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How Design Rules Emerge and Evolve:

A Co-evolutionary Architectural Perspective on Firm and Industry Organization

by

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ABSTRACT

This paper elaborates how design rules emerge and evolve as firms' micro-level choices of product and organization architectures co-evolve with changes in product markets and an industry's competitive and cooperative dynamics. We suggest that the design rules a firm adopts will vary according to firms' strategic choices of *product and organization architectures* that they believe are or may become feasible in a given industry. Building on the Mirroring Hypothesis that product designs a firm adopts will influence the organization designs it uses, we develop a model that identifies key relationships that influence firms' strategic choices of product and organization architectures and associated design rules. We then elaborate key interactions between firm-level architectural choices and the architecture-enabled competitive and cooperative dynamics that obtain in an industry.

Our model identifies strategically important aspects of *open-system and closed-system architectures* and *modular and non-modular architectures* that impact industry structures, interfirm interactions, and resulting industry dynamics. Drawing on these analyses, we suggest how firms' strategic choices of architectures are influenced by their assessments of both (i) the potential for capturing value through *gains from specialization* and *gains from trade* that firms believe will be enabled by their architectural choices, and (ii) both *ex-ante* and *ex-post transaction costs* implied by their architecture decisions. We conclude by suggesting how the perspective on firm's strategic architectural decisions we develop here enables new approaches to understanding evolutions of both product markets and industry structures for serving product markets.

Keywords:

Architectures, design rules, open systems, modularity, mirroring hypothesis, transaction costs

INTRODUCTION

The strategic interplay between product architectures, firm strategies, organization designs, and industry structures is evident across a spectrum of research streams, including systems decomposability (Simon, 1962), communication structures (Conway, 1968), software development (Parnas, 1972), and architectural innovation (Henderson and Clark, 1990). An initial theoretical formalization of these relationships was suggested by Sanchez and Mahoney (1996) in their paper on the influence of modular product architectures on organization structures and market strategies. They proposed (somewhat provocatively) that "Products design organizations," in the sense that the interface specifications between components in a modular product architecture create an information structure that can provide efficient embedded coordination of the various processes undertaken in developing new products.

In their 2000 book, Baldwin and Clark extended the concept of information structure under the rubric of *design rules*[1] to suggest in greater detail how the technical structure defined by a product architecture can be used to coordinate new product development processes. In this discussion, we seek to extend the concept of design rules by suggesting further strategically important ways in which a firm's choice of product architecture is likely to influence its choice of organization architecture -- and *vice-versa*. In particular, we suggest how decisions to adopt *open-system* versus *closed system* and *modular* versus *non-modular* product architectures influence the kinds of design rules a firm adopts for organizing product development, production, and service and support activities for new and existing products. We suggest that firms essentially choose among a limited set of *alternative pairings of product and organization architectures*, each of which is facilitated by distinctive kinds of design rules governing not just the technical relationships between product components in an architecture, but also the organizational and managerial processes to be followed in developing a new product architecture.

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[1] Baldwin and Clark (1997) note that the term *design rules* was introduced by Carver Mead and Lynn Conway in their 1980 book *Introduction to VLSI Systems.* Most recently, the concept of design rules has been extended by Sanchez and Shibata (2021) to include the *managerial processes* needed to implement technical design rules.

Our analysis focusses on the factors that influence a firm's choice of product and organization architecture, and on how the firm's product and organization architectures co-evolve with the market preferences a firm serves and the industry dynamics the firm believes it currently faces or could feasibly face in the future. The strategic choices of product and organization architectures a firm makes then determine the design rules the firm will adopt for its development strategy as it seeks to create and capture value from its products.

Despite the popularity and importance of design rules, thus far a formal theoretical framework that identifies and reconciles the causal relationships among product architectures, organization designs, and industry structures has yet to be put forward (Campagnolo and Camuffo, 2010). We attempt to rise to that challenge by developing a *co-evolutionary architectural perspective* on how a firm's strategic decisions about its product architectures and associated design rules are likely to be influenced by its evaluations of the relative advantages of alternative kinds of organization architectures that the firm believes may be feasible in its evolving industry environment. This perspective provides insights into how firms' decisions about their product and organization architectures are likely to affect and be affected by current and potential competitive and cooperative interactions among firms in their industry (Ethiraj and Levinthal, 2004; Jacobides *et al.,* 2006; Zirpoli and Camuffo, 2009; Fang and Kim, 2018).[2] More specifically, we are concerned with the following research questions:

RQ1: What factors are likely to influence firms' decisions about their product and organization architecture and associated design rules, and how?

RQ2: How do the systemic interrelationships between an industry's macro-level evolution and firms' micro-level architectural decisions shape the co-evolution of products, firm, and whole industries?

To elaborate the concept of design rules, we use concepts from both systems theory and modularity theory (Sanchez and Mahoney, 1996; Schilling and Steensma, 2001; Hoetker, 2006; Fixson and Park, 2008;

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[2] We note the ongoing development of the ecosystem literature and the prospect that ecosystems may come to replace traditional notions of "industries" as a prevailing unit of analysis. However, for definitional clarity in this discussion, we use the terms *industry* and *industry structure* to refer to level of any industry system in which a given firm is embedded and operates.

Sanchez, 2008, 2012; Helfat and Campo-Rembado, 2016) to explore how firms assess current, emergent, and potential industry structures and dynamics, and how those assessments are likely to influence their strategic choices of alternative pairings of product and organization architectures. To develop this co-evolutionary architectural perspective on firms' strategic organizing decisions, we propose a general model elaborating a set of systemic interdependencies between firms' choices of product architectures and organization architectures, on the one hand, and the industry structures and inter-firm competitive and cooperative dynamics that emerge in an industry, on the other (Boisot and Sanchez, 2010).

Harkening to Williamson's (1985) notion that firms simultaneously choose their firm boundaries and technology employed, we suggest why firms' organization architectures are unlikely to follow unilaterally from firms' choices of product architectures, and we suggest how firms are likely to evaluate and choose among alternative pairings of aligned product and organization architectures (and supporting design rules). We arrive at these propositions by suggesting how architecture-enabled competitive and cooperative interactions between firms in an industry result in some product and organization architecture pairings offering greater advantages than other pairings within actual, emergent, or potential industry dynamics.

