasons for the rapid rate of change in semiconductor technology are discussed in Chapter 12 below.

[67] Simon (1991), p. 29.

It is possible to specify a set of necessary and sufficient conditions for distributed modular complementarity to exist as a dynamic equilibrium in the larger economy. Given rational, value-maximizing actors,[68] the requirements can be stated as follows:

- The actors' value functions are separable;
- The costs of integration outweigh the benefits;
- The actors' individual costs are aligned with the value each can capture.

The mathematical derivations of these conditions may be found in the Appendix to this chapter.

Intuitively, separable value functions arise when each resource has positive stand-alone value, as shown in Figure 5-2. Given separable value functions, users can ask and answer questions of the form: how much am I willing to pay to add this module or feature to my present system? For example, given my present computer system, how much is this new application worth to me? Or, given my present factory layout, how much is an upgraded machine worth to me? As a seller on a transaction platform, how much money will I receive from my next sale? As a buyer on the same platform, what is my expected consumer surplus from the good I plan to purchase? As an advertiser on a communication platform, what is another view worth to me? As a sender or receiver of messages, how much is the next completed message worth to me? Strong complements do not have separable value functions.

Benefits and costs of integration are caused by the centripetal and centrifugal forces described in the previous two sections. This condition defines what it means for those forces to be in balance.

Finally, even when complements have stand-alone value, they may be costly to create or bring into the ecosystem. If the cost of a complementary good is greater than its stand-alone value in the ecosystem, the resource owner will not have reason to make the investment. However, we shall see that cost misalignment can be solved via transactions within the ecosystem.

The equilibrium envisioned in this analysis is dynamic. It is a pattern of interaction that is sustained over many cycles of action, reward, and reaction by a group of rational actors. At the end of each cycle, the actors individually capture enough value to survive and their beliefs about the system are confirmed. As a result, the pattern of interaction continues in the next round.[69]

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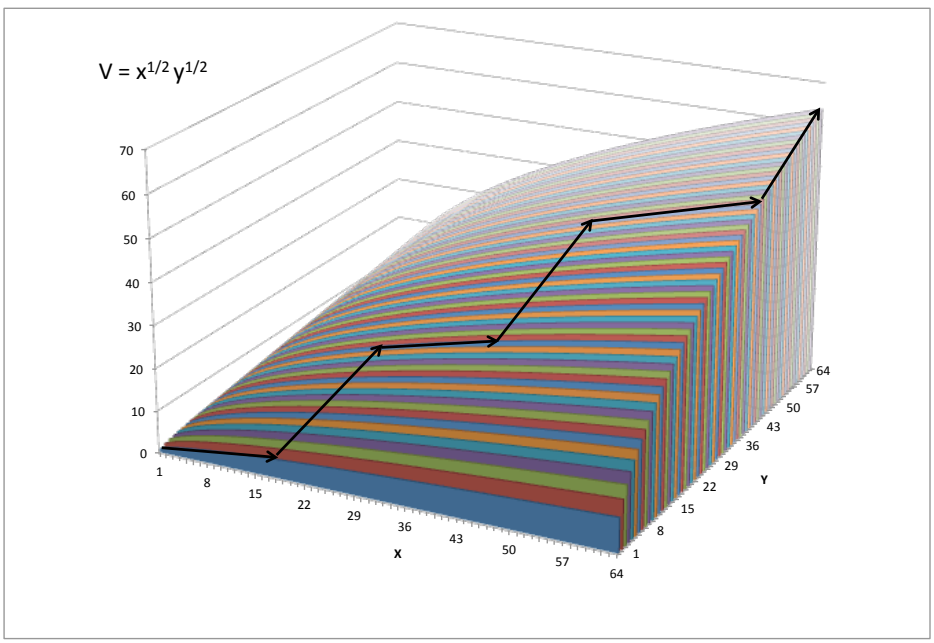
[68] Rational, value-maximizing actors make decisions in a logical and systematic way. They also agree on common (supermodular) value functions, which can be expressed in terms of a single numeraire (money). These assumptions, which are standard in the economics and management literatures, impose fairly strong consistency requirements on the preferences and beliefs of both firms and individuals.

[69] Masahiko Aoki (2001) calls these stable patterns of interaction "institutions." He analyzes them as repeated games with "self-confirming" beliefs. His is precisely the definition of equilibrium I am using.

