Ecosystems and Open Innovation

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The Forces of Ecosystem Evolution

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Marcus Holgersson[1], Carliss Y. Baldwin[2], Henry Chesbrough[3,4], and Marcel L. A. M. Bogers[3,5,6]

SUMMARY

Ecosystems are the result of a delicate balance between centripetal forces that push economic activities toward integration, and centrifugal forces that pull economic activities out onto the market. Ecosystems evolve when these forces change. For example, technological complementarities—the main source of centripetal force—are dynamic and may be commoditized, generalized, or standardized over time. Management and coordination also change: for example, open innovation practices enable firms to move innovation activities from the in-house R&D lab out into the ecosystem. This article discusses how such dynamics in technologies and management lead to ecosystem evolution.

KEYWORDS: business ecosystem, business model, complementarity, design, ecosystem emergence, innovation ecosystem, modularity, open innovation, platform, standard

This article introduces the forces and related dynamics of ecosystem evolution. An 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."[1] Ecosystems as organizational forms—an alternative to firms and markets—are enabled by the design of modular technological systems.[2] System modularization reduces the need for tight control

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[1]Chalmers University of Technology, Gothenburg, Sweden
[2]Harvard Business School, Boston, MA, USA
[3]University of California, Berkeley, Berkeley, CA, USA
[4]Luiss Guido Carli University, Rome, Italy
[5]Eindhoven University of Technology, Eindhoven, The Netherlands
[6]University of Copenhagen, Copenhagen, Denmark

and coordination, and it simplifies the coordination of innovation across firm boundaries.

Ecosystems first came to the attention of managers and management scholars in the 1990s and early 2000s. Beginning with the IBM PC in 1981, the success and rapid pace of innovation in the computer industry showcased the power of modular technical systems in combination with managed business ecosystems.[3] The value of this business model has been validated by a number of hugely successful firms who have prospered from participating in and controlling ecosystems. Today an increasing number of firms are looking to grow the ecosystems they are involved in, especially as technologies from the computer industry are diffusing through the rest of the economy.[4]

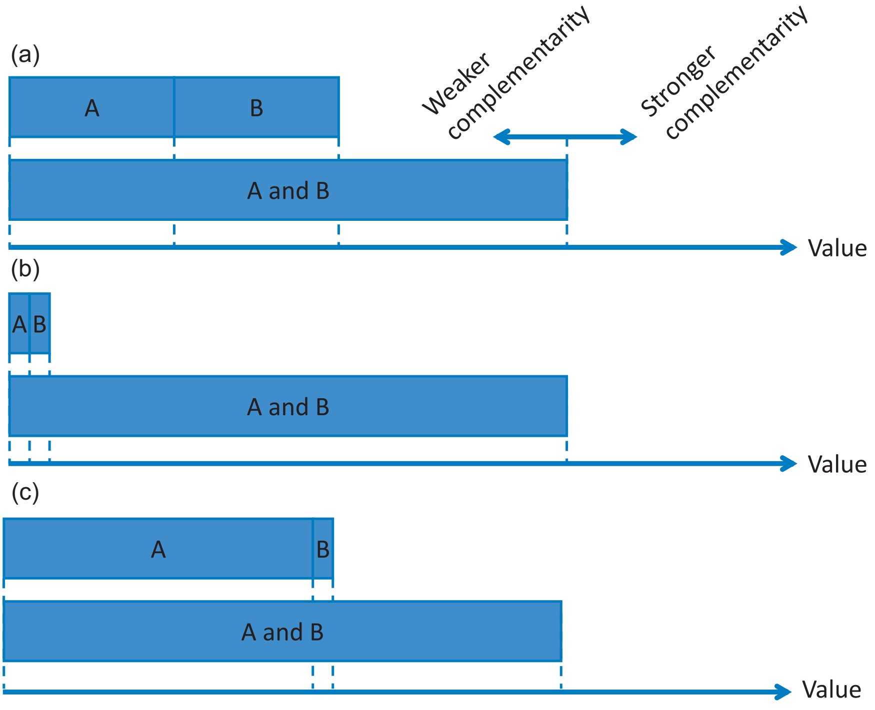
However, ecosystems are not a one-size-fits-all solution that can be easily designed and set up by any group of firms. On the contrary, sustainable ecosystems are the result of a delicate balance between, on the one hand, forces that push economic activities toward integration into a single corporation and, on the other hand, forces that pull economic activities out onto the market. We call these forces centripetal and centrifugal forces, respectively, following recent work by one of the authors.[5] In explaining how these forces work, we draw specifically on the economic theory of complementarities between different components of a technical system.[6]

The forces affecting ecosystem structure change over time. Due to these dynamics, ecosystems are seldom stable but often in a state of flux.[7] With this article, we want to explain how centripetal and centrifugal forces shape ecosystem structure and influence ecosystem evolution. Both *technological innovations* and *new styles of management* may shift the balance between centripetal and centrifugal forces in all or part of an ecosystem.

