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Architectural Dualities in Complex Systems: Components, Interfaces, Technologies and Organizations

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ARCHITECTURAL DUALITIES IN COMPLEX SYSTEMS: COMPONENTS, INTERFACES, TECHNOLOGIES AND ORGANIZATIONS

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Abstract:
Research on technological innovation and product development has long recognized the importance of product architecture, and many scholars have explored its relationship to the organizational structure of the product development process. Product architecture, in turn, has long encompassed both the allocation of functionality to components and the pattern of linkages between them. In this paper, we forge new connections among these established ideas by examining them as two pairs of dual relationships. First, we draw attention to the duality between components and interfaces. While innovation and product development researchers have historically emphasized the partitioning of products and systems into components, economic research on product compatibility standards focuses on the definition of the interfaces. We identify a small but growing body of work that bridges these communities, and suggest opportunities to strengthen the ties between them. Second, we examine the duality between technological and organizational architecture. This relationship has been explored under the heading of the mirroring hypothesis, but there exists a distinct literature on organization design that could serve as a natural counterpoint to the literature on product design. We propose to view these two dualities as orthogonal. This perspective reveals a fourth quadrant that concerns organizational interfaces -- that is, relationships at the boundaries of organizational units, including firms. Here the literature is more diverse and even less integrated with the core concepts of architecture in complex systems, but it is also where we see the most intriguing possibilities for theory development and empirical investigation.

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Abstract

Research on technological innovation and product development has long recognized the importance of product architecture, and many scholars have explored its relationship to the organizational structure of the product development process. Product architecture, in turn, has long encompassed both the allocation of functionality to components and the pattern of linkages between them. In this paper, we forge new connections among these established ideas by examining them as two pairs of dual relationships.

First, we draw attention to the duality between components and interfaces. While innovation and product development researchers have historically emphasized the partitioning of products and systems into components, economic research on product compatibility standards focuses on the definition of the interfaces. We identify a small but growing body of work that bridges these perspectives, and suggest opportunities to strengthen the ties between them. Second, we examine the duality between technological and organizational architecture. This relationship has been explored under the heading of the "mirroring hypothesis," but there exists a distinct literature on organization design that could serve as a natural counterpoint to the literature on product design if their common concerns were more fully developed.

We show how these two dualities are orthogonal dimensions. This perspective reveals that the literatures we have considered so far occupy three quadrants of a 2×2 matrix. The fourth quadrant concerns organizational interfaces — that is, relationships at the boundaries of organizational units, including firms. Here the literature is more diverse and even less integrated with the core concepts of architecture in complex systems, but it is also where we see the most intriguing possibilities for theory development and empirical investigation. We conclude with a summary of the concepts that relate the four quadrants to each other, and a call for research that further explores these connections.

Introduction

Research on technological innovation has distinguished between two types of high-technology goods produced through different kinds of innovative activity. “Science-based” goods, like new chemicals and pharmacological compounds, reflect discoveries driven by intensive R&D efforts, typically building on advances in fundamental knowledge (Pavitt, 1984). “System-based” goods, like complex mechanical equipment and most products based on information and communication technologies, are created primarily through the integration of components whose physical properties are well understood (Hobday, 1998).

For system-based goods, returns to innovation can accrue both from novel changes to the individual components and from changes to the relationship between these components. The latter possibility has led scholars to examine product architecture (Henderson & Clark, 1990; Ulrich, 1995) and system integration (Iansiti, 1995; Dosi et al., 2003) as sources of appropriable rents and competitive advantage. The successful integration of components typically requires coordination at their interfaces, which is often achieved through the adoption of formal or de facto compatibility standards (Saloner, 1990; Katz & Shapiro, 1994; West & Dedrick, 2000).

The research literature has also emphasized that innovation is not confined to the boundaries of an organization, but often spans organizational boundaries. Research in this area has emphasized both the process by which such innovations are coordinated (Teece, 1992) and the strategic motivations for sourcing innovations outside the firm (Chesbrough, 2003). The need for such coordination is particularly acute in industries and product categories that require integrating components from a wide range of sources, as with personal computers (West, 2006).

Taken as a whole, the body of research on system-based innovation and product development spans an enormous range of phenomena. Moreover, it intersects with a variety of other literatures across several disciplines — including engineering, economics, and organizational theory. This paper is motivated by our desire to make sense of this vast and complex intellectual landscape to better understand the process of distributed production of a complex system.

We focus on the concept of *architecture*, which refers to the structural aspects of a designed system. While this focus excludes many important concerns of technology and innovation scholars (e.g., processes and capabilities), it leaves a rich set of concepts on the table. In particular, two pairs of relationships are pervasive: between components and interfaces as design elements, and between technological and organizational domains of design. We note that both relationships are *dualities* in the sense that when one member of the pair is in the foreground, the other is invariably in the background. Thus any discussion of components necessarily involves interfaces (even if only implicitly), because an interface is by definition what lies at the boundary of a component. Likewise, any technological discussion necessarily involves the organizational domain (again, perhaps implicitly), because technologies are realized as goods and services by people working in organizations.

