07-057

From Manufacturing to Design: An Essay on the Work of Kim B. Clark

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March 2007

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We thank Didier Chabaud and Yannick Perez for giving us the idea to write this paper. We are extremely grateful to Robert Hayes and Steven Wheelwright who spoke to us at length about the history and intellectual environment of the POM/TOM group in the 1980s and 1990s. And we thank Eric von Hippel for very helpful comments on an earlier draft. Any mistakes or omissions are ours alone, and we apologize for them in advance.

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Abstract

Kim Clark occupies a unique place in management scholarship. As a member of the Technology and Operations Management unit of Harvard Business School, he participated in several major research initiatives during the 1980s and early 1990s, before becoming Dean of the School in 1995. And even as Dean, he continued to pursue research until 2005, when he left Harvard to become President of Brigham Young University—Idaho. In this paper, we describe Clark's research and discuss his contributions to management and economics. We look at three distinct bodies of work. In the first, Clark (in conjunction with Robert Hayes and Steven Wheelwright) argued that the abandonment by U.S. managers of *manufacturing* as a strategic function exposed U.S. companies to Japanese competition. In the second research stream, conducted with Wheelwright, Bruce Chew, Takahiro Fujimoto, Kent Bowen and Marco Iansiti, Clark made the case that *product development* could be managed in new ways that would lead to significant competitive advantage for firms. Finally, in work conducted with Abernathy, Rebecca Henderson and Carliss Baldwin, Clark placed *product and process designs* at the center of his explanation of how innovation determines the structure and evolution of industries.

Key words:

manufacturing—new product development—innovation—industry evolution—dominant design—product architecture—architectural innovation—design theory—modularity—user innovation—theory of the firm

JEL Classification:

B31, M1, O31, O32

1. Introduction

Kim Bryce Clark, a labor economist educated at Harvard University, joined the Harvard Business School faculty in the Production and Operations Management (POM) area in 1978. Shortly thereafter he began collaborations with colleagues William J. Abernathy, Robert H. Hayes and Steven Wheelwright.[1] These associations were to have a profound effect on the direction of Clark's work, which up to that time had focused on the determinants of structural unemployment (Clark and Summers, 1982) and the impact of unionization on productivity (Clark, 1980a & b; 1984). Clark was active as a researcher at Harvard Business School from 1978 to 1995, when he became Dean of the School. Even then, he continued to pursue research until 2005, when he left Harvard to become President of Brigham Young University—Idaho.

Early in his career, Clark came to believe that management plays a fundamental role in companies' performance and therefore in the economy. This conviction would guide all of his subsequent research: it also explains why he was drawn to senior management roles, first as dean of a business school and then as president of a university.

In this paper, we describe Clark's research and discuss his contributions to management scholarship and economics. We look at three distinct bodies of work. In the first, Clark (in conjunction with Robert Hayes and Steven Wheelwright) argued that the abandonment by U.S. managers of *manufacturing* as a strategic function exposed U.S. companies to Japanese competition in terms of the cost and quality of goods. In the second, conducted with Wheelwright, Bruce Chew, Takahiro Fujimoto, Kent Bowen and Marco Iansiti, Clark made the case that *product development* could be managed in new ways that would lead to significant competitive advantage for firms. Finally, in work conducted with Abernathy, Rebecca Henderson and Carliss Baldwin, Clark placed *product and process designs* at the center of his explanation of how innovation determines the structure and evolution of industries.

Clark's work occupies a unique place in management scholarship for three reasons. First, he tended to focus on little known and under-appreciated management groups: manufacturing managers, product development managers, and product and process architects. Thus he intentionally positioned

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[1] From the mid 1980s, the group was called "Technology and Operations Management" (TOM) which, as we shall see, was emblematic of the evolution of the group's research agenda.

himself outside the "traditional" management disciplines of strategy, finance, marketing and organizational behavior. Second, Clark swam against prevailing methodological currents by relying heavily on comparative and longitudinal *field studies*. As was the tradition at Harvard Business School, he observed practice in detail before trying to build theory or design empirical studies. His work on the automobile industry (Abernathy, Clark and Kantrow, 1983; Clark, Chew and Fujimoto, 1987; Clark and Fujimoto, 1991) is an example of what can be gained from this deeply grounded approach. Third, Clark looked beyond the boundaries of his own field to design theory, the engineering sciences, and finance for frameworks that would help him address the questions he sought to answer. As time went on, his theories became increasingly broad-based and inter-disciplinary. His crossing of disciplinary boundaries may explain why Clark's work is usually not included in collections of works by leading scholars in the fields of management and organization theory.

This paper is organized as follows. Section 2 describes Clark's work with Hayes and Wheelwright on manufacturing. Section 3 describes his seminal work on new product development. Section 4 considers early work with Abernathy on innovation and industry evolution and the development of the ideas leading up to the breakthrough article (with Rebecca Henderson) on architectural innovation and the failure of established firms (Henderson and Clark, 1990). Section 5 looks at his work (with Carliss Baldwin) on design structure, dynamics, and value, and on the power of modularity to change industry structure. Section 6 describes later works that build on this theory of design. Section 7 concludes by looking at the convictions that guided Clark throughout his career and assessing his intellectual legacy.

The references in this paper are divided into two sections. The first contains a chronological list of Clark's publications. The second contains all other references in standard alphabetical order.

2. Surviving Japanese Competition: The Importance of Manufacturing

The latter part of the 1970s was marked by a sharp increase in the U.S. trade deficit, particularly with Japan. U.S. companies, which had dominated world trade since the end of World War II, were increasingly faced with competition from Japanese firms, especially in symbolic markets such as autos, steel and semiconductors (Table 1). Moreover, government statistics pointed to a significant slowdown in

U.S. productivity growth compared with that of other developed countries.

Table 1 : Changes in world market share of U.S. companies by major industry 1960-1986

Industry	%
Iron and steel	- 58
Electrical equipments and electronics	- 47
Chemicals	- 38
Autos and trucks	- 33
Computers and office equipment	-11

Source : Chandler (1994), quoted in Baldwin and Clark (1994)

This was a sudden reversal for the United States. After World War II, the Japanese and European economies were rebuilt with the help of U.S. companies and capital. And during the 25 years following the war, U.S. companies had served as a management model for companies around the world (Servan-Schreiber, 1967; U.S. edition 1979). Today, however, Japan is the destination of choice for studies of manufacturing productivity. And in the 1970s, it became abundantly clear that many Japanese firms were superior to their American and European counterparts in terms of cost, product quality and even innovation.

A heated debate arose in the U.S. over the reasons for the productivity growth slowdown and loss of competitiveness. One side argued that these trends were caused by *macroeconomic* factors, specifically insufficient savings by U.S. citizens, which, it was said, led to a high cost of capital and low rates of investment by U.S. companies. Behind this argument lurked the economic theory of comparative advantage, which holds that a country with lower factor costs (eg, cheap labor or a low cost of capital) will dominate in industries with low transportation costs. But comparative advantage did not explain why U.S. firms often lagged behind their Japanese counterparts, not just in cost, but also in product quality, reliability and innovation. And it did not explain why some U.S. companies in embattled industries like autos and steel were prospering even though they were subject to the same macroeconomic conditions as the companies in decline (Hayes and Abernathy, 1980).

The other side argued for a *microeconomic* explanation. Those in this camp asserted that poor performance was the result of short-sighted decision-making on the part of U.S. managers. Two prominent advocates of the microeconomic point of view were Clark's senior colleagues Hayes and Abernathy. In a hard-hitting article, "Managing Our Way to Economic Decline," published in the *Harvard Business Review* in 1980, they argued that American companies were suffering from "competitive myopia" and "listlessness."

> By their preference for servicing existing markets rather than creating new ones and by their devotion to short-term returns and "management by the numbers," many [managers] have effectively foresworn long-term technological superiority as a competitive weapon. In consequence they have abdicated their strategic responsibilities. (Hayes and Abernathy, 1980, p. 70.)

Clark, who had researched the productivity of cement plants in his doctoral dissertation, was soon drawn into the microeconomic camp.[2]

Because of the ongoing debate over competitiveness, the question "how do Japanese firms compete?" was at the center of research in the POM group at Harvard Business School in the early 1980s. The group, led by William Abernathy and Robert Hayes, initially focused on the impact of *manufacturing management* on the comparative performance of U.S. and Japanese firms. It was evident that the methods Japanese companies used to manage their manufacturing operations differed significantly from U.S. practices and were a mainstay of their competitiveness (Hayes, 1981). However, manufacturing management had fallen out of favor in U.S. companies. Most managers and academics believed, to quote John Kenneth Galbraith (1958), that companies had "solved the problem of production." Indeed Harvard's POM group was one of the few academic departments in the country that saw manufacturing as a worthy subject of research.

Wickham Skinner, a senior member of POM, had long argued that manufacturing was "the missing link" in corporate strategy (Skinner, 1969). And in the early 70's, members of the group conducted a number of case studies of manufacturing performance across a wide range of industries. (These cases formed the curriculum of the Manufacturing Policy course in the early 1970s.) Their field research led several members of the group to become vocal critics of "scientific management," a set of ideas put forward by Frederick Taylor in the early twentieth century, which were still very influential in the 1970s. (On Taylor's views, see Hatchuel, 1994.) In contrast to Taylor's static optimization approach, the POM faculty as a group were moving toward a dynamic, learning-oriented view of manufacturing, a

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[2] This research showed how changes in labor cost due to unionization forced management to change its methods and processes. It already underscored the link between productivity and management (Clark, 1980a & b; 1984).

view that emphasized the crucial role of problem solving in determining performance (Hayes and Wheelwright, 1984; Wheelwright and Hayes, 1985; Bohn and Jaikumar, 1986).

Beginning in 1978, Kim Clark joined Hayes and Wheelwright in a series of research projects aimed at developing this new view of manufacturing. Their collaboration culminated in the book, *Dynamic Manufacturing*, published in 1988.

Before we discuss this book, we should describe the research methodology that members of the POM group saw as distinguishing their work. The methods were rooted in the field research traditions of Harvard Business School. They were:

- Longitudinal studies of specific plants, to acquire a clear understanding of how the organization operated and how its operations changed over time;
- Comparative analyses of several plants making similar products and using the same type of process, to determine how practice varied across sites.

These methods were applied, not only by Clark, Hayes and Wheelwright and by Clark's students, Bruce Chew and Takahiro Fujimoto, but by others in the group including Ramachandran Jaikumar, Roger Bohn and David Garvin. The methodology came to be emblematic of the POM (later TOM) group's approach to empirical research.

Clark augmented these field research methods with a toolkit from economics. For example, a key problem in manufacturing research was to assess the performance of a given plant. Rather than employing traditional physical productivity indicators, which they considered too simplistic,[3] Hayes and Clark (1985a & b; 1986) introduced a concept from economics, Total Factor Productivity (TFP). TFP metrics compared a plant's total production against a weighted average of all factors of production (capital, labor, materials and energy).[4]

The use of this tool led to remarkable results. First, plants considered efficient based on traditional metrics turned out not to be efficient when measured by TFP. Second, application of TFP to different plants belonging to the same company revealed significant disparities in performance despite the fact that the products manufactured, the processes used, and the accounting systems were the same.

To understand the reasons for these differences, Hayes, Wheelwright and Clark undertook an extensive study of 12 plants from a number of industrial sectors in different countries. The results,

[3] Pre-existing measures focused on labor productivity, at a time when labor inputs were diminishing in many sectors.

[4] For the TFP calculation method, see Hayes and Clark, 1986, or Hayes, Wheelwright and Clark, 1988, p. 144 *et seq.*

synthesized *Dynamic Manufacturing* (1988), demonstrated the superiority of Japanese management methods.[5] The most efficient plants were those that applied the following Japanese principles (then seen as revolutionary by many American managers):

- Downstream production planning based on a just-in-time approach guided by customer demand.
- Elimination of inventories perceived as a sign of production system failure.
- Elimination of defects and faults through the implementation of a total quality process and preventive maintenance aimed at precluding their occurrence.
- Organization of employees into autonomous teams responsible for managing and improving the overall production system.
- Ongoing assessment of cost, quality and delivery time standards to ensure continuous process improvement (Kaizen).
- Collaboration with suppliers to this same end.
- Priority given to long-term performance, even if it reduced short-term productivity.