First, technological innovations enable and are enabled by ecosystems. New technologies may affect a single component in a larger technical system, causing the component to become commoditized or generalized. They may affect a group of components, as happens when critical interfaces become standardized. Or they may affect the whole system, causing the ecosystem to expand, contract, or, in some cases, collapse. On top of that, a modularized system in itself reduces the cost of experimentation and customization, thus increasing the value of new technologies.[8] Modularization also allows multiple actors with different capabilities to contribute innovations that can then be combined to create new value propositions.[9]

Second, new management techniques affect the costs of coordination in ecosystems.[10] For example, novel ways of contracting may reduce the need for control through ownership and open up possibilities to organize activities in ecosystems rather than within firms.[11] Furthermore, new ways of managing *within* a firm can increase the level of collaboration *across organization boundaries*.[12] In this article, we draw from our understanding of organizing and managing open innovation[13] to explain how managerial developments lead to ecosystem evolution.

FIGURE 1. Standalone and joint values of two complements, A and B.
(a) Weak complementarity. (b) Strong two-way complementarity. (c) Strong one-way complementarity.



In the remainder of this article we introduce the sources of centripetal and centrifugal forces, respectively. We explain how ecosystem evolution is caused by the dynamics of technology as well as by new developments in management and coordination. We then describe several instances where technical and managerial dynamics were interdependent and both contributed to ecosystem evolution. We end by discussing how managers can plan for and/or guide ecosystem evolution. Throughout, we illustrate our argument with well-documented empirical examples, including cases presented in the other articles in this Special Section of *California Management Review*, all of which were initially presented at the seventh annual World Open Innovation Conference in December 2020.

Centripetal Forces, Centrifugal Forces, and Complementarities

Centripetal forces push firms together toward integration. Complementarity is the main source of centripetal forces. *Weak complements* are goods that are valuable on their own, but more valuable together than the sum of their separate values (see Figure 1a). A map and a compass are weak complements. Both are useful on their own, but provide much more powerful navigation when used jointly. *Strong complements* are objects that are (almost) useless on their own but valuable together (see Figure 1b). Examples are a lock and its specific key and the left and right shoes of a pair. Complementarity is not necessarily symmetric, however: one complement may depend more on the presence of a second complement than vice versa. For example, a software application must typically run on an operating system, but the operating system does not require any specific application to function. In such a case, there is strong *one-way* complementarity (see Figure 1c). (Some software applications can run on multiple operating systems, which weakens the one-way dependency.)

The stronger the complementarity, the larger the need for coordination and the greater the centripetal force. At the extreme, centripetal forces push firms together to form a single corporation. For example, a lock and a key must match perfectly, and therefore they need to follow the same template.[14] The design of the lock and the design of the key are interdependent, and achieving the right match requires coordination. Centripetal forces are also generated by incomplete contracting and unobservable effort.[15] When (complete) contracting between firms is costly and effort is difficult to observe across organizational boundaries, firms are pushed toward integration.[16] Finally, when long-lived co-specialized investments are needed, firms have incentives to combine or form tight relationships to avoid holdup and haggling over which firm will move first. For example, large, co-specialized investments needed in battery manufacturing and electric vehicle technology, respectively, were undertaken by firms in close partnerships. Tesla partnered with battery manufacturer Panasonic, and battery manufacturing startup Northvolt partnered with BMW, Scania, Volkswagen, and others.[17] In the latter case, the partnership involved both equity investments (co-ownership) and tens of billions (US$) worth of long-term contracts to purchase Northvolt's future supply of batteries.[18]

Centrifugal forces pull units apart by encouraging loose affiliations and arm's length transactions. In the extreme, prices alone may suffice to provide all the coordination that is needed to maximize joint value. As noted by Friedrich Hayek:

> 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.[19]

But even when centrifugal forces are strong, the price mechanism is not necessarily sufficient for coordination as we will come back to below.

