The interaction of design hierarchies and market concepts in technological evolution *

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This paper develops a conceptual framework for analyzing the sequence of technological changes that underlie the development of industries. The framework examines the interaction between design decisions and the choices of customers. Using examples from autos and semiconductors the paper argues that the logic of problem solving in design and the formation of concepts that underlie choice in the marketplace impose a hierarchical structure on the evolution of technology. The nature of the evolutionary process has implications for the dynamics of competition and the management of innovation.

1. Introduction

In an age of gene splicing, computers on a chip, and telecommunication marvels, it is difficult to think of technological innovation in terms that do not evoke images of scientific breakthroughs, and radically new products and markets. Experience with technology since World War II has reinforced a conception of innovation that emphasizes the spectacular and novel, and neglects seemingly mundane refinements that improve existing concepts. But histories of many industries show clearly that refinement and extensions of established design concepts play a central role in technical advance. [1] Furthermore, these changes in technology do not emerge all at once. Products and processes develop through a sequence of changes that tend to build on past experience. While the end result of a long period of such technical development may be a product (or process) that is quite different from very early designs, the differences between a new version and the one just preceding it are small.

In this paper I develop a conceptual framework for analyzing the sequence of technological changes that underlie the development of industries. The paper examines the interaction between technical innovation and customer demands from an evolutionary perspective. The notion that technology develops in an evolutionary fashion has been an important theme in recent work on innovation and competition. [2] The framework developed here builds on research in the history of technology and on theoretical work on evolutionary models. Although the variety of models that have appeared vary in details and focus, they all emphasize the importance of uncertainty, search behavior and learning in the process of technical development. Further, existing research underscores the pervasive influence of technology. The implication is that as the technology of product and process evolves, so too do associated systems of organization and managerial practice. Moreover, there appear to be patterns in the evolutionary process that are common across industries and technologies.

A descriptive model of these patterns developed by Abernathy, Utterback and their associates illustrates many of the common themes in evolutionary models, and thus serves as a useful starting point for the discussion that follows. [3] In general terms, what I shall call the A-U model describes the evolution of products and processes as a transition from an early, "fluid" state, to one that is highly "specific" and rigid. In the early, "fluid" period of development, performance criteria for new products are not well defined and market needs or process difficulties are approached through a variety of different product or equipment designs. Innovation is relatively rapid, and funda-

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1 The list of studies documenting the importance of refinements and extensions is lengthy. Representative work includes Abernathy [1], Miller and Sawers [18], and Enos [12].

2 Nelson and Winter [19] provides a theoretical framework for evolutionary models along these lines. See in addition: Porter [21], Abernathy and Utterback [4], and Abernathy and Townsend [3].

3 Abernathy [1,Ch.2]. See also Abernathy and Utterback [4].

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mental. The production process in turn, must be highly flexible, relatively labor intensive, and somewhat erratic in work flow.

As development proceeds, however, technological diversity gives way to standardization. Particular design approaches achieve dominance, production volumes increase, and performance criteria and processes are more clearly specified. The transition to a "specific" stage of development entails a change in the nature of innovation. In contrast to the fundamental changes introduced in the "fluid" phase, innovation in the "specific" stage is likely to alter only a small aspect of the basic product, and any changes introduced serve to refine the established design. On the process side, work flow is rationalized, integrated and linear, unlike the fluid and flexible job shop of the early period. Further, general purpose machines and skilled workers are replaced by dedicated, highly "specific" equipment.

In their work on the theoretical foundations of evolutionary processes in innovation Nelson and Winter have emphasized the importance of uncertainty about technical alternatives and the search for new information. [4] In an earlier paper I argued that the kind of evolutionary development described in the A-U model is predicated on uncertainty in both customer demand and technology. [5] On the producer's side, there must be at the outset both a non-trivial set of available product technologies, each with its own distinctive capabilities, and substantial uncertainty about which technologies will best satisfy perceived customer needs and preferences. On the buyer's side, there must be uncertainty about the mix of services a given set of technologies will deliver and about demands among them. Without uncertainty of this sort the evolutionary process would be a trivial selection of a known design to meet a known set of needs.