Distributed modular complementarity may lead to a dynamic pattern in which the members of the ecosystem make a series of alternating, complementary investments. For example, actor *X* might find it worthwhile to invest some amount at *t=0*, with no expectation of a move by *Y*. However, by the property of increasing differences, *X*'s investment enhances the return on investment to *Y* encouraging her to invest. *After Y moves*, again by the property of increasing differences, the marginal returns to the next round of investment by *X* will increase, and she may invest on the second round.

Figure 5-5 depicts this alternating investment pattern. Here the value function $V(x, y)$ is separable, but displays diminishing marginal returns to each input. However, it has the property of increasing difference: Each time X invests, investment returns to y increase.[70] The same is true for Y's investments. *Thus investments in x make investments in y more valuable*, *and vice versa*. This pattern is indicated by the zigzag arrows along the surface of the graph.

Figure 5-5 Value Function with Decreasing Marginal Returns to Each Input but Supermodular Increasing Differences



In principle, if distributed modular complementarity holds as a dynamic equilibrium, a *group of autonomous firms*, coordinated by prices alone, can create a functional and evolving ecosystem. As indicated in Figure 5-5, resource owners can take action on different dimensions, specializing in the production of modules, the execution

[70] The function is a member of the Cobb-Douglas family of production functions. The second-order partial derivatives are negative: $\frac{\partial^2 V}{\partial x^2} < 0$; $\frac{\partial^2 V}{\partial y^2} < 0$. The crosspartial derivative is greater than zero: $\frac{\partial V}{\partial x \partial y} > 0$. This last condition is the Edgeworth-Pareto definition of complementarity. See Samuelson (1974).

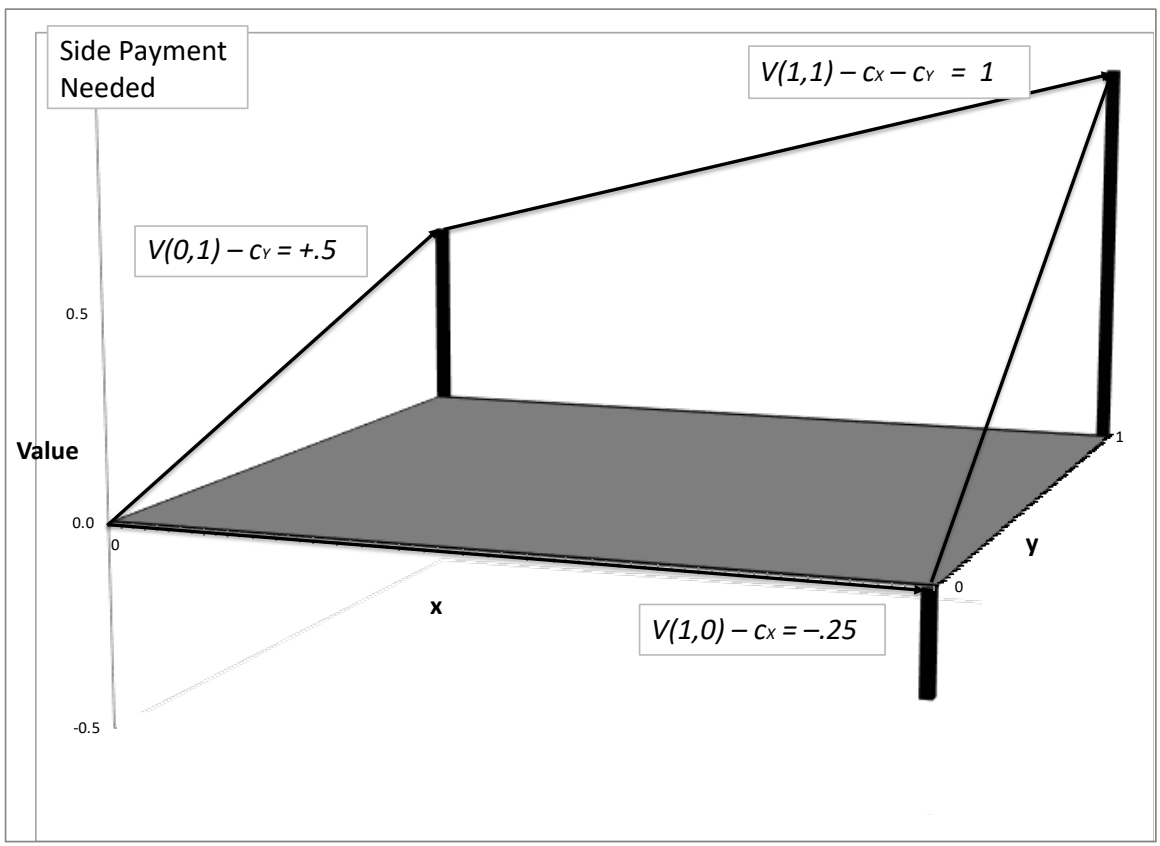
of transactions, and the sending and receiving of messages. Members of the group will obtain the benefits of complementarity while independently pursuing their own self-interest. Because their actions are supermodular complements, over time, each will benefit from investments by the others.