There are several sources of centrifugal forces. One important source is dispersed knowledge. When the knowledge needed for creating large technological systems is distributed across several different individuals, it is difficult and costly to create an organization that attracts all the necessary expertise.[20] Moreover, distributed (control of) knowledge across multiple actors translates into stronger entrepreneurial incentives.[21] Another source of centrifugal forces is when users value options provided by other users—that is, when there are network effects. In such situations, integration will result in lost opportunities and revenue. For example, a manufacturer could integrate forward into retail stores and force customers to purchase the in-house products. But both the manufacturer and its customers may be better served by independent retailers offering multiple brands. Finally, modularization is also a major source of centrifugal forces. Modularization relaxes task interdependencies, which lowers transaction costs at module boundaries. Container shipping provides a good example of how powerful modularization can be, with profound impact on global trade and the world economy. The introduction of modern containers lowered transportation costs in general, and the standardized module design of containers meant that the need for coordination decreased significantly. This opened up a global network of transportation technologies (ships, trains, trucks, etc.) and transportation companies who could collaborate in transporting containers from one part of the world to another, with relatively limited coordination.[22]

Ecosystems arise when there is a balance between centripetal and centrifugal forces, that is, when there are benefits of coordination as well as benefits of autonomy.[23] Due to the need for coordination, in an ecosystem, market prices alone do not lead to optimal outcomes: other means of coordination (or "governance") are needed.[24] Several coordination mechanisms are available, including bilateral contracts, multilateral negotiations and standards, systems integration, and platforms.[25]

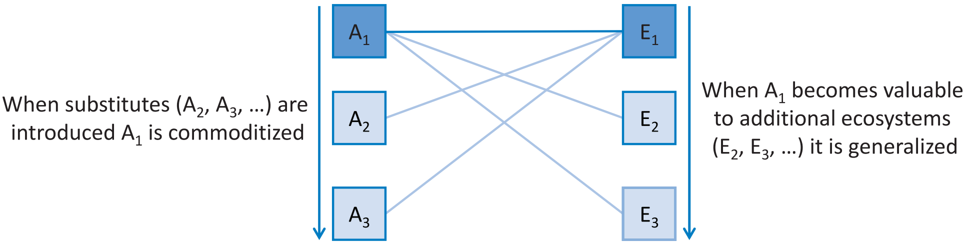
Ecosystem evolution can therefore be understood as resulting from a changing balance between centripetal and centrifugal forces. In the following, we will focus, first, on how technological innovations and, second, on how new management tools impact ecosystem evolution.

The Dynamics of Technological Complementarities

In a world with a high rate of technical change, the countervailing centripetal and centrifugal forces will be changing, and with them local incentives to integrate or split apart. While a rapid pace of innovation in general favors modularized technological systems, technological innovation will continue to change the nature of complementarities within such systems. Over time, some complements may be *commoditized* while others are *generalized*, and linkages among some components may be *standardized* through the use of common interfaces. These changes in relationships and status of components will change the balance of forces locally, causing the ecosystem to evolve.

As substitutes are introduced for a given component, the incremental value of any one to the system decreases.[26] The complementarity becomes weaker. This phenomenon is generally called *commoditization*.[27] Commoditization is caused by the entrance of substitute (competing) complements.[28] As substitutes increase, the incremental value of any particular one declines. While still being complements, a class of inputs may reach the point where only price and convenience matter. Owners of complements typically strive to avoid commoditization as it devalues their products.

FIGURE 2. Commoditization and generalization of component A_1 in ecosystem E_1.



A commoditized complement loses its uniqueness[29] and becomes generic.[30] Firms can then "draw on it with little concern for governance structure or risks of misappropriation."[31] According to Jacobides et al.,[32] generic complementarities are not considered part of an ecosystem, "because they do not give the parties any vested interest to align and act as a group." Hence, for purposes of strategy, one can ignore commodities for which the only coordination needed is through the price system. Indeed, firms that continue to make generic complements in-house may find themselves in an "integrality trap," in which the internally provided complement no longer competes effectively and efficiently against market-based complements.[33] The degree of complementarity is so weak (their incremental contribution is so low) that the rule of thumb becomes "buy the version for which the all-in price is lowest." Thus, the process of commoditization may lead to ecosystem contraction to the benefit of markets.

