Industries in the making: Product modularity, technological innovation and the product lifecycle

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The trouble with our times is that the future is not what it used to be.
Paul Valery (1871-1945)

Abstract

In this paper, we examine the implications of two competing assumptions in the innovation literature. On one hand, product lifecycle theory assumes that technological innovation is propelled and stabilized by increasing synergistic specificity (Schilling, 2000) between organizations, technologies, and markets. On the other hand, modules in modular products are flexibly reconfigurable or synergistically non-specific. In this paper, we ask whether changes in synergistic specificity within the product spills out to undermine the linkages between organizations, technologies and markets, and hence the product lifecycle. We find that progressive modularization of products undermines product lifecycle theory. Instead, the product lifecycle is replaced by the interactions among lifecycles of architectures and modules. We outline the implications that the resultant mesh of S-curves, dubbed the "S-mesh," has for patterns of product and process innovation, the nature of the product lifecycle, capturing of economic rents, and competitive organizational capabilities. We then consider implications for industrial organization and the construction of industries. Given the increasing domination of modular product architectures in the software, telecommunication, computer, and automotive industries, this argument has broad implications.

Key Words: Modularity, Product Life Cycle, Innovation.

Introduction

Patterns of technological innovation and the determinants of their success have drawn the attention of management of technology researchers since this problem area emerged as a research domain (Schmookler, 1966; Marquis, 1969). Subsequently, Utterback's and Abernathy's early work (Utterback, 1974; Utterback and Abernathy, 1975), and Abernathy's study of Ford and the automotive industry (Abernathy, 1978) provided insights into the logic of product and process innovation and generated significant intellectual momentum (e.g., Abernathy and Clark, 1985; Tushman and Anderson, 1986; Utterback, 1994). The design of products links this macro-world of technological evolution and patterns of innovation with the micro-world of technology strategy and product development in technology-based organizations, as managers and designers strive to optimize across the conflicting dimensions of time, resources, performance and reliability, to compete in the marketplace (Abernathy and Clark, 1985).

Many studies of the computer industry and its recent integration with telecommunications focus on the phenomenon of modularization of products and systems (Henderson and Clark, 1990; Langlois and Robertson, 1992; Garud and Kumaraswamy, 1993; Baldwin and Clark, 1997a)[i]. While automobile manufacturers have been out-sourcing pre-assembled modules and components from fabrication divisions and external suppliers since the beginning of the 20th century (Abernathy, 1978; Abernathy and Clark, 1985; McAlinden, Smith, and Swiecki, 1999), this behaviour has progressively increased to the present (Clark, 1989; Clark and Fujimoto, 1991; Baldwin and Clark, 1997b; Christensen, Verlinden, and Westerman, 1999; McAlinden et al., 1999). Sanchez and Mahoney (1996 Table 1, 67) cite studies published between 1986 and 1994 that examined examples of modularization in aircraft, automobiles, consumer electronics, household appliances, personal computers, software, test instruments and power tools. Most recently Gawer and Cusumano (2002) show how the concept of technological platforms hinges upon modularity.

The Abernathy and Utterback model (Abernathy and Utterback, 1978) and its extensions (e.g. Abernathy and Clark, 1985) is one of the most widely accepted frameworks for research on the management of technological innovation. Their premise about the synchronicity of innovation and market development has been supported by industrial economics (e.g. Mueller, 1969; Jenkins, 1975; Jovanovic, 1994; Klepper and Simons, 2000a; Sinclair, 2000) and management of technological innovation research (e.g. Foster, 1986a; Tushman and Anderson, 1986; Tushman and Rosenkopf, 1992). In addition, both the marketing literature related to the product lifecycle (e.g. Weitz and Wensley, 1988; Urban, 1991) and the operations management literature, which relates operational competencies and strategies to the product lifecycle (e.g. Hayes, 1988) accept and build upon these principles.

In this paper, we examine central concepts in innovation strategy, namely the logic of the product lifecycle and the relationship between the product lifecycle and patterns of technological innovation. Given that product and process modularity is a permanent and pervasive part of the technological and business landscape, we ask whether the modularization of products fundamentally changes the basis of technology strategy. We find that modularization brings into question central ideas about dominant designs, the product lifecycle, and even how we think about industries. The theory of the product lifecycle is based on the assumption that, as industries evolve, there is a general increase in alignment between product and the processes. Schilling (2000: 316) calls this synergistic specificity, or “the degree to which a system achieves greater functionality by its components being specific to one another.” The product lifecycle is driven by progressive increases in synergistic specificity between product, process, the organization, and the market. We find that the non-specific synergies of the components in modular systems can undermine the synergies between the organization, the technology, and the market, which drive the Abernathy and Clark model.

Products on a continuum from integrated to modular

An end-product is a set of components that are linked together so as to be useable as a relatively stand-alone unit by an end-user.[ii] Products vary on a continuum from integrated to modular (Schilling, 2000; Gawer and Cusumano, 2002).

At one end of the continuum are modular products. In essence, a modular system is built of parts so that their internal complexity is hidden from other parts and from the environment external to the system (Baldwin and Clark, 1997a; Baldwin and Clark, 1997b; Baldwin and Clark, 2000). A module is a component of a modular system, and an interface is a set of formal well-codified rules that define how modules will interact with each other. The set of interfaces that make up a modular system is its architecture. A system is modular in as far as its architecture supports the substitutability of modules (Sanchez, 1995; Sanchez and Mahoney, 1996; Victor and Boynton, 1998; Schilling, 2000). That is, a system is highly modular if it can support many substitutions.

It is useful to consider two types of architectures, defined in the literature as open and proprietary (or closed) (Garud and Kumaraswamy, 1995). With open architectures, the interfaces are available to essentially all players in the industry and are determined either by the dominant player or through some standard-setting process. Open architectures breed network externalities but yield very little control to one player, unless it can control the standards defining the open architecture and innovate faster than the competition (Garud and Kumaraswamy, 1995). An architecture is proprietary if it is restricted to a small group of companies, typically comprising a central company and its suppliers. With proprietary architectures, the company derives benefits from modularization, but not from network externalities (e.g. Sanchez and Collins, 2001). It does, however, retain complete control over the architecture, which can give it more control over the competition. Most proprietary architectures are actually hybrids. For instance, an industrial robot with a proprietary architecture is still likely to use public interfaces for its memory chips and power supply.

At the other end of the spectrum are integrated products. In contrast to modular products, integrated products are those with synergistically specific interfaces. That is, for integrated products, the functionality of the system declines if one tries to substitute one component for another.

After discussing the drivers of modularity, this paper addresses two questions. First, as we move along the continuum from integrated products to modular products, what happens to the product life cycle? Second, as we move along that continuum, what is the impact on optimal forms of intra-firm and inter-firm organization?

Product modularity and non-specific synergies

While, as we have seen above, integrated products are synergistically specific (Schilling, 2000), modular products are synergistically non-specific. That is, the product system can achieve equivalent or alternative levels of performance if the various components are either arranged differently or are substituted. For example, a user can replace the Cathode Ray Tube (CRT) screen on her computer with a Liquid Crystal Diode (LCD) display if she wishes. She achieves the same level of utility with the CRT screen as she would if it were integrated into the computer (as was the case with the *Apple II*). As such, the CRT screen and the computer are synergistic. However, the fact that she is able to swap the CRT screen for the LCD display means that the achievement of that utility is not specific to the CRT screen. The computer is synergistic with the CRT screen, but it is also synergistic with the LCD display. The CRT screen and the computer are synergistically non-specific.