Dynamic Manufacturing directly challenged Taylor's principles of scientific management. U.S. companies had relied on Taylor's ideas since the advent of mass production in the early twentieth century. But, according to Hayes, Wheelwright and Clark, Taylor's methods led to a production system frozen in time. Japanese methods, in contrast, relied on learning capacity and collaboration to attain continuous improvement of the process. Japanese companies were able to improve productivity by identifying problems, experimenting with new solutions, and applying the solutions quickly to their production lines. Hence there was a "new paradigm" in manufacturing:

> "continual learning" … emphasizes problem-solving at all levels, is cross-functional, combines top-down and bottom-up approaches, and violates most of Taylor's assumptions about human behavior and motivation" (Hayes, Wheelwright and Clark, 1988, p. 250).

Table 2, adapted from *Dynamic Manufacturing*, summarizes the key differences between the old and new manufacturing paradigms.

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[5] It is striking to note the evolution of issues from Hayes and Wheelwright's earlier book, *Restoring Our Competitive Edge* (Hayes and Wheelwright, 1984) to *Dynamic Manufacturing*. The former book dealt mainly with structural decisions, typically capital investments. However two chapters were devoted to the German and Japanese approaches to manufacturing. In effect, Hayes and Wheelwright challenged the primacy of U.S. manufacturing methods by describing the nature and performance of alternative models.

Table 2 : Old and new manufacturing paradigms

	Command and Control [Taylor]	**Continual Improvement [Japanese]**
Assumptions underlying the manufacturing architecture	Optimized defined tasks Productivity : adherence to best practice Decisions deferred to higher levels Narrow job definitions Staff over line	Improve evolving tasks Productivity : develop better practices Decisions pushed down to lower levels Broad job definitions Line over staff
Role of the work force	Physical efforts Minimize skills (deskill) Process should be worker independent Maintain process stability (changes made only by staff groups)	Mental efforts Maximize worker's skill (both technical and problem solving Worker can add value to the process by improving it Process improvement is everybody's job (many made by workers)
Information needs	Coordination (what and when) Fixed responses to problems through standard operating procedures Performance evaluation based on adherence to procedures	Problem-solving (cause-effect and problem elimination) Flexible responses to problems as they arise Performance evaluation based on success of the business
Management control	Direct control (variance analysis, direct supervision, and inflexible procedures) Boss knows the answer Strict hierarchy and status	Second-order (systems and procedures) and third-order (norms and values) control Boss supports and helps Peers working as a team

Source : Hayes, Wheelwright and Clark, 1988, p. 251

All in all, *Dynamic Manufacturing* made three important points. First, as we said, it argued that the principles governing competitiveness in manufacturing had changed, and thus paved the way for further research on the subject (notably Womack, Jones and Roos, 1991, discussed below). Second, it observed that the common denominator among the most efficient plants was learning capacity. Third, it strongly argued that *management* was what made the development of learning capacity possible. In other words, learning capacity arose, not because of a nation's culture or workers' attitudes, but because of the way work was organized and performance was measured and rewarded.

The last two chapters of the book looked ahead to future research. The authors' field studies of manufacturing plants highlighted the critical importance of *product and process designs*, which were developed prior to the start of production itself. Specifically, the field research revealed that changes in product or process designs after a new product was launched had dramatic, negative effects on manufacturing performance. Such changes were highly disruptive, especially because in most cases managers simply allowed them to happen. *Dynamic Manufacturing* thus pointed to the importance of activities that preceded production, thus contributing to a new area of study: *product development*.

3. The strategic role of new product development

New product development became an important focus of Kim Clark's research in the mid-1980s. The shift in focus was not an accident: Clark and his colleagues believed that *innovation* would be the next battlefield of international competition, and as field researchers, they wanted to be where the action was. The Dean of Harvard Business School, John McArthur, agreed. With his consent, Production and Operation Management (POM) was renamed Technology and Operation Management (TOM) in 1986 to symbolize the group's new direction.

Within the TOM group, Clark elected to focus on new product development, a field which was largely unexplored at the time.[6] Working with his colleague and friend, Steve Wheelwright, and with doctoral students, Bruce Chew and Takahiro Fujimoto, Clark helped open up this new area of research. In particular, he and his coauthors were among the pioneers in: (1) understanding product development as an information processing and problem solving process; and (2) theorizing about the organizational structures suited to the management of such processes.

3.1 Product Development in the World Auto Industry—The Pioneering Study

Clark and his colleagues began in an industry Clark knew well, whose products he loved: automobiles. In their first study, Clark, together with students Bruce Chew and Takahiro Fujimoto, analyzed 29 product development projects for new vehicles. This was a comprehensive, global study involving 20 U.S., Japanese and European automobile manufacturers. The team used quantitative data plus interviews with participants to obtain a detailed picture of how the projects were carried out. Their findings were published in the *Brookings Papers on Economic Activity* in 1987 (Clark, Chew and Fujimoto, 1987).

This paper showed that, in addition to manufacturing advantages, Japanese auto companies also had a substantial edge in new product development. Japanese firms brought new products to market more quickly, consumed fewer resources, and delivered higher quality designs. Their high level of performance in product development in turn allowed Japanese companies to:

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[6] Other early entrants to the field were Kenochi Imaï, Ikujioro Nonaka and Hirotaka Takeuchi (Imai, Nonaka and Takeuchi, 1985; Nonaka and Takeuchi, 1986). The first of these articles was presented at a symposium organized by Clark and his colleagues at Harvard Business School in 1984. Contributions to the symposium were collected in *The Uneasy Alliance* (Clark, Hayes and Lorenz, 1985).

- Reduce design costs;
- Offer a wider variety of products;
- Quickly update the product line to respond to changes in demand;
- Provide improved customer satisfaction thanks to the quality of the products offered.

These findings met with a considerable response from researchers and auto executives alike. They became a key part of the argument set forth in the influential book, *The Machine that Changed the World*, which coined the phrase "lean production" to explain the competitive superiority of Japanese automakers (Womack, Jones and Roos, 1991). Indeed Chapter 5 of *Machine* was largely a summary and interpretation of the "Clark team's" work.[7] The key table from that chapter, summarizing their most important findings, is reproduced below. (See Table 3.[8])

The 1987 study was followed by two books: *Product Development Performance* (1991, with Takahiro Fujimoto) and *Revolutionizing Product Development* (1992, with Steven Wheelwright). Both books relied on field research within firms, including interviews, observation of problem solving processes, and involvement in project teams. Clark and Fujimoto focused exclusively on the automotive industry, while Wheelwright and Clark explored other sectors, especially medicine and electronics. These books were fundamental contributions to our modern understanding of how to manage new product development. We discuss them in detail in the next two sections.

[7] Womack, Jones and Roos (1991), Chapter 5 and endnotes.

[8] For an update of this data showing the US catch-up in the 1990's see Ellison *et. al.* (1995) and Fujimoto (1999).

Table 3 : Product development performance by regional auto industries, mid–1980s

	Japanese producers	American producers	European Volume Producers	European Specialist Producers
Average Engineering Hours per new Car (millions)	1.7	3.1	2.9	3,1
Average Development Time per New Car (in Months)	46.2	60.4	57.3	59,9
Number of Employees in Project Team	485	903	904	
Number of Body per New Car	2.3	1.7	2.7	1,3
Average Ratio of Shared Parts	18%	38%	28%	30%
Supplier Share of Engineering	51%	14%	37%	32%
Engineering Change Costs as Share of Total Die Cots	10-20%	30-50%	10-30%	
Ratio of Delayed Products	1 in 6	1 in 2	1 in 3	
Die Development Time (months)	13.8	25	28	
Prototype Lead Time (months)	6.2	12.4	10.9	
Time from Production Start to First Sale (months)	1	4	2	
Return to Normal Productivity after New Model (months)	4	5	12	
Return to Normal Quality after New Model (months)	1.4	11	12	

Source : Clark Chew and Fujimoto (1987) and Fujimoto (1989); summarized in Womack, Jones and Roos (1991, p. 118)

3.2 Product Development Performance

Product Development Performance became one of Clark's most influential and widely cited works. Clark and Fujimoto started with the performance data, described above, that showed the superiority of Japanese firms. They went on to present a detailed comparative analysis of product development practices at automakers around the world.

Conceptually, the authors regarded new product development as a set of *information processing* *and problem solving activities*.[9] The intermediate outputs of the process were *information assets*, in particular, product-specific knowledge and product and process designs.[10] The aim of the overall process was to ensure the product's *integrity*, i.e. its intrinsic qualities and its ability to meet the customer's expectations. For a complex product like an automobile, the greatest management challenge was to establish organizational structures and practices that ensured adequate *integration* of diverse skills and knowledge, including the customers' knowledge about what it was like to use the product (Clark and Fujimoto, 1991, Chapter 2).

The book brought into focus three important new management ideas: (1) heavyweight product managers; (2) overlapping problem-solving cycles (also called concurrent engineering); and (3) the integration of customers and suppliers into product development activities. Clark and Fujimoto were not the only academics to elucidate these concepts, but their analysis was backed up by extraordinary amounts of field data, hence their arguments carried great weight.

Heavyweight product managers: "To the extent that product performance is more than just the sum of component performance or technical specifications," Clark and Fujimoto argued, "firms need to worry about integrity and thus integration" (p. 250). They defined two types of integration: (1) *internal integration*, which aimed to coordinate the various groups within a company; and (2) *external integration*, which aimed to coordinate the company with customers and suppliers. Clark and Fujimoto observed that, in their sample, the highest levels of external and internal integration were achieved (by Japanese firms) through having a "heavyweight product manager." This manager was committed to the project through its entirety; was empowered to make key decisions; and had the status, experience and resources to exert influence on both team members and senior managers.[11] At least in the auto industry, heavyweight project managers were a pre-requisite to success in product development. In other words,

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[9] Clark and Fujimoto cited Marquis (1978), Allen (1977), Freeman (1982), Galbraith (1973), Tushman and Nadler (1978), Kotler (1988), Engel, Blackwell and Kollat (1987) and Bettman (1979), Weick (1979) and Nonaka (1988) as sources of the "information paradigm" used in the book (Clark and Fujimoto, 1991, Chapter 1, notes 2 and 9). This perspective opened new territories for research on new product development (see the surveys by Brown and Eisenhardt, 1995 and Krishnan and Ulrich, 2001). Interestingly, Clark and Fujimoto did not mention design theorists like Alexander (1964), Simon (1969) and Marple (1961), although Clark was aware of their work and cited them in other writings (discussed below). Though Clark was active in several fields at once, he maintained intellectual divisions between different strands of work. His work on product development was managerial, thus he sought to connect it with the prior management literature, not with design theory. He was eclectic, but only to a point.

[10] At this time, Clark and his colleagues did not make a crisp distinction between background knowledge and designs. That came later, in *Design Rules* (dicussed below).

[11] On the origin of this so-called "shusa" system at Toyota in the 1950s see Fujimoto, (1999, pp. 73-74).

management matters!

Overlapping Problem-Solving Cycles (Concurrent Engineering)**:** The phrase "concurrent engineering" was not in common use when Clark and Fujimoto were conducting their research, and it does not appear in the book.[12] Nevertheless, Clark and Fujimoto identified and advocated practices that are now the hallmark of concurrent engineering, specifically: (1) overlapping the stages of the product development process; and (2) "high-bandwidth" and "bilateral" communication between those involved in each stage. The aim of overlapping stages was to anticipate downstream problems and fix them early, thus shortening development time. Clark and Fujimoto argued that this practice could be effective only if the upstream and downstream participants communicated in real time from the beginning of the process. This in turn meant that the work of project participants would change significantly. Those involved in the early stages (design) had to propose solutions that were not yet fully approved and monitor the project to completion, while those involved in later stages (production) had to participate in the project very early on. Overlapping cycles might shrink end-to-end development time, but at the cost of drastically expanding each department's scope of activity and interactions with other departments!

