**Product complexity, the speed of component change and the Mirroring Hypothesis**

The coordination of complex product development has a long tradition (ie, Galbraith, 1977; Williamson, 1971) and more recently theorists within the modularity tradition have hinted at the potential benefits of a “mirror” between the structure of a product development firm and the technical product it designs (Henderson and Clark, 1990; Sanchez and Mahoney, 1996, Baldwin and Clark, 2000). Put plainly, the mirroring hypothesis seeks to examine two important and pervasive relationships: the extent of an architectural mapping between firms’ strategic choices of product architecture and firm architecture – within-firm mirroring - and between firms’ architectural choices and industry structures – across-firm mirroring.

In a recent literature review of empirical studies concerning the mirroring hypothesis, Colfer and Baldwin (2010) find that the hypothesis received *uniform support* in 68% of ‘within-firm’ cases and 47% of ‘across-firm’ cases, but found notable exceptions[[1]](#footnote-1). These inconsistent findings concerning the mirroring of product and organization/industry architectures has led to calls for a more nuanced view of the mirroring hypothesis. In response, there has been some recent empirical work that starts to investigate those factors that may limit the clear mapping across different levels suggested by the mirroring hypothesis in air-conditioning and motor vehicle industries. Furlan, Cabiguso and Camuffo (2014) examine the across-firm mirroring hypothesis in the air-conditioning industry, and find that the ‘mirror’ becomes misted by high rates of product component change, with firms engaging in rich collaborative relationships, even where the underlying components had modular characteristics. Writing with Zirpoli, Cabigiuso and Camuffo (2013) in a study of the motor vehicle industry, suggest that the mirroring hypothesis may become misted as firms seek to integrate external sources of innovation into complex product development.

We develop similar ideas pertaining to the roles of the rate of component change and product complexity, and consider how this may also mist up the mirror in respect of organization architecture. In developing these ideas, we present a stylised product architecture typology that recognizes that modular or integral architectures rarely conform to these ideal types. Thus we consider how both ideal and imperfect architectures – specifically hybrid product architectures – may mirror across different architectures. By further developing a contingent view of the mirroring hypothesis that helps uncover when mirroring or misting may emerge or even be beneficial, we highlight the need for managers to understand how select factors may influence the trade-off between high levels of information-exchange to spur innovation and the possible ‘embedded coordination’ benefits that may occur with modular structures.

**Typology of product architectures**

In any given product market, it is possible that a number of different architectures might be strategically feasible, each with different combinations of performance, quality or cost. A more complete understanding of how different product architectures emerge and then establish themselves, as well as how such architectures correspond to firm and industry architectures is therefore a critical issue for academic research. In defining product architecture, many theorists adopt a definition that encompasses the relationship between a product’s functions, its components and its interfaces; Sanchez and Mahoney (1996: 64) suggest that a product architecture is “ *a way in which the total functions that a design is intended to achieve have been decomposed into specific functional components, and secondly, it defines the way in which the functional components that make up the design will interact when the components function together as a system – known as the interfaces*”. Ulrich (1995) classified product architectures into two ‘ideal types’ – integral or modular. At one end of a continuum, an integral architecture is where the components, interfaces and their relationship is complex, interdependent and non-standardised. At the other end of the continuum, a modular architecture has relationships between components and interfaces that are simple, independent and standardised.

***The integrated - modular continuum***

Modularity theory is based upon the notion of the decomposability of a system into subsystems or components (Simon, 1962, Alexander, 1964) and information-hiding and parallelism (Parnas, 1972). The characteristics of product architectures, therefore, often differ fundamentally in the degree to which components and interfaces are independent or interdependent (Ulrich, 1995). The degree of independence/interdependence depends upon the extent to which a change in the design of one component requires design changes in other components.

Product architectures with significant integrated characteristics often cannot be easily adapted without redesigning the entire architecture or many other interdependent components (Ulrich, 1995). Often, an integrated product architecture is one that has been designed for strategic optimisation, such as maximum performance or lowest cost (Sanchez, 2008) resulting in significant interdependencies being ‘designed in’ to the architecture throughout an often sequential product development process (Baldwin and Clark, 2000). In comparison, modular product architectures occur where components are loosely-coupled – interdependencies exist within components but not across or between components (Simon, 1962; Baldwin and Clark, 2000) - and such architectures can either emerge or be purposely developed through a process of specifying design rules (Baldwin and Clark, 2000, Sanchez, 2008). Modularisation often therefore creates ‘thin crossing points’ in the product architecture; breaking up interdependencies that may generate the potential to use market-based transactions without the need for extensive managerial control (Baldwin, 2008). Modular product architectures, therefore, can often provide a form of “embedded coordination” (Sanchez and Mahoney, 1996; Galvin and Morkel, 2001) that supports in-parallel component development by loosely-coupled teams or even loosely-coupled organisations.