Researchers present essentially two arguments as to why non-specific synergies might be preferable in some markets. Some authors (e.g. Garud and Kumaraswamy, 1993; Victor and Boynton, 1998; Baldwin and Clark, 2000; Schilling, 2000) see modularization as being driven fundamentally by a change in the competitive environment, and particularly by a market need for flexibility in product design. For example, modularization of open architectures can be driven by network externalities. In particular, if someone who wishes to produce a new product can purchase key elements as modules in the open market, it is cheaper and faster to simply create a set of modules compatible with the open architecture standards than to design a proprietary product. Furthermore, such a manufacturer is less vulnerable to changes in the technical landscape as a result of innovations in the modules, they have chosen to purchase rather than develop. Finally, if they can sell some of their modules in the market, they may choose an open architecture over a proprietary one for the remaining modules. This further increases the network externalities. Gawer and Cusumano (2002, pp.4-5) contend that:

> An increasing number of industries today consist of *different* firms that each develops one component of a big jigsaw puzzle. This evolution has happened in the computer industry, where companies like vertically integrated IBM and Digital Equipment Corporation (DEC) have left center stage for specialist hardware component maker, Intel, and specialist, software component maker, Microsoft – and the plethora of complementary developers around them. The reasons industries evolve this way are widely discussed, but a central tenet of many theories is the concept of modularity. (Italics in original)

Other authors (e.g. Sanchez and Mahoney, 1996; Baldwin and Clark, 1997b), building on authors such as Simon (1981), have argued that products are essentially bundles of embodied knowledge, either physically embodied in the artifact, or embodied through the process of design and manufacturing. In order to avoid unmanageable complexity as a result of that embodiment, designers modularize their wares. If that is the case, we would expect modular products to be cheaper and faster to design and manufacture. As pointed out by Sanchez (1999:102) comparative cost analytics are hard to come by, but "...broad measures suggest the substantial impact that modular architectures can have on technologically determined economics of product creation." Sanchez (1999) goes on to point out that *Chrysler Corporation* has reduced the time to create a new model from a typical 60 to 72 months to less than 30 months. Additionally, the cost has been reduced from $2-3 billion to less than $1 billion, and the development team has been reduced from as many as 5000 people to only 700-900 people. *Chrysler* is not the only automaker to reap cost benefits from modularization. *General Motors* built its modular plant in Brazil with the intention that engineers and workers would be twice as productive (to 100 cars per worker per year) (Wheatley, 2000), while it would have a shorter assembly line, and cost about half the usual $1 billion to build when completed (Kerwin, 1998) compared to a conventional plant. When it opened in July 2000, the pre-assembled modules reduced the number of parts by 50% (Anonymous, 2000) and the number of suppliers by 60% (McClellan, 2000:72). Productivity targets haven't been achieved as yet due to a sharp decline in the demand for cars in Brazil in the last couple of years. These cost-savings are not limited to the automobile industry. Sanchez and Collins (2001) report that at GE Fanuc Automation, the modular approach to product creation reduced the human resources and the development time required by as much as 50% to 60%. Langlois (2000) argues for the benefits of modularity in semiconductor wafer fabrication equipment.

More recently Gawer & Cusumano (2002: 206) illustrate the benefits of modularity with *Handspring*, the company started by the *Palm Pilot* entrepreneurs who left *Palm* after it was acquired by *3Com*:

> ...As of mid-2001 Handspring was a leader of the emerging Palm economy-the group of firms building complements to the Palm Pilot...Handspring adopted a platform approach to product design...Handspring engineers designed the hardware around this concept in a bold move to make modules or peripherals as easy as possible to connect. The expansion modules literally snapped into the

> expansion slot on the back of the Visor PDA. Palm devices lacked such a simple mechanism for expansion when Handspring introduced this innovation...But Handspring also encouraged external companies to develop products that acted as accessories or modules to Visors (Gawer and Cusumano, 2002, 206).

They go on to list about ten such modules which range from financial calculator add-ons to wireless modems to digital cameras to AM-FM radios, all of which seamlessly work with the *Handspring* platform.

In spite of the above evidence, we stop short of arguing that modular systems are always dominant over their integrated counterparts. There are conditions under which integrated products can provide higher utility. One could argue, for instance, that the trend towards modularization of management education, whereby knowledge products are reduced to bite-sized chunks, reduces its value because it is harder to teach big ideas in small modules. Big ideas need to be built up, and so require synergistic specificity. Furthermore, the cost of modularization may not be justified if the product is not complex and neither its market nor the underlying technology is changing quickly.

We now turn to our two questions: What happens to the product lifecycle as products become more modular, and how does modularization affect organization? We will answer these questions by using an ideal type analysis, in which we consider perfectly integrated products and perfectly modular products, with the full knowledge that all real products lie somewhere in between. We will start by summarizing contemporary theory of the product lifecycle and show how it rests on the assumption of increasing synergistic specificity, not only between the components of the product, but also between the product, the organization which designs it, and the market which consumes it. We then present a framework for analyzing modular systems. By examining each element of a framework in turn and how it impacts upon the core predictions of the product life cycle, we show how the core predictions of the product lifecycle break down in modular systems.

The Product Lifecycle Model

> **All the effects of nature are only the mathematical consequence of a small number of immutable laws.**
> *Pierre-Simon de Laplace (1749-1827)*

The product lifecycle and patterns of innovation

The Abernathy and Utterback model (Utterback, 1974; Utterback and Abernathy, 1975; Abernathy, 1978; Abernathy and Utterback, 1978) and its extensions (e.g. Abernathy and Clark, 1985) have become an accepted framework for research on the management of technological innovation. The idea of a product lifecycle in technological innovation research was articulated by Utterback and Abernathy (1978) who noted that the nature of innovation around a product could vary during its life. At its core there is a temporal and causal connection between the logic of the product life cycle and the evolution of technologies that support and enable it. While the former is predicated upon the experimentation and learning by and about customers and users necessary for the diffusion of a new product, the latter is based upon the economics of innovation, from novelty products to mass production and commoditization. The transition from novelty products to mass production is marked by the emergence of a dominant design.

The Abernathy and Clark (1985) model can be summarized as follows. The evolution of the industry begins with the introduction of a novel product. The innovation creates a new market, so there are no pre-existing links to customers, or it completely reorganizes the value chain linking producers to customers. It also requires technical competencies that were previously non-existent in that market space. Abernathy and Clark (1985) call this an architectural innovation, because it "lays down the architecture of the new industry." (1985: 60).[iii] Because the technical capabilities are new, the players in this nascent industry are either all start-ups or are players in related industries. At this stage, the product is still evolving and numerous firms participate in its refinement and production, experimenting with features, materials and design with a view to creating product configurations that might appeal to the market. The industry is quite attractive economically, with numerous firms sharing in the high returns and growing demand.

Eventually, one player develops a "breakthrough" product that is attractive to a large segment of the market. This company is able to achieve a dominant market share (Anderson and Tushman, 1991) and to derive profit advantages on the basis of economies of scale. During the shakeout that follows, companies that are able to imitate the dominant design survive and succeed as participants in an oligopolistic market (Klepper and Simons, 2000b), while the rest deteriorate and exit the industry, retreat to market niches not serviced by the dominant product, or perish altogether. The remaining players produce essentially the same configuration (Rosenbloom, 1987; Cusumano, Mylonadis, and Rosenbloom, 1992; Utterback, 1994; Christensen, 1997) and compete on the basis of price and performance (Abernathy, 1978, Table 2.6: 43).

As competition moves from between-configuration competition to within-configuration competition, the locus of innovation moves from product innovation to process innovation (Abernathy and Utterback, 1978; Henderson, 1995). The industry becomes more rigid (Leonard-Barton, 1992), and price and reliability become the main factors that separate winners from losers. This is demonstrated most clearly by Abernathy's study of the evolution of the *Ford* motor-car (Abernathy, 1978).

Over time, the dominant design gets refined in two ways. Along one dimension, new platform innovations are developed out of it, creating channels to new customers (niche innovations). On the other, the main design itself gets progressively refined, and new product offerings are clustered around it (Tushman and Murmann, 1998). Abernathy and Clark (1985) call this progressive refinement regular innovation. The act of regular innovation, through various means,[iv] erects barriers that prevent the owner of the dominant design from detecting novel or emergent designs and/or implementing them even if detected. Thus, core competencies become core rigidities (Leonard-Barton, 1992). The market sits wide open for a new entrant to the market to come in with a radical innovation that, once again, transforms the industry and the competencies that underpin it (Tushman and Anderson, 1986; Anderson and Tushman, 1990; Tushman and Rosenkopf, 1992; Tushman and Murmann, 1998)[v]. Foster (1986b) has argued that these punctuations are more likely to occur when there has been sufficient regular innovation so that marginal returns to research have started to decline.[vi] These processes are summarized in Figure 1.

Insert Figure 1 about here.