5.11 Coordination via Side Payments

However, actions coordinated by prices alone may not be sufficient to take advantage of the all complementarities offered by the underlying technology. To reach their full productive potential, members of ecosystems may need to use other means of coordination. Coordination beyond prices is especially necessary when costs are misaligned.

Figure 5-6 is an example of a DMC failure, caused by misaligned costs. Here the height of each column represents value captured *net of the actor's cost*. The figure represents a case where, if *X* acts alone, he loses money: his expected revenue minus cost is $ – .25 per unit of output. In contrast, if *Y* acts alone, she obtains a *profit* of $ .5 per unit. However, if both invest, their joint profits will be $ 1 for each system containing both x and y.

Figure 5-6 DMC Failure when Costs are Not Aligned: Optimally *X* will not Invest



Faced with an expected loss, *X will not invest*. Thus, the predicted outcome for two value maximizing agents (firms) is for *Y* to invest, while *X* does not. Yet if *X* does not invest, the joint payoff of $1, which is high enough to pay *X*'s out-of-pocket cost *and Y*'s opportunity cost, will not be realized. The cost of the DMC failure is the difference between the sum of the payoffs given independent action and the supermodular payoff to the value-maximizing joint strategy: $1 – $.5 = $.5 per system.

As a pair of agents, *X* and *Y* fail to satisfy the second and third conditions of distributed modular complementarity. The two firms acting separately obtain less than a single firm under unified governance because their separate costs are not aligned with the value each expects to capture. The price system alone cannot solve this market failure: market prices are already built into the stipulated outcomes. More direct methods of coordination are needed to make the ecosystem competitive with one big firm under unified governance.

The complementarity between inputs x and y creates a classic externality: by not investing, *X* imposes an indirect cost on *Y*. According to Ronald Coase, if *X*'s actions inflict a cost on *Y* and transaction costs are low, the two parties should be able to arrange a side payment from *Y* to *X* that makes both better off.[71] In other words, according to Coase, *Y* can propose a *bilateral contract* where *X* makes the requisite investment and *Y pays X* her cost plus a (small) profit. For example, *Y* can contract to purchase *X*'s output, combine it with her own products (with an opportunity cost of $ .50 per unit). and sell the combinated good for a profit of $ .25 per unit. *X* and *Y* together become members of an ecosystem coordinated by a bilateral contract in addition to prices.

Alternatively, a systems integrator, *Z*, may pay *X* enough to cover the cost of his investment and pay *Y* the going market price for her output. The system integrator can then combine the two products and sell the system for $ 1. The system integrator will also make a profit of $ .25 per unit. *X*, *Y* and *Z* together then become members of an ecosystem coordinated by multilateral negotiations and systems integration.

As Coase famously demonstrated, for any number of actors, given low enough transaction costs, there is always a system of side payments that can achieve a Pareto-efficient outcome. The side payments are transactions, thus subject to transaction costs. Nevertheless, if the underlying technical system is modular, then the side payments will take place at thin crossing points, where transaction costs are generally low.

Side Payments and the "Chicken-and-Egg" Problem in Platform-based Ecosystems

The "chicken-and-egg" problem associated with multi-sided platforms is theoretically identical to the DMC failure depicted in Figure 5-6. Rather than single firms or individuals, let *X* and *Y* represent distinct groups of individuals and/or organizations. To draw these different parties into a complementary relationship *on the platform*, the platform sponsor must arrange to pay *X*'s costs and increase *Y*'s profits. This requires a

[71] Coase (1960).

combination of subsidies to *X* and a superior value proposition (higher revenue or lower cost) for *Y*. The platform sponsor's profit comes from the incremental value created by bringing the complements x and y together.