The *generalization* of complements is the process of complements becoming applicable "more broadly in many environmental settings."[34] Generalization is an example of the modular operator *porting*. Porting takes a module developed for one system and makes it work in other systems.[35] Thus, the complement may remain equally valuable in one ecosystem while becoming increasingly valuable in other ecosystems. Generalization therefore leads to overlapping or even converging ecosystems. Generalization can happen to any complement, or (in a platform-based ecosystem) to the platform itself. For example, Li-ion batteries have been important complements of portable electronic devices, such as laptops and smartphones, for decades. More recently, they also became key components in electric vehicles.

Both commoditization and generalization involve the process of shifting from co-specialized to specialized assets,[36] but the direction of dependence is different. With commoditization, the components are specialized to a particular technical system and related ecosystem. As the number of substitutes grows, they compete to occupy the same "niche" (see Figure 2). As the system designers' alternatives increase, the value of any one option declines. With generalization, the components are not specialized to a given system, but can work in different technical systems and multiple ecosystems. If the component is unique, that is, there is no substitute, then as it is deployed in different settings (ecosystems), the number of "niches" grows. Because the component is unique, system designers have no alternative but to use it to perform its function. As the number of niches grows when the component is generalized, the value of the component will consequently increase.[37]

The dynamics of commoditization and generalization can run in parallel. For example, Nvidia was for decades dominant in producing graphics processing units (GPUs) for the video gaming industry. In that niche, it faced increasing competition from Intel, AMD, and Apple. But in parallel to the increasing competition in its first and main market, Nvidia found new and valuable uses for its GPUs. These new use cases included media streaming, video editing, high-performance computing, artificial intelligence (AI), and self-driving cars, and over a 3-year period (January 2019 to January 2022), Nvidia's market capitalization increased by a factor of 7.5, despite the increasing competition in video gaming.[38]

A related type of dynamic, which may include elements of both commoditization and generalization, is *standardization*. Standards provide design rules that "cause the modules of a complex technical system to function together *as a system*."[39] The creation of a standard is, in fact, a special case of the modular operator *inversion*.[40] Sometimes, a common problem occurs in different parts of a technical system, which may lead to several alternative (redundant) solutions being implemented in the system. Inversion means that the designer of a system identifies the different implemented solutions (e.g., components, routines) to a common problem and separates one solution into a module with a standard interface that is then accessible by the other parts of the system that need to solve the problem. Consider, for example, the "Print" function in software applications. Originally, almost every application on a PC implemented its own print subroutine. Microsoft Office standardized printing across the following three applications—word processing (Word), spreadsheets (Excel), and presentations (PowerPoint). Later, much of the print function was relegated to the computer's operating system, and there was no longer a need to develop specific print routines for individual applications.[41]

Oftentimes standardization focuses primarily on the interface to enable interoperability of multiple alternative components. For example, the standardized design of the shipping container lets different parts of the transportation system function together without much concern for what is inside the container or what the next mode of transport will be, and the standardization of telecommunications enables users across different networks to seamlessly connect to each other without worrying about the compatibility of the counterparts' equipment.

Standardization weakens some complementarities while strengthening others. When interfaces are standardized, previously independent components (e.g., phone calls on different networks) become complements. However, when access to an interface is opened up to multiple competing actors (becoming an "open" or "industry standard"), strong complementarities may become weaker, and the dependent complements may be commoditized.[42]

Conversely, if specific modules or components are formally or informally selected to be a part of a standard, complementarities among them grow stronger. Some components of the standard may be both essential (necessary) to the standard[43] and owned by a profit-seeking firm. When the standard is implemented, the owner of the essential component may demand significant licensing fees *ex post*. For example, Rambus Inc. developed and patented dynamic random-access memory (DRAM) standards technologies for memory chips. Beginning in

2000, the company became embroiled in numerous patent lawsuits against large memory manufacturers, seeking higher licensing fees and claiming damages. Litigation (including antitrust suits by the FTC[44] and the European Commission[45]) continued for over a decade. The basic claim against Rambus was that the company engaged in a "patent ambush," that is, it withheld critical information about a patent while participating in the development and setting of a standard. Today, most standard organizations require members to disclose and grant licenses to patents they hold (or have applied for) that are relevant to the standard under development, in order to mitigate the opportunism that could otherwise follow from including unique and proprietary technological components in standards. This leads into the issue of how developments in management and coordination affect ecosystems as organizational forms.

