20. Modularity and economic organization: concepts,theory, observations and predictions

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This chapter addresses modularity as a basis for organizing economic activity. We first define the key concepts of architecture and of modularity as a special form of architecture. We then suggest how modular systems of all types may exhibit several properties of fundamental importance to the organization of economic activities, including greater adaptability and evolvability than systems that lack modular properties. We draw extensively on our original 1996 paper on modularity and subsequent research to suggest broad theoretical implications of modularity for: (1) firms' product strategies and the nature of product market competition; (2) the organization designs firms may adopt and the industry structures that can result when significant numbers of firms adopt modular product architectures; and (3) learning processes and knowledge structures at the firm and industry levels in modular product markets. We also discuss an evolutionary perspective on modularity as an emergent phenomenon in firms and industries. We explain how modularity as a relatively new field of strategy and economic research may provide a new theoretical perspective on economic organizing that has significant potential for achieving important integrations of microeconomic and macroeconomic theory. We suggest some areas for further research that may be especially fruitful in this regard.[1]

INTRODUCTION

At the most general level, this chapter addresses modularity as a fundamental approach to organizing complex systems of all kinds – technical, social and economic. A complex system is one made up of a large number of parts that may have many different kinds of interactions. Modularity is a way of hierarchically[2] ordering complex systems into quasi-separable subsystems. This ordering may be applied recursively to subsystems until the lowest level of elementary components is reached. Within this hierarchical ordering, modular systems have the property of 'near decomposability' in which intra-component linkages within subsystems are stronger than inter-component linkages among subsystems (Simon 1962). As a result of this characteristic, modular systems of all types exhibit several properties of fundamental importance to the organization of economic activities, including greater adaptability and evolvability than systems that lack modular properties.[3]

In the following discussion, we draw extensively on our original paper on modularity (Sanchez and Mahoney 1996) as well as on a growing body of modularity research to outline the major implications for economic organization of the use of modularity in product, process, and organization designs.

We begin our discussion with formal definitions of modularity and several related

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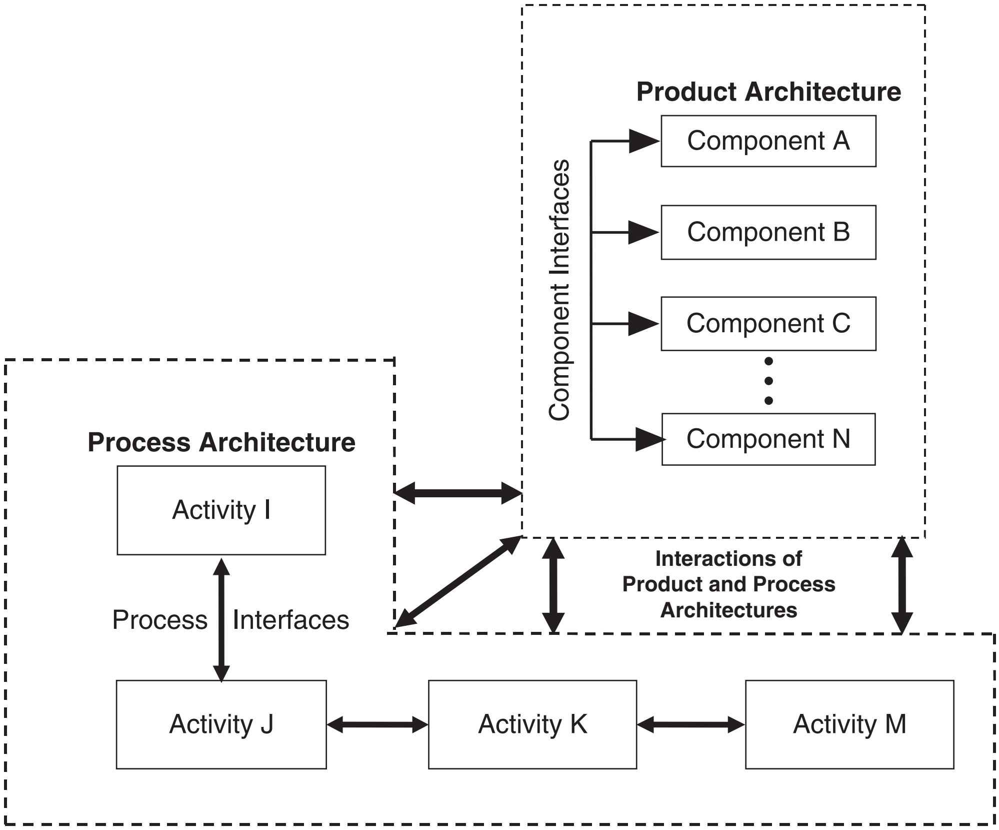
concepts that are important in our exposition of the implications of modularity for economic organization. We then draw on our original paper and related research to suggest three broad theoretical implications of modularity for the ways in which the economic activities of creating, producing, and supporting products and services can be – and increasingly are – organized. We consider in turn the predicted impacts of modularity on: (1) firms' product strategies and the nature of product market competition; (2) firm organization and industry structures; and (3) learning processes and knowledge structures at the firm and industry levels. We also provide some observations to support these predictions. We then discuss a relatively new perspective introduced by Boisot and Sanchez (2010) on modularity as an emergent phenomenon in firms and industries.[4]

Finally, we conclude by suggesting the further potential of the modularity concept – and more generally, of an architectural perspective on economic organization – to provide an integrated theoretical view of the dynamic interdependencies that link firms and industries. We suggest that further development of the modularity and architectural perspectives may provide a new conceptual basis for integrating micro- and macro-level theories of economic organization that can deepen our understanding of both the micro-processes and resulting macro-outcomes of economic organizing – that is, of both the formative processes and emergent forms of economic systems of all kinds – that are as yet not clearly articulated in strategy or economics theories.