Theoretically, we argue that firms assess the relative attractiveness of alternative pairings of product and organization architectures by evaluating their respective (i) *ex-ante and ex-post transaction costs* (Langlois, 2006; Baldwin, 2008) and (ii) potential to capture *gains from specialization* and *gains from trade* (Jacobides, 2005; Jacobides and Billinger, 2006; Sanchez, 2008, 2012). We seek to contribute to the literature on design rules by suggesting that firms' strategic choices of aligned product and organization architectures and supporting design rules both influence and are influenced by – and thus *co-evolve* with – the architecture-enabled competitive and cooperative dynamics that firms believe currently exist in an industry or may emerge in the future (Pitelis and Teece, 2009). We suggest that understanding these systemic interdependencies is critical to building a firm's dynamic architectural capability to "manage bottlenecks, modules, organizational boundaries, and property rights in pursuit of…competitive advantage" (Baldwin, 2015:43).

We first suggest the basic features of the strategic decision process that firms may undertake when making architectural decisions, and we suggest a typology of strategically different types of product and organization architectures that are the basis for a firm's market strategy and that ultimately determine the kinds of competitive and cooperative dynamics that obtain in an industry. Drawing simultaneously on both open-systems *versus* closed-systems and modular *versus* non-modular systems perspectives then enables us to elaborate how firms' architectural choices are likely to both influence and be influenced by the inter-firm competitive and cooperative dynamics in an industry. Using these two perspectives enables identification of four basic combinations of architecture choices and resulting industry dynamics that may be available to firms, each of which entails different kinds of competitive or cooperative dynamics.

We conclude by suggesting implications for both strategy theory and theories of economic organizing that follow from our architectural perspective on the co-evolution of product and organization architectures with industry competitive and cooperative dynamics.

DESIGN RULES AND THE MIRRORING HYPOTHESIS

Design rules have proved to be a useful, even essential theoretical lens for understanding system-level innovations (Baldwin and Clark, 2000), innovation regimes affecting many forms of costs (Baldwin, 2008; Baldwin and von Hippel, 2011), complementor strategies during platform transitions (Venkatraman and Lee, 2004; Kapoor and Agarwal, 2017), strategic repositioning in response to innovation shocks (Argyres *et al.*, 2019), collaboration with strategic partners (Sanchez and Shibata, 2021), and complementor responses to innovation at the platform level (Argyres *et al.*, 2022). Building on this more focused research, we now suggest how decisions about design rules at the firm level more broadly affect and are affected by evolutions of competitive and cooperative interactions among firms in an industry. We begin by suggesting why firms' strategic architectural decisions fundamentally consist of choosing among alternative pairings of product and organizational architectures that offer efficient alignments of product and organization architectures suggested by the mirroring hypothesis (Colfer 2007).

The mirroring hypothesis can be seen as an extension of Sanchez and Mahoney's (1996) suggestion that the product architecture a firm adopts will significantly influence the organization architecture the firm uses to develop, produce, and support its products.[3] Empirical research has found considerable support for the mirroring hypothesis across a range of industries by examining variables such as the division of labor, extent of communication and information-exchange, and co-location in development processes (Colfer and Baldwin, 2016). While it has been argued that various contingent factors may explain cases where the mirroring hypothesis is not supported (Sorkun and Furlan, 2017), considerable mirroring (i.e., isomorphism) is often (though not always) observed between a firm's product architecture and its organization architecture in the division of labor within and across firms (Burton and Galvin, 2022; MacCormack *et al.,* 2012; Zirpoli and Camuffo, 2009).

Colfer and Baldwin (2016:709) noted that the mirroring hypothesis "*predicts correspondence but does not impose a direction of causality*." The majority of research considered by Colfer and Baldwin (2016) aligns with the Sanchez and Mahoney (1996) proposition that product designs influence organization designs. Evidence from some studies, however, also support a *reverse mirroring hypothesis* alluded to by Colfer and Baldwin (2016) in which a firm's current or potential organization design may influence the product designs it creates (Henderson and Clark, 1990; Colfer and Baldwin, 2016). To the extent that evidence exists for both the mirroring hypothesis and the reverse mirroring hypothesis, the causal relationship between product and organization architectures may best be viewed as intrinsically systemic and thus bi-directional (Fixson and Park, 2008). Sako (2003) observed, for example, that Japanese firms' suppliers' capabilities and relationships appear to influence Japanese automotive firms' choices of components—and thereby the component structure of the firm's product architectures. Similarly, MacDuffie (2013:9) suggested that "even when product and organization evolve to mirror each other, the starting point may be an organizational change as readily as a technical or product change."

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[3] The mirroring relation between a firm's product architectures and the organizational processes and structures through which a firm develops architectures has been extended to recognize corresponding relationships between a firm's product architectures and the firm's enabling knowledge processes and structures -- i.e., its *knowledge achitecture* (Sanchez and Collins, 2001; Zirpoli and Camuffo, 2009).

Instead of firms' organization architectures emerging unilaterally from firms' choices of product architectures or *vice versa*, we suggest here that firms are likely to evaluate and choose among alternative pairings of aligned product and organization architectures and supporting design rules. In line with Williamson’s (1985) notion that a firms' choices of technologies inherently determine their respective organizational boundaries, we suggest that the alignment of product and organization architectures to be sought by firms and implemented through appropriate design rules will be one that enables the efficient coordination of a firm's product development, production, and support processes through its organizational structures and processes -- i.e., the efficient alignment of a firm's product, process, and supply chain domains in Fixson’s framework (2005) and of a firm's component interfaces and activity interfaces in Sanchez’s framework (2008).

STRATEGIC CHOICE OF PRODUCT AND ORGANIZATION ARCHITECTURES

Although a number of factors may influence a firm's overall product strategy, we suggest now that the decisions a firm makes to have an open-system or closed-system and modular or non-modular architecture will have a broad and fundamental impact on the design rules a firm will adopt in creating a new product architecture.