The problem of getting *X*, *Y*, and other potential platform users "on board" is known as the "chicken-and-egg" problem.[72] It is classically solved via differential pricing. Different members of the ecosystem are charged or paid different amounts depending on their outside options and the value they bring to the table. However, for differential pricing to work, the platform sponsor must be able to divide ecosystem members into distinct classes ("sides"), each with predictably different preferences and behavior.

Side payments, system integration, and platform management of "sides" involve stronger forms of coordination than the "invisible hand" of the price system. To structure a bilateral contract, *X* and *Y* must communicate with one another and build a modicum of trust. In addition to direct communication, multilateral negotiations and systems integration generally require "orchestration" by firms or individuals with recognized standing in the community of actors.[73] Finally, to create a sustainable platform-based ecosystem, the platform sponsor must understand the needs of different types of users *and* convince them that their dependence on the platform will not be exploited after the fact.

These different ways of coordinating autonomous firms and individuals can be used to resolve failures of distributed modular complementarity caused by misaligned costs. Overall, they reduce the benefits of integration, and make it more likely that an ecosystem can be sustained as a dynamic equilibrium over the long term.

5.12 Conclusion: How Technology Shapes Organizations

In the last three decades of the 20th century, digital technology drove computation and communication costs down at a rapid pace. At the same time, engineers and managers in the computer industry used the principles of modularity to divide complex products and processes into quasi-independent modules. The rapid rate of technical change increased the value of modular systems that could be upgraded piecemeal.

Changing technology can create new opportunities and technical requirements, causing old ecosystems to collapse and new ones to emerge. Beginning around 1970, fast-changing digital information technology combined with a new understanding of modularity changed the dynamics of the greater computer industry. Clusters of specialized firms making modules replaced vertically integrated corporations.[74]

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[72] Rochet and Tirole (2003; 2006); Evans, Hagiu and Schmalensee (2008); Hagiu (2009); Seamans and Zhu (2013).

[73] Teece (2018).

[74] Grove (1996); Baldwin and Clark (2000) Ch. 14.

Thus if Simon's visitors from Mars had tracked the computer industry through the 1970s, 1980s and 1990s, they would have seen many large green circles shrink or disappear; and many smaller green circles appear. More firms means more interfirm transactions, thus there would also be more red connecting lines.

At the same time, beginning around 1995, the Martian observers would have noticed changes in the organization of trade and communication. While previously many transactions and messages occurred bilaterally or through local intermediaries, increasingly they passed through centralized digital hubs. Using digital technology, these hubs eliminated many of the inefficiencies in the older, decentralized systems of trade and communication. The new digital exchange platforms created new ecosystems of buyers and sellers of goods and senders and receivers of digital messages.

Ecosystems arise because of complementarities among autonomous firms and individuals. Each member adds to the value of the others. None can be excluded without diminishing the value of the rest.[75] The superadditive value of the whole does not come about purely by accident, however. The contributions of each member must conform to the requirements of the underlying technical recipes. To reach the degree of consistency required by their underlying technologies, members of ecosystems cannot rely on the price system alone, but must use prices in conjunction with bilateral contracts, multilateral negotiations and platforms.

The modern economic theory of complemenarity can shed light on why ecosystems exist and when they are sustainable over the long run. Complementarities may be strong or weak. Strong complements have no value (or greatly diminished value) unless they are used jointly. Weak complements have stand-alone value, but are worth more together than apart.

Each owner of a strong complement has the power to destroy the value of the whole by withdrawing his contribution. For this reason, transaction cost economics and property rights theory advise that strong complements should be placed within a single firm under unified governance. Within a single firm, owners and managers can use hierarchy and direct authority to ensure that no contributor holds up the rest.

Ecosystems represent a different approach to the problem of coordinating complementary resources. Members of ecosystems are autonomous firms and individuals whose actions are not subject to hierarchy or direct authority. As a form of organization, ecosystems are at an advantage in the "middle ground" where complementarities require consistent action and decision-making, but there are also benefits to autonomous search and independent experimentation.

[75] In any social group, including ecosystems, there may be parasites who do diminish the value of the whole. Parasites must be dealt with, but strictly speaking, they are not members of the group of complementary producers.

Firms in ecosystems are subject to economic forces pulling them in different directions. Centripetal forces reward integrated operations, tight control, and mergers. They are caused by task interdependency, non-contractible actions and unobservable effort, and the need to make long-lasting, co-specialized investments. In contrast, centrifugal forces encourage distributed operations, loose control, divestitures and breakups. They arise because of dispersed knowledge, technical modularity and network effects.