DEFINITIONS

Modularity is a special form of architecture, and thus to define modularity we must first clarify the meaning of an architecture. An architecture is a way of describing or defining the design of a system – whether the design is an intended system design for a product, process or organization (Sanchez & Mahoney 1996), or an emergent system design for an organization, industry or economy (Boisot & Sanchez 2010). An architecture is a two-part concept. Firstly, an architecture defines the way in which the overall functions that a design is intended to perform have been decomposed into specific functional components – that is, the functional 'building blocks' of the design (Sanchez & Collins 2001; Tu et al. 2004). Secondly, an architecture also defines the ways in which the functional components that make up the design will interact when the components function together as a system – what are most commonly known as the interface specifications that define how components will connect or otherwise interact together (Sanchez 1995; Sanchez & Mahoney 1996). Figure 20.1 provides an illustration of product and process architectures meeting this definition.

Describing an architecture requires identifying (1) the type of function each component will or does perform, and (2) the kinds of interfaces through which the functional components will or do interact with each other and/or with their surrounding environment. *Defining* a specific architecture requires: (1) specifying the functional and behavioral properties of each component to a degree sufficient to determine the exact nature of the interactions that will take place between each component and all other components and between each component and its surrounding environment; and (2) specifying the exact component interfaces that will enable the functional components to function together as a system in a defined context and/or across some identified range of conditions. Sanchez



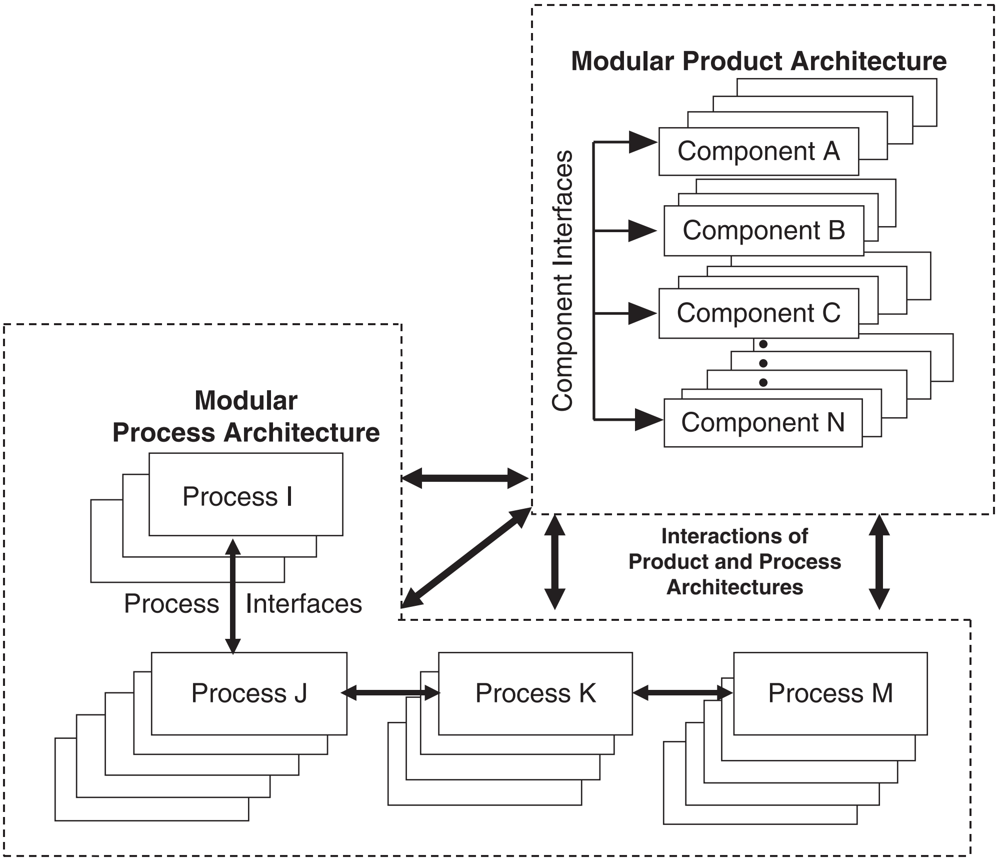
Source: Sanchez (1999).

Figure 20.1 Product and process architectures

(1999) has defined six major types of interfaces that exist in product architectures; related types of interfaces exist in process and organization architectures (Sanchez 2012 and forthcoming).