We propose to view the two dual relationships as orthogonal, yielding the 2×2 matrix shown in Figure 1. In the remainder of the paper we review prior research that places in the foreground the concepts of each quadrant, as well as research that explicitly links two or more quadrants. Some of these links are more fully developed than others. At the end of the paper we take stock and suggest opportunities for strengthening the weaker links through theory development and empirical investigation.

For expositional clarity, we build up the story from bottom to top and left to right. We first examine the prior technology-focused research on the role of components and interfaces in product architectures (quadrants I and II). We then turn to the literature on organization design (quadrant III) and its links to product architecture. Finally, we consider the literature on interfirm coordination (IV) and its links to both adjacent quadrants. The key research questions considered by each quadrant, and at each boundary between two quadrants, are summarized in Table 1.

The Architecture of Products and Systems

Research on the creation of complex products and multi-product systems highlights the importance of *product architecture*, including the role of components and the interfaces that link them. Much of this literature focuses on systems that are partitioned into *modules*: components or subsystems with strong internal interdependencies but relatively weak linkages to the rest of the system. An architecture specifies the essential modules and their functions, along with a set of *interfaces* that describe how the modules interact (Ulrich, 1995; Baldwin & Clark, 1997).[1]

An important milestone in the development of modular product architectures was the use of a modular design for the IBM System/360 family of computers in the mid-1960s. This new system architecture included approximately 25 modules, each with substitutable components and well-defined interfaces. Unintentionally, it also enabled entry by third-party suppliers of modular replacements for IBM subsystems (Amdahl et al., 1964; Pugh et al., 1991). In the wake of the System/360's success, a new subfield of computer science arose in the 1970s to focus on design principles for the architectures of computer systems (see Baldwin & Clark, 2000, ch. 7).

In the economic and management literatures, however, different research communities have focused on different aspects of product architecture. In particular, the innovation and product development and innovation management communities have tended to focus on components as the primary objects of design, while the systems competition and technology standards communities have focused on interfaces.

I. Modularity in Product Design

Product development research examining product architectures has accorded a primary role to the creation of components, with a secondary emphasis on interfaces. As Ulrich (1995) opens his influential paper on product architecture in manufacturing firms:

> Product architecture is the scheme by which the function of a product is allocated to physical components. … I definite product architecture more precisely as: (1) the arrangement of *functional elements;* (2) the mapping from *functional elements* to *physical components;* (3) the specification of the *interfaces* among interacting physical components. (Ulrich, 1995: 419–420).

From this, he developed a theory of how modularity in product architecture affects product quality, variety, and ease of development. His discussion of architecture emphasizes component design, with interfaces important to the degree that they couple (or decouple) the design interdependencies between the components.

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[1] The terms "component" and "module" are often used interchangeably, although Baldwin suggests reserving the latter for components of modular systems (personal communication, 2008). As an example of a non-modular component, consider the keystone of an arch. While the keystone is a distinct and separable component of the arch, the other components (as well as the overall structural properties of the arch) depend on it in an integral way.

Research on modularity traces the effects of component substitutability based on standardized interfaces, but tends not to dwell on the content of those interfaces or the processes by which they become accepted as standards. Schilling (2000) is typical in this respect:

> *Modularity* is a general systems concept: it is a continuum describing the degree to which a system's components can be separated and re-combined, and it refers both to the tightness of coupling between components and the degree to which the "rules" of the system architecture enable (or prohibit) the mixing and matching of components. …
>
> Many systems migrate toward increasing modularity. Systems that were originally tightly integrated may be disaggregated into loosely coupled components that may be mixed and matched, allowing much greater flexibility in end configurations. (Schilling, 2000: 312)

Modularity can increase the value of a given product architecture in several ways. Modularity enables the creation of a wide variety of components through the division of labor (within or outside an organization) and thus distributed innovation among component suppliers (Langlois & Robertson, 1992). Modularity also enables knowledge reuse and thus creates economies of substitution (Garud & Kumaraswamy, 1995). When modularity is used to create product platforms, it enables traditional economies of scale and scope, as well as the rapid evolution of product designs (Robertson & Ulrich, 1998; Baldwin & Woodard, 2008).

II. Standards and System Compatibility

In contrast to the modularity literature, economic research on system compatibility and standards competition focuses on the definition of the interfaces, with the system components either taken as fixed or treated as subordinate to interface-related choices.