But uncertainty is more than a precondition for evolution, it is also a determinant of its pattern. With a menu of technical choices and with little understanding of customer needs or the link between technology and preferences, innovation and customer choice will be characterized by search, extensive information processing, and learning. The pattern of innovation that emerges from this process, the kinds of changes introduced, the timing of particular changes and so forth, will depend in part on the pattern of uncertainty, and the way in which new understanding is developed.

The framework developed in this paper provides a detailed description of the forces shaping the pattern of innovation that emerges from this process. The framework examines both the decisions of producers in the design of products (and processes) and choices of customers. I argue that the logic of problem solving in design and the formation of concepts that underlie choice in the marketplace impose a hierarchical structure on the evolution of technology. The pattern of innovation, the kinds of design changes introduced and their timing and sequence, not only depend on the technical alternatives but on the interaction between the internal logic of the product and the evolution of customer requirements.

The remainder of the paper is divided into four parts. I first examine the evolution of product technology from the standpoint of product design (section 2). Section 3 focuses on the formation of customer concepts and their interaction with product technology. Section 4 is concerned with the development of production processes. Principal examples are drawn from the auto industry, with supplementary examples taken from the development of semiconductors. The paper concludes with brief remarks on implications for the analysis of innovation and competition, for managerial practice and for further research.

2. Problem solving and the logic of design

From the standpoint of the firm the search for competitively successful products and processes can be characterized in terms of the problems of design. Alexander has defined the process of design succinctly:

> Every design problem begins with an effort to achieve fitness between two entities: the form in question and its context. The form is the solution to the problem; the context defines the problem. In other words, when we speak of design, the real object of discussion is not the form alone, but the ensemble comprising the form and its context. [6]

[4] Nelson and Winter [19,Ch.12] focuses on search processes in R&D and innovation.

[5] Clark [10].

[6] Alexander [6].

The central focus in this paper is not a particular design at a point in time, but rather the sequence of design decisions that emerge over time. It is this sequence that determines the pattern of change in product and process technology. The history of technology in specific industries contains numerous examples of design sequences that conform to more general patterns of development. In industries as diverse as automobiles, semiconductors, aircraft and petroleum refining, innovative activity seems to be characterized by a few major innovations that are followed by a long sequence of refinements. [7] The specific pattern of search for improvements, however, seems to depend on the nature of the technology, and the context in which a particular design must fit. Rosenberg has argued that the direction of technological change in manufacturing industries – the particular sequence and timing of innovative activity – has been strongly influenced by technical imbalance between interdependent processes and components. [8] These imbalances create incentives for change that lead to other obvious changes in a sequence that Rosenberg terms "compulsive."

While recognizing the validity of Rosenberg's interpretation in some cases, Nelson and Winter argue that the search for improvement and thus the direction of innovative activity is also driven by engineers' understanding of the potential in a given set of design concepts. [9] Knowledge of potential and existing constraints give rise to what Nelson and Winter call "natural trajectories." Like the search for jet engine designs with higher inlet temperatures and higher pressures at combustion, these trajectories are particular sequences of designs whose direction and objective are defined by a specific set of technical opportunities and constraints. Such trajectories may exist within a particular product technology, but may be apparent across many technologies at the level of the sector or nation (e.g. mechanization in manufacturing).

The work on technological history and the interpretive analyses of Rosenberg, Nelson and Winter and others have identified the importance of technical interdependence, the tendency for designs to build on one another, and the role of perceived technical opportunities in determining the pattern of technical advance. The framework developed here builds on this work in two ways. First, I use Alexander's theory of design to develop a more detailed characterization of the process of problem solving that lies behind sequences of innovations in a specific product. Although much previous analysis has focused on innovation at the level of industry or sector, it is clear that the implications pertain to very detailed design choices for a specific product or process. [10] Second, and more important, the framework goes beyond the technical aspects of design and traces the connection to customer choice. While technical interrelationships obviously play a central role in shaping innovation, interaction with market demands is likely to be important as well. What is of interest here is not only the possibility that feedback from the market will influence technical development, but that design choices may also influence the evolution of concepts that guide customer choice.