The Dynamics of Management and Coordination

Ecosystem evolution is caused not only by dynamics of complementarities, but also by dynamics of management theory and practice in firms, markets, and hybrid organizations such as alliances and consortia. The allocation of activities to markets and hierarchies and where to place the boundaries of a firm have been central themes in management and economics research for almost a century.[46] James F. Moore was one of the first researchers to call attention to ecosystems as an emerging form of organization[47] and to locate their origins in the computer industry:

> And over the course of thirty-five years of making and managing these [ecosystem] relationships, the executives of [the computer] sector have refined first a practice and then a theory of business ecosystems, and have gone to great lengths as well to share it with their clients and allies in other economic sectors. Thus, while business ecosystems have always been with us, the managed business ecosystem organizational form grew up in the paradigmatic innovation industry of the late 20th century: the high technology computer business.[48]

Moore's research tells us that management practice—in addition to modular technologies—was central to the success of ecosystems in the computer industry. And while digital technologies paved the way for modular design of systems technologies in this development, they also lowered coordination costs, including costs for search and monitoring, which further improved the usefulness of ecosystems for organizing economic activity.[49]

Over the last decades, research and developments in management theory and practice have further strengthened the case for ecosystems as alternatives to firms and markets by providing a better understanding of how to manage and coordinate activities in relations across firm boundaries. For example, Dyer and Singh's seminal work[50] on the relational view of competitive advantage outlines several determinants of relational rents, including relation-specific assets, knowledge-sharing routines, complementary resources and capabilities, and effective governance. In line with this, the relational view identifies subprocesses by which firms can facilitate relational rents—for example, safeguarding against opportunism, incentive alignment, and identification of complementarities. In other words, firms can learn how to create and capture more value in ecosystems, and this changes the balance between centripetal and centrifugal forces.

A major management development related to coordination across firm boundaries is the emergence and refinement of open innovation. Open innovation is "a distributed innovation process based on purposively managed knowledge flows across organizational boundaries, using pecuniary and non-pecuniary mechanisms in line with the organization's business model."[51] Research on open innovation has, among other things, taught us that while openness indeed improves firms' innovativeness and competitiveness when properly managed,[52] too much openness may eventually hamper performance.[53] This resonates well—albeit on a different level of analysis—with the view of ecosystems arising from a balance between centripetal and centrifugal forces. As firms have found ways to better manage open innovation that balance has also changed to the benefit of ecosystems.

As value creation takes place across actors in ecosystems, firms need to find new business models to enable distributed value creation while capturing sufficient value. Hence, value creation and value capture in ecosystems lead into a specific coordination challenge, namely, that of balancing cooperation and competition.[54] Part of the solution resides in how firms manage the control of and access to technologies.[55] While the relational view primarily makes the case for informal governance,[56] much open innovation research has found that formal governance with intellectual property (IP) rights and license agreements is conducive to the success of open innovation.[57] Thus, firms have learned to use formal governance to control and differentiate the access to technologies, not to strictly protect it from outsiders.[58] Interestingly, here is where research on open innovation and research on modularity coincide, as modular architectures are used to separate between open and closed components in order to enable openness without leaking closed technologies.[59]

New entrants may need to "buy into" these formal mechanisms of open innovation governance when entering an ecosystem. For example, when Google developed its Android operating system for smartphones, Google acquired Motorola to get hold of its telecommunications patents. By that time, technologies and collaborations in the mobile telecommunications ecosystem were governed by patents and associated (cross-)licensing agreements, and infringement disputes were common. Google needed a relevant patent portfolio to play on an equal footing with everybody else. The purchase price of US$12.5 billion made it clear just how much it was worth for Google to buy into the ecosystem's established mode of coordination.[60]

In line with the definition of open innovation, research has investigated a multitude of mechanisms for managing knowledge flows across firm boundaries, from firm- and technology-level mechanisms—as briefly introduced earlier—to individual- and idea-level mechanisms both within and outside firm boundaries.

These are also highly relevant for the management in and of ecosystems. For example, research has shown that open innovation requires a change in in-house research and development (R&D) professionals' identities,[61] that firms can better access and influence external communities by assigning individuals to join them,[62] and that firms can motivate external contributors by providing the right type of attention.[63] We do not intend to review and synthesize all these contributions here, but we want to highlight the relevance of these management developments for the balance between centripetal and centrifugal forces.