This large and active body of research emphasizes the processes by which interfaces are created, controlled and modified, as well as the economic implications of interface evolution. One of the earliest authors to explicitly examine the role of interfaces in high-technology competition was Saloner (1990):

> Traditionally, computer vendors have provided a range of mutually incompatible systems, both in that machines manufactured by different vendors are not easily

> physically networked and in that peripherals and software written for one machine are not easily adapted to another. Recently, however, there has been a major trend towards an alternative paradigm in which there are *no proprietary boundaries* between the product offerings of different vendors. The goal of the proponents of so-called “open systems” is to provide nonproprietary standards specifying *how the components at the interfaces interact*. (Saloner, 1990: 135; emphasis added)

The benefits of such interfaces to enable interoperability between components are often assumed to be limited to cases of standardization,[2] which Farrell & Saloner (1992) define in terms of cooperation between organizations to create shared technical interfaces:

> Compatibility may be achieved through standardization: an explicit or implicit agreement to do certain key things in a uniform way. Standardization occurs when computer manufacturers use the same interfaces for attaching peripherals, when cameras are designed to use a common 35mm film format, or when software designers adopt a common user interface. Standardization can be achieved through the independent actions of market participants, through the formal coordination activities of voluntary industry standards committees, or through government action. (Farrell & Saloner, 1992: 9)

Saloner was among the first to describe how the proprietary control of interfaces can serve as a barrier to entry by suppliers of complementary products, which standardization (or simple reverse engineering) can erode:

> Designing a set of compatible product offerings in this way means engineering interfaces between machines and between machines and applications software which incorporate a degree of standardization. This then introduces the possibility that “third-party” vendors will gain a sufficient understanding of those interfaces to be able to supply their own products meeting the interface standards. (Saloner, 1990: 141)

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[2] The “interface” and “standard” constructs are often aggregated (if not confounded) through the term “interface standards” (e.g., David & Greenstein, 1990; Farrell & Saloner, 1992) or “standard interfaces.” They also tend to be aggregated in practice (Baldwin & Clark, 1997; Langlois, 2002). Baldwin & Clark (1997) consider a standard to include measures to evaluate the degree of compatibility across components, as distinct from the interface specification itself.

Controlling a new set of interfaces means controlling the benefits that accrue from the supply of third-party products (West & Dedrick, 2000). In addition to control, firms may seek proprietary advantage by creating non-public interfaces that deter entry by suppliers of complementary products (West, 2007).

I + II: Interfirm Issues in Product Architecture

A growing body of research has sought to bridge the dual concerns of component and interface design. This work puts the relationships between interfaces and components on an equal footing, and specifically considers how the adoption of standard interfaces can reshape a product's component structure (and vice versa). In our typology of Figure 1, this work spans quadrants I and II.

These two fundamental types of design elements are inherently related. Interfaces define both the technical and economic relationships between components, whether sold by distinct firms or as complementary offerings of the same firm. In general, the more complete the interfaces and the greater the extent to which they encapsulate the underlying functionality of the components, the greater the modularity, substitutability and thus economies of substitution that an architecture provides (Sanchez & Mahoney, 1996; Baldwin & Clark, 2000; Schilling, 2000; Garud & Kumaraswamy, 1995).

Some research considers cases where an interface *fails* to fully encapsulate a component, letting design information "leak out" in a way that may be useful to developers of complementary components, but also prevents "mix-and-match" compatibility. Schilling (2000) introduces the term "synergistic specificity" to refer to the degree to which a specific component (or group of components) are optimized to work with component(s) on the opposite side of an interface:[3]

> The degree to which functionality is achievable only through component specificity is related directly to the availability and effectiveness of standard interfaces (Baldwin & Clark, 1997; Garud & Kumaraswamy, 1995; Sanchez, 1995; Sanchez & Mahoney, 1996). The function of a standard interface is to make

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[3] This differential ability to optimize may be a source of competitive advantage for firms that supply mutually complementary products, like platforms and applications. During the 1990s, Microsoft was alleged to engage in incomplete disclosure of its operating system programming interface specifications to benefit its own applications (Sheremata, 2004).

> assets *nonspecific*, thereby facilitating the adoption of a modular structure. Without such an interface, firms might be able to provide components that could be mixed and matched with other vendors by developing *specialized* interfaces that coordinate the functions among a particular set of vendors' components, but the costs of developing such specialized interfaces would be very high, and the choice among configurations would be constrained to those configurations predetermined by the vendors that had produced the interfaces. (Schilling, 2000: 322)

Schilling views the case of optimized modules as an intermediate case between full modularity and a fully integrated system. She predicts that changes in interfaces intended to increase modularity will also increase component substitutability:

> However, greater market demand for flexibility might induce the manufacturer to begin to offer the system with a few different product configurations, each composed of the firm's own components. Should customers prefer to be able to combine the minicomputer with external components (such as off-the-shelf software or peripherals made by other vendors), the minicomputer manufacturer eventually might adopt a standard input-output protocol (a standardized interface) that makes the product compatible with other firms' components (employing interfirm product modularity). If pressure continues for even greater flexibility, the company might uncouple many of the functions of its core system and begin to sell them as modular components, which may then be combined in a greater number of product configurations with both the company's own components and other vendors' components. In each of these stages, the product has become increasingly modular. (Schilling, 2000: 319)

How does such a shift occur in practice? In their empirical study of bicycle components, Fixson & Park (2008) examine how an architectural shift reduced both modularity and fragmentation in the bicycle industry. The industry began with a modular architecture that enabled substitutability. The technical benefits of integration were used by the leading vendor to reduce product modularity, allowing it to obtain a dominant market share.