To justify the increased costs of concurrent engineering, Clark and Fujimoto developed constructs to measure the overlap, intensity and effectiveness of interdepartmental communication. They combined these metrics into a a single "integrated problem-solving index." (Combining metrics into an index was one of Clark's favorite ways of dealing with complex data.) They went on to show that Japanese firms generally had higher index scores, but, more importantly, that high scores were correlated with superior performance in terms of lead time, development productivity and product quality.

Co-development: a new role for customers and suppliers**:** By the late 1980s it was well known that Japanese firms were less vertically integrated and relied more heavily on their suppliers than their western counterparts. Clark and Fujimoto's contribution was to show how vertical relationships affected product development. In their view, the ideal state of "integration," which gave rise to product "integrity," did not stop at the boundaries of a firm, but extended backward to its suppliers and forward to its customers as well. *External integration* by definition took place across a firm's boundaries. The idea

[12] Nevins and Whitney's classic text *Concurrent Design of Products and Processes*, which set forth the principles of concurrent engineering, appeared in 1989, but Clark did not become aware of this work until after *Product Development Performance* was written.

was to shorten overall development time and improve the quality of the product by involving customers and suppliers in the early stages of product design (Clark, 1989). These practices allowed mutual adaptation of product and process designs to take place, which in turn led to improvements in product functionality, cost, quality, and delivery time.

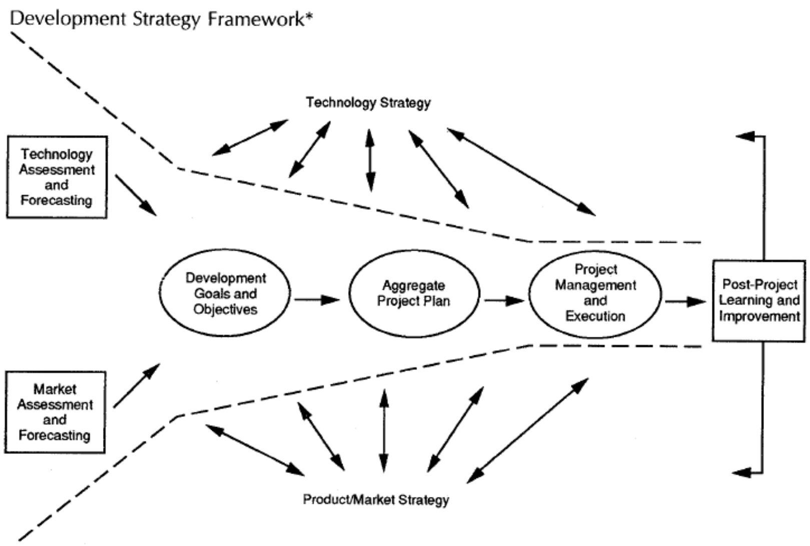
Clark and Fujimoto documented major differences, not only in the degree to which Japanese automaker were vertically separated, but also in the ways customers and suppliers participated in new product development. For example, U.S. firms used armslength contracts to manage suppliers and relied mostly on off-the-shelf parts for their new vehicles. In contrast, Japanese automakers brought their suppliers into the product development process and, as a result, had much higher percentages of newly designed parts in their new vehicles (Clark and Fujimoto, 1991, p.151, Figures 6-8).

3.3 Beyond Projects: Corporate Strategy for New Product Development

Although the management of *projects* was crucial to successful product development, Clark was convinced that there were other levels of the product development process where management mattered as well. In *Revolutionizing Product Development*, working with Steven Wheelwright, Clark looked beyond individual projects to how companies could make product development *as a whole* a source of lasting competitive advantage.

Projects, Wheelwright and Clark observed, were the end result of a larger process, which could be viewed as a *funnel* (Figure 1). The funnel in turn served to highlight two fundamental managerial roles: portfolio selection and cross-project learning. In the first place, general managers played a key role in defining and managing the company's *project portfolio*. They chartered projects so that resources were not scattered and the overall strategic thrust was consistent. Furthermore, efficiency and effectiveness in the execution of projects were correlated with how well senior managers could explain (1) a project's objectives; and (2) how it fit into the company's strategy. Wheelwright and Clark's classification of projects—research and advanced engineering, breakthrough, platform and derivatives—is now a standard in project portfolio management.

Figure 1 : The development funnel (Clark and Wheelwright, 1992)



Source : Wheelwright and Clark, 1992, p. 35.

Projects also created opportunities to learn. Wheelwright and Clark emphasized time and time again that the gains from a particular project were not limited to the profits from selling the end product. Projects also played a key role in the firm's knowledge creation process. Each project should therefore have built-in feedback loops, through which the knowledge gained by the project team could be captured, analyzed and disseminated within the organization.

Wheelwright and Clark thus saw project porfolios as one of a firm's main engines of growth and renewal. Indeed in a series of *Harvard Business Review* articles and a book, Clark, writing with Kent Bowen, Charles Holloway, Steven Wheelwright and Dorothy Leonard-Barton, spoke of two roles for projects within a company. First, projects were an excellent way to marshall the knowledge and capabilities lodged within business units to create innovative solutions. Far from being at odds with one another, projects and functional departments could interact in positive ways to develop and exploit a company's learning capacity (Bowen *et. al.*, 1994). Making the same point, Iansiti and Clark (1994) described in glowing terms the co-evolution of projects and organizational capabilities at Nissan and NEC from one product generation to another:

> The essence of integration is the generation, fusion and accumulation of knowledge: the capacity to merge new knowledge about the impact of possibilities with deep accumulated knowledge of

the complex capability base of the organization" (Iansiti and Clark, 1994, p. 602).[13]

Projects were also a way to train the organization's future managers. Managing a project required the person in charge to go beyond his or her original business unit and adopt a cross-functional point of view. In this fashion, functional managers were forced to develop general skills that would later be valuable to the organization. Projects thus served the twofold purpose of integrating a manager's skills and improving them (Leonard-Barton *et. al.*, 1994).

3.4 The importance of management and management systems

Overall, Clark's work on manufacturing and product development showed that performance differences among companies arose not because of the technologies used or the companies' environment, but rather because of the ways resources, people and technology were managed. By focusing on management, Clark and his colleagues offered an original explanation for the decline of U.S. companies in the late 1970s and helped open up a new line of research on product development. It is thus not surprising that Clark's works (Hayes and Clark, 1985; Hayes, Wheelwright and Clark, 1988; Henderson and Clark, 1990; Clark and Fujimoto, 1991; Iansiti and Clark, 1994) were among the most quoted in the seminal paper by Teece, Pisano and Shuen (1997), which defined "dynamic capabilities" and argued that such capabilities lay at the core of a company's competitive success.

However, the research summarized above failed to explain why U.S. firms did not adopt Japanese methods sooner. Japanese methods were not "foreign"— paradoxically they were based on management principles taught to the Japanese after World War II by American professors (Hayes, Wheelwright and Clark, 1988). Clark and his colleagues believed that the inertia of U.S. firms was linked, first, to the enduring influence of Taylor's scientific management principles, and second, to the dominance of financial and marketing managers, not manufacturing managers, in the top ranks of U.S. companies (Hayes and Abernathy, 1980). But this explanation led to a conundrum: if the new management methods were truly valuable, why did financially sophisticated top managers not see their worth?

This puzzle led to Clark's first collaboration with Carliss Baldwin, a colleague in the Finance unit of Harvard Business School. A financial economist by training, Baldwin was strongly influenced by

[13] On this question of knowledge creation, see also, Nonaka and Takeuchi (1995).

Stewart Myers' (1984) rebuttal the TOM group's arguments about American managers' short-termism and "myopia" (see above). According to Myers, the problems Hayes and Abernathy (1980) and Hayes and Garvin (1982) identified arose, not because finance theory was "wrong," but because it was misapplied by managers in the field.

Adopting Myers' logic, and drawing on earlier work on resource allocation by their colleague, Joseph Bower (1970), Baldwin and Clark (1991, 1994) subjected the new paradigms of manufacturing and product development to the analytic methods of finance. The new paradigms, they noted, required investment in the following organizational capabilities:

- External integration, leading to quality;
- Internal integration, leading to speed and efficiency;
- Flexibility, leading to responsiveness and variety;
- The capacity to experiment, leading to continuous improvement;
- The capacity to cannibalize, leading to radical innovation.

From a financial perspective, these capabilities were not simple investments, but were "platforms" that in turn generated "options." (In finance, an option is "the right but not the obligation to take a particular action.") The benefits derived from such investments were thus necessarily complex and difficult to quantify—in the language of finance, the investments had complex, contingent payoffs. At the same time, opportunities to make these investments generally arose quite low in the organization—on the factory floor, in engineering departments, and in the new product development groups of the company. In these "non-strategic" areas, financial analysis was generally based on simple discounted cash flow calculations, which were not capable of recognizing option values, much less option platforms.

Therefore, Baldwin and Clark argued, there was a fundamental mismatch between the nature of the investment opportunities in manufacturing and new product development and the methods used (in U.S. corporations) to assess their financial worth. This mismatch had a *systematic and pernicious effect* on investment decisions: it caused managers to favor short-term profitability over the creation of capabilities and learning capacity. Ironically, companies with less rigid capital budgeting systems were better off than those applying "the most advanced" financial methods—because the methods used were not advanced enough!

Baldwin and Clark's research into resource allocation systems showed the complexity of the capability creation process and the effects of various routines, which, while seeming to steer companies in the right direction, could potentially lead them to failure later on. Firms that experienced success at a given time were not necessarily those that would survive and prosper over the long term. Thus contrary to the reasoning of evolutionary theorists like Dosi (1988): "The more technical progress is cumulative at a firm level, the more success breeds success" (p. 1161), Clark's work showed that success could put the company on a trajectory that would ultimately lead to its downfall. Indeed, "the failure of established firms" was the overarching theme of Clark's work with William Abernathy, discussed in the next section. Success breeding failure was also central to the thinking of Clark's colleague, Clayton Christensen, who was beginning to develop his own theory of "disruptive innovation" at this time (Christensen and Rosenbloom, 1995; Bower and Christensen, 1996; Christensen, 1997).

4. Opening the "black box" of technology

4.1 Early Work with Abernathy

Alongside his work on manufacturing and product development, Clark developed a third area of research focused on innovation, competition, and industry evolution. Indeed, Clark saw very early on that typical economic theories of innovation were insufficient for understanding how firms, products and technologies evolve. One of the difficulties encountered by these theories involved the unit of analysis, which was usually a country, a sector, or a technology. (See Freeman and Soete, 1997 for a survey.) The high level of aggregation in their observations prompted economists to develop concepts that were too general for understanding the dynamics of individual firms. Clark, influenced by economic historian, Nathan Rosenberg (1982), was convinced that this difficulty "flow[ed] in part from a reluctance to break open the 'black box' that is a specific technology in order to understand its competitive and organizational implications" (Henderson and Clark, 1989, p. 8).

Clark's work on technological and industry evolution began in close cooperation with William Abernathy, whose impact on Clark's thinking was profound. First, in a *Harvard Business Review* article published in 1981 and a book, *Industrial Renaissance*, which appeared in 1983, Clark and Abernathy, together with Alan Kantrow, advanced the argument that many firms in mature industries in the U.S. were facing a new type of industrial competition caused by the "de-maturity" of their underlying product and process designs. De-maturity had the potential to bring down established firms if they did not adapt to their new circumstances (Abernathy, Clark, Kantrow, 1981, 1983).