2.1. The logic of design

The distinction between form and context is central to understanding how the design of a product and its production process evolve, and is the starting point for the framework. To begin the analysis, consider the task of designing a product in the fluid stage of the A–U model; for the purposes of illustration I shall use the automobile at the turn of the century in the United States. In this case the general context was the economic and social environment of late 19th century America, but its more specific dimensions involved the state of roads, the patterns of commerce, geography, and the habits and preferences of customers with respect to transportation. The form – the emerging automobile – can be defined in terms of its basic functional parameters: motive power, steering, stopping, regulation of speed, load capacity, and so forth. Each parameter pertains to a functional domain, but within any particular domain, there exists a set of alternative concepts among which the designer may choose.

[7] See footnote 1 for references in automobiles, aircraft and petroleum refining. For information on semiconductors see Braun and McDonald [9].

[8] These ideas are developed in Rosenberg [22].

[9] Nelson and Winter [20].

[10] Alexander [6] emphasizes the absence of misfit. Asimow [8] discusses the notion of design criteria.

The task at hand is to choose design concepts for functional parameters that result in a form that "fits" the context well. "Fit" is a property of the interaction between form and context, or in other words, of the use to which the product is put. Some writers define "goodness of fit" in terms of the absence of gross incongruities or "misfits"; others use a set of criteria that a well fitting design must meet. In either case, the quality of a particular design can be gauged in terms of a set of requirements. [11] Thus, the designer's choice among alternative concepts is assumed to be governed by an assessment of how well they meet perceived requirements.

The implications of uncertainty in technology and customer demands are evident. If the context were well specified so that requirements could be developed with precision and confidence, if the functional implications of alternative design concepts were likewise well known, the design problem at a given point in time would be trivial. One would only have to select the set of concepts that satisfied the requirements. Moreover, if the context and the set of design concepts remained stable over time, the selected design would persist. But where product concepts are new and ill defined, where experience in use is limited and the context of use complex, product design becomes a search for information and new understanding.

The designer of a 1900 automobile, for example, might have begun with a rough perception of the requirements of the market, and some understanding of engines and drive trains. Part of the challenge of design thus lay in the absence of knowledge about the technology itself, and part in limited understanding of the emerging context. And too, any given designer faced uncertainty about the possible actions of rival firms. It is true that a design problem would have existed had there been only one designer, but the possibility of competitive alternatives adds an important element of uncertainty to the calculation. [12]

Yet the presence of rivals is likely to be an important element in the creation of new understanding. The reason lies in the necessity for customers to actually use the product in order to generate information about the requirements of the context and the relative value of alternative approaches. Clearly, some insight may be developed by introspection and experimentation in a laboratory setting. But with the kind of fundamental uncertainty that exists at the beginning of a product's development, Arrow's "fundamental paradox of information demand" seems to apply: without customer purchase and use of a product one cannot acquire information about its technology, nor how the services provided satisfy preferences. [13] The possibilities for developing insight into the emerging form and its context may thus be enhanced by participation of several producers.

It is, of course, important that there be variety in competing designs. But that is a condition likely to be met. In the first place it is unlikely that customers have identical prior beliefs about which of the alternative concepts will best meet their as yet ill defined needs. Likewise it seems unlikely that the rival firms and designers would all read the context in exactly the same way. The upshot is that customers for a product in the "fluid" stage of development are likely to be faced with and are likely to support a variety of approaches to the product.

2.2. Patterns of innovation

Given alternative design concepts and competition among rival producers, uncertainty about technology and customer preferences leads to a diversity of technology in the products vying for customer acceptance. Diversity at this stage of development is not of a trivial sort. In the case of the 1900 automobile design problem, the alternative design concepts in engines included electric, gasoline, and steam. Each had very different operating characteristics and thus fit the context in

[11] Although I refer to the "designer" in the singular throughout this discussion, it should be noted that design is often a group activity. The nature of the group, its structure, orientation and experience may influence the choices made. This implies that there is likely to be an interaction between the nature of the design problems encountered and the nature of the design group. For further discussion, see Clark [11].