The articles in this special section of *California Management Review* provide additional cues on how to coordinate innovation activities across firm boundaries in ecosystems. For example, the analysis of IBM's AI technology Watson by Yang et al.[64] shows the challenge of introducing broad, powerful general purpose technologies (GPTs) and the need to properly match the technology with open innovation and ecosystem strategy. The power of Watson was showcased in the televised game show Jeopardy. It was a highly visible application of AI, where IBM had a clear technical lead. But when IBM later chose to deploy its AI in the healthcare industry, more specifically to diagnose cancer in radiology studies, it struggled to succeed. This was partly due to an overly closed strategy that failed to create an ecosystem to leverage the go-to-market decision for Watson.

To its credit, IBM invested significantly in Watson, and created a new business division, cognitive computing, to market it. In Teece's profiting from innovation (PFI) framework,[65] one would expect IBM to receive the lion's share of the profits from this innovation. Yet, that is not what happened. Instead, IBM had to exit several important customer contracts, and ended up with relatively little of the profits from its early lead in artificial intelligence. Yang et al. suggest that IBM might have done better to enable a broad ecosystem of complementors for Watson to explore several possible uses of Watson in parallel. But this would have required IBM to open up its black box of Watson technology through application programming interfaces (APIs) and by training system integrators to develop and deploy the technology across different actors and in several different markets.

Another example is provided in the article by Sjödin et al. in this issue. It shows that orchestrating ecosystems is challenging, but that some challenges can be mitigated by improving management.[66] More specifically, it identifies legacy barriers for manufacturing firms that venture into the creation and orchestration of ecosystems as part of their digitalization efforts. It then outlines activities for ecosystem revitalization and realization.

Ecosystem Expansion, Contraction, and Reconfiguration

Above, we have made the case that technological developments may lead to both expanding and contracting ecosystems. For example, technological modularization typically increases centrifugal forces,[67] but sometimes technological developments lead to decreasing modularity,[68] causing greater centripetal forces.

Similarly, management and coordination developments do not always favor hybrid organizational forms such as ecosystems; they can cause both integration and fragmentation. For example, much effort has been made to bring in the benefits of markets and ecosystems—such as autonomy and experimentation—within corporations, with managerial innovations such as the multidivisional firm[69] and the customer development model.[70]

Technological and managerial dynamics are often interrelated. A change in technological complementarities may stimulate a change in coordination and management techniques, and vice versa. For example, the push toward roaming, interoperability, and economies of scale caused the technology of mobile telecommunications to transform from incompatible regional systems to a global standardized and modular system based on hundreds of standards and thousands of complementary components. Management and coordination of the ecosystem evolved in tandem with the technologies, leading to *ecosystem expansion*. For example, standards-setting organizations developed Fair, Reasonable, and Non-Discriminatory (FRAND) licensing principles to mitigate patent holdup and patent holdout problems, such as occurred with Rambus. Corporations also funded large in-house IP departments with sophisticated knowledge of patent portfolios and experience in coordinating technologies and innovation processes under distributed governance.[71]

Another example of ecosystem expansion is provided in this issue's article by Liu et al.,[72] showing how the COVID-19 pandemic led to the identification of complementarities between old and previously unrelated technological components controlled by several different firms. The pandemic caused an urgent need for ventilators, which could not be met by existing supplies. Based on an initial design specification, manufacturing firms gathered in an ecosystem called VentilatorChallengeUK. The ecosystem was coordinated by the High Value Manufacturing Catapult (HVMC), a group of seven university-based research centers with a joint purpose to investigate innovative manufacturing technologies and scale up new products and processes.[73]

In a process of "modular exaptation," existing technologies, components, and manufacturing capabilities spread across more than 100 firms were repurposed to new functions needed to design and produce mechanical ventilators. The ecosystem delivered more than 13,000 ventilators over the course of only a few months during the peak of the pandemic. Due to the urgency, accelerated innovation was a necessity, and "finding existing technologies that could be repurposed was the only feasible approach." The rapid growth and success of this specific ecosystem were the result of the combination of a modular technical system matched with an organization whose members, although autonomous, had a shared mission, management and coordination provided by HVMC, and a high degree of mutual trust and organizational complementarity.