The "new industrial competition" argument was in fact an extension of Abernathy's earlier work on industry evolution. In the 1970s, Abernathy, writing with James Utterback (1978) and alone (1978), argued that industrial competition was driven by the staged evolution of products and production processes. In the early or fluid stage of industry development, customers' requirements were not well understood. Competition at this stage involved much experimentation and a rapid turnover of product designs. The production processes appropriate to this stage were commensurately small-scale, flexible and labor-intensive, with low barriers to entry. At some point, however, some dimensions of product design (the so-called "core concepts") became standardized, that is, fixed for a large part of the market. This transition was called the emergence of "a dominant design" (Abernathy, 1978, p. 75; Abernathy and Clark, 1985, p. 14). After this point, competition would focus on cost reduction, quality enhancement, and variety within the constraints of the dominant design. Large-scale capital investments were often the key to success in this second stage. As a result, after the advent of a dominant design, smaller firms would exit and the industry would consolidate until only a few large firms remained.

The Abernathy-Utterback theory of industry evolution explained patterns of development in many industries in the late nineteenth and early twentieth centuries. However, it did not explain what was happening to U.S. firms in the 1970s as they confronted Japanese competitors using the new manufacturing and product development paradigms described above. Thus Abernathy, Clark and Kantrow took on the task of expanding the Abernathy-Utterback framework to include this new form of competition.

Reading *Industrial Renaissance* today, it is amazing to see how many of Clark's design theoretic ideas are present here in embryonic form. They include:

- Designs embody a "series of technological choices," which can be described as a set of "parameters" and "attributes;"
- Design choices form "problem-solving hierarchies," one for producers and one for users ("buyers");
- Learning —by both producers and users—involves working down the hierarchies, "weeding out unattractive alternatives, thereby reducing uncertainty;"
- Such learning "shrinks the universe of acceptable technological alternatives," leading eventually to "the establishment of [fixed] design hierarchies based on specific core concepts."

These insights formed the basis for all of Clark's later theorizing about design and industry evolution.

According to Abernathy, Clark and Kantrow, hierarchical problem solving, which was the natural mode of technological evolution, would lead in the end to a mature, but stagnant industry:

> Competition proceeds along narrowing lines until, in a mature industry, the technological positions taken by the major producers are indistinguishable…. Attributes that had once been "open" to technological experimentation become over time fixed or "closed." (Abernathy, Clark and Kantrow, p. 27)

But, they were quick to say, the process could be reversed. Given an exogenous shock in technology or demand, an industry could return to an earlier, "more open" state of competition. Such changes entailed "working back up through the same design hierarchy" by reopening previously "frozen" design parameters. This was the phase of "de-maturity,"when established firms could face innovations that:

> [make] obsolete existing capital equipment, labor skills, materials, components, management expertise, and organizational capabilities. [They destroy] the value of present competence … [and may] attract new entrants into an industry or even redraw an industry's competitive boundaries. (Abernathy, Clark and Kantrow, p. 28)

Abernathy, Clark and Kantrow and later Abernathy and Clark (1985) thus provided the foundations for the seminal work by Anderson and Tushman on competency enhancing and competency destroying innovations (Tushman and Anderson, 1986; Anderson and Tushman, 1990). But, as was typical in much of Abernathy's work, key points in the argument were simply asserted and not developed or defended. Tragically, Abernathy did not have enough time to nail down all the parts of his grand theory before his death.

The deep structure—"the logic"—of Abernathy, Clark and Kantrow's argument was based on the concept of two co-evolving hierarchies, one for producers and one for buyers. But the authors did not attempt to document these hierarchies empirically. For empirical purposes, they introduced a simpler construct: the "transilience matrix" (Abernathy, Clark and Kantrow, pp. 109 *et. seq*.) This matrix appeared several times in Clark's writings of the 1980s (Abernathy and Clark, 1985; Clark and Rothman, 1986; Clark, 1987). It is sometimes confused with, but is in fact different from the more famous Henderson-Clark matrix of innovations (discussed below). Abernathy and Clark were concerned with the impact of innovations on firm competencies. They distinguished between "technology/production" competencies on the one hand, and "market/customer linkages"on the other. Henderson and Clark omitted market/customer linkages from their picture and looked simply at the location of innovations in a complex technological system. Hence the key phrase "architectural innovation" has fundamentally different meanings in the writings of Henderson and Clark vs. Abernathy and Clark.

For Abernathy and Clark, design hierarchies and transilience maps were complementary ways of describing how innovations affected the evolution of industries. Design hierarchies were closer to the basic phenomenon and logically more robust, but harder to observe. Transilience matrices were easier to operationalize in empirical work, but were basically *ad hoc* and tautological. What was needed then was a deepening of the theoretical and empirical base on which these concepts rested. William Abernathy, the originator of many of the ideas, died in 1984. After his death, Clark continued to work on Abernathy's theoretical agenda, even as he was participating in the major empirical studies of manufacturing and product development described above. Indeed, in the mid 1980s, Clark's field research and empirical analysis, as well as his reading outside of fields of economics and management, began to have a significant impact on his theory development.

4.2 Innovation Studies meet Design Theory

The new depth in Clark's thinking was first evident in "The Interaction of Design Hierarchies and Market Concepts in Technological Evolution," published in 1985 in *Research Policy* (Clark, 1985). In this article, Clark for the first time drew on the scholarly work of design theorists, specifically Christopher Alexander (1964) and David Marple (1961). He took key ideas about the evolution of organizations from Richard Nelson and Sidney Winter (1982) and about users from Eric von Hippel (1976).

Clark used other scholars' ideas plus his own experience to construct a microeconomic rationale for the twin hierarchies that lay at the core of Abernathy's theory of innovation. He also shifted his focus away from "innovations" and "industries" to "designers" and "users." Because of his work on product development, Clark had come to believe that understanding innovation required an understanding of how designers responded to the changing desires of users.[14]

From Alexander (1964) and Marple (1961), Clark took two important ideas:

- The objective of all design work is to ensure "fitness" between the object designed and its context of use.
- Design work is a form of problem-solving and is hierarchical by nature. Some decisions necessarily precede others. High-level decisions (e.g., what fuel will an automobile use) create an agenda of subsequent problems-to-be-solved.

The first of these ideas—fitness—established that designs were subject to competition and evolution: "more fit" designs competed with and replaced those that were "less fit." Moreover, the arbiters of "more fit" were users, whose own preferences might change as they learned about new products. The second

[14] Interestingly, although he drew on the work of von Hippel (1976), Clark did not go so far as to make users designers in their own right. In this respect, he followed the taste of the TOM group and most design theorists.

idea—hierarchy—was already the backbone of Clark's earlier work with Abernathy. In effect Clark used design theorists to justify what he had previously merely asserted. For example, in defense of hierarchies, he included a lengthy quote from Alexander which began: "The organization of any complex physical object is hierarchical… " (p. 241). And he reproduced Marple's drawing of the actual design hierarchy of the ducts and valves of a nuclear reactor (p. 242).

But Alexander and Marple were silent on the possibility of changing customer preferences. Thus arguing from first principles and using automobiles as as an example, Clark claimed that customer preferences were necessarily based on experience and evolved in a hierarchical fashion as well. This was his "hierarchy of concept:"[15]

> [C]ustomer learning is focused initially on the higher order concepts… . It was, thus, no accident that early customer decisions about automobiles were framed in terms of a choice between a "horseless carriage" and a "carriage with a horse." …[A] set of subordinate concepts … gave further definition [to the concept of automobile]: speed, mobility, endurance, payload and so forth. … One could not imagine widespread use of words like "roadster" or "touring car" or "coupe" in the 1890s when the "horseless carriage" was first introduced. These were distinctions and categorizations that rested on years of customer experience, on new habits of transportation, *and of course, on the development of the product itself*. (Clark, 1985 pp. 245-6, Emphasis added.)

These were the same basic ideas as in *Industrial Renaissance*, but the arguments were set forth with much greater depth and rigor. Building on design theory and his knowledge of the history of automobiles, Clark showed readers what it meant for two related hierarchies—of product designs and user concepts—to co-evolve, each influencing the other.[16] Process design, he said, worked the same way, except that *its* hierarchy of concept reflected the desires of producers—for low cost, rapid cycle time, and high reliability. (Clark and Abernathy did not make rigid distinctions between products and processes, nor between products and services. Their overarching concern was with the structure of problem solving—hence design—whatever the context.)

Discussing the implications of his "co-evolving hierarchies," Clark restated the arguments about competition found in *Industrial Renaissance*:

> Movements down the hierarchy are associated with the refinements or extension of higher-order concepts. Innovation of this kind … entrenches the established approach.
>
> [In contrast] movements up the hierarchy are associated with departures from existing

[15] Alexander also proposed a "hierarchy of concepts," but defined it as the way a designer would organize his problem solving. Thus Alexander's hierarchy of concepts corresponds to Clark's hierarchy of design. (Alexander, 1971, pp. 60-63)

[16] Clark (1983) contained a preview of parts of his argument.

> approaches… . [They] destroy the value of established commitments and competence, and call forth new skills and resources. (Clark, 1985, p. 249)

One of the things Clark did *not* do in this paper was identify problem-solving hierarchies with architecture. This omission is noteworthy because Herbert Simon *had already linked architecture to hierarchy* in his famous paper, "The Architecture of Complexity," which first appeared in 1962 and was included in the second edition of *The Sciences of the Artificial* published in 1981 (Simon, 1962; 1981). In fact, Clark referenced Simon in connection with hierarchy:

> As Simon has suggested hierarchy is often used to deal with complex phenomena, and hierarchical structures have been widely used in models of memory and linguistics. (Clark, 1985, p. 241)

But his knowledge of Simon appears to have been gleaned indirectly from a consumer behavior text by John Howard (Clark, 1985, footnote 17, p. 241). Howard's reference in turn was to the first edition of *The Sciences of the Artificial*, which did not include "The Architecture of Complexity" (Howard, 1977; Simon, 1969).

Nevertheless, although Clark apparently did not have much knowledge of Simon's prior work, he *was* following in Simon's footsteps in that he was looking to represent products and their designs in a more formal way. This quest would eventually lead to his breakthrough paper with Rebecca Henderson, in which architecture and architectural innovation occupied center stage (Henderson and Clark, 1990). But in 1985 that paper still lay in the far-distant future.

4.3 Architectural Innovation—Trial Runs

The question, why do establish firms fail, took hold of Clark's imagination in the 1980s and seemingly would not let go. Eventually, he provided an answer to this question that was deep, creative and compelling. But his path to the answer was not smooth: in the late 1980s, Clark struggled mightily to bring his ideas into focus. Between the "Interaction of Hierarchies" in 1985 and "Architectural Innovation" in 1990, Clark wrote three other papers all of which addressed the same basic question. In these trial runs, he rehearsed and refined his ideas about the structure of products, knowledge and organizations.

The first of these papers, "Managing Technology in International Competition: The Case of Product Development in Response to Foreign Entry," was written in 1985, and published (essentially unchanged) in 1988. This paper did two things. First, it presented evidence from a range of industries showing that established U.S. firms often failed when confronted by certain kinds of innovative challenges. Not only in autos, but in radios, copiers and integrated circuit packaging, relatively large, experienced U.S. companies had lost ground to smaller, less experienced foreign entrants who made *seemingly minor innovations* in the basic product or production system. Thus there was a larger pattern to be explained.

In the "Foreign Entry" paper, Clark also began to develop an information-processing and problem-solving view of "the archetypal firm." These sections of the paper were heavily influenced by Ramachandran "Jai" Jaikumar, who, together with Roger Bohn, was at this time attempting to formulate a theory of the stages of knowledge in manufacturing organizations (Jaikumar and Bohn, 1986; Bohn and Jaikumar, 1986). Indeed many of the concepts found in this paper—for example, complexity, ambiguity and uncertainty, and know-how vs. know-why—were due to Jaikumar and were only peripherally related to the problems Clark was trying to address. Today the paper reads as a provocative jumble of empirical evidence and partially worked out theoretical concepts. It was full of ideas, but they were not coherent.