***The open and closed continuum***

Product architectures may also be conceptualised along a continuum of being either open or closed (Sanchez, 2008). A perfectly closed architecture is one that is not able to be used by other firms; it is proprietary and a firm may hide, encrypt, patent or copyright components and interface specifications. However, a closed product architecture may also exhibit modular characteristics if a firm expends significant effort, time and resources to understand and minimise component interdependencies within firm boundaries. This process may involve strategically partitioning and decomposing the integrated architecture into modular components and ‘specialised’ (or ‘firm-specific’) interfaces (Schilling, 1998). Closed and modular product architectures, therefore, may offer a firm the potential to benefit from both rent appropriation, as well as increase product variety through mixing and matching firm-specific or self-manufactured modular components.

In contrast, a perfectly open architecture is one whose interface specifications are open and standard, dispersed across firms in an industry in order to support widespread interoperability, unencumbered by intellectual property rights and other means of secrecy, and firms interested in developing components or complementary goods can often ‘plug and play’.

***Intermediate or hybrid architectures***

Product architectures may either be open or closed, integrated or modular, however, some product architectures are not easily classified along these continuums. Firms may often control the degree of openness or modularity of their product architectures, perhaps seeking to control which components are proprietary and which are not, and which interface specifications are specialised and which are open and standardised. In other words, a firm can pursue an architecturally-hybrid product strategy and potentially exert some degree of influence or control over the openness of the product architecture. Such intermediate or hybrid architectural strategies allow for one component or interface at a time to be opened or closed. We thus propose four stylised product architecture types: closed and integrated; closed and modular; intermediate and hybrid; and, open and modular.

**Mirroring or misting**

The idea of mirroring has its roots in many different disciples from organizational design to industrial organization economics. To this extent, it is conceivable that firms and products should be architecturally aligned (Sanchez and Mahoney, 1996; Henderson and Clark, 1990; Fine, 1998; Baldwin and Clark, 2000). Colfer (2007: 4) identifies four types of architectural structures that are amenable to mirroring: the product; the firm; the division of labour and the division of knowledge. While the mirroring hypothesis examines the relationship between one structural layer of a system and another, Colfer (2007) observes that differences exist in how scholars define the relationship between architectural layers.

Colfer and Baldwin’s (2010) review of empirical work pertaining to the mirroring hypothesis found considerable support for mirroring, but there were clear exceptions. In understanding when the mirror gets misted up, Furlan, Cabigiosu and Camuffo (2014) found that in cases of fast-changing product components, modularisation may *not* provide a form of embedded coordination and the need for hand in glove supply relationships persist regardless of the level of component modularity. Similarly, Cabigiosu, Zirpoli and Camuffo (2013: 673) argue that it is the level of knowledge held by the firm and its “*ability to predict the technical interdependencies characterising the design of the product over the life of the project*” (p. 673) that determines product design choices. In other words, ex-post information-exchange can only be minimised if the firm has sufficient knowledge to scope ex-ante the required component interfaces. Thus, in complex product markets (such as motor vehicles and commercial aircraft, for example Ethiraj and Levinthal, 2004; Sosa, Eppinger and Rowles, 2004; Brusoni and Prencipe, 2006; MacDuffie, 2012), it is likely that firms may often lack the knowledge over a broad range of specific components, and how they integrate effectively into the overall system architecture.

Therefore, misting of the mirror may occur under two contingencies. Firstly, in order to remain competitive, firms often need access to external sources of innovation if component technologies change quickly. As a consequence, the ability of firms to integrate external sources of innovation is seen as a paradox to modularity – the modular benefits of information-hiding may be at odds with the need to access external knowledge (Cabigiousu and Camuffo, 2012; Cabigiuso et al, 2013). In other words, accessing external sources of knowledge necessarily requires a high degree of information-sharing, even in the presence of modular components. A second broad theme is that ‘misting’ may arise in complex product markets because of the scope of knowledge domains (Cabigiosu et al, 2013) and that only firms who know more than they make have the knowledge to invest ex-ante in defining component interfaces; investments in defining modular entities are ex-ante in order to observe any benefits ex-post (Gomes and Joglekar, 2008). Therefore, in complex settings, firms who rely on stocks of external knowledge owned by suppliers may not possess the required component level knowledge to design ex-ante modular components. Despite assertions that modularity is a useful way to manage complexity (Ethiraj and Levinthal, 2004), we argue that in the case of product architectures with high levels of complexity and/or high rates of product component change, modularity may in fact have an inverse relationship to the usual logic of information-hiding and embedded coordination.