[12] As was the case with automobiles, emerging industries are often populated by many producers, most of whom are relatively small. In the discussion here, I have assumed that to be the case. How the number and size distribution of firms affects the design process will not be examined in this paper, but is a subject worthy of close study.

[13] See Arrow [7].

Table 1
Patterns of innovation in U.S. automobile engines and transmissions, 1895–1940

Section A	Time 1900	1910	1920	1930	1940			
Engines								
Cylinder configuration	o o oMo		M X	o	M		o	
Starting	oooMM	o Xoo	M				o o	
Exhaust	o o	o		M			o	
Fuel delivery	o	o	M o	o	M	M		
Valves	o	o	o				M	
Camshaft				M	X			
Materials	M o		o	M			oo	
Transmissions								
Clutch	M o	o o						
Modulation	M o				o		oo M	X
Selection	o			o			o	o o
Placement						oo		M
Section B								
Engine process	M o	MMM			Mo	Mo	o MM oMXm	

o = minor refinement; M = advance over past practice; X = major change in approach.
Source: Abernathy, Clark and Kantrow [2, appendix D, table 1].

very different ways. But not all approaches are equally attractive. Diversity within some functional domains may diminish as evidence accumulates. In the case of the automobile, for example, designers soon learned that a steering wheel fit the emerging context much better than a tiller. Yet in other parts of the product, early approaches to a facet of the product subsequently were challenged by a new concept (e.g. torque tube versus chain drive), and in others diversity persisted over fairly long periods of time (e.g. size of engine).

Is there a pattern to the narrowing of approach in some dimensions and the emergence of new approaches in others? And if so, what is the logic behind the sequence of developments? These questions are central to an understanding of the changing focus of customer valuation and innovative effort, and thus of the forces driving evolution. The logic of design sketched out above suggests that answers to these questions must be found in the interaction between form and context.

A complex product like the automobile develops through a sequence of decisions about functional parameters. These decisions grow out of problems in the fit between form and context. Over time, the search for well adapted designs resolves certain problems, and confronts new ones. Framed in these terms, problem solving is the source of innovation. The changing level and focus of innovative effort depends on the nature of design problems, and the sequence in which they occur.

Table 1 illustrates the shifting pattern of innovative effort and design problem solving with data taken from the U.S. auto industry from 1895 to 1940. [14] Section A tracks instances of innovation in engines and transmissions. Within each system changes in specific parameters have been identified. By graphing the frequency with which a new approach to a particular parameter was introduced and by assessing the significance of that approach one can track the pattern of innovative effort within the product over time. Section B presents a similar summary of the pattern of innovations in the engine production process.

Several patterns emerge in this data. Perhaps most striking is the precedence of innovation in engines over transmissions up until the late 1920s and then the dominance of transmission innovation during the decade of the 1930s. It is also clear that within the engine category, the number and configuration of cylinders and the starting/firing of the engine were the focus of significant effort over several years, while other parameters within the engine were the subject of little innovation until well into the 1920s. One also sees bursts of activity in certain parameters and then long periods of no innovation followed by a significant change sometime later.

Two patterns are evident in the relationship between product and process change. As Abernathy's work has shown, process innovation is relatively less frequent in the early phases of industry development. This is consistent with the notion that process development is dependent on the resolution of major design differences and thus stability in product parameters. Yet there is indication of a distinctive and very significant interaction between product and process innovation in the period 1907–1908, and the early 1930s. In both instances, new product developments grew out of process innovation, particularly the development of components made from new materials, and the techniques to produce them.