A number of subsequent authors have enriched the Abernathy and Clark model and made it more explicit. However, none have challenged the basic premises, namely, that technological innovation evolves throughout the product lifecycle from focusing on the product and its functionality and performance to process improvements that reduce costs, improve service, and facilitate delivery. Other authors either build a model with similar premises (e.g. Mueller, 1969; Jenkins, 1975; Jovanovic, 1994; Klepper, 1996; Klepper and Simons, 2000b; Klepper and Simons, 2000a; Sinclair, 2000) or essentially assume its premises about the synchronicity of innovation and market development in building their arguments (e.g. Foster, 1986a; Tushman and Anderson, 1986; Tushman and Rosenkopf, 1992). Utterback (1994) offers a qualifier that for non-assembled goods, in contrast to assembled goods, process and product innovations are tightly intertwined and contemporaneous. Two other bodies of literature implicitly accept or explicitly build on the model, namely the marketing literature related to the product lifecycle (e.g. Weitz and Wensley, 1988; Urban, 1991) and the operations management literature, which relates operational competencies and strategies to the product lifecycle (e.g. Hayes, 1988).

The product lifecycle and synergistic specificity

The product lifecycle model hinges on the concept of dominant design, which drives both the beginning and the end of the product lifecycle. Utterback and Suarez (1993: 49) define a dominant design as "a specific path, along an industry's design hierarchy, which establishes dominance among competing design paths." Reiterating prior work (Abernathy and Utterback, 1978), they argue that the adoption of such a design can dramatically affect the nature and direction of competition, and the structure and evolution of the industry. The emergence of the dominant design at the top of the cycle leads to the shakeout that rationalizes the industry and enables its owners to both build their skills and market position (Utterback and Suarez, 1993). Early authors emphasized the role of specialization, scale economies (Abernathy and Clark, 1985), and embedded competencies (Henderson and Clark, 1990; Leonard-Barton, 1992), in locking in a design. All three of these correspond to increases in synergistic specificity (Schilling, 2000). In the first case, the skills of the product designers and production engineers become specific to the particular design. In the second, the entire production system becomes specific to that design. In the third, the cognitive systems of the people involved with the product become aligned with the dominant design (Henderson and Clark, 1990; Leonard-Barton, 1992; Tushman and Murmann, 1998). Other authors also see a role for network externalities (David, 1985; Garud and Kumaraswamy, 1993) coupled with competencies in the creation of the dominant design. In this case, dominance is created through specific synergies to particular complementary assets (Teece, 1988), such as the videotape to the VCR (Rosenbloom, 1987), the typewriter to the typing school (David, 1985), or the *Sparcstation* to the *Unix* operation system (Garud and Kumaraswamy, 1993).

The dominant design permits more stable and reliable relations with suppliers, vendors, and customers, and from the customer's perspective, a dominant design reduces product-class confusion and promises dramatic decreases in product cost (Anderson and Tushman, 1990). All of these correspond, once again, to increased synergistic specificity. In this case, it is between the product and suppliers and customers.

Specific synergies are important for the end of the cycle. They are the fundamental source of the core rigidities that prevent firms from responding to competitive threats posed by radically new technologies. These rigidities might reside in the production system (Anderson and Tushman, 1990; Leonard-Barton, 1995) or in channels to customers (Christensen, 1997). After the radical new technology has broken through and transformed the industry however, the system is re-stabilized by the reintroduction of specific synergies between the cognitive systems of product designers, skills and production systems of manufacturers, market channels, and the expectations of the market.

In summary, the central assumption of product lifecycle theory is that systems evolve towards and are stabilized by increasing synergistic specificity. When and if a radical technology transforms the system, those synergies must be re-established to re-stabilize the system.

Given this, we can rephrase the first question which motivates this paper by asking what will be the effect of eliminating specific synergies between the components of the product on the synergies in the product system, namely, between the product, the organization, competencies, production technology, suppliers and customers. Will the synergies in the product system which stabilize the product lifecycle be maintained?

Product lifecycle without specific synergies

As noted above, the product lifecycle is stabilized by the advent and evolution of the dominant design. Its role in the product lifecycle hinges on specialization, scale economies, embedded competencies, and network externalities. Given this, we need to ask whether, for modular products, the product design or manufacturing process still leads to specialization, scale economies, embedded competencies, and network externalities, and if so, whether these in turn lead to specific synergies between the product, organizational competencies, production technology, suppliers, and customers.

With regard to specialization, there is considerable evidence that companies which pursue a modular strategy develop tremendous specialist expertise, both in the design and manufacturing of particular modules, and in the design of product architectures

(Sanchez, 2001). However, that expertise does not lead to specific synergies between the organization and its competencies and production technology, but the contrary. Because the product is modular, it becomes possible for the organization to modularize the group which either designs or manufactures it, even to the point of out-sourcing it. Consequently, entire parts of the organization or its production technology can be substituted in and out without disrupting the rest of the organization.

Modularization has two impacts on scale economies, both of which serve to reduce the minimum efficient scale of production, and hence the specific synergies. First, imagine an integrated product with a certain minimum efficient scale, which is subsequently modularized into two modules. Each of those modules will have a minimum efficient scale that is smaller than or equal to that of the integrated product. Consequently, even though it may cost more to produce the modularized product, the modularized product has at worst the same minimum efficient scale as the equivalent integrated product. Second, because our integrated product is now modularized, it becomes possible to use the two modules in other products. For instance, a flat-screen display can be attached to a television tuner as easily as to a computer. Therefore, the minimum efficient scale for our production system may be quite different from the minimum production run for our product. Consequently, the scale of production is much more loosely coupled to the size of the market for a given product for modular products, and so specific synergies are much weaker.

Modularization also undermines embedded competencies. As a general rule, modularization forces organizations to make tacit knowledge explicit (Sanchez, 2001) in as far as that tacit knowledge is relevant to the interactions between modules.

Furthermore, the remaining embedded knowledge and associated competencies are confined within the boundaries of individual modules. Consequently, they cannot pervade the entire organization. As a result, there is a much lower likelihood of specific synergies forming between particular sets of embedded knowledge and competencies and larger organizational, technological, and market systems.

Finally, lock-in associated with network externalities results from specific synergies between particular products and complimentary assets in the marketplace (David, 1985). In as far as those complimentary assets are substitutable; the extent of the lock-in is reduced. Modularization enhances substitutability. Consider for instance the paradigmatic case of the competition between VHS and *Betamax* (Cusumano et al., 1992). VHS and *Betamax* could have co-existed just like electric and gas cooktops stoves (or 5.25" and 3.5" floppy drives) if people had only used video-cassette recorders to play back home videos and to record and replay television shows. VHS only triumphed decisively over *Betamax* when video rentals took off. Among other things, the need for store-owners to manage inventories meant that the specific synergies between the tape format and the VCR become much more important (Cusumano et al., 1992). If the VCRs were modular however, and so manufacturers could simply substitute the VHS playing module for the *Betamax* playing module, while leaving the rest of the machine as it was, even that specific synergy would have become irrelevant.

In summary, if we look at the four principal drivers of lock-in for dominant designs -- scale economies, specialization, embedded competencies, and network externalities -- we see that modularization serves to reduce, and in some cases even eliminate, their importance. Consequently, we expect the product life cycle to be dramatically attenuated, if not obliterated, in modular systems. In the next section we introduce the S-mesh, and use it to map that attenuation process.

The S-mesh framework for analyzing innovation in modular systems

One of the principal heuristic devices for the analysis of integrated systems is the "S-Curve". If technology, product, and market are synergistically specific then the lifecycle of a product involves its technical evolution towards a physical limit (Foster, 1986b), as it diffuses through a finite market (Rogers, 1983). Given appropriate simplifying assumptions (see Rogers, 1983; Foster, 1986b) both technical progress and market diffusion through time can be expected to approximate a cumulative-logistic distribution (hence the term S-curve). The technology proceeds up an S-curve through regular innovation (Foster, 1986b). As it proceeds up that S-curve, it diffuses to fill the market circumscribed by the limits of the needs it can satisfy. The diffusion curve is also S-shaped (Rogers, 1983)[vii]. At some point, this evolution/diffusion process is truncated by punctuation from a novel technology.