Open-system vs. Closed-system Architectures

The first strategic decision a firm must make in choosing an architecture is whether it would be more advantageous to use a *closed-system architecture* to leverage its own capabilities or to adopt an *open-system architecture* that would help it to draw on the resources and capabilities of other firms. Two factors determine whether an architecture will be an open system or a closed system: (i) technical understanding of how a given architecture works, and (ii) intellectual property rights (IPRs) that control who may or may not use a given architecture.

To use an architecture, a firm must have an adequate technical understanding of the way a given architecture can be partitioned into functional components and of how the interfaces between components enable them to function together as a system. A firm may be able to create a closed-system architecture for its exclusive use if it has technical knowledge about how the architecture works that other firms lack (Baldwin and Clark 2000). Conversely, if a firm wants to use an open-system architecture to engage other firms' capabilities, the firm will have to reveal to other firms how its architecture works technically (Sanchez 2002). The withholding or sharing of knowledge about an architecture works is therefore an essential determinant of whether an architecture becomes a closed-system or an open-system in an industry.

Similarly, if a firm has IPRs (patents, copyrights, and/or trade secrets) that confer the right to exclusive use of an architecture, it may choose to create a closed-system architecture by forbidding other firms from using its architecture, or it may choose to create an open-system architecture by authorizing other firms to use its IPRs.

Thus, whether an architecture is an open-system or a closed-system is not determined by the technical properties of the architecture *per se*, but rather by the strategic decision of a firm either to share its knowledge and IPRs relating to the architecture with other firms (open system), or to keep its architectural knowledge confidential and restrict its architecture to its own proprietary use (closed system). For example, GE-Fanuc Automation opened up its proprietary architecture for factory automation systems by publishing key interface specifications so that other firms can develop sensors and controls that can "plug and play" in its architecture (Sanchez and Collins, 2001). Similarly, Apple licenses developers to use key interface specifications in its proprietary architectures that enable thousands of firms to create new apps for its iPhones, iPads, and Mac computers (Boudreau, 2010).

Modular vs Non-modular Architectures

Both open-system and closed-system architectures maybe either *modular or non-modular.*

In a modular architecture, interfaces are specified to allow the substitution of a range of component variations that can readily plug and play in the architecture to configure product variations (Garud and Kumaraswamy, 1995; Sanchez, 1995). Firms that participate in an architecture that is both open-system and modular may then use the architecture as a "platform" for exchanging a range of architecturally compatible product component variations as well as various organizational activities that can plug and play in the architecture's various development activities. Development and exchange of components and activities among firms using a common open-system modular architecture may enable them to undertake product strategies in which they configure large numbers of modular product variations and/or rapidly upgrade products as new and higher-performing modular component variations are developed and exchanged within the common architecture (Garud and Kumaraswamy, 1995; Sanchez, 1995, 2008; Sanderson and Uzumeri, 1996; Tee, 2019).

By contrast, firms in less technically sophisticated product markets often use traditional non-modular open-system architectures. For example, firms in traditional product markets like furniture, clothing, and simple hand tools typically use very simple, widely emulated non-modular architectures for their products. The long-standing use of traditional architectures in these product markets has often led to the adoption of various kinds of *industry standard components* like metal brackets for connecting furniture parts, zippers and pockets that can be sewn into all kinds of clothing, and various kinds of handles that are used by almost all makers of hand tools. In such markets, a firm that adopts an established non-modular open-system architecture may realize significant cost-savings by using standard components that are produced at large scale and achieve significant economies of scale.

Analogously, closed-system architectures may also be modular or non-modular.

A firm may choose to adopt a non-modular closed-system architecture when it believes a relatively limited and stable offering of its products produced at only its own scale of production will succeed in the market. By contrast, a firm may choose a modular closed-system architecture when it feels the need to configure greater product variety and/or more rapidly upgrade products (Sanchez, 1995; Worren *et al.*, 2002; Kotha and Srikanth, 2013). A firm may develop component variations for its modular closed-system architecture exclusively through its own internal capabilities or may subcontract for specific development, production, or support services (while retaining exclusive use of the architecture). Because of the idiosyncratic nature of the components and modular interfaces in a closed-system architecture, however, a firm may face significant technical challenges and costs in trying to coordinate development and other activities with other organizations whose architectural knowledge and design rules differ from its own.[4]

Strategic Architecture Decision Process

Traditional views of strategy and of firms' strategic decision processes have focused on defining competitive strategies that individual firms may pursue in their product markets (Porter, 1980). The architectural perspective on the interactions between firms in an industry that we develop here, however, suggests that at least some firms may be engaged in broader, more multidimensional forms of strategizing about both competitive and cooperative interactions with other firms. The product and organization architectures that a firm chooses will largely determine the resources and capabilities a firm will be able to use in creating, producing, and supporting its products. Thus the nature of the competitive and/or cooperative strategies a firm can pursue will be significantly enabled or limited by the product and organization architectures a firms chooses. An architectural perspective on firm strategies suggests that a firm's strategic choices may vary significantly not just with its own capabilities relevant to the current structure of the product market it chooses to compete in, but also with the kind of interfirm relationships and industry dynamics the firm chooses to participate in -- or to try to create.

At the firm level, the strategic decision process for identifying, evaluating, and selecting alternative kinds of open-system *versus* closed-system and modular *versus* nom-modular product architectures, their derived design rules for coordinating both internal processes and cooperative processes with other firms,

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[4] The technical expertise that firms accumulate in developing, producing, and supporting a product architecture will become structured in *knowledge architectures* that reflect the firm's accumulated expertise about functional component designs and about interfaces that are effective in controlling the interactions between functional components in their product architecture. Incompatibilities among the knowledge architectures used by firms in an industry are also likely to lead to significant differences in the design rules the firms follow and thereby to limit possibilities for collaborative activities among those firms (Sanchez, 2000).

and resulting competitive and cooperative dynamics in an industry is likely to be a highly complex process.[5] In the aggregate, the collective architectural decisions of individual firms may either preserve current modes of competition in an industry, or as we suggest here, they may drive the emergence of alternative industry architectures, structures, and dynamics for creating and providing products to a market.