**PROPOSITIONS**

***Degree of mirroring in closed and integrated architectures***

Product architectures with closed and integrated characteristics are often complex and poorly understood by the people who design them, information exchange patterns are often complicated, and the knowledge underpinning the numerous product component interdependencies is often largely tacit. As firms are often more efficient than markets at resolving conflicts (Williamson, 1991) and facilitating communication flows (Monteverde, 1995), product development tasks are often encompassed within the boundaries of a single, focal firm. The usual logic is that firms sponsoring a closed and integrated product architecture tend to internalise production (see for example early works by Stigler, 1951; Chandler, 1977) in the face of perceived opportunities for rent appropriation, as well as to minimise knowledge appropriation through IPR or other secrecy mechanisms. Under these conditions, small numbers bargaining issues (Williamson, 1985) are likely to also impose prohibitive transaction hazards because market, technological uncertainty and asset specificity are high, reducing the perceived benefits of ‘supply-side externalities’ (Sanchez, 2008). In sponsoring its own product architecture, a firm is likely to deny access to potential collaborating external firms that may exist in the intermediate market due to concerns over contracting hazards which, in turn, may also help the firm focus on its own integral capabilities. The firm may also seek to develop its own demand-side externalities (Sanchez, 2008) such as using penetration pricing, marketing or branding to create a significant installed user base and propel it towards the dominant industry standard (Schilling; 1998) thereby increasing its embeddedness in a product market.

Firms that choose to sponsor a closed and integrated product architecture are likely to engage in ‘thick’ (Baldwin, 2008) information-exchange patterns in order to improve products and processes as changes in one component often have significant and unforeseen changes in other components. High levels of complex information-exchange that is tightly structured around the interdependencies within the product architecture allows firms to more efficiently manage the interaction effects between technical elements and to exchange information freely without worrying about ex-post opportunism in the intermediate market. Thus, our first propositions are that there is a mirrored architectural relationship as follows:

*P1: Closed and integrated product architectures are positively associated with high levels of information-exchange between product developers within the boundaries of a single product development firm*

***Degree of mirroring in closed and modular architectures***

The process of modularisation within firm boundaries is not easy and straightforward as the product development teams’ knowledge and understanding of the interdependencies are imperfect (Baldwin and Clark, 2000). A commitment to ex-ante investments in order to define components and interfaces is often needed to identify and clearly delineate component boundaries. The specification of modular components and specialised interfaces within a significantly closed architecture may over time begin to supplant existing interdependencies across the product architecture. This process may initially take seed where increased component mixing and matching or speed to market may offer a firm competitive advantage in a product market.

Where the closed and modular product architecture can be characterised as *simple*, the emerging modularisation of its components may permeate throughout a significant proportion of it. This is likely as the firm will often possess a broad scope of component level knowledge in order to scope ex-ante component boundaries and specialised interfaces leading to ex-post information exchange being minimised. However, if the product architecture is *complex*, there is often a need for organisational actors to maintain high levels of ex-post information exchange, even where the components are stable. Product complexity may affect how a component interacts with other components increasing the potential for unforeseen design and system integration problems across the architecture.

The architectural mirror may often be influenced by the rate of underlying product component change (Fulan, Cabigiosu, and Camuffo, 2014). Where the modular components within a simple product architecture are *stable* ex-post, the need for rich ex-post information-exchange between component development teams within firm boundaries is often reduced, as the specialised interfaces may begin to provide a form of ‘embedded coordination’ that replaces overt managerial control (Sanchez and Mahoney, 1996; Galvin and Morkel, 2001; Cabigosu and Camuffo, 2012). However, where the components are fast-changing, either as part of a complex or simple product architecture, ex-ante investments will often be required to understand how the technological changes affect other components. For example, component technological change is likely to increase coordination needs (Galbraith, 1973), affect the performance uncertainty of the components (Parmigiani, 2007), and make it harder for internal buyers and suppliers to monitor each other’s performance and value shadow price contracts. Therefore, where a product component is subject to technological change, frequent ex ante and ex-post information exchange may often be required in order to coordinate the integration of the product component into the overall architecture, manage performance uncertainty, and to nurture component-specific knowledge so as to “identify potential novelties” (Brusoni and Prencipe, 2001: p613) that may emerge. Thus, there is a within-firm mirrored architectural relationship only when closed and modular product architectures are simple and component technologies are stable as follows:

*P2a: Closed and modular product architectures are negatively associated with high levels of ex-post information-exchange between component developers, only when product architectures are simple and component technologies are stable*

However, as modular product architectures are usually associated with market contracting, the across-firm mirror will become misted:

*P2b: Closed and modular product architectures are positively associated with product development activities within the boundaries of a single product development firm*