The Architecture of Organizations and Firms

We now turn to the second duality in our typology, between the technological and organizational domains of architecture. Organizational scholars have long recognized that, like products, many (if not most) organizations are comprised of separable but interlinked parts arranged in a hierarchical structure. The concepts are analogous, although the terminology differs somewhat: instead of components or modules, organizational units are more likely to be labeled departments or divisions — or firms, in an industry context.

In this section, we briefly review the literature on organization design (quadrant III in our typology), followed by the literature that spans the technological and organizational domains with a focus on the modular structure of products and firms (quadrants I and III).

III. Organization Design

The idea of treating organizational structure as a design problem was widely explored in the 1960s and 1970s (Thompson, 1966; Perrow, 1972; Galbraith, 1977; Miles & Snow, 1978), and research in that line continues today (see Snow et al., 2006 for a review and prospectus). Even the early work on this topic recognized an explicit parallel with the design of technological systems (Haberstroh, 1965), as it sought to uncover principles for achieving an optimal design in a given environment.

In this research, the term “organizational architecture” has been used to describe the formal structure, such as organizational hierarchy, as well as the pattern of informal linkages between individuals and subunits within an organization. “Components” may refer, in this context, to either discrete organizational units or informal elements of the organization such as culture and routines (Nadler et al., 1992; Nadler & Tushman, 1997). The concept of an interface is mostly implicit, for example in the ideal of “alignment” between the various interdependent aspects of organizational design that impact firm performance (Waterman et al., 1980).

A more recent body of work grapples with issues of organizational design and adaptation using computational simulation models. Levinthal (1997) shows that tightly coupled organizations are subject to high rates of failure in changing environments, while more loosely coupled organizations can simultaneously explore new solutions to problems while exploiting successful past solutions, making them more adaptable. Marengo et al. (2000) focus on problem-solving behavior in organizations, and explore the trade-offs between the way a problem is decomposed into sub-problems and the efficiency of solving it through decentralized search. Rivkin & Siggelkow (2003) examine the nature of interdependencies between organizational design elements, and find that they arise from the need to balance the ability to search broadly while stabilizing around good decisions.

Ethiraj & Levinthal (2004) explore the conditions under which organizational design efforts can be successful. They find that when the underlying problem structure is hierarchical, boundedly rational agents can successfully choose an appropriate organizational structure to match, even if the hierarchical elements are tightly coupled to each other. However, when hierarchy is violated, agents perform better on loosely coupled problems than tightly coupled ones.

I + III: Mirrored Modularity

From our typology, we would expect to find research that spans quadrants I and III. In fact, scholars have been exploring the linkages between technological and organizational architecture almost as long as they have explored either kind of architecture on its own.

A common theme of this research is the “mirroring hypothesis,” which suggests a theoretical, normative or empirically validated relationship between the architecture of a product and the organizational structure employed to create it. As Colfer (2007) summarizes prior research:

> [T]his hypothesis holds that the structure of a product development organization must “mirror” the architecture of the product it develops. In other words, because a specific architecture is thought to imply a certain partitioning of product development tasks, it is also thought to determine the feasible/optimal structure of the corresponding product development organization. …
>
> Stated in terms of the concept of modularity, the mirroring hypothesis holds that *an integral organization is necessary for developing an integral product, while a modular organization is only capable of developing a modular product.* (Colfer, 2007: 1–2).

Because the mirroring hypothesis and organizational modularity are overlapping yet distinct constructs, here we use the term “mirrored modularity” to refer to research that postulates parallel degrees of modularity in product and organization.

Simon (1962/1996) began this stream by offering a theory of “nearly decomposable” hierarchical systems that he applies both to product and organizational hierarchies. Building on Clark’s (1985) work on hierarchies in innovation and product development, Sanchez (1995; Sanchez & Mahoney, 1996) argued that while complex systems normally require a managerial hierarchy for their development, “modular product designs that have well-specified, standardized interfaces between components that define the intended inputs and outputs of all components” can support a decentralized mode of production in which component interactions are reduced.