The concept of architecture defined above may be used to describe or define the design of a product, a process, an organization, an industry or any other system that performs some kind or kinds of definable functions. In this discussion, we apply the architecture concept as defined above in characterizing not just product architectures, but also process architectures, organization architectures and industry architectures. Thus all of these terms refer to a specific way of representing a system design – a representation that defines: (1) the functional component structure of the design; and (2) the interfaces between components that determine how the functional components interact in their particular instance of a system design.

Architectures may be modular or non-modular. A modular architecture is one in which the interfaces have been specified (either as the result of a strategic intent or as an emergent outcome) so that a range of component variations can be introduced into the system design without having to make changes in either other functional components or



Source: Sanchez (1999).

Figure 20.2 Modular product and process architectures

in any interface specifications, as suggested for both product and process architectures in Figure 20.2.[5] In effect, a modular architecture is one in which some range of functional components – whether product components or process activities – can readily 'plug and play' in a system design.

The ability to introduce component variations into a modular architecture enables a given modular architecture to configure potentially large numbers of specific design variations by 'mixing and matching' component variations.[6] Thus, when modularity is intentionally 'designed into' an architecture, or when modularity emerges in a natural system through an evolutionary process, it confers a range of configurability on the system that endows the system with a resulting capacity to adapt or be adapted to changing environmental demands or opportunities, thereby enabling the system to serve a range of purposes across a range of conditions.

A non-modular architecture is a system design in which the introduction of a new component variation would require redesigning the architecture to some extent by making changes in the types or variations of functional components used in the architecture, and/or by creating new interface specifications to manage the interactions between the new component variation and other components. Such system designs may sometimes be created to serve a single intended purpose under well-defined and stable environmental conditions, but they cannot be adapted to new purposes or new conditions without a significant re-architecting of the system design.

In fundamental respects, creating any kind of system design is an exercise in optimization, a process in which designers have one of two tasks: either maximize some performance attribute(s) subject to cost or other resource constraints; or minimize cost or some other resource considerations subject to some performance constraint(s).[7] Thus, a fundamentally important design difference between modular and non-modular architectures is that modular architectures are system designs that are *dynamically optimized* to adapt to some range of changing purposes or conditions (either by overt design or through processes of emergence), while non-modular architectures are typically *statically optimized* to meet a single purpose under constant conditions (Sanchez 1994).

Finally, modular architectures may have one of two types of modularity properties (Sanchez 2008). What Sanchez (2009) refers to as 'technical modularity' exists in any architecture when at least some interfaces between two or more components happen to allow the introduction of some range of component variations into the architecture. Technical modularity is often used in 'back office' engineering activities to simplify or 'rationalize' designs through reuse of pre-existing interface specifications (Sanchez forthcoming).

'Strategic modularity', on the other hand, is created through a strategically motivated design process in which designers consider the various ways in which the overall functions of the design could be decomposed to create the most strategically desirable range of configurability in the architecture – a process that Sanchez (2000a, 2008) refers to as strategic partitioning of the architecture. The basic intent of strategic partitioning is twofold: firstly, to technically isolate components that do not need to change during the intended lifetime of the design from those that it would be desirable to be able to change; and secondly, to achieve a 'one-to-one mapping' of each strategically important function to be delivered by the architecture into a single functional component (or single subsystem in larger architectures). Appropriate strategic partitioning of a modular architecture enables a range of strategically (or evolutionarily) important design variations to be configured through simple, direct introductions of component variations into the architecture.

THEORETICAL IMPLICATIONS AND OBSERVATIONS

Research into the influence of product architectures on organizations and their development processes began with the pioneering work of Miller and Sawyers (1968) and Gardiner (1986). Drawing on this early research, Henderson and Clark (1990) suggested that the influence of a firm's product architecture on its internal communication flows during product development may have significant competitive and strategic consequences. They suggested that when a firm's communication flows in product development processes become structured around a firm's current product architecture, the firm may have difficulty recognizing possibilities for innovating new architectures, which may lead to a 'failure of established firms' to innovate architecturally and thereby maintain market leadership (however, see note 8).[8]

Subsequently, Garud and Kumaraswamy (1995) examined Sun Microsystems' strategy in the workstation market and suggested that firms may be able to pursue new kinds of product strategies based on open-system product architectures that give their customers the ability to use industry standard components in configuring their systems. Concurrently, Sanchez (1995) identified modular product architectures as a potentially significant source of strategic flexibility to quickly configure new product variations and to rapidly upgrade products technologically in dynamic product markets. These two papers helped to stimulate a growing awareness in the strategy field of the important roles that open-system and/or modular product architectures can play in enabling new kinds of product strategies that had not previously been recognized in the field.

The Sanchez and Mahoney (1996) paper published in *Strategic Management Journal* is generally recognized as the first to suggest that modularity as a form of system design has important implications not just for competitive strategies, but more broadly for economic organization. The arguments made in the paper about modularity's impacts on product market competition, on the design of organizations and the organization of industries, and on processes for generating, structuring and managing knowledge in firms and industries all put forward a number of propositions that have spawned new streams of theory development and research in strategy, organization theory, knowledge management and economic organization.