Figure 1 identifies the essential questions a firm must answer in its strategic architectural decision-making process, as well as the four logically possible outcomes of that decision process. Although individual firms' approaches to answering these questions may vary, we suggest that a strategic architecture decision process must include (i) assessing whether a firm's own capabilities enable the firm to create a strategically viable "stand-alone" closed-system architecture; (ii) identifying and evaluating what possibilities exist for the firm to draw on the capabilities of other firms by creating a new open-system architecture or by joining an emergent or existing open-system architecture; (iii) deciding the relative attractiveness and feasibility of adopting a closed-system architecture compared to whatever possibilities the firm has identified for adopting open-system architectures.

<<<<----- Insert figure 1 here ----->>>>

Choosing to create a closed-system architecture is essentially a strategic decision to rely on the firm's own resources, capabilities, and internal coordination processes to create and use an idiosyncratic product architecture to compete against other firms. Choosing to create or join an open-system architecture in which other firms participate, on the other hand, is effectively a decision to adopt an architectural platform strategy that will require defining design rules for accessing and coordinating the resources and capabilities of cooperating firms in bringing the firm's products to market (Sanchez and Collins, 2000; Argyres and Bigelow, 2010).

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[5] Launching and sustaining different kinds of organizational architectures and attendant value-creation processes in multiple product markets can create considerable management complexity for large, multi-product firms. We suggest that large, multiproduct firms engaging in multiple forms of architecture-enabled competition will tend to "economize on bounded rationality" (Williamson, 1981:1556) by organizing their different architecture-enabled value-creation processes in separate, focused organizational units -- providing a contemporary architectural perspective on the persistence of the large, multi-divisional ("M-Form") enterprise (Chandler, 1962, 1977).

HOW ARCHITECTURES ENABLE VALUE CAPTURE

Central to the strategic decision process described above is the assessment of a firm's opportunities for creating and capturing value through alternative kinds of product and organization architectures. Zajac and Olsen (1993) suggest that the division of labor and resulting firm specializations in an industry are likely to reflect firms' collective beliefs about the relative profitability of various kinds of strategies they may pursue. We now suggest that the structure and dynamics of an industry will reflect firms' beliefs about the relative potential for *net value capture* -- i.e., the value they can create less the transactions costs they must incur -- that may be enabled by alternative kinds of architectures that firms may adopt as vehicles for realizing their strategies.

We first consider how heterogeneous capabilities across firms in an industry may create differential possibilities for firms to capture *gains from specialization* and *gains from trade* through use of either open-system or closed-system architectures. We also analyze how modular versus non-modular architectures are likely to affect firms' *ex-ante* and *ex-post transaction costs* in their interactions with other firms. We then combine the firm-capabilities and transaction-costs perspectives on firms' strategic organizing decisions to suggest how these fundamental economic concerns are likely to influence a firm's choice of open-system versus closed-system and modular versus non-modular architectures.

Impacts of Architectures on Gains from Specialization and Gains from Trade

We next adopt a firm capabilities perspective to suggest how a firm's choice of open-system vs. closed system architecture is likely to affect its ability to capture gains from specialization and/or gains from trade (Jacobides and Hitt, 2005; Baldwin, 2008).

Economic theory has long recognized that firms that specialize in a particular productive activity may ‘deepen their expertise’ in ways that result in lower costs and/or better quality for their products, thereby realizing gains from specialization in productive processes (Smith, 1981). When at least some firms specialize in the various "technologically separable activities" (Williamson, 1985) that collectively compose the overall productive process in an industry, other firms may realize gains from trade with specialist firms by obtaining lower-cost and/or higher-quality components and supporting activities that enable them to offer more successful and profitable final products (Stigler and Sherwin, 1985).

In addition to the transactions costs that firms may incur in bilateral exchanges with other firms (Williamson, 1985:193-195), we suggest here that the potential for capturing gains from specialization and/or trade may vary considerably depending on whether exchanges between firms are taking place within an open-system or closed-system architecture regime, in large part because of the differences in appropriability usually associated with the two kinds of architectures (Teece, 1986).

Gains from specialization and gains from trade in a closed-system regime

A strategic choice to adopt a closed-system architecture is likely to be driven by a firm's belief that it can obtain its greatest strategic benefits by using its own specialized capabilities to develop, produce, and support distinctive products. A firm that adopts a proprietary architecture is therefore likely to rely on vertically integrated activities coordinated by its own set of design rules to develop and provide key components and activities (Klein *et al.*, 1978).[7]

In effect, when a firm chooses to create and use its own closed-system architecture, it is essentially making a strategic decision to engage in atomistic, stand-alone, Porterian competition with other firms in its industry and with its suppliers (Porter, 1980). Although a firm choosing a closed-system architecture may also try to capture gains from trade by licensing its technology or developing components for other firms, design rules for coordinating such transactions may be difficult to implement because of architectural differences in the firm's components, interfaces, and knowledge base compared to other firms. Value capture by firms using closed-system architectures is therefore likely to be primarily sought through gains

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[7] Nevertheless firms using closed-system architectures may engage in arm's-length subcontracting for development and/or production of components in which they believe they do not have an advantage.

from specialization that can be captured by profitably selling distinctive products made possible by their specialized capabilities (Jacobides, 2006).

Gains from specialization and gains from trade in an open-system regime

The strategic partitioning of an open-system architecture into well-defined types of components and interfaces creates opportunities for firms to specialize in specific types of product components and support activities that are useful to other firms using the same open-system architecture. When an open-system architecture is supported by a well-defined and stable set of design rules that facilitate developing and exchanging compatible components and activities, open-system architectures often attract the participation of firms whose distinctive capabilities give them comparative advantages in developing, producing, and supplying specific kinds of components and activities (Jacobides, 2005; Sanchez, 2008; Windrum *et al.*, 2019). When a market for components and support activities forms around an open-system architecture, win-win, positive-sum transactions are likely to result in which component specialists capture gains from specialization while assembler firms capture gains from trade with the specialist firms.