***Degree of mirroring in intermediate/ hybrid modular architectures***

Product architectures with closed and modular characteristics often exhibit thinned-out crossing points that may eventually lead firms to outsource some or many ‘internally modular’ product components. Motivated by latent gains from trade (Jacobides, 2005) and the need to access external sources of innovation, firms transacting with the market for some components but seeking gains from integration around other components will create a hybrid product architecture. Product complexity and a fast rate of underlying product component change is likely to, however, affect the basis of contracting relationships with external firms such as increasing asset specificity and technological uncertainty (Williamson, 1985) and “*require more complex inter-firm devices (and hence more information-sharing)”* (Furlan, Cabigiosu and Camuffo, 2014: 791). Therefore, as we have noted before, where a product architecture is *complex* frequent ex-post information exchange may often be required in order to coordinate the integration of both insourced and outsourced product components into the overall architecture (see for example, Lau and Yam, 2005; Zirpoli and Becker, 2011; Furlan, Cabigiosu and Camuffo, 2014). Low levels of ex-post information exchange may diminish a firm’s ability to orchestrate activity across its intermediate/hybrid product architecture because it represents a challenge of accumulating and consolidating diverse technological developments, both within- and across-firms.

When components are stable, firms often outsource both the design and production of components (Brusoni, Pencipe and Pavitt, 2000), however, firms tend to internalise product component specific knowledge for rapidly changing and complex components in order to exploit novelties that may arise from the interplay or modularity and integration. When product components technologically evolve at uneven rates, there is the potential for technical imbalances which often requires a ‘cognitive overlap’ (Furlan, Cabigiosu and Camufo, 2014) in order to control or exploit them. A cognitive overlap can either be achieved through either keeping some components within firm boundaries or through remaining engaged in thick collaborative relationships with external firms. Where fast-changing components are outsourced, firms need to develop collaborative relationships with external firms in order to absorb component-specific knowledge, even when the component is modular. In sum, in intermediate or hybrid product architectures, modularity does not mitigate the need for high levels of ex-post information exchange, as such architectures often tend to be either complex or subject to fast rates of product component change. Thus, there is a within-firm mirrored architectural relationship only when intermediate/hybrid product architectures are simple and product component technologies are stable as follows:

*P3: Intermediate/hybrid product architectures are negatively associated with high levels of ex-post information-exchange between and across component developers/firms, only when product architectures are simple or where component technologies are stable*

***Degree of mirroring in open and modular product architectures***

In cases where product components are outsourced to external firms and component interfaces are defined, a product architecture can often be characterised as open and modular. As we have noted, where the product architecture can be characterised as *simple* andwhere underlying product components are *stable,* contracting firms invest ex ante in high levels of information exchange in order to define product component boundaries and standard interfaces, and then may switch to a low level of ex-post information-exchange. However, in complex architectures, or with fast rates of product component change, firms often rely on rich information exchange in order to orchestrate a diverse range of product component technologies across a number of external firms. Thus, there is a within-firm mirrored architectural relationship only when open and modular product architectures are simple and product component technologies are stable as follows:

*P4: Open and modular product architectures are negatively associated with high levels of ex-post information-exchange between product developers/firms, only when product architectures are simple and where component technologies are stable*

**Concluding remarks**

Despite the intuitive appeal of the mirroring hypothesis, we hypothesised that the extent of mirroring and non-mirroring is contingent upon the product architecture type, its degree of complexity and the rate of product component change such that the correspondence between architectural levels is only likely to be witnessed where the stylised product architecture type can be characterised as simple and where the underlying product components are stable.

However, where a stylised product architecture is characterised as complex – such as in the case of empirical studies of the software, motor vehicle and aircraft industries - we hypothesise that firms may not resort to low levels of ex-post information exchange between product developers, either within or across firms as there will be a need to effectively orchestrate the integration of diverse product components, access external sources of knowledge and manage unforeseen integrative consequences as they arise. As such, we hypothesise that even where product components are modular and stable, high levels of information exchange tend to be required to ensure effective integration into complex product architectures.

The overall framework, therefore, is one in which phase-shifts in the character of product architectures may often result in reconfigurations of information-exchange. Responding to the call for a nuanced theory of the mirroring hypothesis, our paper extends the ideas of writers such as Furlan, Cabigiosu and Camuffo (2014) and proposes how the contingencies of the stylised product architecture type, its complexity and the underlying rate of product component change may either be associated with phases of higher-levels or lower-levels of information-exchange. It may be the case that as product architectures evolve across time, there may be periods where mirroring yields strategic benefits, and yet in other periods a failure to shift the information exchange needs to ‘misting’ may have negative consequences for competitive sustainability.

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1. Colfer and Baldwin (2010) found uniform support for the within-firm mirroring hypothesis in 68% of studies, but 77% supportive when partial or mixed results were incorporated. Similarly, the across-firm mirroring hypothesis found uniform support in 47% of studies, but 74% when partial or mixed results were incorporated. [↑](#footnote-ref-1)