The opposite of ecosystem expansion is *ecosystem contraction*. It can be exemplified by the case of bicycle drivetrains, as beautifully described by Fixson and Park.[74] The bicycle drivetrain industry consisted of more than 50 firms in the early

1980s. Each firm produced one or more of six main components of the modular drivetrain product architecture. Less than 10% of all bikes had all six drivetrain components delivered from a single supplier. But during the second half of the 1980s, drivetrain manufacturer Shimano made two major improvements to drivetrains—the Shimano Index System (SIS), introduced in 1985, and the HyperGlide freewheel (HG), introduced in 1989. These innovations depended on an integral product architecture that made Shimano's new drivetrains incompatible with components supplied by the rest of the industry. Shimano's new products quickly gained popularity among users, triggering a rapid consolidation of the industry. By 1990, Shimano's SIS + HG drivetrains accounted for 78% of mountain bikes sold and 57% of road bikes. Both markets were dominated by three vertically integrated firms. The ecosystem based on modular components had disappeared.

Another example of ecosystem contraction caused by dynamics in complementarities is that of Microsoft Office. In the 1980s, different productivity software applications were dominated by different providers, including WordPerfect for word processing, Lotus 1-2-3 for spreadsheets, and Harvard Graphics for visual presentations. Over time, there was an increasing demand among users to integrate content created in one application into another application. But these applications were standalone and not completely compatible, and they did not leverage the potential complementarities across applications. Microsoft took advantage of this and developed an integrated and fully compatible productivity offering in its new Office suite. By integrating the three productivity applications, Microsoft changed users' expectations about the underlying technology. A common command structure and seamless cutting and pasting between applications became *sine qua non* capabilities.

Microsoft further integrated Office with the graphical user interface of its next-generation operating system, Windows 3.0. To take full advantage of Office, users had to upgrade to Windows. To appeal to these users, developers of software applications for personal computers had to write new programs using Windows APIs. The de-modularization of the operating system and software applications encouraged sales of both Office and Windows and helped Microsoft make the transition to their next generation of products.[75]

Clearly, technology does not always progress from more integral to more modular. There is a cycle of development that recurs, as any individual technical system reaches the limits of its architecture.[76] For example, the early personal computers were based on 8-bit microprocessors. An extensive network of complementors in hardware and software leveraged the 8-bit design, fostering modularity. At some point though, the 8-bit design became a severe restriction on system performance. Intel introduced the 16-bit 80286 chip in 1982, which IBM used in the PC AT introduced in 1984. Such a generation shift poses difficulties in a modular and distributed system, as complementors may need to re-architect their products for the new design.[77] (Intel solved this problem by designing the chip so that it could execute most software written for earlier 8-bit processors.) If it is not clear to complementors that this investment is justified, the modular and distributed system may be subject to architectural inertia.[78] This stage may thus create a (temporary) centripetal force to integrate, for example, by partnering with selected complementors during the shift to the next design generation.[79]

For example, in 1985, Intel chose to be the sole source of the 80386 and subsequent generations of microprocessors. Reflecting its position as a monopolist, Intel set a high price on the 386 chip: US$156 compared to US$8 for the previous 286. As Intel's largest customer, IBM elected to stay with the older generation of chips. However, with Intel's active support (in the form of technical assistance), a new startup, Compaq, embraced the new chip and built it into the Deskpro 386, announced in September 1986. Compaq's machine was a resounding success: PC Tech Journal named it their 1986 Product of the Year for 1986. IBM introduced its own 386 machine 7 months later, but it was too late to capture the market. Compaq, thereafter, became the technology and market share leader in the market for "IBM-compatible" computers.[80]

Hence, changes in centripetal and centrifugal forces do oftentimes not simply lead to contracting or expanding ecosystems, but rather to *ecosystem reconfigurations*—with some actors and/or components being replaced by others. Complementarities may grow stronger between previously independent technologies—a process we sometimes categorize as technological convergence[81]—while some complements are commoditized.[82] This issue's article by Sjödin et al.[83] gives an additional account of how technological change affects old and new complementarities in ways that lead to ecosystem reconfiguration. In effect, the process of digitalization among manufacturing firms led to new and stronger complementarities in some areas and weaker complementarities in others. Again, the dynamics of technological complementarities were accompanied by new developments in management and coordination.