How modularity affects value creation in open-system versus closed-system architectural regimes

The gains from both specialization and trade available to firms participating in either open-system or closed-system architectural regimes may be enhanced significantly when the architectures are modular. Most notably, as Sanchez and Mahoney (1996) suggest, the fully-defined interface specifications that are an essential feature of modular architectures provide an information structure that greatly facilitates bilateral contracting between component specialist and assembler firms in both open-system and closed-system regimes. The information structure created by modular interface specifications enables specialist firms to capture gains from specialization by developing and/or producing components that are compatible with a given architecture. Likewise, assembler firms may capture gains from trade by sourcing modular components from specialist firms that enable assemblers to configure more product variations and achieve higher quality and performance levels in their products (Galvin *et al*., 2020; Sanchez, 1995; Sanderson and Uzumeri, 1996).

We further suggest that both component specialists and assembler firms may also benefit from a number of important *architectural externalities* that are created when open-system architectures are modular (Sanchez, 2008; Boudreau, 2010). On the supply side, the well-defined functional structure and interface specifications of a modular architecture generally reduces the technical information search and processing costs for firms that are interested in entering an industry, including the costs of specifying, designing, testing, and maintaining products in an industry. The widespread adoption of a modular architecture by firms in an industry may also stimulate the education of engineers and training of technicians in the design and servicing of components and products compatible with the modular open-system architecture, thereby relieving individual firms of incurring such costs (Sanchez, 2000; Funk, 2008).

On the demand side, the well-defined functional component structure and interface specifications of a modular open-system architecture may facilitate market understanding and thus acceptance of new product concepts, as well as stimulate market demand by helping customers understand available levels of product performance and differences among alternative modular product variations (Sanchez, 2002). In addition, the larger scale of production of components and products within a modular open-system regime (compared to production levels likely to be achieved within a stand-alone architecture) may further stimulate demand by lowering initial product costs, costs of replacement parts and components, and costs of maintenance and repair. Modular open-system regimes may also be viewed as preferable by customers concerned to avoid the lock-in that use of products based on non-modular closed-system architectures often entails (Arthur, 1994). Modularity-enabled externalities like these may help to reduce both actual and perceived costs and thereby increase market demand for products leveraged from modular open-system architectures, resulting in more rapid new market formation and growth that increases gains from both specialization and trade by firms participating in a modular open-system regime.

The architectural externalities created by modular open-system architectures may give rise to significant levels of "co-opetition" among firms in an industry, typically in the form of upstream cooperation in developing and supplying modular components occurring simultaneously with downstream competition in finished products configured from a modular open-system architecture (Nalebuff and Brandenburger, 1996; Gnyawali *et al.*, 2006; Golnam *et al.*, 2014). While some firms may have special capabilities that are relevant only to specific components, other firms (especially large firms) may have both special capabilities relevant to one or more components as well as more general capabilities useful to a producer and marketer of final products. Such firms may—and often do—decide that they have comparative advantages in developing and producing specific components that make it possible to pursue dual-distribution strategies in which they capture gains from specialization by supplying modular components to themselves and gains from trade by supplying he same or similar components to other firms using the same open-system architecture (Jacobides, 2005; Safizadeh *et al.*, 2008). For example, Philips, Sony, Matsushita, and other major consumer electronics firms have (or have had) business units that both sell various modular components to other industry participants as well as supplying components to their own final-product business units (Parmigiani, 2007; Sanchez, 2008).

Impacts of Architectures on Transaction Costs

A firm's strategic choice of architecture and associated design rules may profoundly affect the *transaction costs* the firm is likely to face in developing, producing, and supporting its products in its industry. How firms' architectural choices are likely to affect both their *ex-ante* and *ex-post* transaction costs should therefore be a central concern in any transaction costs analysis (Langlois, 2006; Baldwin, 2008). While the open-system or closed-system nature of an architecture has a broad effect on the ability of firms to capture value from specialization and trade, whether a firm's architecture is modular or non-modular will usually be the primary architectural determinant of the transaction costs a firm will face.

Ex-ante and ex-post transaction costs

In classical transaction costs economics (TCE), ex-ante transaction costs represent the "costs of drafting, negotiating, and safeguarding an agreement" (Williamson, 1985:20). Ex post transaction costs include (i) the costs of "maladaptation…when transactions drift out of alignment," (ii) "haggling costs incurred if bilateral efforts are made to correct *ex post* misalignments," (iii) "the set-up and running costs associated with the governance structures to which disputes are referred," and (iv) "the bonding costs of effecting secure commitments" (Williamson, 1985:21).

Both *ex-ante* and *ex-post* transaction costs are influenced by the three critical dimensions of economic transactions: uncertainty, frequency, and asset specificity (Williamson, 1979:239; Macher and Richman, 2008). Uncertainty increases the ex-ante costs of trying to write adequate contracts and results in some degree of 'incompleteness' in a contract (Hart, 1995; Baldwin, 2008). Any resulting contractual incompleteness may lead to ex post costs arising from unforeseen contingencies that may require further negotiations, or from 'hold up' if transaction partners engage in opportunistic behavior (e.g., price gouging). The frequency of transactions acts as a multiplier on the ex post transaction costs associated with each contract a firm makes. Asset specificity creates a risk that any specific-use assets on which a contracting firm's processes depend may not be available (or may not be available on pre-agreed terms) when needed by the firm.

Influence of modular architectures on ex-ante and ex-post transaction costs

In highlighting and analyzing the effects of modularity on transaction costs, Baldwin (2008:156) suggests that the classical concepts of ex-ante and ex-post transaction costs can be further elaborated by distinguishing certain kinds of architecture-determined "mundane transaction costs" that can be incurred ex ante in order to reduce ex-post "opportunistic transactions costs."

Baldwin characterizes the costs of creating modular architectures and associated design rules as an ex-ante mundane transaction cost that reduces ex post opportunistic transaction costs involved in developing and producing products. Ex-post transaction costs can be reduced, for example, by ex ante using modular interface specifications to define the technical properties of modular components to be transacted for and to develop specific measures for assessing component quality and performance, thereby enabling use of the market price mechanism in ex post transactions for components. Langlois (2006) further characterizes the creation of legal, technical, and organizational standards as mundane transaction costs that help to reduce ex-post opportunistic transaction costs. For example, ex post transaction costs can be reduced when firms use the full specifications of components and interfaces required for a modular architecture to define technical standards to be met in developing new components, standard contracts for developing modular components, and standard contracting and monitoring procedures for inter-firm transactions within a modular regime.[8] We now extend this line of reasoning to suggest that firms need to consider carefully the trade-offs that may be available between ex-ante and ex-post transaction costs in deciding whether to participate in a modular open-system or modular closed-system architecture regime.