We next consider the three strategic aspects of modular architectures identified by Sanchez and Mahoney (1996) from which they and later researchers derive propositions with significant theoretical implications for economic organization. We subsequently consider a fourth perspective on modularity suggested by Boisot and Sanchez (2010) that introduces an evolutionary theoretical perspective on modularity as an emergent phenomenon in economic organizing.

Modularity's Impact on Product Strategies and Product Competition

Extending the argument originally introduced by Sanchez (1995), Sanchez and Mahoney (1996) suggest that the ability to design rapid, low-cost configurability into modular product architectures endows firms with the strategic flexibility to offer more product variations and more rapid technological upgrading of products than can be accomplished through traditional (i.e., statically optimized) product designs, *ceteris paribus*. A strategically important consequence of the configurability of modular product architectures is that firms that learn how to design modular product architectures may start to offer more product variations and more frequent technological upgrades in their products, resulting in more dynamic and more finely segmented product markets and enabling the possible mass-customization of products (Sanchez 1999).

The use of modular product architectures to generate more product variety targeted at more finely grained market preferences is likely to establish new patterns and levels of competition in which modular design becomes an essential firm competence (Sanchez & Collins 2001; Sanchez 2004a). In product markets in which product variety, rapid technological upgrading to improve performance, and/or speed to market are important in achieving competitive advantage, modularity is likely to become a new ‘dominant logic’ (Prahalad & Bettis 1986). Both casual observation and empirical research in a growing number of product markets have broadly confirmed these predictions (e.g., Langlois & Robertson 1992; Schilling & Steensma 2001; Worren et al. 2002).

Modularity’s Impacts on Organization Designs and Industry Structures

Sanchez and Mahoney (1996) advanced a broad proposition suggesting a fundamentally important relationship between the product architectures a firm uses and its own organization architecture:

> We suggest that although organizations ostensibly design products, it can also be argued that *products design organizations*, because the coordination tasks implicit in specific product designs largely determine the feasible organization designs for developing and producing those products. (1996: 64)

In effect, Sanchez and Mahoney (1996) suggest that the product architecture a firm uses will significantly influence – and thus will tend to be reflected in – the firm’s choices of organization architecture for developing and producing the products to be derived from its architecture. In the current research literature, this proposition is usually referred to as the *mirroring hypothesis*.[9] For example, if a firm develops a non-modular architecture – which was ostensibly was the type of architecture used by the photolithography firms studied by Henderson and Clark (1990) – then the decomposition of the overall product development task into specific component development tasks will reflect the component structure in the product architecture, and communication channels in the development process may become tightly structured around key interfaces between components, as suggested by Henderson and Clark (1990) as well as by Miller and Sawyers (1968) and Gardiner (1986) before them.

Sanchez and Mahoney (1996) went on to suggest, however, that the standardized interfaces in modular product architectures can provide essential embedded coordination of loosely coupled development processes (and production processes as well) and may therefore enable new kinds of modular organization designs and ‘self-organizing’ industry structures. The potential impact of modular architectures and their standardized interfaces on organization designs suggested by Sanchez and Mahoney (1996) works like this: if a firm adopts a modular architecture development process in which it first focuses on defining and then standardizing (i.e., freezing) the interfaces between the functional components in a modular architecture, and then constrains the development of all components to conform to the standardized interface specifications for the modular architecture, then the tasks of developing individual components become ‘loosely coupled’ and can then be undertaken simultaneously by distributed development processes (see p. 71, Figure 2).[10]

If development of a new product architecture is undertaken in this way by a firm, then functional component development activities performed by different teams within or external to a firm can ‘plug and play’ in a modular development process and will not require intensive communication flows or significant managerial intervention to achieve coordination.[11] In effect, adopting this ‘modular process architecture’ for developing a modular product architecture enables a modular development process to be undertaken through a modular organization design (Brusoni & Prencipe 2001; Sanchez 2000a, 2004b; Sanchez & Collins 2001; Sturgeon 2002).[12]

Note, however, that Sanchez and Mahoney (1996) do not assert that a firm's use of modular product architectures will *necessarily* lead to its adoption of a modular organization design – only that modular product architectures *enable* the use of modular organization designs. Managerial, organizational and industry strategic factors may also affect a firm's choice of organizational form. Managerial and organizational factors, for example, center around issues such as: (1) Do managers realize that there would be important speed and flexibility advantages in adopting a modular development process and modular organization design? (2) Are managers willing and able to undertake the strategic organizational change required to implement modular development processes and organization designs? (3) Will technical development staff have the discipline to adhere to the principles of the modular development processes – especially the discipline required to constrain development of new components to conform to the standardized interface specifications of the modular architecture under development? (See Sanchez 2000a, 2008, and forthcoming for further discussion of these key issues.)