In a free capital market, firms are free to combine, split up, enter, and exit. As a result, an ecosystem of autonomous firms and individuals is sustainable if and only if its members experience a rough balance of centripetal and centrifugal forces.

I have labeled the state of balance "distributed modular complementarity" or DMC for short. Ecosystems characterized by DMC are sustainable as long-term, dynamic equilibria within the larger economy. Necessary conditions for DMC are: (1) members must face separable value functions so that each can be rewarded for taking unilateral action; (2) the costs of integration must outweigh the benefits, so that (most) firms do not have incentives to merge; and (3) each member's costs must be aligned with the value it can capture.

If some members costs are not aligned with value, they can be brought into alignment via side payments, that is, transactions within the ecosystem. Side payments can be structured as as bilateral contracts, multilateral negotiations, transactions with systems integrators, or asymmetric payments to different "sides" of a platform.

Ecosystems are the last organizational building block we need to build a theory of how technology shapes organizations. Ecosystems, we have seen, exist because of complementarities—things are more valuable when used together than apart.

But why and where do complementarities arise?

An important set of complementarities arise from human preferences and especially social affiliations. A person may simply *like* a particular arrangement of objects or another person. People are born into families and define themselves in terms of social groups, including classmates, clubs, colleagues, and coworkers.

The other major source of complementarity is technology. Technologies are far from being random sets of actions. A technical recipe specifies that certain inputs may be brought together in a particular way to change the material world to serve a human purpose. The inputs, the processes used to combine them, and the purpose are *mutually supportive complements*. The essence of developing a technology is recognizing the implicit complementarities among physical objects and controlled actions, and manipulating them in a way that creates value by serving the intended purpose.

However, at this time in the social sciences, we lack a general way of identifying and describing technologies that spans all products and processes. The modern theory of complementarity due to Topkis and Milgrom and Roberts is rooted in formal mathematics. The theory asserts that complementarities create value, but it does not say how. And every technology seemingly creates value in a different way.

The difficulty of characterizing technologies in a general way has not prevented humans from creating and using technologies they perceive will make them better off. Human technology is older and more universal than written languages *or* formal mathematics. Writing and mathematics greatly assisted the development of some technologies, but technology came first.

The next two chapters develop a set of *technological* building blocks. Here I will propose a means of representing technologies as systems of "functional components" linked by different complementary relationships. This method can be applied to any technology at whatever level of detail is convenient for the analyst. Moreover, each functional component can be "tracked back" to a technical recipe and to a particular set of tasks and transfers in the larger task network.

I will use this non-mathematical but structured way of representing technologies to interpret the evolutionary paths of three different early-stage ecosystems: early aircraft; high-speed machine tools; and container shipping. My aim in presenting these examples is to show how a functional view of technologies can be used to (1) identify opportunities to create value in a large technical system; and (2) predict which agents are most likely to capture the surplus created by the technical system as a whole.

Chapter Appendix

Necessary and Sufficient Conditions for Distributed Modular Complementarity (DMC)

This Appendix derives necessary and sufficient conditions for distributed modular complementarity (DMC) to hold as a dynamic equilibrium in an ecosystem.

To begin, I assume that there exists a technology for which the existing task network is near-decomposable. In other words, the network is modular except for a small number of between-module dependencies, which can be addressed via interfirm communication. The modules are complementary: each increases the value of the entire system. I also assume that all firms and individuals are self-interested and seek to maximize their own economic rewards.

Condition 1—Separable Values

The first necessary condition for DMC is that the joint value function $V(\cdot)$ is divisible into *N* separable value functions, one for each autonomous actor. For example, if there are two inputs, *x* and *y*, there must exist two value functions: $V_X(x, y_0)$ and $V_Y(x_0, y)$.

Each agent's own value is an increasing function of his (her) own input variable and the "starting value" of the other input. Each actor views the other input as an environmental parameter, not subject to his (her) control. *Separability requires that the value of separate, unilateral action is greater than zero and can be captured by the person taking the action.* In Figure 5-2, these values appear as $V(1,0)$ and $V(0,1)$.

For now, I ignore costs (they will be dealt with below).