For example, the ex-ante mundane transaction costs of organizing cooperative development processes for modular open-system components must be weighed against the ex-post costs incurred when a single firm undertakes internal development of modular components for a closed-system architecture.[9] A firm considering a closed-system architecture is likely to face relatively low *ex-ante* mundane transaction costs for organizing its own development processes, primarily because there will be no need for achieving ex-ante coordination and agreement on design rules with other firms. However, choosing a closed-system development process essentially commits a firm to bearing ex-post all the costs incurred in internally developing components for its closed-system architecture.

By contrast, in decision processes for evaluating adoption of a modular open-system architecture, a firm may face greater ex-ante costs (and possibly time delays) in organizing component development processes and agreeing on design rules with various development partners. However, to the extent that two or more firms can share the ex-post costs of developing new components (and also reduce time-to-market

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[8] TCE focuses on transactions between firms -- most notably, between a firm and its suppliers. Sanchez (2002) suggests, however, that many of the ex-ante factors that affect ex-post transaction costs between firms also apply to a firm's transactions with customers and end-users of its products. In particular, the uncertainty reduction that comes from clear and complete specification of modular product components and their performance standards not only enables the price mechanism to be used in inter-firm supply transactions, but may also facilitate the acceptance and pricing of new products in consumer markets.

[9] In fast-moving product markets, the *opportunity costs* associated with different times-to-market offered by alternative approaches to organizing and performing development processes may have greater economic importance than actual out-of-pocket costs for organizing and carrying out development processes.

by undertaking concurrent component development processes), the *ex-post* transaction costs that individual firms incur in developing components for a shared open-system architecture are likely to be relatively low compared to the *ex-post* costs incurred by a single firm in developing components for a closed-system closed-system architecture.

Recalling Langlois' (2006) and Baldwin's (2008) arguments that ex-ante costs of creating modular architectures and associated design rules may significantly reduce several kinds of ex-post transaction costs, and recalling our suggestion that use of modular open-system architectures may enable firms to adopt similar design rules and engage in cooperative development processes that lower both the ex-ante costs of organizing and the ex-post costs of developing and producing components for an open-system architecture, we now advance the general proposition that *adopting a modular open-system architecture may significantly reduce both ex ante and ex-post transaction costs* for firms that participate in the open-system regime, relative to the costs of a firm creating its own closed-system architecture.

Moreover, to the extent that modular open-system architectures enable significant reductions of total transaction costs compared to the costs of adopting closed-system architectures or non-modular open-system architectures, we further propose that *open-system architectures that emerge in an industry are likely to be modular,* and that *adoption of modular open-system architectures will be increasingly common* in industries where modular architectures enable use of similar design rules that reduce overall transaction costs, *ceteris paribus* (Sanchez, 2003; Baldwin, 2008). For example, Galvin and Morkel's (2001) study of the global bicycle industry suggests that use of a modular open-system architecture rapidly became a "dominant logic" (Prahalad and Bettis, 1986) in that industry after an emergent modular architecture pioneered by new Asian firms such as Shimano, Nitto, and Ukai demonstrated that it could lead to significantly reduced *ex-ante* and *ex-post* transactions costs for both established firms and new entrants.

ARCHITECTURE-ENABLED COMPETITIVE AND COOPERATIVE INTERACTIONS

Within the architectural perspective on firms' strategizing processes we have outlined above, we suggest that an individual firm's strategic deliberations and resulting decisions about architectures and design rules are likely to revolve around two questions: (i) Whether to compete against other firms through a "stand-alone" closed-system architecture, or to seek the benefits of cooperating with other firms through an open-system architecture; and (ii) whether its chosen architecture should be modular or non-modular. We suggest that these two fundamental aspects of a firm's architectural choices are strategically critical because a firm's decisions to use a closed-system *versus* open-system architecture and/or a modular *versus* non-modular architecture effectively commits the firm to pursuing one of *four distinct kinds of competitive or cooperative interactions with other firms* in its industry. These four types of architecture-influenced inter-firm interactions are summarized in **Figure 2.** Examples of each of the four types are discussed below.

<<<<-----Insert figure 2 here----->>>>

Adopting a closed-system architecture implies that the firm controlling and using the architecture will primarily engage in Porterian competitive interactions with other firms in its industry and will rely largely on its own internal capabilities and on arm's-length contracting[14] to create and assemble components and conduct support activities for its products. Modularity may be used in a closed-system architecture if the controlling firm intends to develop significant component variations and upgrades in order to configure product variations and improve product performance. Sony and Philips in consumer electronics, Apple and Samsung in smart phones, and most large firms in the automotive industry pair their modular closed-system architectures with modular organizational designs to coordinate globally-dispersed business units (Kapoor and Agarwal, 2017). This pairing of product and organization architectures allows such firms to use modularity to gain the benefits of increased product variety and reduced costs of components while maintaining a closed system for controlling which firms can provide components and services for their closed-system architectures (Elia *et al.,* 2019; Meissner *et al.,* 2021).

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[14] We retain a Porterian view of contracting for components or services by a firm that chooses to compete through a closed-system architecture and therefore characterize arm's-length contracting as essentially competitive interactions between buyer and supplier (Porter, 1980).

However, if a firm believes its market does not require the introduction of many product variations and that its own scale of production provides an acceptable cost basis for its components relative to the price it can obtain for its products, a firm may choose to use a (largely) non-modular closed-system architecture. Specialist producers of very high-end stereo equipment and speaker systems, such as Geithain and Backes & Mueller typically use non-modular closed-system architectures for their limited ranges of highly distinctive products (Galvin *et al*., 2020), as do specialist makers of exotic automobiles produced in limited production runs (like Aston Martin, Bugatti, Ferrari, and Lamborghini).