Some research (usually based on cross-sectional industry data) that has sought to test the 'mirroring hypothesis' has found mixed results (e.g., Hoetker 2006; Parmigiani & Mitchell 2009; Sosa et al. 2004). Moreover, some interpretations of the mixed empirical results have inferred (incorrectly, we believe) that modular product architectures offer only weak incentives to adopt modular organization architectures. By contrast, longitudinal research into firms that have managed to implement modular product, process and organization architectures has confirmed that adopting modular development processes and organizational structures has conferred considerable strategic benefits in the form of increased speed and flexibility in development and more effective knowledge capture and retrieval, among other benefits (Sanchez and Collins 2001; Sanchez 2000a, 2000b, 2004b, 2008). We suggest therefore that the predictive power of the mirroring hypothesis is more likely to be confirmed if greater empirical attention is given to the moderating effects of managerial and organizational factors – especially those relating to managerial cognitive limitations and risk-averse behaviors (Sanchez and Heene 2004).

As Sanchez and Mahoney (1996) also noted, widespread adoption of modular product architectures in an industry can also profoundly influence industry structures:

> We observe, for example, that modularity in product designs can facilitate modularity in manufacturing processes as well as in development processes. In industries whose products are typically most modularized (e.g., personal computers), production, assembly, and servicing of components are commonly carried out by globally dispersed, loosely coupled organizations. (1996: 74, n.8)

In effect, Sanchez and Mahoney (1996) suggest that an industry's adoption of modular product architectures may (eventually) lead to the emergence of a modular industry architecture in which 'globally dispersed, loosely coupled organizations' can freely plug and play in developing, producing, assembling and servicing the components used in the industry's modular product and process architectures.

The industry-level implications of modular product architectures are further explored by Sanchez (2008, forthcoming) and Sanchez et al. (2012), who suggest that industry structures and dynamics are fundamentally determined by the open versus closed system and modular versus non-modular nature of the product and process architectures used by firms in the industry. In particular, Sanchez (2008) contrasts the industry structures and dynamics of two polar architectural cases. At one end of the architectural spectrum, industries based on use of closed-system (i.e., firm-specific) and non-modular product and process architectures are likely to be characterized by high levels of vertical integration by firms within the industry, and by almost exclusively competitive interactions between firms at all stages of the industry value chain. Such competitive behaviors tend to be driven by the significant risks inherent in creating and competing with stand-alone, firm-specific product architectures.

At the other end of the architectural spectrum, however, industries based on open-system, modular product and process architectures are likely to be characterized by significant use of outsourcing and partnering relationships to develop and produce components and products, as well as by high levels of upstream firm cooperation to set standards and agree on 'industry standard architectures' based on product architectures with standard types of components interconnected by standardized interfaces (Sanchez 2008; Sanchez et al. 2012). Sanchez (2002) provides an in-depth analysis of the incentives for technological and architectural cooperation in adopting standard open-system, modular product architectures in an industry.

Relatively recent research into 'industry architectures' suggests that there is now growing awareness of the implications for strategy and economic organization of Sanchez and Mahoney's (1996) observations about industry structures. However, the concept of 'industry architecture' invoked in this research is often rather vaguely defined or is defined at a very high level of description (such as 'a set of products, processes, and players' or the like). We suggest that the definition of an architecture suggested in the 'Definitions' section of this chapter would provide a more precise conceptual basis for characterizing industry architectures – and for examining interrelationships between product architectures, process architectures, organization architectures and industry architectures in a conceptually consistent way.

Modularity's Impact on Learning Processes and Knowledge Structures at Firm and Industry Levels

Sanchez and Mahoney (1996) also put forward a number of both specific and broad propositions about the impacts of modular product and process architectures on organizational learning and knowledge management at both firm and industry levels.

At the firm level, non-modular development processes typically focus on developing components and then trying to manage the evolution of interfaces between the components as component-focused development processes move forward. As Sanchez and Mahoney (1996) and Sanchez (2000b, 2001) point out, however, this approach to technical learning while developing a product or process architecture inherently 'tightly couples' many ongoing processes for developing new technical solutions for specific components in the architecture, thereby making it very difficult to isolate, analyze and manage specific cause-and-effect relationships between specific pairs of components. Thus, non-modular development processes are unlikely to be conducive to high levels of architectural learning during development projects (Sanchez 2001). Moreover, the idiosyncratic and unstructured nature of non-modular development processes often makes collaborating with other firms in developing products and processes highly problematic.

As Sanchez and Mahoney (1996) note, however, when a firm implements a modular architecture development process in which the interfaces between components have to be fully specified before beginning development of individual components, modularity can have a major beneficial impact on a firm's learning processes and on the way a firm structures and develops its technical knowledge. First developing interface specifications that assure that a contemplated set of component types will interact reliably in an architecture primarily involves architectural and technological learning – a form of learning that can largely be decoupled from more focused technical design learning subsequently undertaken during individual component development processes. Intentionally decoupling these two forms of organizational learning can significantly improve the effectiveness and efficiency of both kinds of learning (Sanchez 1994, 2000a, forthcoming).

If a firm's managers assume that developing the architectural knowledge needed to specify component interfaces before undertaking component development processes is too risky to attempt – or if they simply lack the sophistication to understand the potential for decoupling the two forms of learning processes – then their firms will be unlikely to adopt modular development processes and to pursue the more systematic approach to architectural and technological learning that is possible in modular development processes.