Garud & Kumaraswamy (1995) show how this decentralization enables the modular production of complements and components through economies of substitution:

> Partitioning a technological system can create an organizational system whose organizational modules (firms) can engage and disengage in response to market and technological changes. … However, to accomplish such ‘flexible specialization’ (Piore & Sabel, 1984), it is important that these organizational modules coordinate among themselves to design and produce compatible components. (Garud & Kumaraswamy, 1995: 100)

Staudenmayer et al. (2005) describe the processes by which such modular partitioning can be coordinated, by defining the product, managing module and task interdependencies, and through processes for coordinating relationships between organizations. Baldwin & Clark (1997, 2000) argue that organizational partitioning even within an organization should be organized by using well-defined interfaces (“visible information”) and global “design rules” to guide the decision-making process.

While most of the early studies of mirrored modularity have been conceptual or even normative, a limited number of empirical tests have been made. Using a dataset of modular laptop computer designs, Hoetker (2006) found limited support for the ability of firms to utilize that modularity to enable decentralized production. He also showed that removing the production from the hierarchy was distinct from utilizing the “loosely coupled” networks of actors to aid that production. Using technical measures of software modularity for five matched pairs of software applications, MacCormack et al. (2008) demonstrated differences in organizational and technical modularity between open-source and proprietary packages, and found that in all cases "the open source product is more modular than that of a product of comparable size developed by a smaller, more centralized team."

Despite this positive evidence, mirrored modularity is by no means universally supported. In a detailed case analysis of Pirelli Tires, Brusoni and Prencipe (2006) reached the opposite conclusion, finding that the introduction of robotic manufacturing technology induced Pirelli to shift from a modular organization to an integrated one in order to successfully produce a product that was transformed by the new production process from integrated to modular. Such conflicting findings may be related to key architectural differences in the products, firms or industries of these studies.

The Architecture of Industries and Institutions

We have now examined both of the "architectural dualities" we identified at the beginning of the paper: components vs. interfaces as architectural design elements, and technological vs. organizational domains of design. However, this leaves one remaining unmapped quadrant in Figure 1.

As noted earlier, the organization design literature largely follows the product development literature in adopting a "component-centric" approach to studying complex structures. That is, they are primarily concerned with the decomposition of an organization or problem-solving process into units or tasks. Just as product development researchers are interested in interdependencies among product components, organization design researchers are interested in how to structure the flow of work, information, and decisions through the organization. But the actual *content* of those flows is of secondary interest, just as the content of programming interfaces, communication protocols, and standards documents is of secondary interest to most product development researchers. We therefore put organizational design in quadrant III, at the lower-right corner of our typology matrix.

What would be found in quadrant IV, at the intersection of "organizational" and "interfaces"? This would include research on how people and organizations interact across organizational boundaries. There is a considerable body of work here, although classifying it is difficult and a complete summary is beyond the scope of this paper. After a brief summary, we examine the two remaining linkages in our typology: quadrants III and IV (the two "organizational" cells), and quadrants II and IV (the two "interface" cells).

IV. Interfirm Coordination

Although the term "organizational interface" is not widely used, either in research or practice, the concept of an *organizational boundary* is well established. In particular, there is a vast literature on firm boundaries; a large but somewhat more manageable literature on alliances, joint ventures, and other institutions for coordinating across firms; and a smaller but influential literature on boundary objects and cross-boundary knowledge flows. This list is surely not exhaustive, and we cannot attempt to provide more than a few illustrative pointers into each literature. Even naming the quadrant is a challenge — we chose *interfirm coordination* because it seems to capture the aspects of these diverse literatures that resonate most strongly with the concerns of the other three quadrants, and also would be recognizable to researchers in this area.

Beginning with the literature that is most clearly defined in scope and most "micro" in its level of analysis, Star (1989) introduced the concept of a boundary object and applied it to help explain how diverse groups of actors successfully cooperate in conducting scientific work. Star & Griesemer (1989) offer the following definition:

> Boundary objects are objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are weakly structured in common use, and become strongly structured in individual-site use. These objects may be abstract or concrete. They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation. The creation and management of boundary objects is a key process in developing and maintaining coherence across intersecting social worlds. (Star & Griesemer, 1989: 393)

Carlile (2002) adopted the concept in his study of new product development, and proposed a "pragmatic view of knowledge" as being localized, embedded, and invested in practice.

In a more general sense, portions of the literature on interorganizational networks (Uzzi, 1997; Gulati & Gargiulo, 1999) and vertical integration (see Lafontaine & Slade, 2007 for a recent review) would be relevant to this quadrant. The former takes firm boundaries as given and asks how firms coordinate across them; the latter deals with transactions across firm boundaries and asks what conditions lead firms to internalize those transactions through integration. However, only some of this literature considers the nature of the interface between organizations, rather than just the structural relationships between them (i.e., organizational modularity).

III + IV: Industry Architectures

Research spanning quadrants III and IV asks how interactions across organizational boundaries reshape or constrain the structure of organizations in a firm or firms in an industry. Although there is undoubtedly work that links organizational interfaces and components at a more micro level of analysis, the most salient connection with respect to the rest of our typology is provided by the concept of an industry architecture. Jacobides, Knudsen & Augier (2006) define an industry architecture as a "template" that circumscribes the division of labor among co-specialized firms in an industry sector.