By contrast, adopting an open-system architecture implies that a firm sees strategic advantage in increasing the ease and efficiency with which it may engage in cooperative activities with other firms. In particular, adopting a modular open-system architecture with well-articulated design rules may enable a network of participating firms to readily develop and exchange component variations in order to increase product variety, upgrade product performance, and lower product costs by obtaining economies of scale in the mass production of common components. Networks of firms using modular open-system architectures to compete against firms using proprietary modular architectures are now a common feature of well-developed markets -- witness the ongoing competition between digital device producers using open-system modular architecture operating systems like Android and producers like Microsoft and Apple using proprietary modular architectures like Windows and Apple iOS for their operating systems.[15]

When market demand for extended product variety and rapid upgrading is low, however, use of a non-modular open-system architecture may enable firms to create distinctive products with their own unique architecture, while achieving some shared cost efficiencies by using "industry-standard" parts and components that are compatible with their non-modular open-system architecture. For example, mass-produced, low-cost off-the-shelf parts and components (like motors, pulleys, bearings, and fasteners) are

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[15] More generally, we suggest that well-developed product markets with market segments that reward a range of performance levels will often include a mix of *both* competitively-priced, acceptably-performing, mass-produced products leveraged by large firms from their modular open- and closed-system architectures, on the one hand, *and* at the same time higher-priced, high-performing, limited-production products leveraged by smaller producers from (largely) non-modular closed-system architectures.

widely used in non-modular closed-system architectures. Companies producing commercial lighting solutions, for example, typically use industry-standard electrical components (wiring, bulbs, sockets, connectors, etc.) in combination with distinctive designs for more visible components to distinguish their company-specific products in the marketplace. A similar mix of firm-specific components and industry-standard, off-the-shelf components can be found in the non-modular open-system architectures commonly used in home appliances, HVAC (heating, ventilation, and cooling) systems, farm equipment, and many other industries (Worren *et al.*, 2002).

SYSTEMIC INTERDEPENDENCIES BETWEEN PRODUCT MARKET EVOLUTION, FIRMS' ARCHITECTURE CHOICES, AND INDUSTRY ARCHITECTURE EVOLUTION

We now develop a general model suggesting how the collective architectural choices made by firms in an industry mediate between *product market evolution* (represented by firms' entrepreneurial responses to changing market preferences and emerging product concepts) and *industry architecture evolution* (represented by changes in the architectures and associated design rules used in an industry and in an industry's resulting competitive and cooperative inter-firm dynamics).

<<<<-----Insert figure 3 here ----->>>>

As suggested in Figure 3, on the product market side, new market opportunities and new product concepts arise from ongoing changes in customer preferences for various kinds of products, changes in regulatory regimes, and changes in available technologies for providing both existing and new kinds of products to markets. Changes in customer preferences may be driven by broad changes in the economy, societal priorities, cultural values, and other macro-environmental factors (Thomas and Gupta, 2005). Regulation plays a crucial role in many industries and while they often provide a level of stability to the industry over time, regulatory changes can be used to open up markets and encourage innovation across industry participants (Burton and Galvin, 2022; Freij, 2021). Further product market change may be driven both by technical developments within an industry and by spill overs of new technologies developed in other industries (Bettis and Hitt, 1995). All these forms of change may present firms with new opportunities to undertake entrepreneurial action to create new and improved products in their current industry or in new industries in formation.

The entrepreneurial action that drives changes in product markets may be a response to Schumpeterian opportunities to upset existing market equilibria by introducing breakthrough innovations in products or market processes (Schumpeter, 1911). More commonly, however, entrepreneurial action may be more incremental in nature and result in a progression of incremental improvements to and a progressive evolution of existing product concepts (Kirzner, 1973). The rate and extent of product market evolution will depend on the extent to which at least some firms seek to "shape rapidly changing business environments" by creating new kinds of products and supporting organizational forms and market processes (Teece, 2012:1395; Pitelis and Teece, 2009). Thus, while much product market evolution is likely to consist of incremental improvements within established product architectures (Worren *et al.*, 2002), from time to time market evolution will create opportunities for firms to create new kinds of product architectures for offering new kinds of products and processes to the market (Sanchez, 1995, 2008; Burton, 2018).

Thus, the architectures that firms choose may *both drive and be driven by* changes in the consumer preferences and technological possibilities in a given product market. A market's evolving interests in new and improved products and firms' perceptions of architectural possibilities for responding to those interests are thus systemically interrelated and co-evolving.

On the industry side of our general model in Figure 3, we have suggested how firms' collective choices of architectures determine the structural "division of labor" and ensuing interfirm dynamics in an industry (Jacobides *et al.*, 2006). Changes in both industry structure and dynamics are driven by the outcomes of individual firms' strategic architecture decision processes suggested in Figure 1.

In our prior discussion and now in Figure 3 we also suggest that the outcomes of firms' strategic architecture decision processes may reflect *both* the mirroring hypothesis (Sanchez and Mahoney; 1996; Colfer, 2007) and the reverse mirroring hypothesis (Colfer and Baldwin, 2016). In effect, we suggest that firms' strategic architecture decision processes as summarized in Figure 1 involve *joint consideration* of the ways in which a firm's organization design could and should reflect its product designs and at the same time the ways in which a firm's product designs could beneficially reflect the actual or potential organization designs a firm uses.

In effect, we suggest that the product and organization architectures in use at any time in an industry may be understood as alternative architecture-enabled industry systems with distinctive kinds of design rules for managing ex-ante and ex-post transaction costs and enabling capture of gains from specialization and trade. Thus, within a given industry, there may well be firms engaging in atomistic competition via closed-system architectures with idiosyncratic design rules, while other firms use modular open-system architectures in which potentially many firms follow common modular design rules to cooperate in developing, producing, and supporting new products.

CONCLUSION

We conclude by suggesting what we believe are some of the most important implications of our co-evolutionary architectural perspective on firms' strategic architecture choices and implied design rules and their implications for firm and industry organization.

Systemic Representation of Product and Organization Architectures

We have suggested that the strategic architectural decisions managers make are essentially a joint choice process in which firms identify, evaluate, and choose among possible pairings of aligned product and organization architectures, each of which will have its own distinctive set of supporting design rules.