Yet firms do exist in many, if not all, industries that do have the managerial vision and organizational discipline needed to implement modular development processes and to derive the benefits of the more systematic processes for architectural and technological learning that are possible in modular development processes (Sanchez 2001; Sanchez & Collins 2001). These firms have often developed explicit, strategically focused and systematically managed architectural learning processes that help them deepen their understanding of the system behaviors of various component designs that they use or could use in their architectures. By using the principle of strategic partitioning (discussed under 'Definitions') to achieve a 'one-to-one mapping' of specific functions into components whose interfaces have been specified so as to isolate them technically from other components in the architecture, learning about component-level design variables can proceed in a relatively straightforward manner in largely decoupled component development processes (Sanchez 2001).

Thus, the way knowledge becomes structured in modular development firms is likely to directly reflect the product and process architectures that the firm designs and uses. Moreover, as Sanchez (2000b, 2001) suggests, when a firm discovers that it lacks adequate knowledge of the system behaviors of one or more components in its modular architecture, it can then target its organizational learning processes on the aspect of the component's system behavior that it does not currently understand adequately. In effect, clearly identifying what one does not know is an important first step in designing a focused and effective architectural learning process (Sanchez 2000b, 2001).

When firms in an industry use or develop a common modular product architecture – that is, an industry standard product architecture (Sanchez 2008; Sanchez et al. 2012) – they can then cooperate in collaborative learning processes by dividing up the task of architectural learning. Because firms will be researching component behaviors and interactions within the same technical structure of functional components, architectural knowledge developed in one firm about a component's system behaviors can directly 'plug and play' into other firms' knowledge structures and development processes. Thus, as Sanchez (2000b, 2001) has noted, it is no coincidence that industries with high levels of adoption of industry standard product architectures (personal computers, telecoms products, and many others) also likely to have high sustained rates of architectural learning (usually driven by collaborative learning processes), leading to high rates of product performance improvements and overall technological progress.

Modularity as Emergent Firm and Industry Phenomena

Boisot and Sanchez (2010) suggest that both specific and generic forms of economic organization can be understood as instances of 'nexus of rules and routines' that emerge from the recurrent interactions of economic decision makers. Boisot and Sanchez further suggest that compared to the rules and routines that obtain in non-modular development processes, modular architectures and development processes can be understood as instances of 'independent rules with high combinatorial potential' (2010: 385, n.8) that can offer both significant economies (reduced development cost and time) and market benefits (greater product variety and more rapid technological upgrading) when modularity is adopted as a basis for economic organizing.

Boisot and Sanchez (2010) submit that trial-and-error learning by firms in experimenting with different approaches to creating and offering products to markets may drive an evolutionary process that leads to the emergence of modularity in an industry's product, process and organization architectures. If managers began to judge that modularity's rules and routines for ordering the creation and realization of a firm's products appear to offer a Pareto-preferable way of organizing the firm's economic activities, and if individual firms in the industry then begin to adopt modularity rules and routines for ordering the creation and realization of their products, then modularity will emerge as an industry-level phenomenon. This prediction provides an evolutionary theoretical explanation for the observation that in product markets in which effective use of modularity can bring competitive advantages, once one firm in an industry 'goes modular', other firms are either likely to follow or will be 'selected out' of the industry, and modularity will eventually become the dominant logic for participating in the new 'modular industry' (Sanchez and Collins 2001; Sanchez 2008).

This prediction also leads to a further theoretical implication that Sanchez at al. (2012) have termed the 'reverse mirroring hypothesis'. This hypothesis suggests that the alternative organization architectures that managers believe are possible for their firm to adopt will influence their choice of product and process architectures. In effect, before deciding on a specific approach to organizing product creation and realization, managers will try to identify all the *strategic options* (Sanchez 1995) for organizing product creation and realization that are available to them – or that could be available as a result of their future efforts to engage other firms in collaborative action. Managers will then jointly choose the product, process and organization architectures that appear to offer the best (Pareto-preferable) basis for organizing their firm's economic activities.

Thus, in terms of the broad evolutionary view of the emergence of organization forms in suggested by Boisot and Sanchez (2010), modular product, process and organization architectures may emerge in an industry as the result of firm-level managerial choices made among the alternative organization forms that are perceived by managers to be feasible for their firms. Once one firm adopts modularity, more managers may begin to perceive that significant economies and benefits may actually be available through modularity, including the benefits that may be created through collaborative action with other modular firms. As more firms contemplate and adopt modularity strategies – creating increasing positive externalities for other firms interested in modularity as a basis for collaboration – the incentives for other firms to adopt modularity increase. Eventually a virtuous circle of increasing positive gains available through modularity may lead to a widespread managerial judgment that modularity offers the best possibility for economic organizing in their industry. In this way, in product markets in which effective use of modularity can bring competitive advantages, modularity may emerge as the dominant logic for economic organizing in an industry (Prahalad and Bettis 1986).