With modular systems, in contrast, technologies, markets, and products can effectively be de-coupled. Modules are not necessarily specific to architectures. Modules can be used in architectures in related product classes – such as "Zip" drives used in personal computers and in industrial robots. Alternatively, modules might transcend entire classes, such as nuts and bolts, which span all constructed objects, musicians who work in the film industry (sound tracks), advertising, and the conventional music industry, or computer chips in domestic appliances and motor-cars. As such, the progress of a given technology embodied in a module might well involve its use in different architectures designed for radically different markets.

Each architecture and module has its own S-curve representing both its technical progress and its market diffusion. So, instead of thinking in terms of a single S-curve for the individual product, it is more useful to think of a mesh of intersecting curves, which we will call an S-Mesh.[viii] In an S-mesh, the columns correspond to the set of architectures associated with the technological system, with each column representing an architecture. In the same way, the rows correspond to the set of modules associated with the technological system, and for every module, there is a row. A product corresponds to an architecture and a set of modules used with it (see Figure 2a). It should be noted that each module and architecture on the S-mesh could be at different point in their lifecycles.

Insert Figure 2a about here

We define the S-mesh along two interrelated dimensions – domain and density. With integrated products, the domain of action is the reach of the firms that control the dominant design up and down the value chain. With modular products the S-mesh maps onto the overlapping set of networks of the architecture and module suppliers.

The density of a mesh can be defined as the proportion of nodes that are occupied. Open and proprietary architectures have radically different mesh densities. With open-architectures, such as in some areas of consumer electronics, the mesh tends to be quite sparse. Headphones, for example, are used across only about ten classes of products, lenses are used across an overlapping three or four, and small motors are used across another overlapping twenty-odd. Headphones have seamlessly become a more prominent feature of personal computers in recent years, with the advent of voice-to-text software and Internet telephone. Notwithstanding, some modules, such as memory and circuit boards are found in all of them, albeit with different configurations. In contrast, with proprietary architectures, modules are likely to be used across a much narrower range of products, and so the mesh will generally be much denser. For example, in their article on industrial automation system design and development at *GE-Fanuc*, Sanchez and Collins (2001) describe the way the organization is set up to maximize the reuse of both product and process modules across different products (and product generations) before creating new ones. Platform products, such as power tools (Meyer and Lehnerd, 1997), have an extremely dense mesh, in that virtually all modules are identical.

Change in an S-mesh can happen in one of four ways. First, a row can be changed by modifying a module; second, a row can be added by creating a novel module; third, a column can be changed by modifying an architecture, and fourth, a new column can be added by creating a new product architecture.

Given this, four types of innovation can happen in a modular system. Designers can modify a module. Henderson and Clark (1990) call this incremental innovation. In incremental innovations, neither the core-concepts which define the way the technology within the module is constructed nor the nature of the interface between this module and other modules changes significantly (Henderson and Clark, 1990). In storage devices for personal computers, most of the 12,000-fold increase in hard drive capacity from 5MB in the mid-1980's to 60 GB today was achieved by progressive refinement of the parts or components within the modules, and the way they interact with each other. Another example would be the progressive increase in CD-ROM drive speed from 1x to 40x at the time of writing. We expect performance to change over time as the product and its technologies progress up their S-curve (see Figure 2b).

Insert Figure 2b about here

Alternatively, designers can replace one module with another (see Figure 2c) – a modular innovation (Henderson and Clark, 1990; Langlois and Robertson, 1995). This is an innovation in which the internal content of the module changes, but the interface standard stays the same. Examples include substituting the second floppy drive on the original *IBM* PC for a hard drive, or installing a "Zip" drive instead of a floppy drive, or a replacing a record player with a CD player, or a VCR with a DVD player (Langlois and Robertson, 1992). In this case, the new module is depicted in the figure at the early phase of its lifecycle. Interestingly, the last two types of innovation are captured by the PlugFest event as described by Gawer and Cusumano (2002: 58), where various component suppliers tested their modules' compliance with *Intel*'s new architecture.

> In August 1998 PlugFest in Milpitas, California, .. Intel reserved nearly all the rooms in a large hotel for the event; each company had a room. As Miller put it, the PlugFest was "like watching the layers of industry come together." Engineers walked from room to room with oscilloscopes, other testing devices, and their own prototype peripheral products to conduct tests (behind closed doors) of interoperability with workstations, computers, and other equipment.

Insert Figure 2c about here

Third, designers can use the same modules but change the architecture -- an architectural innovation (Henderson and Clark, 1990). For example, there have been significant innovations in hard-drives which have affected the way the drive interacts with the rest of the computer. The most obvious of these architectural innovations has been the change in size from 8” to 5.25” to 3.5” to 1.75”. These different physical sizes have allowed the drives to be used in different ways. Other changes have been in the interface between the drive and the rest of the computer (e.g. MFM, IDE, SCSI). With pure architectural innovations, the interface standard changes though the core concepts within the module are preserved (Henderson and Clark, 1990). An example of a purely architectural innovation is move to the USB (Universal Serial Bus) serial port on personal computers from a nine-pin serial port. Many devices (e.g. printers, personal organizers) moved to the USB interface with minimal internal changes. Depending on its qualitative nature, an architectural innovation can take one of two forms. Either, the new architecture is a variant of a prior architecture, in which case, the set of architectural innovations over time is part of the movement up the S-curve, such as the progressive changes in bus design on a personal computer mother-board (see Figure 2d). Alternatively, the new architecture can reconfigure the fundamental relationships between the modules (Henderson and Clark, 1990), in which case it makes more sense to think of it as representing a new column in the S-mesh (see figure 2e).

Insert Figure 2d about here

An architecture is essentially a set of interface standards. Open architecture interface standards are set in one of three ways. First, a standards committee sets a standard in advance, and companies then design and manufacture products to the standard. For example, a group of companies decided on the USB interface standard, and now designers design to it. Second, a novel product might come to dominate the market and its standards will become the *de-facto* industry standards. This might involve a fight, as in the fight between *Apple* and *IBM* computer operating systems, or between VHS and Beta videotapes (Cusumano et al., 1992). Finally, a dramatically new module might come to market, and conform to the existing architecture in as far as it interacts with it. At the same time, it might in effect "extend" the architecture by adding a new interface. For instance, the "Zip" drive conformed with the interface standards of computers while adding a new standard interface for the removable "Zip" disk.

For proprietary architectures, Sanchez (2000a) lays out a normative process in which designers look at what they are capable of doing with modules to determine a new architecture and a research agenda for designed improvements in the next generations of architectures. They then develop the modules and configure a product. With the new modules that are the products of the research from the prior round, they determine the new architecture for the next round, and so forth. If organizations manage these processes properly and create a clear separation between architecture creation and module creation, they derive big advantages in reduced product complexity (Sanchez and Mahoney, 1996), reduced complexity of the design process (Sanchez and Mahoney, 1996), improved knowledge management (Sanchez, 2000a), and improved ability to manage uncertainty (Sanchez and Mahoney, 1996). If developers cannot control this process, all those advantages may be lost.

Finally, designers can develop new products. The laptop computer is a product with a different architecture but functional modules that are nearly identical to those in a personal computer (see Figure 2e). So are the *Sparcstation* and the *Macintosh.* It should be noted that in this type of innovation, we depart from the integrated world of Henderson and Clark (1990), whose fourth type -- radical innovations -- is not found within an existing modular architecture as defined by the S-mesh framework. Instead, their radically new products would involve a substantially new architecture and substantially new modules operating in the same product market (Henderson and Clark, 1990). In contrast, we contend that in the modular world new products are likely to involve new architectures, some new modules, and a number of old modules, some of which have been incrementally improved or modified. This does not imply the overthrowing of cognitive frames or competencies implicit in the Henderson and Clark (1990) definition of radical innovation.

Insert Figure 2e about here

The S-mesh and the unit of analysis for innovation research

In a recent article, Tushman and Murmann (1998) argued that the advent of modularization did not change the logic of the product lifecycle. Instead, they argued, all we have to do is move the level of analysis down to the module level. Then, we could expect the "product lifecycle logic" to occur within the module, and the overall logic can be kept intact. Unfortunately, such an argument assumes that all innovation occurs within the modules – that the S-mesh has only rows. Because the S-mesh contains columns, Tushman and Murmann miss the possibilities of modular and architectural innovation. As we will see in the next section, these possibilities fundamentally change the dynamics of the product lifecycle, because it is no longer stabilized by synergistic specificity.