As indicated, the individual value functions (excluding costs) are supermodular in the input variables.[76] The system-level value function $V(x, y)$ equals the sum of the value functions of the individual actors:

$$V_X(x, y) + V_Y(x, y) \equiv V(x, y) \quad . \qquad \text{(A-1)}$$

Sums of supermodular functions are supermodular, thus the joint value function satisfies Equation (2) in the text.[77]

[76] Thus the actors are engaged in a supermodular game. Formally, in a specific supermodular game, distributed modular complementarity holds when the equilibria of the game (including all costs) are also Pareto-efficient. In such cases, centralizing decision-making (collapsing the game) and distributing the joint output cannot make all players better off. On general supermodular games, see Topkis (1998) and Amir (2005).

[77] Milgrom and Roberts (1995).

Separable value functions for complementary goods arise when the system is assembled out of modular (or nearly modular) components, none of which is unique and essential.[78] Each module is a distinct object that can be mixed and matched with other objects at the users' option.[79] Separable value functions also arise in transactions where (by definition) the seller receives the price of the good and the buyer gets the benefit of the good itself. Finally, separable value functions arise in communication systems where the sender gets benefit from sending a message and the buyer gets a separate benefit from receiving the message.

Value functions that exhibit strong two-way complementarity do not have separable value functions. In these cases, joint value can be realized only if both inputs are present. There is no reward for unilateral action.

Condition 2—High Costs of Integration

A second necessary condition for DMC is that the total value obtained under distributed goverance is greater than the value obtained under unified governance. On balance, integration must be costly.

Define $V_U(x_U, y_U)$ as the total value of the system if a single actor chooses all input variables. The second necessary condition can be written as:

$$V_X(x, y) + V_Y(x, y) > V_U(x_U, y_U) \quad . \tag{A-2}$$

The benefits and costs of integration map exactly onto the centripetal and centrifugal forces discussed in the text. Centripetal forces reward integrated organizations. They are caused by dense, interdependent task networks, by incomplete contracts and unobservable effort, and by the need to make long-term co-specialized investments.

Centrifugal forces reward distributed governance. They are caused by dispersed knowledge, modularity, and network effects.

In a free capital market, value-seeking mergers, acquitions, and divestitures, as well as entry and exit can continue piecemeal until Equation (A-2) is close to an equality for most members. At that point, centripetal and centrifugal forces will be in rough balance within each organization and throughout the ecosystem.

[78] If a particular module is unique and essential, then it is a strong complement to all other modules, and its value is no longer separable from the rest of the system. A basic platform may be unique and essential to the user, but upgrades of the platform are neither unique nor essential unless the platform sponsor withdraws support for earlier models.

[79] Mixtures of input variables make up the sublattice on which the supermodular value function is defined. See Topkis (1998); Milgrom and Roberts (1990; 1995).

Transition Costs of Integration and Separation

If Equation (A-2) is satisfied and the the tasks are initially performed by separate firms, the ecosystem will survive as an equilibrium even though unified governance exists as a possibility. However, if the tasks are initially located within a single firm, then transition costs may outweigh the benefits of changing the organization's structure. It is costly to modularize integrated products and processes and to spin off business units as separate firms. Vertically integrated incumbent organizations are likely to resist making costly internal changes to obtain uncertain rewards.[80]

In these cases, a transition from a few large firms to an ecosystem form of organization will take time. The eventual ecosystem may eventually be made up of new entrants that are not wedded to legacy systems.

Symmetrically, if the inequality in Eq. (A-2) is reversed, and the tasks are initially performed by separate firms, there will be transition costs of combining the firms' operations into an integrated whole. The combinations will also take time and the large firms that eventually dominate the industry may not have been members of the original ecosystem.

Condition 3—Cost Alignment

The third necessary condition for DMC is that the actors' costs are aligned with the separate value each can capture.

Formally, the condition of cost alignment differs depending on whether we assume the actors move simultaneously or sequentially. I will look at the simultaneous case first, then the sequential case.

Simultaneous Investment

Let us assume the current state of the inputs from each actor is 0. Actor X contemplates an increase of magnitude x to his input; and Actor Y simultaneously contemplates an increase of magnitude y to her input. The costs incurred by X and Y are respectively c_x and c_y. For simplicity, I assume that the investments and their costs are discrete, i.e., the investors make all-or-nothing decisions.