CONCLUSION

Our reprise of the main implications of modularity for economic organization developed since the publication of our 1996 SMJ paper leads us now to suggest that there are still fundamentally important implications of modularity for economic theory that have yet to be elaborated, and thus form a fruitful domain for further theory development and empirical research. In particular, we suggest that modularity as a field of strategy and economic research provides a new theoretical perspective on economic organizing with significant potential for achieving a useful integration of microeconomic and macroeconomic theory.

As a special form of architecture, modularity has inspired research in management that is now leading to new understanding of not only the interrelationships of firm-level strategies, structures and processes, but also of how those factors and their interrelationships shape – and thus are reflected in – industry-level structures, processes, and competitive and cooperative dynamics. At a fundamental systems view of economic organizing (Sanchez & Heene 1996, 2004), the architecture concept defined in this discussion enables a well-defined concept of industry architectures that can bring new and deeper meaning to the sometimes amorphous notion of industry structures that has long been a theme in industrial organization economics (Porter 1979, 1980). The rigorous and consistent application of both architecture and modularity concepts at the industry level would enable a more fundamental, comprehensive and integrated view of the structures, processes and dynamics of economic organizing at the industry level. We further suggest that ongoing research on architectures and modularity may eventually – and perhaps sooner rather than later – lead to much sharper understanding of the fundamental systemic interrelationships between managerial decision-making about economic organizing made at the firm level (as studied by Sanchez & Mahoney 1996) and the evolutionary trajectories of structures, processes and dynamics at the industry level that result from the aggregated economic organizing decisions of entrepreneurs and managers (as suggested by Boisot & Sanchez 2010).

In effect, the adoption of modular architectures in product designs makes it possible to reflect ('mirror') the modular architecture in an organization design and indeed in an industry structure. However, the mixed empirical results in tests to date of the 'mirroring hypothesis' suggest that there are significant cognitive, managerial and organizational challenges to be overcome in reshaping organizations and industries to mirror any modular product architectures they may use. How individual firms and collectivities of firms make the decision to adopt modular architectures, how they then (perhaps) decide to reorganize to reflect their modular architectures in their organization designs, and how they then go about implementing such decisions organizationally at firm and industry levels – these fundamental cognitive processes in creating modular firms and modular markets are as yet poorly understood and little researched.

Nevertheless, it is clear that both firms and industries with modular architectures reflective of their product architectures do exist and continue to emerge. Indeed, modular products and modular organizations appear to be an increasingly common phenomenon and an increasingly dominant strategy for participating in many kinds of product markets (Sanchez & Collins 2001; Worren et al. 2002). Further elaboration of the 'reverse mirroring hypothesis' recently proposed by Sanchez et al. (2012) is now needed to identify the technical, competitive, and other strategic conditions that are likely to broadly induce firms to adopt modular product and organization architectures.

Combined with the mirroring hypothesis, a more fully elaborated reverse mirroring hypothesis may provide the essential conceptual link now necessary to 'close the loop' between firms and industries in developing an integrated theoretical representation of the organizational structures, processes and dynamics that inextricably link firms in an industry in a dynamically evolving feedback system (Forrester 1960; Sanchez & Heene 1996, 2004).

If so, perhaps it may eventually come to pass that a dynamic architectural perspective on economic organizing – within which achieving a close alignment of modular product, process and organizational architectures at firm and industry levels often appears to be an optimal case – will provide the conceptual lens that enables a new synthesis of micro and macro levels of organizational economics theory.

NOTES

1. We thank Peter Galvin and Norbert Bach for helpful discussions on industry architectures, and Anna Grandori and Chiu Liu for their insightful comments on earlier drafts of the chapter. The usual disclaimers apply.
2. The current chapter uses a more general conception of 'hierarchy' than is usually invoked in organizational economics (e.g., Williamson 1975), where hierarchy typically denotes subordination to an authority relationship. Our interest here, however, is in understanding hierarchical systems for creating new products in which there is little or no overt exercise of managerial authority (Sanchez & Mahoney 1996). Thus, 'hierarchy' in our discussion refers to a structural decomposition of a complex system into an ordering of successive sets of subsystems in the manner suggested by Simon (1962); that is, a partitioning of a system into subsystem relationships that collectively define the parts of any whole.
3. Advanced technological knowledge about component interactions can be used to fully specify and standardize the component interfaces that make up a modular product architecture, creating a system of nearly independent, loosely coupled components (Sanchez & Mahoney 1996). The interface specifications in a modular product architecture can in turn provide an essential form of embedded coordination that makes possible the concurrent and autonomous development of components through loosely coupled organization structures (Orton & Weick 1990; Williamson 1975). The architectural concepts of functional decomposition and interface specification have strong parallels in classic organization theory's concepts of specialization and differentiation among and integration of organizational subunits (Lawrence & Lorsch 1967; March & Simon 1958). Thus, as Sanchez and Mahoney (1996) suggest, both product designs