Implications of Modular Systems for the Product Lifecycle

The product lifecycle model is both driven and stabilized by increasing synergistic specificity between components. Modular systems, in contrast, are synergistically non-specific and have their evolution driven by the dynamics of a two-dimensional S-mesh. In this section we examine first how the introduction of modularity affects patterns of innovation and the dynamics of the product lifecycle. Then, we examine how these changes are likely to impact the structures of organizations and industries.

Patterns of innovation

If the product lifecycle is driven by progressive increases in synergistic specificity, which also serve to stabilize the entire value chain, we expect the innovation process to become progressively more orderly with time. As the various elements become progressively more aligned, the innovation will become more incremental and component based. Occasional punctuations will either open up new market niches or fundamentally transform a dimension of technical competition (Foster, 1986b; Tushman and Anderson, 1986). Notwithstanding the disruption, the system will quickly stabilize once more.

Insert Figure 3 about here

Under the assumptions that products are synergistically non-specific and that innovation occurs along two dimensions at once, we can expect a much more chaotic process (see Figure 3). Innovation no longer stabilizes the system, but rather destabilizes it. The three types of innovation -- architectural, modular, and incremental (either incremental innovations to modules or architectures) -- can happen in any order (see Figure 4). Products might start with an architectural innovation, in which pre-existing modules are organized in a different architecture. This may create demand for many new modules. For instance, the creation of a high-speed data port on personal computers opened up the market for external devices that could process audio and video, and software to manage the content. Similarly, the creation of specific modules to fit these new architectures is likely to drive the creation of new products that can use those new modules. For instance, the development of small motors and high-fidelity headphones for personal cassette players facilitated the invention of the personal radio, the personal CD-player, the personal MP3 player and the personal mini-disc player. Alternatively, products might start with a modular innovation in which a new module is inserted into an existing architecture, as with CD players being added to Audio systems (Langlois and Robertson, 1995) (and then find their way into a multitude of products such as computers as components). They may also begin as a combination of both modular and architectural innovations, where a few modules are combined with old ones into a partially new architecture, as with the transition from analogue to digital home-video cameras.

Insert Figure 4 about here

Consequently, the four critical variables that define the S-curve under the product lifecycle model – the total size of the market, the upper technical limit of the technology, and the rate constants for take up in the market and progress of the technology – all start to lose meaning as systems become more modular. To consider a palpable example of this, consider the diffusion curve for personal computers. While it may have started in 1980, we are yet to see any significant plateaux either in technical capabilities or market size. Furthermore, the size of such a curve depends strongly on the devices we choose to include -- the curve that includes laptop computers and personal digital assistants is different from the curve that just includes desktop machines.

Product lifecycle

Given this, how does the product lifecycle change as product systems become more modular? To answer this question we will exploit the fact that technologies are on a continuum from integrated to modular and assume that a product follows the product lifecycle and consider the impact of making it marginally more modular. We see that architectural and modular innovation affect it in two phases -- during the establishment of the dominant design, and during the discontinuous changes that dislodge it.

Tushman and Anderson (1990: 12) argue that for the product lifecycle:

> A revolutionary innovation ... ushers in an era of experimentation as organizations struggle to absorb (or destroy) the innovative technology. This era of ferment is characterized by two selection processes: competition between technical regimes and competition within a new technical regime.

If the product is modular, then the contrast does not have to be as stark. The innovation can involve embedding a novel technology in a module within an existing architecture, such as a "Zip" drive inserted into a PC. This has a number of implications for commercialization of the new technology. For instance, the number of niches occupied by the given technology can be much larger because the new technology can be embedded into a number of different architectures. "Zip" drives can be incorporated in PC's, laptops, workstations, and industrial robots at low cost. At the same time, the host architecture becomes reconfigurable by swapping modules, and so it can also occupy more niches (Sanchez, 1999). Therefore, the space between dominant designs, both in time and in portion of the market space they occupy, is much larger. In terms of spatial niches, the essence of mass customization is a generic capacity to serve the exact needs of a wide variety of customers by interchanging modules (Pine, 1993). Von Hippel (1998: 5) uses construction architecture to illustrate the connection between mass customization and modularity:

> To develop their custom design, developers will find it useful to have access to standard component parts and standard design tools that will help them to carry out the trial-and-error cycle of problem-solving work. Thus, a team of architects who are designing a custom office building will find it very useful to have access to a library of standard components, for example a range of standard structural support columns with pre-analyzed structural characteristics, that they can incorporate into their building design. Similarly, users who are designing a document with the aid of a desktop publishing system will find it useful to have standard formats and standard "clip art" illustrations that they may choose to incorporate into their custom design.

Temporally, a PC of the near future -- a very high-powered machine, possibly with a photonic processor, embedded in a network with input by voice and graphical manipulation, output to a flat-panel screen or the Internet, and storage on an optical disk – will have no parts in common and no physical resemblance to the product from which it has evolved, the original *IBM* PC. Notwithstanding, the same “product” will have dominated the same “niche” for about 20 product generations. Consequently, the module and the host architecture that incorporates it can occupy many more niches than equivalent integrated products. Also, a given dominant product may evolve incrementally into a radically different product (See also Orlikowski, 1996).

Similarly, the "era of experimentation" is likely to be less significant. Because consumers can select between modules in a given architecture, the costs of experimentation with novel designs are very low for consumers, as are the sunk costs. If their "German to English" translation software does not work properly, they can buy another package at low cost, or just throw it out. In the meanwhile, their bad choice of program has not affected the rest of the functionality of the machine. Similarly, if they bet on *Apple* and the world goes *IBM*, they can change platforms and take their scanner, their printer, their digitizer, and all their files with them. If they had access to the source code, they could also take most of their software. For software developers, except in graphics intensive applications, the *Apple* versus *IBM* bet is of equally low cost. From this it follows that the majority of potential adopters is much less likely to await the emergence of an industry standard before purchasing a new product or installing a new process technology. It also follows that the emergence of an industry standard will not be a prerequisite to mass adoption and volume production of a new generation of technology (see Anderson and Tushman, 1990).

The product lifecycle model requires that the incumbent dominant design be removed discontinuously. The dominant design must be entrenched in the market by synergies to inputs, outputs, the production system, and complementary assets. Its entrenchment keeps competitors at bay but prevents the manufacturer from responding to new entrants. With modular architectures, the dominant product is likely to be much less entrenched. Because the dominant product is modular, it is possible for a new entrant to adopt many of the attributes of the existing product by purchasing modules from existing suppliers. *Dell* entered the PC market with a logistics innovation but purchased all its hardware and components.

More recently, Gawer and Cusumano (2002: 198) show how the two mindsets – the modular, or platform, and the integrated – collided in the case of *Palm Pilot*, after its acquisition by *3Com*. While *3Com* management were used to premium pricing of the product very early in the product lifecycle, before the emergence of the dominant design standardized and commoditized the product, Donna Dubinski of *Palm* (she left soon after to start *Handspring*) believed that for platform business it is critical "to get as much market share and installed base as possible, to draw as many developers as possible... And when we get high barriers to entry and lots of support, the network effects kicks in." This principle has significant ramifications for rent capturing as well .

Competence change and innovation

In their discussion of the conventional model, Anderson and Tushman (1990: 11) distinguish between competence-enhancing and competence-destroying discontinuities: "A competence enhancing discontinuity builds on know-how embodied in the technology that it replaces," and strengthens the position of the incumbent, while a competence-destroying discontinuity does the opposite. With modular and architectural innovations, competence enhancement stops being as clear a concept or a phenomenon. For example, Christensen (1997) argues that the 3.5" hard-drive was competence enhancing for the 3.5" manufacturers and competence destroying for the 5.25" manufacturers, as Tushman and Anderson predict (cf. King and Tucchi, 2000). In addition, however, the 3.5" drive increased the capabilities of the computer assemblers, since it enabled them to develop portable machines. This meant that enhancement and destruction occurred in different locations in the market place. As a result, the move from 5.25" to 3.5" drives was not terribly dramatic: while 3.5" drives turned up in small machines, 5.25" drive manufacturers continued making drives for PC's and workstations. Eventually, the 5.25” drives disappeared, and the 3.5” drives made their way into the bigger machines. Some 5.25” manufacturers made the transition, while others did not. New portable computer manufacturers entered the market. Consequently, whether or not an innovation is competence enhancing or competence destroying, depends on the role of the actor in the innovation network.