The second paper was an undated working paper from about 1988, entitled "Knowledge, Problem-solving, and Innovation in the Evolutionary Firm." Here Clark abstracted and slightly formalized the theoretical arguments of the "Foreign Entry" paper. The ideas were mostly the same, but Clark appears to be grasping for his own "architecture," that is, a structure that would clarify his vision. One can almost hear a mentor, perhaps Paul Lawrence (who is mentioned in the acknowledgements), saying "just write it all down Kim, write down what you mean."

This paper is also noteworthy because here, for the first and only time until *Design Rules* (2000), Clark directly cited Herbert Simon's *Sciences of the Artificial* (1969). However, he alluded to Simon's cognitive model of problem solving and cited the first (1969) edition. (Recall that "The Architecture of Complexity" was not included in the first edition, but appeared in the second and subsequent editions.) Thus Simon's ideas about the division of work, hierarchy, architecture, and "near-decomposability" did not enter into Clark's thinking at this time.

Indeed if Christopher Alexander and Herbert Simon today are viewed as the progenitors of modern design theory, Clark was very much in "the Alexander line." Even *Design Rules* (written with Carliss Baldwin), although it acknowledged Simon and retold the fable of Tempus and Hora, was not steeped in Simon's thinking. Clark did not see himself as working on Simon's agenda, striving to create a new "science of design" (Simon, 1969, 1981; Chapter 5). His focus was always on people working in organizations, not on the abstract structure of the designs they worked on.[17]

The third paper in this series was the working paper that preceded Henderson and Clark's breakthrough paper: "Architectural Innovation: The Reconfiguration of Existing Products and the Failure of Established Firms" (Henderson and Clark, 1990). In contrast to "Foreign Entry", in this case the differences between the working paper and the final published version were profound! The working paper offered some exciting ideas and a lot of evidence, but the main line of argument was obscure and difficult to follow. Henderson and Clark had not yet found the right balance between authoritative description and mind-numbing detail.

Indeed this working paper would not be worth mentioning but for the fact that it contained the seeds of an important idea. Taking their lead from Alexander (1964), Henderson and Clark worked out a mathematical representation of the design of a room fan.[18] The fan's design, they said, could be represented as a *hierarchical set* of mathematical relationships in which *component* parameters determined *system* parameters, and system parameters in turn determined *performance* on dimensions users cared about. The ultimate worth of a design could then be represented as a *utility function* defined over user requirements. Thus design selection and evalution could be framed as an economic choice problem.[19]

None of the work on the mathematical representation of designs made it into the final published version of the paper. This is understandable: the ideas were sketchy and did not hold up well under scrutiny. But the characterization of complex designs as hierarchies of parameters and dependencies reappeared ten years later in *Design Rules.* And the idea that design selection could be framed as an economic choice problem became the fundamental premise of that book, captured by the axiom, "Designers see and seek value."

In the short run, however, what made it into print was the room fan. Even this humble artifact,

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[17] In contrast, the abstract structure of designs was one of Baldwin's primary concerns, because structural representations were pre-requisites to the application of financial valuation tools.

[18] It seems likely that key sections of the paper were drafted during the hot summer months of 1989 in a room without airconditioning.

[19] Simon had done this already, but was not cited (Simon, 1969, 1981; Chapters 2 and 5).

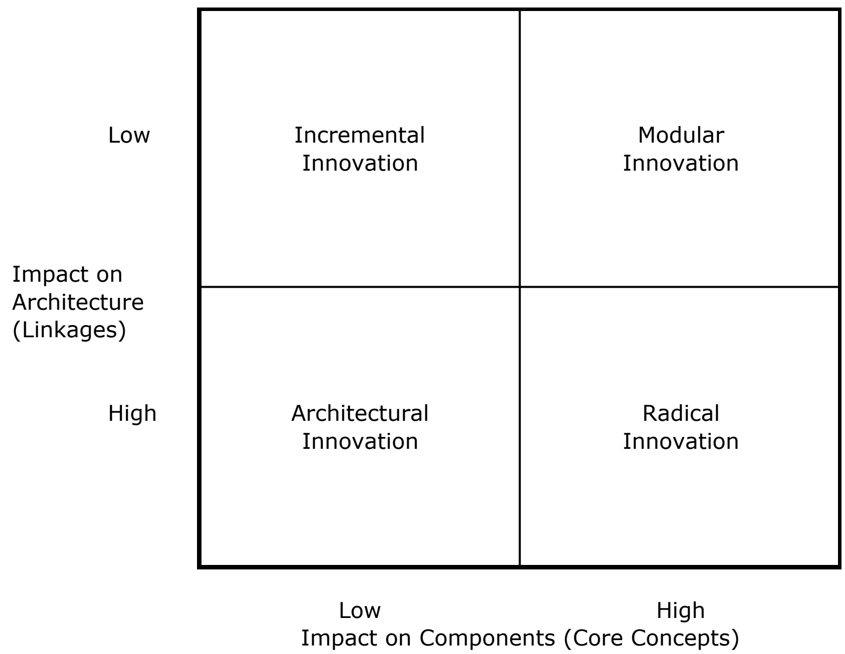
Henderson and Clark said, could be deconstructed into a set of *components*—motor, base, blades—and an *architecture* that specified the linkages between components.

4.4 Architectural Innovation—The Real Thing

Henderson and Clark's "Architectural Innovation" paper, published in *Administrative Sciences Quarterly* in 1990, brought a new point of view into studies of innovation—a view based on *the material properties of objects and processes and concomitant constraints on their designs*. When the paper was published, the prevailing classification scheme for innovations was a unidimensional scale. At one extreme, innovations were "radical"; at the other, they were "incremental." Henderson and Clark contended that, in light of the complex actual structure of products, this scale was too simple. They then introduced the concept of a *product architecture*. This idea was the direct descendant of Abernathy and Clark's "design hierarchies," but was now defined as "how the components [of a product] will work together." And as indicated, Henderson and Clark explained the key concepts of "components" and "architecture" using the homely example of a room fan.

Although the existence of architecture was a necessary premise for the argument in the paper, architecture was not in fact what the paper was about. Its true focus was *how knowledge works in organizations*. Thus Henderson and Clark moved quickly from architecture to knowledge, asserting that "successful product development requires two kinds of knowledge[:] component knowledge… [and] architectural knowledge." (p. 11). From these two categories, Henderson and Clark derived a 2x2 matrix for classifying innovations. The old categories, radical and incremental, appeared on the main diagonal. Two new categories—*modular* and *architectural*—appeared on the off-diagonal blocks (Figure 2).

Figure 2: Henderson and Clark classification scheme for innovations



A *modular innovation*, according to Henderson and Clark, "changes only the core design concepts of a technology," and not the architecture. Their example of such an innovation was the substitution of a digital for an analog phone. But Henderson and Clark were not much interested in modular innovations,[20] thus they moved on as quickly as possible to *architectural innovations*:

> The essence of an architectural innovation is the reconfiguration of an established system to link together existing components in a new way. (Henderson and Clark, 1990, p. 12)

They then tied their notion of architectural innovation to Abernathy and Utterback's (1978) concept of dominant design:

> [T]he emergence of a dominant design … is equivalent to the general acceptance of a product architecture. … A dominant design incorporates a range of basic choices … that are not revisited in every subsequent design. … [P]rogress then takes the shape of improvements in the components within the framework of a stable architecture. (Henderson and Clark, 1990, p. 14)

Given a dominant design, basic choices did not have to be revisited, hence experimentation with different

[20] Henderson and Clark adopted the 2x2 framework at the suggestion of an anonymous *ASQ* reviewer—surely one of most insightful reviewers in the history of the journal. The 2x2 had an extra quadrant, which needed a name and a definition. Thus "modular innovation" was thrust on Henderson and Clark by the exigencies of their new framework. Sometimes architecture matters!

ways of linking components, i.e., different architectures, would disappear:

> Firms cease to invest in learning about alternative configurations of the established set of components. (Henderson and Clark, 1990, p. 14)

This contention led to the crux of Henderson and Clark's argument. In large, complex organizations, they said, the product's architecture was not seen as a whole, but became invisibly embedded in "the communication channels, information filters and problem-solving strategies" of the organization (pp. 15 *et. seq.*) On the one hand, such embedding was efficient because it streamlined the flow of work. On the other hand, problems would arise if and when the organization was confronted by a competitor's architectural innovation. In those circumstances, the organization would not be able to retrieve its architectural knowledge, hence it would not be able to adapt its products and processes to meet the competitive challenge.

Henderson and Clark backed up their theory with detailed evidence from the photolithographic equipment industry. They showed how, over several generations, established firms failed to adapt to architectural innovations introduced by upstart challengers. For example, Kasper, a maker of contact aligners and the market leader at one point, failed to respond to—or even understand—the threat posed by Canon's new proximity aligner. Kasper did not see, quite literally, what Canon had accomplished:

> The Canon aligner was evaluated by a team at Kasper and pronounced to be a copy of a Kasper machine. Kasper evaluated it against the criteria that it used for evaluating its own aligners—criteria that had been developed during its experience with contact aligners. The technical features that made Canon's aligner a significant advance [which had to do with the way components were linked together] … were not observed because they were not considered important" (Henderson and Clark, 1990, p. 26).

In the end, Kasper disappeared from the market. A few years later, essentially the same scenario recurred, between Canon and Nikon. This time, the new incumbent, Canon, disappeared![21]

Henderson and Clark's theory of why established firms fail was predicated on what they claimed was a "natural tendency" of organizations:

> [T]here appears to be a tendency for active learning among engineers to focus on improvement in performance within a stable product architecture. In this context, learning means learning about components and the core concepts that underlie them. Given the way knowledge tends to be organized within the firm, learning about changes in the architecture of the product is unlikely to

[21] The dynamic Henderson and Clark described was similar to that of "disruptive innovation," in the theory later developed by Clayton Christensen (Christensen and Rosenbloom, 1995; Bower and Christensen, 1996; Christensen, 1997). Christensen was a doctoral student at Harvard Business School in 1990 and joined the TOM faculty in 1992. His theory of disruptive innovation had to do with changing customer demands and market linkages, while Henderson and Clark's theory focused on the embedding and retrieval of technological knowledge in a firm. The two theories were not mutually exclusive, but dealt with complementary facets of the same, very complex phenomenon.

> occur naturally. Learning about changes in architecture … may therefore require explicit management and attention." (Henderson and Clark, 1990, p. 28)

However, if we adopt a wider point of view, the tendency they described is not universal. Indeed in some settings, ongoing architectural learning appears to be the norm. For example, in buildings, the core concepts—floors, windows, doors— have been stable for hundreds of years, but enormous variety can be realized by combining these concepts in different ways (Alexander, 1979). Thus while Henderson and Clark's theory of embedded architectural knowledge might hold in some cases, it almost certainly did not hold in all.

Nevertheless, the fact that the theory was not universally true did not lessen its importance or impact. Henderson and Clark's accomplishment was to set forth the *first coherent argument backed up with evidence about how design structure affects competition among firms*. The argument deserved to be taken seriously, and it was. It was what Pareto called a "fruitful error…, full of seeds, bursting with its own corrections." And one of the most promising seeds lay in the neglected quadrant of the 2x2 matrix, the one labeled "modular innovations."

5 The Power of Modularity

5.1 The Setting

In the early 1990s, the themes of architecture and modularity were in the air. Scholars in many fields were seeking to understand complex systems, architectures and modules more deeply. It is beyond our scope to trace the many parallel and intersecting lines of work, so we will mention only a few of the works that significantly influenced Clark's thinking.

First, coming to management from mechanical engineering and building on design theorists Pahl and Beitz (1984), Hubka and Eder (1988) and Nam Suh (1990), Karl Ulrich (1995) clarified the meaning of the term "product architecture" and proposed a typology. (Henderson and Clark had simply asserted that "architectures exist.") Ulrich was the first to distinguish between "modular" and "integral" architectures, a fundamental distinction that survives today.[22]

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[22] Clark did not like the term "integral." From his work on product development, he associated "integrity" and "integration" with good qualities in a design, whereas "integral architectures" were non-modular and in that sense bad. He preferred the term "interdependent."