In contrast to most of the literature on organization design, these authors are explicit about the interfaces between firms and their dual relationship to the component structure (i.e., the division of labor among firms) of an industry sector:

> With the birth of a new industry, a range of possible architectures may be viable. Gradually, as an architecture becomes stable, a system of interfaces among economic agents emerges. We define interfaces quite broadly, as the technological, institutional, or social artifacts that allow for two or more independent entities to divide labor. Interfaces are both the catalysts and the evidence of co-specialization between players. They can emerge through conscious action or through happenstance; they both reflect and amplify the division of labor among industry participants. … Such a system of interfaces moderates a set of productive units (firms) whose functions are co-specialized so their interaction is based on a well-defined distribution of roles (division of labor). To the extent that the individual players receive positive feedback, the emergent interfaces and co-specialized players will tend to coalesce, inviting newcomers to define their business in a way that aligns with the emergent architecture. …
>
> Often, as "winners" emerge in some parts of the value chain (because of their idiosyncratic, superior capabilities), potential upstream suppliers or downstream

> retailers come to cospecialize. Thus, an industry architecture will emerge on the basis of the interfaces defined by firms that initially happen to hold superior capabilities, in terms of technical efficiency (Jacobides and Winter, 2005). The stability of such a system increases with positive feedback from current operations and negative feedback from trying to change the architecture (cf. Padgett et al., 2003). This results in one, or, at most, a small number of rival "platforms", co-specialized "business ecosystems", with their own sponsors, orchestrators, and keystone members (Gawer and Cusumano, 2002; Iansiti and Levien, 2004). Sectors thus become interdependent "systems" (Dalziel, 2005). (Jacobides et al., 2006: 1203–1204)

Langlois (2002) is an important precursor to this work. This paper was an early effort to link the literature on modular design with the literature on property rights. Baldwin (2008) builds on this foundation to provide a more complete account of the relationship between modularity, transactions, and the boundaries of firms.

II + IV: Technological and Institutional Interfaces

Research in this area considers how interface standards affect the relationships among stakeholder organizations, and vice versa. Like the research on mirroring, this work addresses design choices in both the technological and organizational domains. But here the objects of design are technological interfaces (e.g., standards) and flows of knowledge or transactions across firm boundaries.

As Farrell and Saloner (1992: 9) note, standardization "can be achieved … through the independent actions of market participants." Various researchers have examined how the process of standardizing shared technical interfaces is either moderated by interfirm cooperation, or how that process leads to interfirm knowledge flow and other forms of interfirm cooperation. In particular, researchers have showed how such standardizing activities create or modify interorganizational institutions.

In their seminal study, Rosenkopf et al. (2001) showed that the individual-level social structure forged through cooperation in standards creation enabled knowledge flows and strategic alliances between their corresponding employers. They also showed that such embeddedness provided the greatest benefits to firms with fewer alliances, thus providing an entry mode for new firms to join alliance networks.

Garud and colleagues (2002) examine the co-evolution of the interface standards with the formal institutions for legitimating and enforcing those standards. Sun Microsystems sought adoption and legitimacy for its Java language and platform through what its CEO termed an "open-control" model. They show how Sun's efforts to control the interface standards poisoned its relationship with complementors and competitors involved in the standardization efforts, and how those poisoned relationships prevented the warring parties from reaching consensus on a shared definition for those interfaces. However, Sun did create institutions for governing Java technologies that helped mobilize opposition to threats from Microsoft. Its institutional entrepreneurship had a lasting effect on the platform structure of the computer software industry, particularly for enterprise servers and mobile phones.

Discussion

We began the paper with the premise that two pairs of dualities are pervasive in the literature on technological innovation and product development — and that the pairs are orthogonal, yielding two axes of a matrix. Now that our tour of the literature is complete, we can summarize it with a more detailed picture (Figure 2). This figure shows the linkages among the four quadrants as well as the main literature for each quadrant.

The horizontal axis contrasts the technical domain of products and multi-product systems with the organizational domain, which includes the arrangements of people and processes that enable the creation of these products and systems. Linkages between these two domains consider how technical design choices impact organizational structure / processes or vice versa.

The vertical axis contrasts research that emphasizes each of the two fundamental types of design elements in the architecture of a technological or organizational system. Research that emphasizes components focuses on how a system is divided into parts (modular or otherwise), while research that emphasizes interfaces focuses on how those components fit together.[4]

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[4] Here we defer considering an important question which is the source of the interfaces. In some cases, the interfaces reflect a bilateral or multilateral negotiation between affected parties (Saloner, 1990). In other cases, interfaces are unilaterally imposed on makers of complementary components, as when Microsoft defined the Windows APIs (West & Dedrick, 2000).