Rent capturing

In the traditional product life cycle model, the dominant design brings with it a shakeout that precipitates a decline in the number of firms in the industry (Utterback and Suarez, 1993). Start-up entrants lack the resources to construct the necessary synergies (such as economies of scale or marketing channels). Existing players have sufficient resources, but are unable to change to develop the necessary competencies (Anderson and Tushman, 1990; Henderson and Clark, 1990; Utterback and Suarez, 1993). Given this shake-out, those that remain and control the dominant design will attract oligopolistic rents (Utterback and Suarez, 1993; Klepper and Simons, 2000b) and exert considerable control over other players in the value chain (Utterback and Suarez, 1993).

For modular products with proprietary architectures, especially in markets where all products have proprietary architectures, the cycle is likely to be similar. The firms that can produce the requisite functionality will capture oligopolistic rents. For modular products with open architectures, it is much harder to capture rents because appropriability is weak, unless a manufacturer has some sort of intellectual property protection. Contrast, for example, the very low profitability of the personal computer industry with the profitability of *Intel* and its patented and copyrighted *Pentium* microprocessors (see also Gawer and Cusumano, 2002). The examples below involve firms exploiting imperfections in the modular market to generate wealth.

Garud and Kumaraswamy (1993) show how *Sun Microsystems* gave away its technology to capture rents from transient monopolies. In fact, *Sun* made the *Sparcstation* the dominant design by giving away the technology and making it the de-facto standard. They then used their organizational ability to exploit the rapid evolution of the market. They captured rents by converting embedded competencies into a network externality (see also Hax and Wilde, 1999). As a more general statement, we argue that being continually first to market is likely to be much more important in modular markets, because the manufacturer can capture transitory advantages. This is likely to drive hypercompetition (See D'Aveni and Gunther, 1994, Schilling, 2000). Second, a company can use its market power to integrate an otherwise modular product and capture a monopoly rent. Virtually the entire *Microsoft* antitrust case can be understood in this respect (http://www.usdoj.gov/atr/cases/ms_index.htm). In particular, *Microsoft* attempted to integrate a browser into its operating system, while *Netscape* was trying to offer a modular alternative. Similarly, *Sun Microsystems* developed *Java* to make computing operating-system-independent (i.e., modularize part of the functions). *Microsoft* attempted to undermine this aspect of *Java* by changing key aspects of the *Windows®* implementation. It manipulated product interfaces by threatening to change the operating system so it would not run with some products (e.g. *Real Audio* and *Quicktime*) and by manipulating the way products were put together through its bundling strategy (e.g. *Internet Explorer*). It manipulated process architectures by withholding licenses from companies at critical times (e.g. *IBM's* license to bundle

Windows 95®) and by withholding key technical information for future versions of *Windows*® from potential providers of competing products (e.g. *Netscape*).

Finally, companies can create transient value by increasing the modularity of the system. In as far as process and product interfaces are implicit (i.e., the interfaces are poorly defined) the module manufacturers and assemblers may be bound to each other through contractual and trust relations. This is expensive both in terms of the cost of maintaining the relationship, and in terms of allocating rents between the parties, since each can potentially hold the other to ransom (Purdy, Astad, and Safayeni, 1994). As interface complexity increases, so does this cost. As a result, if the companies do not hold the product as a joint monopoly, one or both has an incentive to create wealth through architectural innovation. So, for example, a contract assembler of computers might offer "design for manufacturing" services and logistics services to clients. In so doing, it simultaneously increases the value of its offering, but rationalizes the process further so as to reduce the rent it can capture from the value it adds. Fasteners provide an extreme case of this: nuts and bolts are so standardized that manufacturers have little opportunity to capture rents from these standard products. As such we expect that, given a relatively stable architecture, and lacking a joint monopoly, firms will constantly attempt to add value by making the product and process interfaces more explicit and, in so doing, they will modularize the relationship even further.

Organizing for modularity

In the above sections, we have shown how the removal of synergistic specificity between components undermines the logic of the product lifecycle. We now turn to our second question and ask how this undermining affects efficient forms of organization.

In the current incarnation of product lifecycle theory, the optimal form of organization is the ambidextrous organization (Leonard-Barton, 1995; Tushman and Murmann, 1998). Such an organization has the discipline and rigidity needed to produce regular innovation while simultaneously being able to reinvent itself and its products. The capacity for regular innovation is critical during the convergent phases of the product lifecycle, while the capacity for reinvention is needed to master the discontinuities. Such an organization dominates its suppliers and the industry in which it is embedded.

A given physical product and the organization that creates it have multiple architectures, each with its own interfaces. Sanchez (2000b; 2001) talks of product, process, and knowledge architectures, all of which are amenable to modularization. The product architecture specifies the physical relationship between modules. While the product architecture is a property of the product, the process architecture is a property of both the product and the organization. The process architecture is concerned with interactions among processes that design, manufacture, service and repair, and dispose/recycle the product. The process is modular if activities are substitutable. That is, they are loosely coupled and can be carried out by different organizational units, in different locations, and/or at different times. Lower levels of process modularization are associated with specific interactions between processes that limit the substitutability of processes (Schilling, 2000). Finally, knowledge architecture is a property of what an organization knows, and is concerned with the way the organization organizes its knowledge for the design, manufacture, service and repair and disposal/recycling of products (Sanchez, 2000b; Sanchez, 2001). Knowledge is modular if it is substitutable (can be applied without modification across multiple products and/or processes).

So, we must ask how the modularization of products affects the modularization of processes and knowledge. If the fundamental driver of organization is interdependence (Thompson, 1967), and modularization enables components to be decoupled, then efficient forms of organization for the design of modular systems will involve two elements. The first will be some sort of meta-level organization to design the architecture and divide it into modules. The second will be decoupled units which design the modules.

Sanchez (2000a; 2000b; 2001; 2001) has examined the closed architecture case extensively. He has found that such an organizational form is, in fact, efficient. The most efficient organizations, which he has studied, oscillate between convergent and divergent phases. In the convergent phases they focus on architectural issues. In the divergent phases, they focus on modular issues. He goes on to point out that the efficient organizations also modularize their processes and knowledge in the same way and put tremendous emphasis on the development and control of organizational process and knowledge architectures in order to derive benefits from modularity. The focus of organizational effort moves to coordinating and managing knowledge within a network of modular component developers and producers. Because the knowledge is managed carefully, this enables them to structure their time efficiently as well. There are fewer unexpected delays, and so product design can be scheduled.

With open architectures, as noted above, architectures are created essentially by three mechanisms: standards committees, standards wars, and extension through a new dominant product. None of these have particularly interesting implications for organizing. If products become separable at the interfaces, then the optimal form of organization would involve two types of organization. One group of organizations would specialize in modules. Another group of organizations would specialize in aggregating modules and assembling them into final products. A module manufacturer might supply a number of assemblers, each assembling modules within one or more architectures. Those assemblers might be in completely different markets, and so might have most of their interactions with fundamentally different sets of different module manufacturers. In such a situation, the optimal form of industrial organization becomes a network of small firms, rather than a dominant manufacturer with subservient suppliers (Piore and Sabel, 1984; Saxenian, 1994; Langlois and Robertson, 1995; Truffer and others, 1998). Hence, we hypothesize that the Silicon Valley phenomenon would be strongest in industrial domains where modularization is possible and is practiced extensively.

In such an environment, we expect to see extensive entrainment of firms (Ancona and Chong, 1996; Eisenhardt and Brown, 1998). Consider two OEM personal computer manufacturers "D" and "C". Suppose that D is the market leader and puts pressure on all its module suppliers to produce new models by June and December, so that it can release its new products at the trade shows in September and March. Because C will have access to the same new modules in June and December, it will then schedule its product releases for the same trade shows, and put pressure on the residual suppliers (who don't supply to D) to deliver in June and December as well. Those suppliers will put similar demands on third tier suppliers, and because of their ability to supply will pressure other assemblers, possibly outside the narrow sectors in which "C' and "D" operate, e.g. "A", to release their products on the same schedule. Once the market (e.g., the computer magazines) gets used to this schedule, it will build its own expectations. Consequently, we can expect an entire complex of firms to be entrained into the same timing schedule. This type of entrainment is implicit in Gawer and Cusumano (2002: 58) description of “PlugFest”.