Second, Ulrich's close colleague, Steven Eppinger developed tools and methods for observing and representing design dependencies using the framework of Design Structure Matrices (DSMs). These matrices made the "linkages between components" and the "communication channels and information filters" of an organization visible for the first time. (Eppinger, 1991; Eppinger *et. al.*, 1994)

Third, Richard Langlois and Paul Robertson (1992) argued that a network of firms working within a modular architecture would innovate faster and more effectively than a large, integrated firm. Writing for practitioners, Charles Ferguson and Charles Morris put a strategic spin on this argument, explaining "How Architecture Wins Technology Wars" (Morris and Ferguson, 1993; Ferguson and Morris, 1993).

Carliss Baldwin began working with Kim Clark in this heady intellectual environment. Their focus was on the fourth quadrant of the Henderson-Clark matrix: modular innovation. As an outsider in the TOM group, Baldwin was struck by how often "modularity," "modular flexibility," and "modular mix-and-match" were cited as sources of competitive advantage in both manufacturing and product product development field studies.

Baldwin and Clark, like many others, were also fascinated by events in the computer industry in the 1980s and early 1990s (Baldwin and Clark, 1997a). The big technological event of this era was the advent of personal computers. At first, the story of PCs appeared to be a counterexample to Henderson and Clark's thesis that established firms fail when confronted by new architectures. IBM, though not the first to introduce a personal computer, entered the market decisively in 1981 with a new (and highly modular) product architecture. Within months IBM was the dominant firm in a vastly expanded and growing market. But by 1990, IBM had lost "control" of the PC architecture to component suppliers Intel and Microsoft. It also faced severe price competition from networked PCs and workstations, and thus was struggling in its other product lines as well.[23] The computer industry thus appeared to be the perfect place in which to study modular architectures and the competitive dynamics of modular innovation.

Design Rules: The Power of Modularity was published in 2000, the result of a decade of work.[24] The

[23] The Langlois-Robertson and the Ferguson-Morris works cited above attemped to make sense of these events. Another key contribution was Andrew Grove's book, *Only the Paranoid Survive*, which told Grove's version of the story of how Intel succeeded where IBM failed. These are only three among a vast library. (Langlois and Robertson, 1992; Ferguson and Morris, 1993; Morris and Ferguson, 1993; Grove, 1996.)

[24] The first working paper on the option value of modularity appeared in 1992 (Baldwin and Clark, 1992b). A preview of the arguments in *Design Rules* appeared in the *Harvard Business Review* in 1997 (Baldwin and Clark, 1997b).

aim of the book was to build on existing theories of design and complex adaptive systems to create an economic theory of design evolution and industry change under modular architectures. The book differed in style from Clark's previous work in three major ways:

- It went to great lengths to define terms and concepts in order to create a common vocabulary among the separate disciplines of economics, management studies, complexity science, and engineering.
- It made extensive and operational use of design theory tools, in particular, Design Structure Matrices and design hierarchies.
- It routinely used mathematical modeling, especially models from finance, to analyze the economic structure of design decisions.

In writing *Design Rules*, Baldwin and Clark adopted two principles. First, they believed that the rate and direction of technical change depended on the "deep structure" of objects and the processes used to design and make them.[25] Thus to understand technological change, one had to go to the designs themselves, i.e., to engineering descriptions of artifacts and processes. Second, they restricted their attention to computer designs and the computer industry. Modular designs and innovations arose in many places, but their preliminary surveys of various engineering literatures indicated that modularity served different purposes in different settings. Modularity could be used to reduce complexity; to enable parallel work; or to permit adaptation to uncertain events (pp. 90-91). Given such a multifaceted phenomenon, Baldwin and Clark felt that a necessary first step was to develop a coherent theory for *one* set of designs. If the theory worked in one setting, they reasoned, it could then be tried out in others. (See Baldwin, Hienerth and von Hippel, 2006, on the role of a base case in theory building.)

5.2 What is Modularity? Where Does It Come From?

The notion of a modular design is the central theme of the book. Baldwin and Clark defined a modular system as one whose architecture allows some subsets of elements to be designed, produced or used independently. Modules, therefore, are units of a larger system that are *structurally independent of one another but work together*. In order for such a system to work there must be *design rules* specifying:

(1) the product's "architecture";
(2) the interfaces between modules; and
(3) the tests that will be used to select modules and integrate them into a functioning whole. [26]

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[25] "But in our search for understanding we must be prepared to dig deep, for the forces that matter are rooted in the very nature of things and in the processes used to create them. … Simply put, this book is about the process of design and how it affects the structure of the industry" (Baldwin and Clark, 2000, p. 1-2).

[26] Baldwin and Clark (2000) distinguished between the "architecture" of a system (the components of a system and what they do) and the "interfaces" of that system (the standards that two or more modules must obey in order to work together). Others, for example, MIT's Engineeering Systems Department Architecture Committee (2004) and

In their seminal works on design theory, Herbert Simon (1962, 1969) and Christopher Alexander (1964) had argued that modularity—or "near-decomposability" in Simon's terminology—was a rational response, and perhaps the only response, to complexity that otherwise threatened to overwhelm the minds of designers. Yet as a matter of historical fact, Baldwin and Clark showed that designs cannot always be modularized with good results. For example, the first computers had extremely integral architectures. Knowledge about computers—their functional components and ways of making them—had to reach a certain threshold before modularizing the products or processes could be considered.[27] The architects of a modular system had to know which interactions could be suppressed or constrained without compromising the whole.

IBM System/360, designed between 1961 and 1966, was the first computer system to have a "truly modular" architecture. The decision to use this type of architecture was dictated by the growing complexity of IBM's product lines and, especially, by the high cost to customers of reprogramming after each equipment upgrade. As envisioned by IBM's top managers and engineers, a modular product line would permit IBM customers to seamlessly upgrade their IT systems as their needs grew or as new and better machines became available.

But creating a modular product line and the necessary supporting manufacturing processes was no easy task. IBM found—as would others—that the use of a modular architecture radically altered the nature of the design process and the organization of a firm. What had been one stage of product development became three:

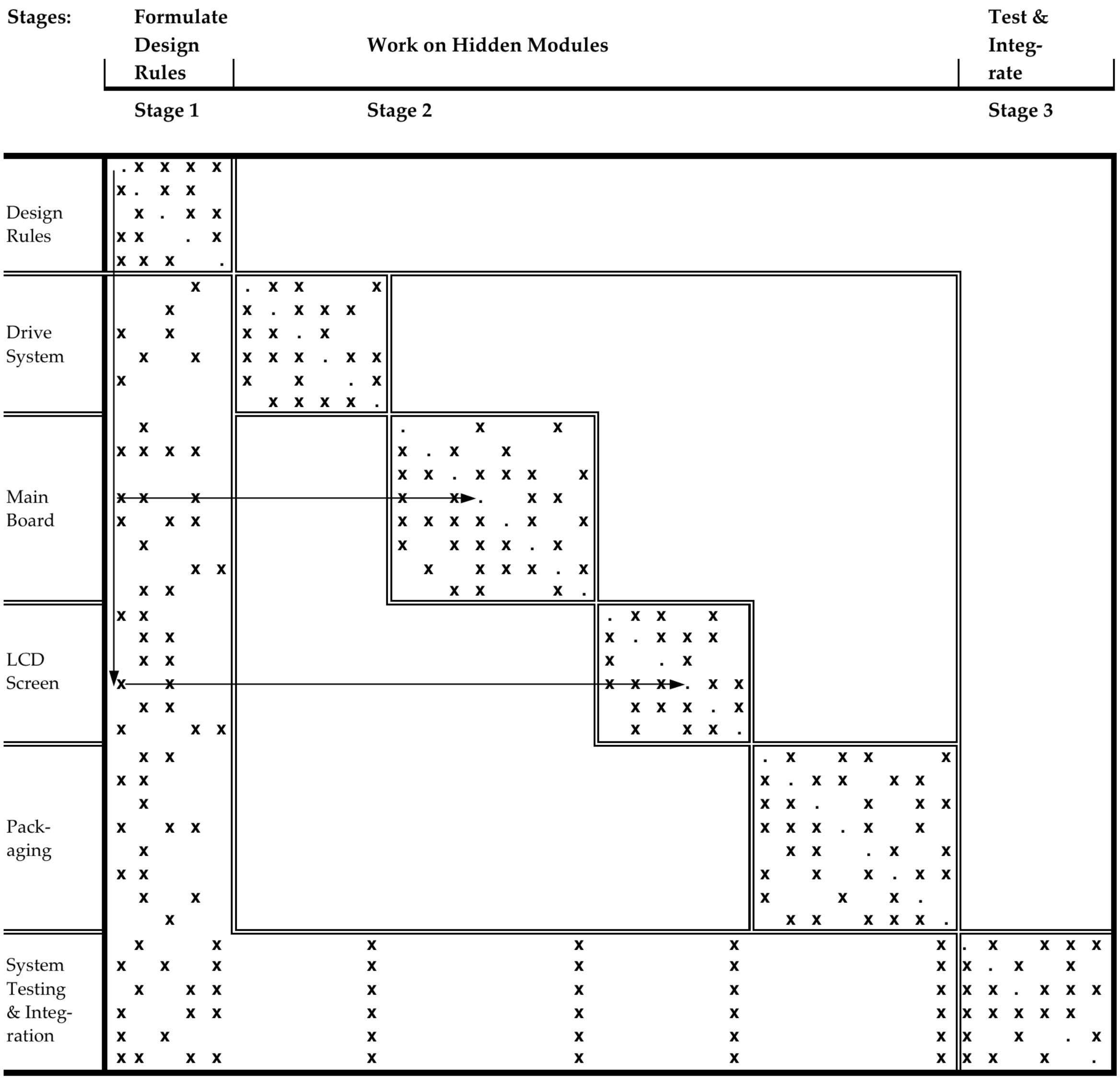
(1) Definition of the design rules: this is the information that will be visible to the designers of the various modules;
(2) Work on the "hidden" modules, with each team being able to work independently as long as the design rules are obeyed;
(3) Integration and testing of the system.

And what used to be one object of design and production became many separate objects (Figure 3).

Fixson (2005), have included interfaces in their definitions of the architecture of a system.

[27] This point was often overlooked in discussions of modularity.

Figure 3: The three stages of a modular design process



Source : Baldwin and Clark, 2000 (p. 74).

In fact, as it made the transition from several integral product lines to one modular product line, IBM floundered and nearly failed at several junctures. In the end, the company succeeded only because of heroic interventions by key managers and engineers. (See Baldwin and Clark, 2000, Chapter 7, for details.) Thus the history of System/360 served to reconfirm Clark's deep-seated belief that "management matters."

5.3 The Consequences of Modularity

After defining modular structures and documenting how such systems emerged in the computer industry, Baldwin and Clark went on to make the following arguments:

(1) Modularization increases the value of a design; and
(2) A modular design can evolve in ways that an integral design cannot.

Modularity affects value, they said, because designs are options. In finance, as mentioned earlier, an option is "the right but not the obligation" to take a particular action. A designer or a user does not have to accept a new design, but can fall back on an older one. Thus all designs are options. The modularization of an integral design in turn multiplies options, creating "at least as many options as there are modules."

Baldwin and Clark used mathematical models adapted from finance to show that modularity can have large effects on the option value of a system. For example, in one thought experiment, they showed that going from a one to twenty-five modules (approximately what System/360 did relative to prior designs) could increase the value of a system by twenty-five times. Such an increase in turn would pay for a lot of experimentation and new entry!

At the same time, modularization radically changed the organization of work. Once a design has been modularized, it is possible to substitute one component for another, to eliminate certain elements, and to add new components. Bringing John Holland's (1975, 1995) theory of complex adaptive systems to bear on designs, Baldwin and Clark defined six *modular operators* (Table 5). These are "moves" that designers can make that will change the design in various ways.