and organization designs are governed by fundamental principles of decomposition and may be designed to achieve the property of 'near decomposability' (Simon 1962).
4. What happens by design at the firm level generates an emergent phenomenon at the industry level – thus modularity as an emergent outcome at the industry level is a logically dependent result of *outcomes by design* at the firm level of analysis.
5. When the designs of a modular product architecture and a modular process architecture (e.g., a flexible production process) are coordinated so that the configurability of both architectures can be used to support a well-defined strategic objective – such as providing a defined range of product variations and/or a plan for upgrading product performance – the combination of the two architectures constitutes a *modular platform* for accomplishing the strategic objective (Sanchez 2004b).
6. This 'power of modularity' is easy to illustrate: imagine a system design consisting of ten different types of components whose interfaces have been specified to allow the 'mixing and matching' of ten different variations of each type of component. The number of specific design variations that be configured within this simple modular architecture is $10^{10} = 10\,000\,000\,000$ design variations. Of course, as a practical matter the range of variations in components that can be introduced into a modular architecture is both enabled and limited technically by the interface specifications in the architecture for each type of component. Interfaces may be specified to be 'flexible' in the sense that they allow a broad range of component variations to be introduced into an architecture (e.g., a USB or Firewire interface), or they may be specified to be 'inflexible' (either as a strategy or by simple default) in the sense that they allow only one or perhaps a narrow range of component variations to 'plug and play' in an architecture (e.g., Sony's proprietary 'Memory Stick' interface). Contrary to popular perceptions, the standardized interfaces in modular architectures may in fact be designed to be quite flexible in their ability to support the mixing and matching of existing and new component variations over an extended period of technological evolution (again, consider the ubiquitous and long-lived USB interface or the standardized 128-field magnetic strip on the back of bank cards around the world.)
7. We note that optimization in the design world usually consists of choosing among alternative imagined designs in a discrete choice context. Discrete system designs are typically selected (at the firm level) and retained (at the industry level) on the basis of their ability to deliver an adequate level of performance given some resource constraint(s) (a relative effectiveness criterion) or their ability to minimize resource requirements while meeting some minimum performance constraint (a relative efficiency criterion).
8. Henderson and Clark's (1990) broad proposition that the structuring of internal communication patterns around a firm's current architecture may lead to 'the failure of established firms' to innovate architecturally is supported in their paper by reports of interviews with managers involved in product development in a few firms in the photolithography industry in the 1970s and 1980s, and by data they present on the changing positions of major firms in the photolithography industry during the same period (see p. 24, Table 2, in their paper). However, Sanchez (forthcoming) suggests that the data presented in their paper appear to be based on an inadequate sample of firms that may have resulted in an incomplete and thus possibly misleading view of firm strategies, entries, incumbencies, and market shares in the industry during the period studied. If so, there may be little actual empirical support in Henderson and Clark's (1990) study for their well-known proposition that a firm's efforts to extend and exploit its current product architecture may significantly contribute to 'the failure of established firms'.
9. One of the earliest uses of the term 'mirroring hypothesis' can be found in Colfer (2007), which was updated in Colfer and Baldwin (2010). This research reviewed 102 empirical studies spanning three levels of organization: within a single firm, across firms and in open-community-based development projects. Colfer (2007) credits Sanchez and Mahoney (1996) for being one of the first to articulate explicitly the mirroring hypothesis, although it was also noted that the use of the term 'mirror' can be found in Henderson and Clark (1990). The mirroring hypothesis was supported in 69 percent of the cases. Support for the hypothesis was strongest in the within-firm sample (77 percent), slightly less strong in the across-firm sample (74 percent), and relatively weak in the open collaborative sample (39 percent). Notable studies providing support in the within-firm sample include: Amrit and Hillegersberg (2008), Herbsleb and Grinter (1999), King (1999), Ovaska et al. (2003) and Sosa et al. (2004). Notable studies providing support in the across-firm sample include: Cacciatori and Jacobides (2005); Consoli (2005); Fixson and Park (2008), Gulati et al. (2005), Jacobides (2005); Monteverde (1995), Novak and Eppinger (2001), Parmigiani (2007), Sahaym et al. (2007), Shibata et al. (2005) and Tiwana (2008a, 2008b). Notable studies that did not support the mirroring hypothesis include: Appleyard et al. (2008), Argyres (1999), Barlow (2000), Bonaccorsi and Lipparini (1994), Helper et al. (2000), Mikkola (2003), Miller et al. (1995), Sako (2004), Scott (2000), Staudenmayer et al. (2005) and Takeisha (2001).
10. The modular development process described here is generally referred to as 'object-oriented development' in the software industry.
11. Sanchez (2000a, 2001, forthcoming) suggests that adoption of standardized component interfaces before beginning development of individual components for a modular product architectures may therefore

help to avoid the problems of narrowly focused communication flows that Henderson and Clark (1990) suggest may afflict firms in development processes and (putatively) lead to alleged 'failure of established firms'.

12. The current chapter focuses on the specific influence of modularity on organization, rather than on the broader topic of technology's influence on economic organization. In this broader topic, an important question arises concerning the degrees of freedom of organization with respect to technology (and the degrees of freedom of technology with respect to organization). This question is beyond the scope of the current chapter, but warrants consideration in future research. We thank the editor, Anna Grandori, for highlighting this research question.

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