Furthermore, entrainment simply helps people manage the ambiguity of a much more complex technical marketplace (March and Simon, 1958). Because there is no longer hierarchical control over the system, entrainment gives people some extra structure. Such structure is likely to increase efficiency (March and Simon, 1958).

Finally, we turn to the somewhat cryptic title of this article. Implicit in the product lifecycle model is a definition of an industry. If organizations, technologies, and markets are synergistically specific, then an industry can be defined as a group of companies "hanging off" a dominant design through particular market linkages and technical competencies (Abernathy and Clark, 1985; Teece, Rumelt, Dosi, and Winter, 1994; Kogut, Walker, and Anand, 2002)[ix]. So, for example, the “automobile industry” comprises vehicle manufacturers, their suppliers, and their distribution channels. Once modules start to appear across significantly different architectures, technologies and markets become decoupled. The underlying technology can no longer form the basis for our definition of the industry. Whereas once industries were technologically distinct, in a modular world, an industry has to be defined exclusively in terms of the product market, ignoring its current, ergo, temporarily configured technological base. This means that an industry is, at least to some extent, independent of a particular knowledge base of the manufacturers, but is dependent on the cognitive categorization systems (Berger and Luckmann, 1967; Rosch, 1978) of consumers. Industries move from being “in the making” to being “in the market”.

Conclusions

In this paper we have contrasted two theories of innovation. Under product lifecycle theory, products are progressively refined by the pursuit of specific synergies and these synergies stabilize the system. In modular systems, synergies are non-specific and innovation occurs along two dimensions. The non-specificity of synergies blunts the predictions of product lifecycle theory considerably and the two-dimensionality of innovation, along with the non-specificity de-stabilizes the system. Given that modular systems are becoming more pervasive, this suggests a progressive movement of our industrial system towards hyper-competition, smaller and more competitive firms, more transient wealth generation, and system stabilization to external drivers such as time-pacing. These are, of course, the characteristics of the "new" economy.

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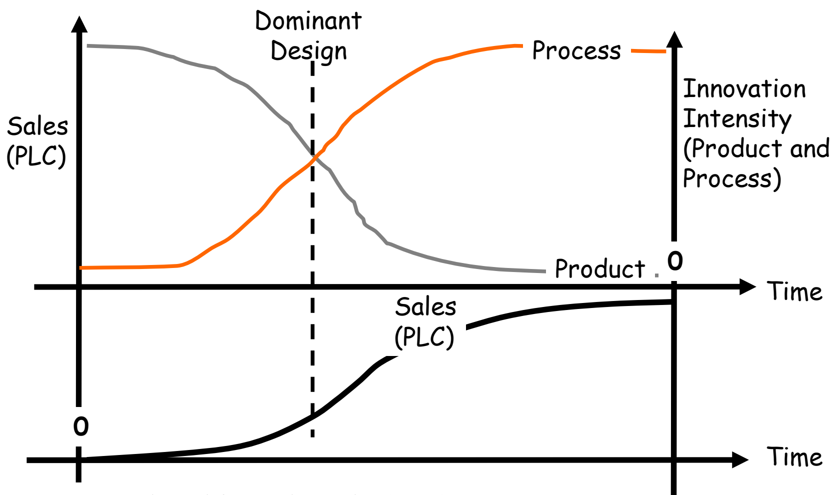
Figures

Figure 1: Product lifecycle and patterns of technological innovation for integrated products



Source: Adapted from Abernathy (1978)

Figure 2a: S-Mesh framework for the analysis of innovation in modular systems

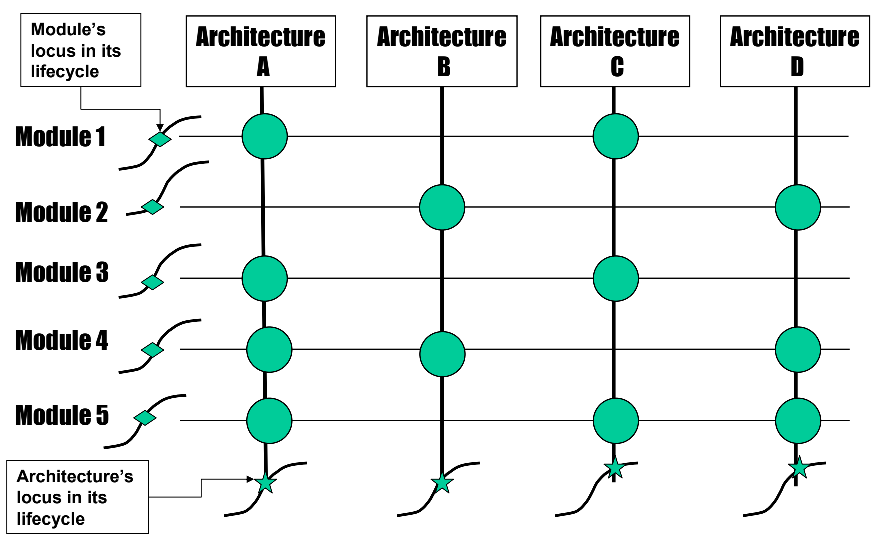
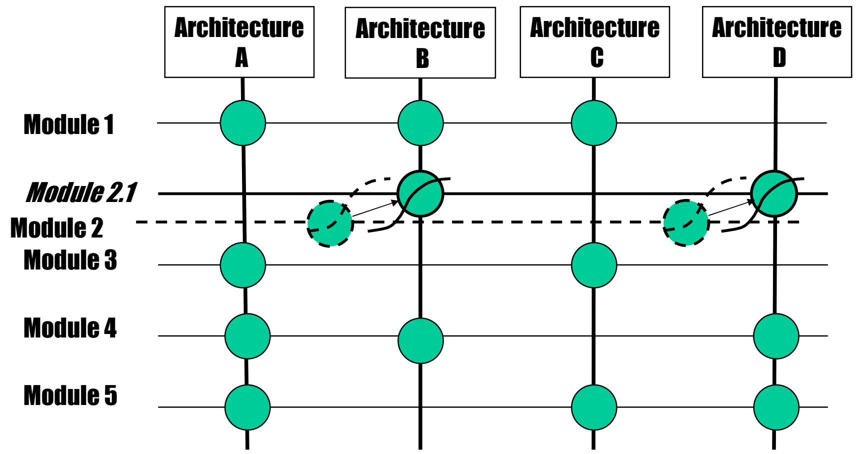
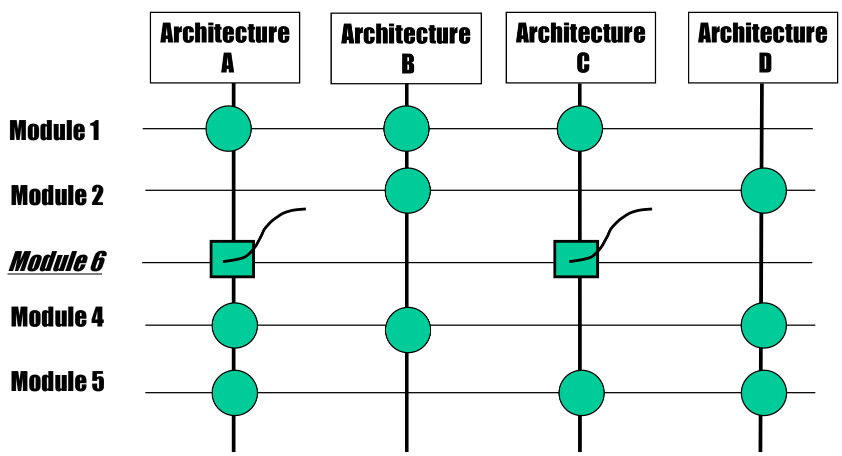