Table 5: Modular operators

Modular operators form a repertory of actions that can be performed in modular systems. Complex changes in a modular system can be represented as combinations of operators. The value of specific operator-moves can be modeled using real options methods from finance.

Operator	*Definition*
Splitting	Divides an interdependent system into modules
Substituting	Replaces one module with another
Augmenting	Adds a new module to the system
Excluding	Takes a module out of the system
Inverting	Creates new design rules and architectural modules
Porting	Makes a module compatible with two or more systems

Source : Baldwin and Clark (2003)

Importantly, the modular operators were *local*: by adhering to the design rules, innovators could work independently and focus on changing *parts* of the system without having to redesign the whole. Baldwin and Clark argued that this aspect of modularity contributed in important ways to the vertical disintegration of the computer industry.[28] Historically, the process of vertical disintegration began immediately after IBM's launch of the System/360. The design rules that allowed components to work together within System/360 were known to a large number of IBM engineers, many of whom left IBM to work for other companies. The companies hiring these engineers used the engineers' knowledge to develop their own products that were "plug-compatible" with System/360, hence could operate in that system's environment. (There was, of course, a great deal of litigation—see Ferguson and Morris, 1993, for an overview.)

What followed was a "balkanization" of the computer industry: a process of fragmentation that began in the 1970s and intensified after the introduction of the PC. (By the time the PC was introduced, essentially all computer systems had modular designs.)

Ironically, *Design Rules: The Power of Modularity* was not the book Baldwin and Clark set out to write. It explained structure, dynamics and value at the level of artifacts, designs, and processes, but it did not address strategy, that is, how firms might use their understanding of structure, dynamics and value to compete. However, in the mid 1990s, Baldwin and Clark faced a quandary. Clark became Dean of Harvard Business School in 1995 and did not have as much time as before to spend on research. At the same time, as the Internet boom was accelerating, there was more to explain. Indeed, in the late 1990s, it seemed that each new day brought new designs, new firms, and new institutions into the game. In response (some would say desperation), Baldwin and Clark decided to split *Design Rules* into two volumes.[29] Volume 1 would deal with the basics—structure, dynamics and value—and would make the case that modular architectures and modular innovations were important (hence "The Power of Modularity"). Strategy would be left for Volume 2.

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[28] Technically speaking, Baldwin and Clark pointed out that the vertically disintegrated industry structure was only one possible configuration among many. For example, it was entirely possible to have modular designs within a monopoly (Baldwin and Clark, 2000; Chapters 14 and 15). Understanding which industry structures will emerge "on top of" a modular architecture requires models of value to be combined with models of strategy.

[29] They were advised to do so by their friend and editor, Barbara Feinberg.

6 Building on *Design Rules*

Kim Clark retired from active research in 2005 when he became President of Brigham Young University—Idaho. However even today, in 2007, much of his later work is still in the pipeline. In this section, we describe three papers that are representative of his later works and demonstrate the fruitfulness of a design theoretic framework.

6.1 Modularity and User Innovation

The open source development process for software, which emerged in conjunction with the Internet in the mid-1990s, took Clark and many of his colleagues by surprise. Clark had been an early proponent of integrating users into a firm's product development process (see above), but nothing in his prior experience led him to think that users might initiate and manage a product development process for themselves. Yet that was exactly what happened in open source development projects. And the largest of these projects—Linux and Apache, for example—were capable of supplying software that was fully competitive with proprietary products in terms of cost, quality, reliability and, yes, innovation!

Nevertheless, just as Clark had brought a toolkit from economics to the analysis of manufacturing, *Design Rules* provided a toolkit for analyzing the structure and value of designs and predicting their evolution. Baldwin and Clark reasoned that, if the toolkit was any good, it should be able to shed light on the open source phenomenon. In particular, was open source development an economically superior way of organizing certain innovation processes, as its adherents claimed? And if so, which processes would most benefit from this method of organization?

"The Architecture of Participation" was Baldwin and Clark's attempt to answer these questions (Baldwin and Clark, 2006a). It was also their first foray into the second phase of their research plan, which aimed to look the economic institutions needed to support design evolution. Taking their lead from Masahiko Aoki (2001), an eminent theorist in the field of new institutional economics, Baldwin and Clark sought to model open source development as a game among user-innovators, a game that would be played "on top of" designs with different architectures.

Their analysis showed that there was a high degree of complementarity between users' participation in a collective development process and the architecture of the underlying system. Specifically, systems with more modular architectures, more divisible task structures, and/or more option value in the modules would attract more voluntary effort. Thus, Baldwin and Clark concluded, a user-driven innovation process based on the free revealing and sharing of designs was a viable institutional form. Open source development was a sustainable "institution of innovation," — one that was competitive with, and in some cases might dominate, proprietary product development processes.

6.2 Modularity and the Theory of the Firm

One of the things that was evident from the history of the computer industry was that new modular architectures not only promoted design evolution, but also permitted the boundaries of firms to be redrawn. Indeed, in the 1990s it was commonly believed that modular product architectures gave rise to modular organizations, which in turn gave rise to clusters of firms (Langlois and Robertson, 1992; Sanchez and Mahoney, 1996; Schilling, 2000). However, before the seminal work of Jacobides, the mechanisms by which firm boundaries changed were not well understood (Jacobides, 2005; Cacciatori and Jacobides, 2005; Jacobides and Billinger, 2006). Jacobides' work in turn raised questions about how firm boundaries were influenced by the underlying product and process architectures.

A desire to relate the modular structure of products and processes to the boundaries of firms prompted Baldwin and Clark (2006d) to take a fresh look at *transactions*. In the modern economic theory of the firm, as formulated by Oliver Williamson (1975, 1985) and Sanford Grossman, Oliver Hart and John Moore (Grossman and Hart, 1986; Hart and Moore, 1990; Hart, 1995), transactions were always located at what Williamson (1985) called "technologically separable interfaces," ie, places where a technological division of work and knowledge already existed.[30] But, Baldwin and Clark reasoned, such interfaces were part of the design of a product and its production process. Thus what Williamson and other transaction-cost and property-rights economists took to be exogenous places in a system of production, were in fact endogenous. Technologically separable interfaces were the result of designers' intent interacting with the physical and logical constraints of products and production processes. In other words, transactions arose in specific locations because designers created technologically separable

[30] More specifically, Williamson (1985, Chapter 4) asserted that the adoption of a particular form of transaction resulted from choices made by those involved. He emphasized, however, that the technological aspect is only very rarely a deciding factor in this decision "[T]echnological separability… is a widespread condition, … the rule rather than the exception. It thus becomes easy and even natural to regard the transaction as the basic unit of analysis" (p. 87). Thus Williamson focused on different ways of organizing and governing transactions, not on their origin. (Our thanks to D. Chabaud for sharing with us his insights on this aspect of Williamson's thinking.)

interfaces that made transactions cost-effective at those points.

Baldwin and Clark then used design theory to analyze the location of technologically separable interfaces (hence transactions) in a system of production. They argued that, because humans are physically and cognitively bounded, *transfers* between people are needed in all but the smallest productive systems. Thus any productive system can be viewed as a network of tasks (nodes) and transfers (links).

However, not all transfers in a given network can be the basis of transactions. For a transfer (or set of transfers) to become a transaction, Baldwin and Clark said, three conditions must be met:

(1) The object(s) transferred must be standardized, implying that there is an understanding and a common definition shared by two (or more) parties.
(2) The object(s) must be counted by means of units (of weight, volume etc.).
(3) The transfer must be compensated, most often in the form of money, implying the existence of a system of valuation and payment in society.

These three activities in turn are costly, which meant that transactions are more costly than simple transfers.

Baldwin and Clark called the costs of standardizing, counting, valuing and paying for goods "mundane transaction costs," to distinguish them from the "opportunistic transaction costs," which were the focus of most economic analyses of the time.[31] Opportunistic transaction costs arose from the fact that humans display what Williamson called "self-interest seeking with guile" (Williamson, 1985, p. 47). Examples of opportunistic transaction costs included an employee's tendency to shirk; the probability that a supplier would provide inferior goods; and the cost of litigation. In some cases mundane transaction costs might be used to reduce opportunisitic transaction costs, but the two types of cost were conceptually distinct.

Baldwin and Clark then argued that mundane transaction costs were lowest at the "thin crossing points" of a network of production: the places where two parts of the system were nearly independent. Thin crossing points in turn arose at the boundaries of modules or near-modules.[32] In effect, then, *module boundaries and technologically separable interfaces were the same thing*. Also when a system was modularized, the number of thin crossing points was multiplied as a consequence of the design change. Therefore the

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[31] The name "mundane transaction cost" was chosen to be parallel with Williamson's idea of "mundane vertical integration" which, he said, occurred between closely linked stages of production (Williamson, 1985, p. 105).

[32] The minimum interaction zones located between the blocks of the matrix in Figure 3 p. 40.

technological act of modularizing a system would necessarily reduce mundane transaction costs at a number of locations in the system. This was why a new modular architecture—such as IBM's architecture for System/360— made it feasible to redraw the boundaries of firms and multiply the number of firms participating in an industry.

In addition to relating modular structure to the transaction costs and property rights theories of the firm, the "Transactions" paper shed light on the knowledge- or capabilities-based view of firms as well (Kogut and Zander, 1992, 1996; Nonaka and Takeuchi, 1995; Conner and Prahalad, 1996). Baldwin and Clark argued that a firm is "a social artifact designed for the purpose of encapsulating complex transfers of material, energy and information" (p. 25). In other words, firms were designed to carry out transfers that could not become (cost-effective) transactions because their implicit mundane transaction costs were too high. Tranfers of knowledge often have high implicit mundane transaction costs, and thus firms were structures ("social artifacts") where time-sensitive, specific knowledge could be developed, stored and moved around as needed.[33]

Thus according to Baldwin and Clark, firms were, *at one and the same time*, entities that economized on transaction costs (as seen by economists) and entities that built, stored and used knowledge (as seen by management scholars). Linking these two apects of the nature of firms was the design principle "information hiding," proposed by the design theorist, David Parnas (1972, 1979). Parnas contended that each (properly defined) module:

(1) should have *interfaces visible* to the outsiders who need to use the module; and
(2) should also *hide information* about how the module actually does its job.

The *visible interfaces* of firms were their transactions (with customers, employees and suppliers). The *hidden information* of firms encompassed their internal processes, problem-solving methods, and routines. In this fashion, the theory of modular designs could be used to enhance the basic contributions of Kogut and Zander (1992, 1996), Nonaka and Takeuchi (1995) and Conner and Prahalad (1996) on the nature of firms.

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[33] However, Baldwin and Clark (2006d) does not contemplate organizational configurations in which various companies can collaborate on matters where the knowledge level is too low for transactions to occur immediately. Yet certain literature, particularly French work, on the organization of the design process has shown that such organizational arrangements are possible and beneficial for both companies. (With regard to co-development, see for example Kesseler, 1998; Garel and Midler, 1998).

6.3 The Strategic Use of Architectural Knowledge

Clark's work in the 1980s and early 1990s focused almost exclusively on the failure of established firms. From this perspective, architectural innovations were exogenous events caused by "shocks" in technology and demand. Thus Clark and his coauthors never addressed the question, what caused the shocks? Nevertheless, Henderson and Clark (1990) ended their paper on a provocative note, hinting at a shift from defense to offense:

> Since architectural innovation has the potential to offer firms the opportunity to gain significant advantage over well-entrenched, dominant firms, we might expect less-entrenched competitor firms to search actively for opportunities to introduce changes in product architecture… . (Henderson and Clark, p. 28).

Recently two papers have appeared that suggest how architectural knowledge might be used—proactively—to change the structure of an industry. Interestingly, the papers describe very different strategies. Because they point in such different directions, we feel it would be misleading to describe one and not the other.