We also suggest that this process of comparative strategic evaluation and decision-making is an ongoing process that is driven by firms' evolving perceptions of the potential to realize net gains by using alternative pairings of aligned product and organization architectures to respond to current and emerging market opportunities. Firms' evolving strategic decisions whether to compete through proprietary closed-system architectures or to collaborate with other firms by using open-system architectures drive the evolution of the architectures, derived design rules, and resulting interfirm competitive and/or cooperative dynamics that characterize an industry at any point in time. This more comprehensive systemic perspective on firms' architectural choices leads us to propose our general model (Figure 3) in which firms' individual and collective architectural decisions mediate between the evolution of industry product evolution and the evolution of an industry's architectures and its resulting competitive and cooperative dynamics.

New Perspective on Industry Structures

We suggest that the architectural perspective we develop here supports some important elaborations beyond Porterian concepts of inter-firm competitive interactions and industry structures (Porter, 1980) by shedding light on ways in which architectures and associated design rules help to shape contemporary industry structures and dynamics.

In a basic sense, the architectures that various firms choose as the basis for their strategies determine the value creation systems that become the basis for the production of goods in an industry. When significant numbers of firms begin to use the component designs, interface specifications, and associated design rules of a shared open-system architecture to coordinate their value-creation activities (e.g., in developing and exchanging modular components), the interactions between firms no longer resemble the atomistic, zero-sum competition that is the staple of the Porterian view of an industry. Rather, interfirm interactions take on the character of "co-opetition" based on positive-sum interactions within networks of firms that mutually benefit from using common product and organization architectures and derived design rules (Galvin and Morkel, 2001; Fixson and Park, 2008; MacDuffie, 2013; Jacobides *et al.*, 2018; Golnam *et al.*, 2014).

In effect, the architectural perspective we suggest here enables us to see industries through a new lens that highlights *competing architecture-enabled industrial systems* for creating and capturing value, some of which consist of stand-alone firms using proprietary design rules and some of which are supported by firms using shared open-system architectures. We suggest that this perspective enables a useful, more contemporary interpretation of industries as architecture-enabled value-creation ecosystems.

Integration of Micro- and Macro-level Views of Economic Organizing

We also suggest that our architectural perspective has significant potential to help achieve a useful integration of micro-economic and macro-economic theories of economic organizing, as well as clarification of the role that design rules play in processes for economic organizing (Sanchez and Mahoney, 2013). The architectural perspective we advance here not only enables identification of important architecturally-enabled relationships among firm strategies, structures, and processes, but also suggests how decisions about those factors made at the firm level interact with and shape industry-level structures, processes, and competitive and cooperative dynamics.

For example, the perspective on firms' strategic architecture decisions that we have elaborated here provides a basis for analyzing and predicting the likelihood that firms will adopt permeable boundaries for various activities in their value chains (Jacobides and Billinger, 2006; Parmigiani, 2007). Likewise, we have suggested how the individual architectural decisions of firms at the micro-level may shape the competitive and cooperative interactions among firms at the macro-level in an industry (Langlois, 2003; Jacobides *et al.*, 2009). We therefore suggest that the architectural perspective on firm and industry organization that we suggest here may help to extend our understanding of the systemic interrelationships between decision-making about economic organizing at the firm level and the emergence of economic structures, processes, and dynamics at the industry level, and the role that design rules play in mediating these two kinds of market processes.

Modular Open-system Architectures as a New Dominant Logic

Our discussion has suggested that a firm that chooses to create or join a modular open-system architecture may both improve its ability to capture gains from specialization and gains from trade *and* reduce its ex-ante and ex-post transaction costs If this is so, then unless a firm has a clearly superior set of capabilities that enables it to capture greater gains from specialization through a stand-alone closed-system architecture, it appears that *modular open-system architecture regimes may offer broadly advantageous avenues for many (if not most) firms to organize their economic activities*. This expectation is consistent with a growing body of research suggesting that extensive vertical disaggregation and use of collaborative development and outsourcing coordinated through shared design rules have become virtual norms in growing numbers of industries based on modular open-system architectures (Cabigiosu *et al*., 2013; MacDuffie, 2013; Kotha and Srikanth, 2013; Jacobides *et al*., 2018).

Moreover, in a world in which the capabilities of firms are rapidly improving, any single firm is increasingly unlikely to have all the capabilities needed to develop and produce successful products on its own (McDermott *et al.*, 2013). Therefore, 'go-it-alone' strategies begin to look increasingly risky and unsustainable. As growing numbers of firms around the world acquire technological capabilities that enable them to develop and produce high-quality components and to provide supporting services for many kinds of products, and as the power of design rules to achieve coordination of processes and reap the benefits of coopetition within shared open-system architectures become better understood (Golnam *et al*., 2014), more firms may find it economically more attractive to create and capture value through open-system modular architectures than through their own proprietary designs (Sanchez and Collins, 2001). We therefore suggest that the increased value-capture benefits and lower transaction costs enabled by modular open-system architectures help to explain why use of modular open-system design rules has already become a *dominant logic* for competing in many, if not most, product markets (Prahalad and Bettis, 1986; Galvin and Morkel, 2001; Sanchez, 2008; Argyres and Bigelow, 2010).

Suggestions for Further Research

A key possibility suggested by our analysis of how a firm's choice of architectures and associated design rules may affect its potential gains from specialization and trade is the prospect that firms using a modular open-system architecture will be able to sell their components and activities to other firms participating in the same regime. By now the 'co-opetition formula' of cooperating upstream in the development, production, and exchange of components while competing downstream in final product markets has become a familiar and readily observable phenomenon in many industries (Lado *et al.*, 1997; Kim and Parkhe, 2009; Peng and Bourne, 2009; Peng *et al.*, 2012).

Thus far, however, both economics and strategy have paid relatively little attention to the emergence and functioning of *efficient markets for exchanging intermediate inputs* (i.e., components and services) within modular open-system regimes. Thus, some shifting of focus in strategy and economics research would now seem in order -- from traditional atomistic perspectives on product market competition among individual firms to developing better theoretical understanding of how modular architectures and their associated design rules enable efficient markets for cooperative, mutually beneficial exchanges of components and activities to emerge within modular open-system regimes. Such research could no doubt contribute to developing a more informed view of the strategic evaluations that managers actually make today in deciding the most advantageous kinds of product and organization architectures on which to base their firm's strategies.

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