Part of the explanation for these patterns may lie in the emergence of new technical knowledge from outside the industry that makes possible a new concept in design. There is no question that new insight and new capability from science and engineering have influenced the timing and pattern of innovative effort. But exogenous development of technical knowledge fails to explain much of what one observes in table 1. Take, for example, the precedence of engines over transmissions, and in particular, the appearance of semi-automatic transmissions in the mid-1930s. From a technical standpoint it is very hard to argue that something like the "freewheeling" transmission on the 1931 Studebaker did not appear earlier because of the absence of a key scientific or engineering insight that later appeared and made that particular design feasible. The evidence on transmission development suggests that the scientific and engineering principles embodied in the semi-automatic and transmissions of the 1930s were available at least by 1920. [15]

[14] The data on which these observations are based have been compiled as part of an ongoing project with W.J. Abernathy and A.M. Kantrow. A summary of the data may be found in W.J. Abernathy et al. [2].

[15] See the data in Abernathy et al. [2,Appendix D].

2.3. The hierarchy of design

Patterns of innovation like those observed in early automobiles are the result of two related processes. The first is the logic of problem solving in design; the second is the formation of concepts that underly customer choice. Both processes impose a hierarchical structure on the evolution of technology. In the case of design, a hierarchy of concept seems to be inherent in physical objects. This may only reflect the way that the modern brain happens to function, but as Alexander notes, there are reasons to think otherwise:

> The organization of any complex physical object is hierarchical. It is true that, if we wish, we may dismiss this observation as an hallucination caused by the way the human brain, being disposed to see in terms of articulations and hierarchies, perceives the world. On the whole, though, there are good reasons to believe in the hierarchical subdivision of the world as an objective feature of reality. Indeed, many scientists, trying to understand the physical world, find that they have first to identify its physical components, much as I have argued in these notes for isolating the abstract components of a problem. To understand the human body you need to know what to consider as its principal functional and structural divisions. You cannot understand it until you recognize the nervous system, the vascomotor system, the heart the arms, legs, trunk, head, and so on as entities. [16]

Part of the reason the evolution of a complex product follows a hierarchy of design, therefore, is inherent in the nature of the object. It is a matter of logic. Design is a search for understanding of what the object or product is, and ought to be given the context in which it must function. The working out of a design involves a process of analysis, of identifying the components of the form, the major systems and sub-systems, and then grouping them in different ways to illuminate their interrelations. Not all elements or components of a system are of equal significance in function or in concept. Moreover, there are choices in the development of a design that create precedents and are logically prior to other choices. These precedents create constraints that give rise to further search for alternative designs along the lives of Rosenberg's "compulsive sequences." These precedents may be inherent in the physical structure of the product or system, or they may arise because of interdependencies between parts. Work on the nuances of combustion chamber design, for example, is likely to follow and depend on choices about energy transformation (i.e. internal vs. external combustion) and power delivery (e.g. pistons vs. rotary).

The implications of physical structure and interdependenc are not limited to the working out of a particular design, nor do they exist only in the mind of the designer. Given the nature of uncertainty that I have assumed, interrelations among aspects of the product are unlikely to be fully understood and contradictions unlikely to be resolved at the initial conception of a design. Clearly a given embodiment of the design must meet minimum standards of functionality given the existing state of demands. But experience will generate insight and greater understanding and pursuit of new approaches as problems are uncovered. Physical interaction and the precedence of some parameters are likely to impose a hierarchical structure on the focus of innovative effort as it is reflected in successive generations of the product.

The hierarchical structure of design may be reinforced by the process through which design problems are solved. 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. [17] The classic statement of the hierarchical nature of the design process in engineering is Marple's "The Decisions of Engineering Design."[18] Figure 1 is taken from that work and illustrates the problem of designing a duct and valve arrangement in a nuclear reactor. The central issue for Marple's engineer was the choice between a flexible and a coaxial duct. Pursuit of those approaches uncovered additional problems as subsidiary parameters (e.g. valve design, valve mechanism, etc.) and their alternatives were addressed. Clearly, the sequence of issues was closely related to the physical structure of the product. But it is also apparent

[16] Alexander [6,p. 129].

[17] Simon [23], cited in Howard [15,p. 96].

[18] Marples [17].