Baldwin and Clark's (2006e) paper was based on the principles of "third generation" computer architecture as set forth in two textbooks by John Hennessy and David Patterson (1990, 1994).[34] According to Hennessy and Patterson, architectural knowledge consists of detailed, quantitative knowledge about the cause-and-effect relationships that constrain product (or process) performance. Given such knowledge, an architect can determine (1) where bottlenecks arise in a given system; (2) how to remedy a bottleneck; and (3) how to *modularize* a system, that is, how to separate components and encapsulate them behind well-defined interfaces.

Baldwin and Clark went on to argue that, with such knowledge in hand, the architect's *firm* can seek to control the bottleneck, and, at the same time, can outsource non-bottleneck components and subsystems. The result is a smaller "footprint", ie, the architect's firm does less inhouse. The smaller footprint in turn translates into a superior return on invested capital, which (the paper showed) allows

[34] The first generation of computer architectures were based on a memorandum by John von Neumann (Baldwin and Clark, 2000, Chapter 6). The second generation involved *modular* architectures. These were initiated by System/360, and their design principles were set forth by Bell and Newell (1971). The third generation of architectures applied quantitative metrics to modular hardware and software designs and used these to develop reduced instruction set computer (RISC) architectures. (Hennessy and Patterson, 1990, 1994). Many successful computer designs of the 1980s and 1990s, including Berkeley Unix and its descendants, Sun Microsystems' and SiliconGraphics' workstations, and Cisco's routers were based on third-generation principles. Hennessy and Patterson's work was anticipated by John Cocke at IBM (Hennesy and Patterson, 1990, pp. 130, 189; Ferguson and Morris, 1993, pp. 38-42).

the firm to drive competitors out of the market. Baldwin and Clark presented evidence that Sun Microsystems (in the late 1980s) and Dell Computer (in the 1990s) competed in just this way.

Fixson and Park (2007) described the evolution of the bicycle drive train industry. Interestingly, as was the case in Henderson's and Clark's photolithographic equipment industry, the critical architectural knowledge in bike drive trains had to do with the alignment of subsystems. If five of the six components in a drive train were aligned just so, the system would support "index shifting," that is, the rider could shift gears without taking his hand off the handlebars. Index shifting turned out to be a very attractive feature for cyclists: so much so that, once it became available, almost all customers demanded it. However, for the essentially same reasons Henderson and Clark described in photolithographic equipment, the capabilities needed to produce a properly aligned drive train were hard to imitate. Thus, within five years of the introduction of the index-shifting drive train, the industry went from being a fragmented, vertically distintegrated cluster to a highly concentrated, vertically integrated oligopoly. Shimano, the first company to introduce the new drive trains, became the dominant firm, going from around 15% to 57% of the road bike market and from 45% to 78% of the mountain bike market. Such is the power of strategic architectural innovation!

7 Conclusion

This paper has reviewed the research contributions of Kim Clark over almost 30 years (1978-2007). Clark is an interesting figure to study not only because of his own contributions, but also because he was at the center of the TOM group at Harvard Business School for almost two decades. There he was strongly influenced by his senior colleagues and contemporaries, including Hayes, Abernathy, Wheelwright, Rosenbloom, Bower, Lawrence, Jaikumar and Bowen. And he in turn influenced his students and junior colleagues, including Chew, Fujimoto, Leonard-Barton, Henderson, Christensen, Iansiti, David Ellison, and Steven Spear.

His intellectual trajectory also mirrored a fundamental change in the basis of global competition. Over the period spanned by his career, firms increasingly have come to compete on the basis of their product development performance, innovation and, more generally, design activities. Clark's work sheds light on the underlying causes of this paradigm shift.

Looking at Clark's life's work, a number of themes stand out. Methodologically, Clark was committed to field research and especially to the analysis of measurable constructs. He liked simple statistics and delighted in constructing indices. He did not mind small samples, but liked to be sure that "all important examples" were included in his research plan. The auto industry study with Chew and Fujimoto was an example of his preferred style of empirical research.

Theory building was also an important part of Clark's methodology. He persistently sought to interpret field data in terms of overarching frameworks and models, *which he developed himself or with his coauthors*. In constructing his theories, he was highly eclectic, wandering far away from management and his home discipline, economics. Clark's theorizing was initially nurtured by Abernathy, who gave him enough ideas to last a lifetime. After Abernathy's death, Clark continued to pursue Abernathy's question, why do established firms fail? And later, in *Design Rules*, he formalized Abernathy's ideas about design hierarchies and design evolution. Thus Abernathy's vision pervades much of Clark's work.

In addition to his methodological preferences for field research and theory building, Clark brought two substantive convictions to all his work. The first was "management matters." Academically speaking, this conviction was sometimes a strength and sometimes a weakness. On the one hand, Clark and his colleagues were able to show exactly how much management mattered in two important arenas: manufacturing and product development. Their work contributed to a better understanding of the role of management and managers who, as noted by David Teece (2006), are generally banished from economic theory. However, Clark also had a tendency to interpret all events in terms of managerial interventions by key players. He never encountered a situation in which he felt managers had no latitude for action and could not—somehow—influence events.

Clark's second strong conviction was that the key to understanding technical change lay in understanding the "deep structure" of products and processes. This close-up view of technology led to some notable successes: *Dynamic Manufacturing*, the auto industry study, the evidence from the photolithographic equipment industry. But his focus on deep structure also sometimes led Clark to over-generalize based on small and non-representative samples. For example, "the failure of established firms" was not the biggest story in the U.S. economy in the 1980s and 1990s. A larger story was the economy's striking ability to generate and fund innovations, and the potential for the capital markets to overshoot. Clark, like many others, was blind-sided by the Internet bubble and crash (Baldwin and Clark, 2003).

Notwithstanding a few blind spots, on the whole, Clark's convictions served him well. They caused him to look at the world in new way—to see things not noticed by most other scholars. And his convictions, deeply felt as they were, nevertheless gave him plenty of room for intellectual growth. Over the course of his career, he moved from manufacturing to product development to design: each time he used insights gained from prior work to inform his next endeavor. For example, *Design Rules*, his last major work, made little use of field research or statistical analysis, but it was based on the direct observation of design structures and it developed new tools to measure design value. Thus even as his focus changed, Clark's fundamental approaches remained the same.

In sum, throughout his career, Clark brought fresh new insights to old questions and opened up new territories of research. He helped to replace Taylor's scientific management principles with the dynamic concepts of continual learning and learning organizations. He showed how product development could be actively managed for greater efficiency and effectiveness. He developed a theory of the embedding of knowledge in organizations, which he used to explain why established firms often fail in the face of "seemingly minor innovations." He showed how changes in the modular structure of products and processes could bring about fundamental change in the structure of industries. And finally, in his later works, he built bridges from design theory to user innovation, transaction- and knowledge-based theories of the firm, and strategy.

In light of these contributions, Clark's intellectual legacy seems secure.

Appendix A: Chronological List of Clark's Publications

Works by Kim Clark are listed in the following order: (1) by year; (2) Clark sole-authored; (3) Clark first author, alphabetically by author; (4) Clark second or third author, alphabetically by author. The list excludes cases and casebooks and all but the most significant working papers.

1980

Clark, K. B. (1980) "The impact of unionization on productivity : a case study," *Industrial and Labor Relations Review*, vol. 33(4): 451-469.

Clark, K. B. (1980) "Unionization and Productivity: Micro-Econometric Evidence," *Quarterly Journal of Economics* vol. 94(4): 613-639.

Clark, K. B. and Freeman, R. B. (1980) "How Elastic is the Demand for Labor?" *The Review of Economics and Statistics*, 62(4): 509-520.

1981

Clark, K. B. and Summers, L. H. (1981) "Demographic Differences in Cyclical Employment Variation," *The Journal of Human Resources*, 16(1): 61-79.

Abernathy W. J., Clark, K. B. & Kantrow, A. M. (1981) "The new industrial competition," *Harvard Business Review*, September-October: 68-81.

1982

Clark, K. B. and Summers, L. H. (1982) "Labour force participation: timing and persistence," *Review of Economic Studies*, 49(4): 825-844.

1983

Clark, K. B. (1983), "Competition, technical diversity and radical innovation in the US auto industry," in *Research on Technological Innovation, Management and Policy*, Volume 1 (Rosenbloom, R. S., ed.), Greenwich, CT: JAI Press.

Abernathy, W. J., Clark, K. B. & Kantrow, A. M. (1983), *Industrial renaissance. Producing a competitive future for America*, New York: Basic Books.

1984

Clark, K. B. (1984), "Unionization and firm performance: the impact on profits, growth and productivity," *American Economic Review*, 74(5): 893-919.

1985

Clark, K. B. (1985), "The interaction of design hierarchies and market concepts in technological evolution," *Research Policy*, 14(5): 235-251.

Clark, K. B., Hayes R. H. and Lorenz C., eds. (1985), *The Uneasy alliance*: *Managing the productivity – technology dilemma*. Boston, MA: Harvard Business School Press.

Abernathy, W. J. and Clark, K. B. (1985), "Innovation: mapping the winds of creative destruction," *Research Policy*, 14(1): 3-22.

Hayes R. H. and Clark K. B. (1985) "Exploring the sources of productivity differences at the factory level" in *The Uneasy Alliance*: *Managing the productivity – technology dilemma* (Clark, K. B., Hayes R. H. and Lorenz C., eds.) Boston, MA: Harvard Business School Press.

Hayes, R. H. and Clark, K.B. (1985) "Explaining productivity differentials between plants : implications for operations research," *Interfaces*, 15(6): 3 –14.

1986

Clark, K. B. and Rothman, E. (1986) "Management and Innovation: The Evolution of Ceramic Packaging for Integrated Circuits," in High-Technology Ceramics: Past, Present and Future (Kingery, W. D., ed.) American Ceramic Society.

Hayes, R. H. and Clark, K. B. (1986), "Why some factories are more productive than others?" *Harvard Business Review*, September-October: 66-74.

1987

Clark, K. B. (1987) "Investment in New Technology and Competitive Advantage," in *The Competitive Challenge* (Teece, D. J., ed.) Cambridge, MA: Ballinger Publishing Company.

Clark, K. B., Chew, W. B. and Fujimoto, T. (1987), "Product development in the world auto industry," *Brookings Papers on Economic Activity*, 3: 729-771.

Clark, K. B. and Fujimoto, T. (1987) "Overlapping Problem Solving in Product Development," *Managing International Manufacturing* (Ferdows, K., ed.) Amsterdam: North-Holland.

1988

Clark, K. B. (1988) "Managing technology in international competition: the case of product development in response to foreign entry," in *International Competitiveness* (Spence, A. M. & Hazard, H. eds.) Ballinger Publishing Company, Cambridge, MA.

Clark, K. B. (undated, probably 1988) "Knowledge, Problem Solving, and Innovation in the Evolutionary Firm: Implications for Mangerial Capability and Competitive Interaction," Working paper, Harvard Business School, Boston, MA.

Clark, K. B. and Fujimoto, T. (1988) "Lead Time in Automobile Product Development: Explaining the Japanese Advantage," *Journal of Engineering and Technology Management*, 6: 25-58.

Clark, K. B. & Hayes, R. H. (1988) "Recapturing America's manufacturing heritage," *California Management Review*, 30(4): 9-33.

Hayes, R. H., Wheelwright, S. C. and Clark, K. B. (1988) *Dynamic manufacturing. Creating the learning organization*, The Free Press, New York.

1989

Clark, K. B. (1989) "Project scope and project performance: the effect of parts strategy and supplier involvement on product development," *Management Science*, 35(10): 1247-1263.

Clark, K. B. (1989) "What Strategy Can Do for Technology," *Harvard Business Review*, November-December: 94-98.

Clark, K. B. and Fujimoto, T. (1989) "Reducing time to market: the case of the world auto industry," *Design Management Journal*, 1(1): 49-57.

Henderson, R. M. & Clark, K. (1989) "'Generational' innovation: the reconfiguration of existing systems and the failure of established firms," Working paper 90-025, Harvard Business School.

1990

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