Conclusion

In this article, we have argued that ecosystems arise when there is a balance between centripetal forces, pushing economic activities into a single firm, and centrifugal forces, pulling activities out onto the market. A major source of centripetal force is complementarity. When complementarities are strong, there may be good reasons for integration to enable coordination and control. But complementarities are not static. Complements may, for example, be commoditized, generalized, or standardized over time, and in this article we have tried to add conceptual clarity to these dynamics.

Centripetal forces are countered by centrifugal forces. Sources of centrifugal force include product modularization, distributed knowledge, and network effects. These also change over time. On top of that, there are dynamics in our methods of coordination and management within and across firm boundaries. Depending on the nature of such management developments, they may favor more or less integrated forms of organization. For example, the emergence and refinement of open innovation has transformed corporate innovation strategies and moved some of corporate investment from the in-house R&D lab out into the ecosystem.

The view of ecosystems as arising from a balance between centripetal and centrifugal forces leads to the understanding that ecosystem evolution results from changes in these forces. In this article, we have especially highlighted the dynamics of technological complementarities, on the one hand, and the dynamics of coordination and management techniques, on the other hand.

The implications for managers who strive to build successful ecosystems are simple yet profound. Managers must understand their technical systems at the level of components and linkages. Broad-brush descriptions of technologies as "general purpose," "radical," "incremental," and "disruptive" are insufficient. Managers need to construct maps of the technical systems their companies inhabit and the status of each major component and interface.

Particular attention should be paid to the functions of each element. Functions carry value within a technical system.[84] If a function is essential, it must be paid for or the system will fail. If there is only one means of fulfilling the function—if the technology for fulfilling the function is unique—then the owner of the technology can claim a share of the complementary surplus, or prevent others from doing so.

Overlaid on the map of technical functions is a map of "who does what"—the ecosystem. Technical functions define "niches" in the ecosystem—places where value is created and might be captured. However, module boundaries established by technology and corporate boundaries established by strategy should always be regarded as both provisional and permeable. At any time, there may be advantages to integrating some technical elements to increase efficiency or modularizing other elements to create new options.

Managers must also explore new ways of coordinating and managing to fully leverage the potential of ecosystems. This may mean acting unilaterally, as Shimano did to bring about an advantageous change in industry structure. It may mean acting as a platform leader (like Microsoft) shepherding an ecosystem through a technological transition. Or it may mean collaborating as an equal with peers to set a new industry-wide or open standard (like in telecommunications). Either way, both internal and external technologies must be managed—in line with the core idea of open innovation—and capabilities need to be developed to remain relevant as centripetal and centrifugal forces change and ecosystems evolve.[85]

To this purpose, the other articles of this special section make important contributions to both research and practice. Liu et al.[86] introduce *exaptation*, a specific type of generalization of complements, and showcase how social and business problems can be addressed at speed through exaptation and ecosystem strategies. Sjödin et al. address a common problem; how established manufacturing firms can engage with ecosystems as part of their digital transformation. The authors identify common legacy barriers and provide strategies for overcoming them.[87] Finally, Yang et al.[88] showcase the danger of trying to hoard control over general purpose technology rather than encouraging the formation of an ecosystem to explore many different commercial opportunities. Taken together, these articles show that when technological modularization is well-matched with distributed governance and the right type of management and coordination, ecosystems may indeed be the most competitive form of organization.

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Author Biographies

Marcus Holgersson is Associate Professor at the Department of Technology Management and Economics at Chalmers University of Technology (email: marhol@chalmers.se).

Carliss Y. Baldwin is the William L. White Professor of Business Administration, Emerita, at the Harvard Business School (email: cbaldwin@hbs.edu).

Henry Chesbrough is Adjunct Professor and Faculty Co-Director of the Garwood Center for Corporate Innovation at the Haas School of Business at the University of California, Berkeley. He is also Maire Tecnimont Professor of Open Innovation at Luiss Guido Carli University (email: chesbrou@berkeley.edu).

Marcel L. A. M. Bogers is Professor of Open and Collaborative Innovation at the Innovation, Technology Entrepreneurship and Marketing (ITEM) group at Eindhoven University of Technology. He is also Affiliated Professor of Innovation and Entrepreneurship at the University of Copenhagen and Garwood Research Fellow at the Haas School of Business at the University of California, Berkeley (email: m.l.a.m.bogers@tue.nl).

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