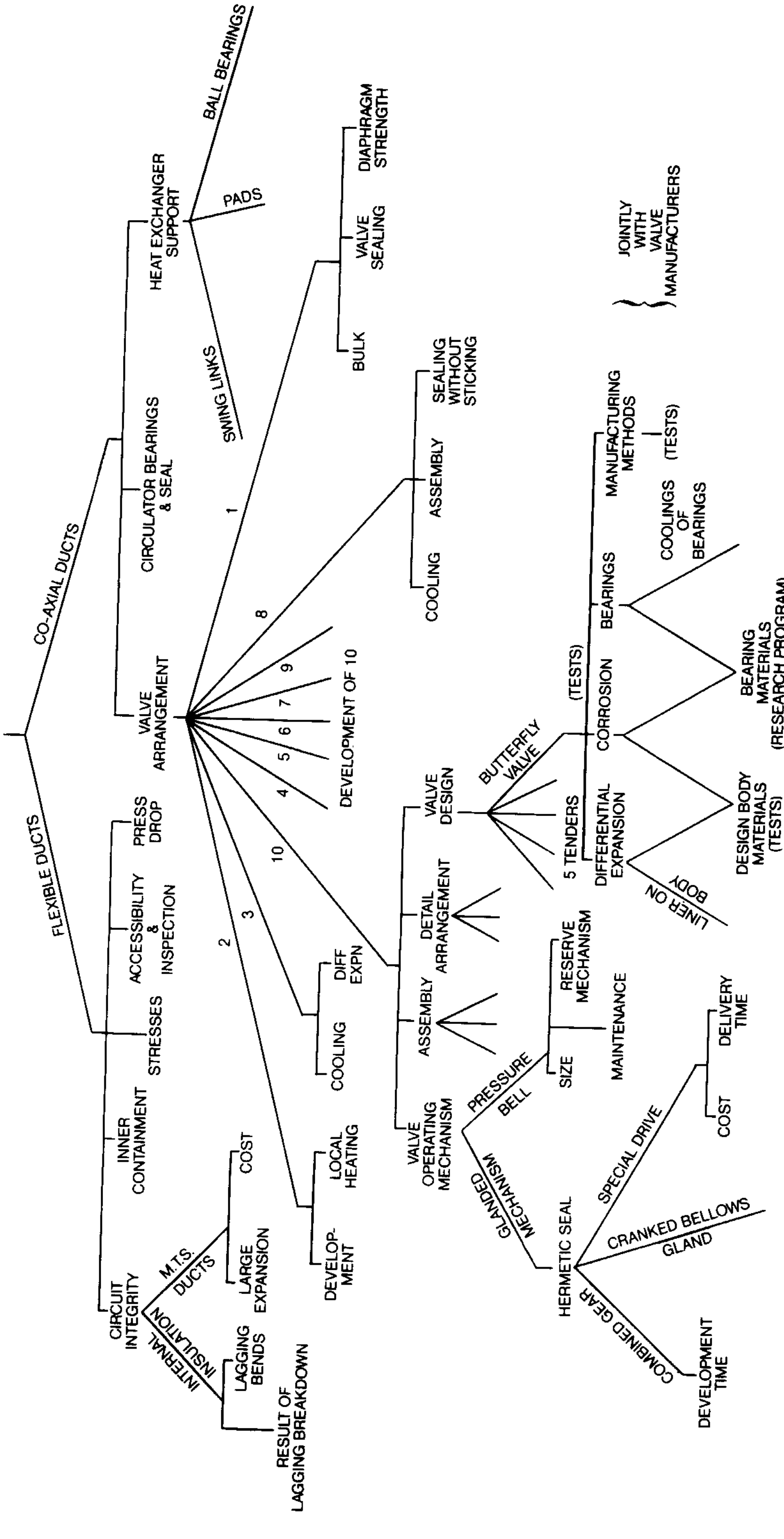

Fig. 1. Marple's ducts and valves problem. Sloping lines are alternatives; vertical lines are subproblems.
Source: Marple's [17,p.60]. "The Decisions of Engineering Design" IEEE Transactions on Engineering Management (June, 1961), p. 60.

that the logic of problem solving employed – breaking the problem into parts, establishing an ordering – reinforced an hierarchical structure of design.