The timing of events is as follows: at $t=0$, each contributor decides whether to invest or not, *based on his or her marginal returns*. At $t=1$, the impact of the investments on $V(x, y)$ are revealed. Because of their complementarity, the impact on total value if both act is higher than the sum of the expected marginal returns to each (see Figure 5-2):

[80] Henderson and Clark (1990); Tushman and Anderson (1986); Tripsas and Gavetti (2000); Jacobides (2005).

$$V_X(x,y) + V_Y(x,y) > V_X(x,0) + V_Y(0,y) \quad . \qquad \text{(A-3)}$$

If cost alignment holds, each member of the ecosystem will invest based on its marginal return minus its own cost, *assuming the other party does nothing*:

$$V_X(x,0) - c_x > 0 \quad ; \qquad \text{(A-4a)}$$

$$V_Y(0,y) - c_y > 0 \quad . \qquad \text{(A-4b)}$$

Equations (A-4a) and (A-4b) together with equations (A-1) and (A-2) are sufficient conditions for distributed modular complementarity to hold assuming simultaneous investments. Each contributor will invest on his or her own account, *and then receive a positive surprise due to the other's investment*. The investors do not have to know the others' identity nor even of their existence. It is as if "the environment" provides an unexpected bonus after the fact.

However, under these circumstances, the positive aftereffects are *surprises*. Members of the ecosystem will not include the positive impact of other members' investments when choosing their own.

Also some member's investments may clear the cost hurdle, while others do not. Those whose calculated returns fall short of *their own cost* will not invest, even though their investments might be profitable after the fact. For example, if

$$V_Y(x,y) > c_y > V_Y(0,y) \qquad \text{(A-5)}$$

then *Y* will not invest *ex ante*, even though after the fact, *the investment would have been profitable*. Thus the ecosystem as a whole displays *underinvestment*.

If Eq. (A-5) holds for all members of the ecosystem, then none will invest. The ecosystem as a whole will then fail to achieve distributed modular complementarity (DMC). If we revise Figure 5-2 to show *value captured net of cost*, the figure would look like Figure 5-1. In effect, the members' inputs become strong two-way complements if separate rewards are less than individual costs for everyone.

Sequential Investment

The problem of underinvestment can be mitigated by staging the contributors' investments. Assume that investments proceed in rounds. In the first round, *X*'s investment clears hurdle (A-4a) but equation (A-5) holds for *Y*'s investment. *X* invests, but *Y* does not.

However, as Eq. (A-5) shows, *after X invests*, the rewards to *Y* will increase because of the property of increasing differences. *Y*'s investment now clears his cost hurdle. (This doesn't have to happen, but given increasing differences, it can.)

Sufficient conditions for *sequential* DMC are thus:

$$V_X(x,0) > c_x \;\; ; \;\; \text{and} \qquad \text{(A-4a)}$$

$$V_Y(x,y) > \; c_y > \; V_Y(0,y) \quad . \qquad \text{(A-5)}$$

Eq. (A-5) is obviously a looser constraint than Eq. (A-4b). *Thus complementary investments that do not take place simultaneously may occur sequentially.*

Necessary and Sufficient

The conditions leading to distributed modular complementarity may be summarized as follows:

- The actors' value functions are separable (Eq. A-1);
- The costs of integration outweigh the benefits (Eq. A-2); and
- The actors' individual costs are aligned with the value each can capture (Eqs. A-4 and A-5).

All three conditions are necessary.

First, if the value functions are not separable then there is no reason for any firm or individual to take unilateral action. The complementary value of the system then cannot be realized by separate firms. (Note that separable value functions imply that the underlying technical system is nearly-modular. Dense task interdependency creates strong two-way complementarity, which in turn implies that values are not separable.)

Second, even if the value functions are separable, if the benefits of integration exceed the costs, members of the ecosystem have incentives to combine into larger enterprises subject to unified governance. Mergers will continue until a balance of forces is achieved.

Finally, if the first two conditions hold, but costs are not aligned with value captured, then some members of the ecosystem will have no incentive to act, and the system as a whole will fail to realize the full value of the intrinsic complementarities.

The conditions are sufficient if firms and individuals are rational and motivated by economic value alone. If members of the ecosystem are not rational, they will not make decisions in a logical or systematic way. If they are motivated by considerations other than economic value, they may rationally decide not to maximize their economic rewards. Either way, given irrational or non-value-maximizing actors, the three conditions alone will not guarantee that an ecosystem will be a sustainable long-term equilibrium.

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