Work that spans both types of elements considers how the interface definitions impact the structure of components, or vice versa.

By suggesting previously unremarked linkages between disparate literatures, we believe this typology reveals potentially fruitful avenues for future research. For example, the research on mirrored modularity has considered parallels in the partitioning of products and organizations into subunits (components), but we know of no similar stream of work that empirically examines the parallels between technical and organizational interfaces.

The typology also calls attention to an area of research that appears relatively neglected by modularity researchers, the quadrant (IV) we label "interfirm coordination." Unlike the other three quadrants, this research has not been closely linked to research on product modularity, and thus it may have significant unrealized potential to inform such research (and vice versa).

Finally, the typology suggests ways to extend previous contributions toward a unified theory of technical and organizational modularity (e.g., Baldwin & Clark, 2000; Schilling, 2000; Jacobides et al., 2006). We believe that efforts to develop the causal implications of the typology could build upon and help further integrate these powerful ideas.

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Figures and Tables

Figure 1: Primary concerns (objects of design) in research on components, interfaces, technology and organizations

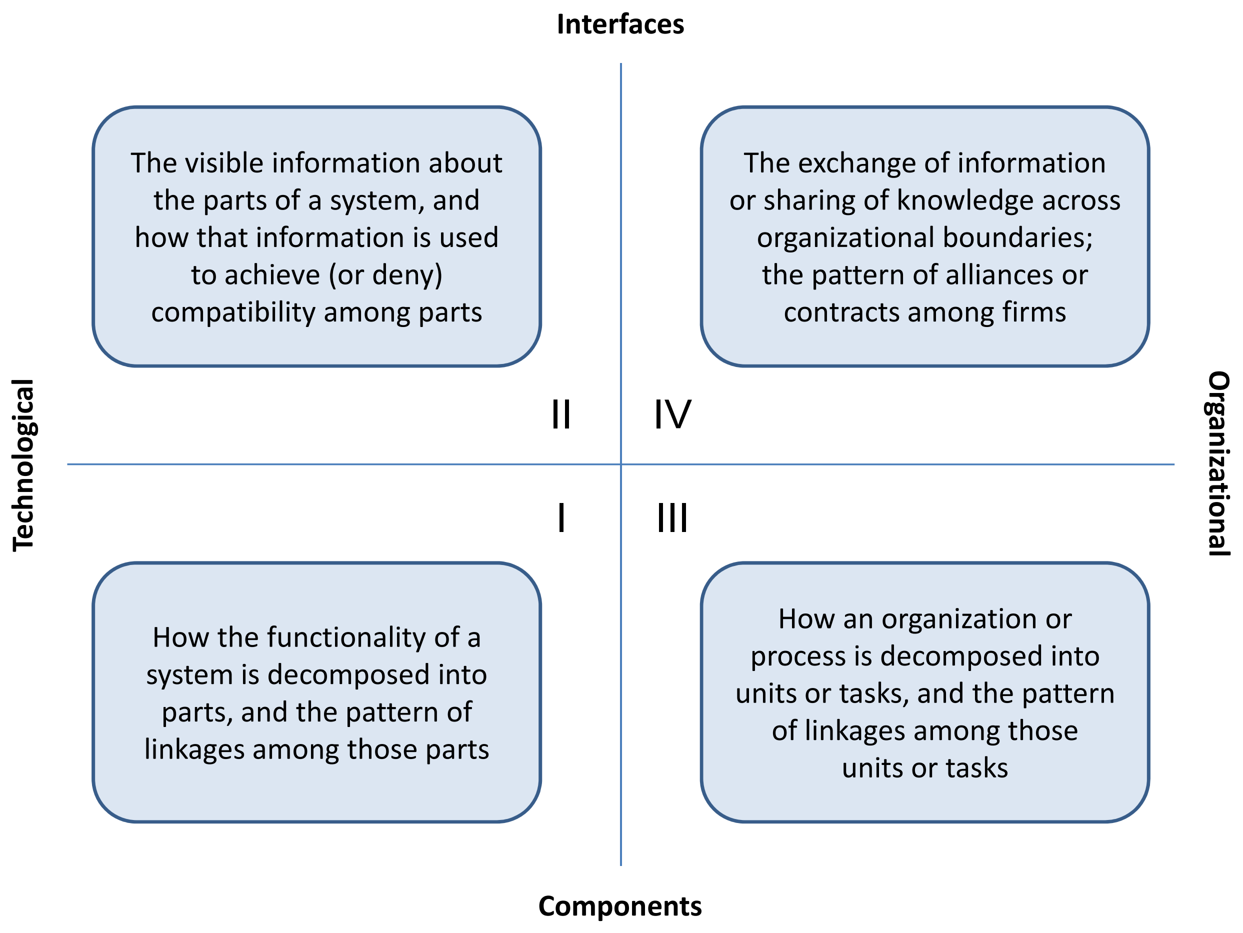

Figure 2: Four principal literatures and the linkages between them

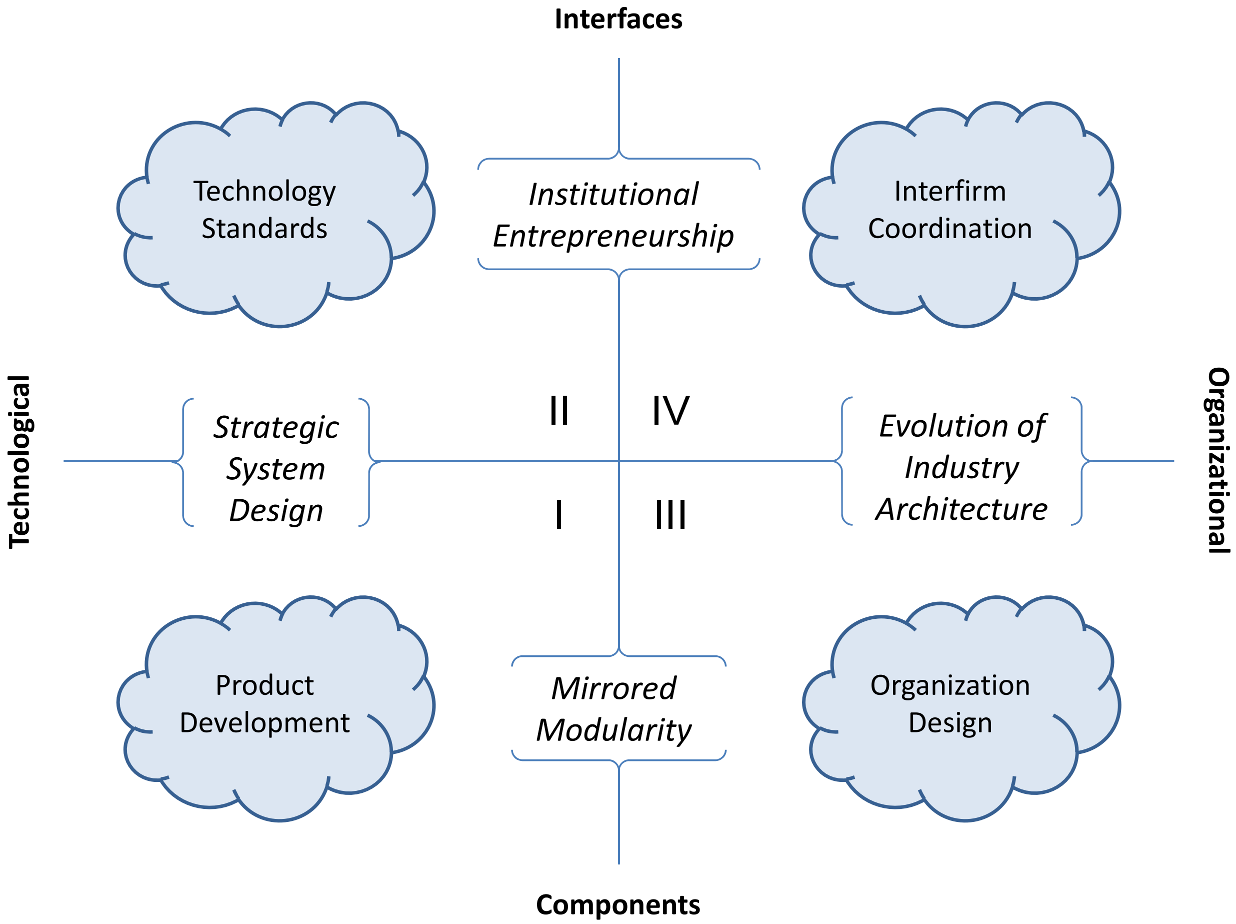

Table 1: Key questions within and between quadrants of the typology

	I. Tech. Components	*II. Tech. Interfaces*	*III. Org. Components*	*IV. Org. Interfaces*
I. Technological Components	**How should a product or system be decomposed into parts? How to structure the interdependencies among these parts?**	How does the adoption of standard interfaces reshape a product's component structure, and vice versa?	How does the decomposition of a product affect the division of labor involved in its design and production, and vice versa?	
II. Technological Interfaces		**What information should be exposed by components, and how can it be used to achieve (or deny) compatibility?**		How do interface standards affect the relationships among stakeholder organizations, and vice versa?
III. Organizational Components			**How should an organization or process be decomposed into units or tasks? How to structure the flow of work, information, and decisions?**	How do interactions across organizational boundaries reshape the structure of organizations in a firm or firms in an industry, and vice versa?
IV. Organizational Interfaces				**How should organizations interact across organizational boundaries? How do these interactions affect incentives and knowledge transfer?**