Figure 2b: S-Mesh for incremental innovation in a module



Note: Module 2 moves up the S-curve as a new release **2.1**

Figure 2c: S-Mesh for modular innovation



Note: Module **6** replaces Module 3 from Figure 2b

Figure 2d: S-Mesh for incremental innovation in an architecture

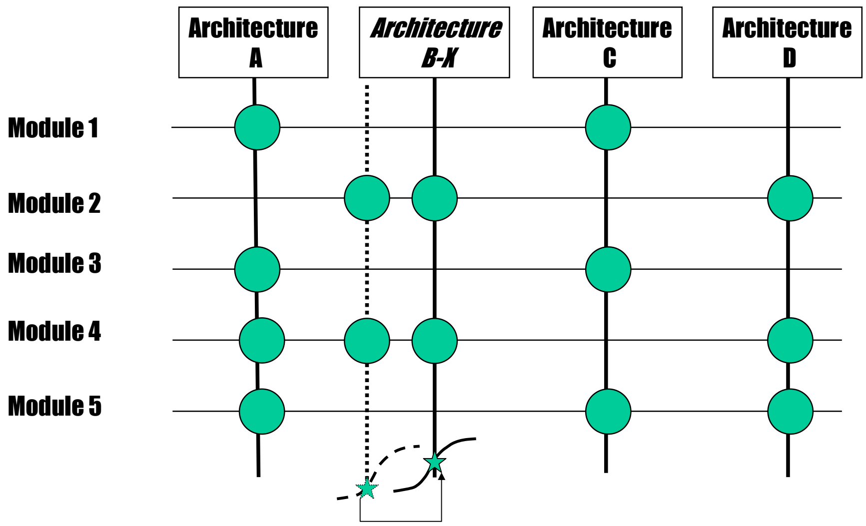
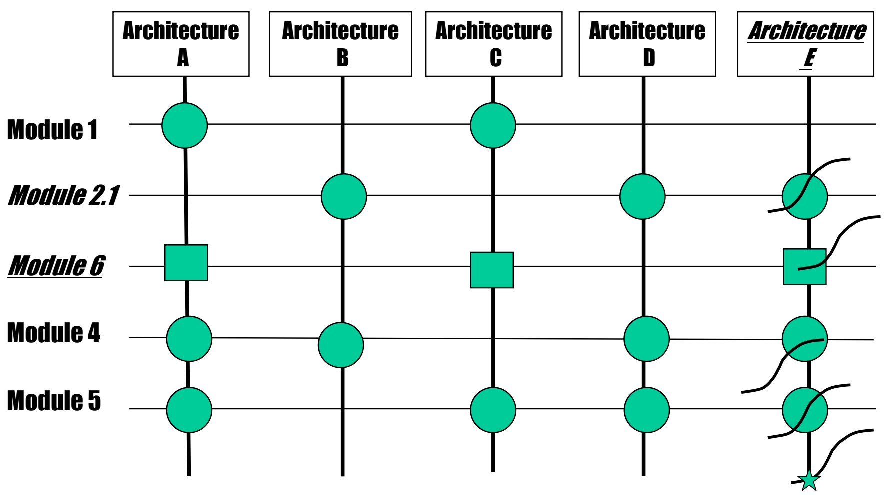


Figure 2e: S-Mesh for a new product



Note: The new product is a recombination of existing modules **1**, **4**, and 5, improved module **2.1**, and new module **6** in a new architecture **E**.

Figure 3: Innovation rates for modular and integrated products

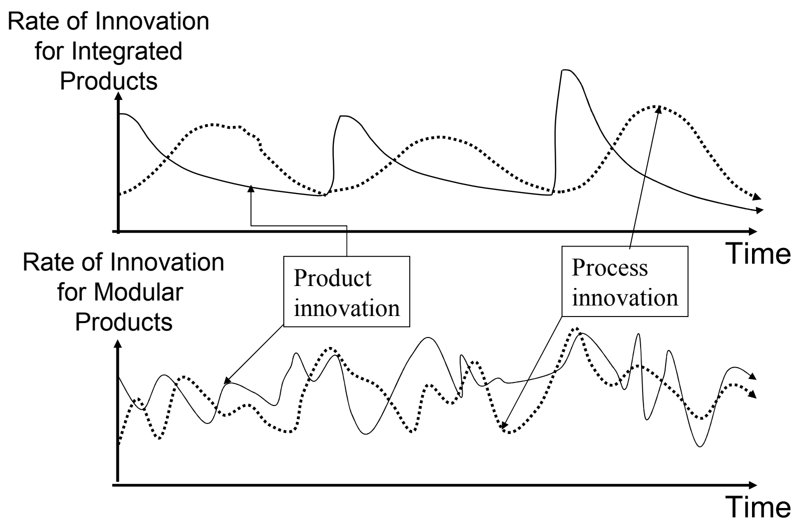
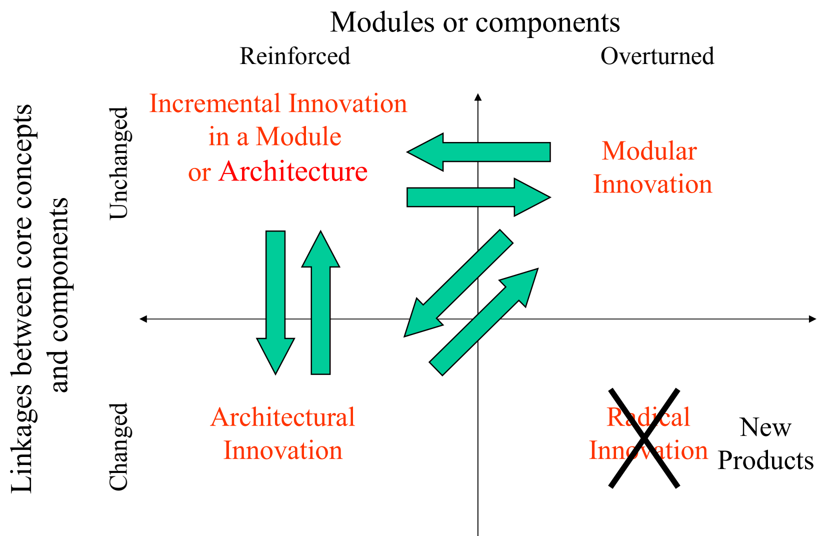


Figure 4: Innovation dynamics for modular products



Note: Adapted from Henderson and Clark (1990).

End notes.

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[i] Two additional sources of information offer additional evidence about product modularization: a) The UMI digital dissertations database (http://wwwlib.umi.com/dissertations) for the years 1994-2000 includes the following dissertations: Constantinides (2000), Du (2000), Glew (2000), Erixon (1998), Schug (1998), and Pangburn (1997); b) Gartner's web-site (http://www4.gartner.com/database) returned 187 research citations for "product modularity" for the period 1996-2001.

[ii] This definition has high heuristic value, but surprisingly little analytical value. For instance, while we think of a printer as being a "product", a printer has very limited use unless attached to a computer.

[iii] Note that the term "Architectural innovation" has two meanings within the literature. In this case, it refers to the creation of a new industry. For most of this article, an architectural innovation refers to a change in the relationship between the modules in a product.

[iv] Particularly the use of specialist machinery, economies of scale, and the development of closed communities of practice within and between firms (Anderson and Tushman, 1990).

[v] See Afuah (1998) for a comprehensive review of dynamic models of innovation.

[vi] Although Christensen (1997) is not a neo-Shumpetarian, and therefore stands outside the conventional theory, he argues that discontinuities in the market will still be observed. He postulates that they will occur when there has been sufficient regular innovation to open up a performance gap so that the needs of a sizeable portion of customers can be met with a product inferior to and cheaper than that currently on offer.

[vii] The shape of the S-curve is predicated on the logic of two-step diffusion, from a source to opinion leaders, and from the latter to the general population, while the leveling off at maturity is predicated upon a finite target population of consumers. The graph of cumulative sales, from early adopters to late adopters, has an "S"-shape

[viii] This argument could be constructed another way, with advantages and disadvantages. In the pure case, and architecture is just a set of interface standards. Given this, one could argue that architectures diffuse but do not change. Every change in architecture could be treated as a new architecture instead. The advantage of this is that all the technology is then moved to the modules and interaction with the market is moved to the product (and architecture plus a set of modules). The disadvantage is that it makes it harder to capture the product trajectories associated with the given family of architectures, such as the progressive changes in the architecture of personal computers (Dosi, 1988).

[ix] It should be noted here that all the above show the conjunction of markets and technologies in industries with data that clearly predates modularization of product technology, Abernathy with mainly data from *Ford*, circa 1900-1935, Kogut et al. and Teece et al with pre-1970 data.