It is inherent in the nature of an hierarchy that the various functional parameters are of unequal significance. At each level in the hierarchy competing alternatives have implications for subsequent decisions, but choice at the apex has ramifications throughout the hierarchy. Within a given functional domain like an engine in an automobile, the structure of associated parameters is hierarchical. One parameter sits at the apex, and is particularly trenchant in its impact on other aspects of the domain. Such concepts are central or "core" in the sense that the choices they represent dominate all others within the domain. That domination arises from the fact that the choice of a core concept creates a set of given conditions with which other parameters must deal. Said another way, choice of a core concept establishes the agenda for a product's technical development within a particular functional domain.

The notion of a technical agenda is clearly related to Nelson and Winter's concept of "technological regime."[19] The problem of adding impurities (i.e. doping) to base semiconductor material to create a transistor illustrates the basic notion. Several methods of doping were available in the mid-1950s, including melting a pellet of impurity during the preparation of germanium or silicon crystal, alloying, and diffusion of vaporized dopants. In conjunction with photographic techniques (masking) to control placement, diffusion gradually achieved dominance. This established an agenda of work in control of vaporized materials, and in photo resist methods. Significant refinements in diffusion and masking took place during the 1950s and 1960s including the development of the planar process, metal deposition, and advances in mask alignment.[20]

The case of the automobile engine provides further evidence of the meaning of a core concept and its implications for technical development. The central functional problem in the evolution of the engine was the choice of fuel and the principle of energy transformation. In the very early days of the industry it was not clear whether steam or electricity or gasoline would dominate. Indeed before 1900 steam and electricity powered vehicles were more reliable. By 1902, however, the dominance of the gasoline engine was largely established. Once the core concept became internal combustion based on gasoline, the technical agenda was set for a variety of subsidiary problems and choices. Starting and firing the engine, size and configuration of cylinders, placement of valves and camshafts, and so forth, were examined and approached in subsequent years as fig. 1 has shown. But such things would have had no place on the agenda established by the electric car. There the relevant focus for supporting technology would have included the chemistry of batteries and the parameters of electric motors. A core concept thus not only poses a series of problems inherent in its form and structure, but it also establishes linkages to specific engineering disciplines and even to basic science.

Given the logic of problem solving, "working through" a particular technical agenda entails a hierarchical exploration of alternative concepts. Thus, even without any changes in context, one would expect to observe a conceptual hierarchy in the sequence of design decisions embodied in successive generations of a new product. But neither the logic of problem solving, nor functional interaction between sets of parameters is sufficient to explain the pattern of specific choices and decisions and thus the particular design hierarchy that emerges. Within a given functional domain, for example, interaction between functional subparameters may create a hierarchy of choices and alternatives, but the choice of a particular approach to a given problem is unlikely to be determined on purely technical grounds.

In the engine case, the choice of four versus six cylinders, or the use of in-line or "V" configuration, did not turn on technical feasibility but on the "fit" between the concept and the context in which it would be used. Likewise, when one looks across broad functional domains within a given product, one often finds core concepts that either bear little relation to one another or are of roughly equal significance in their impact on other design parameters. In such cases the focus of innovative attention turns not on technical interaction, but on

[19] See Nelson and Winter [19,Ch. 14].

[20] For a brief discussion of the evolution of semiconductors, see Braun and MacDonald [9]. Other examples from the semiconductor industry have been taken from research by M. Therese Flaherty and Anne T. Coughlan [13].

the problems posed by the context. Thus, to understand the hierarchy of design as it emerges in the sequence of design choices over time one must understand not only the internal logic of the product, but the evolution of the requirements of customers. One must not only understand the technical agenda, but the sequence of problems posed by the emerging context.

3. Formation of customer concepts

A new product, like the automobile in the late 19th century, or the transistor in the early 1950s, confronts the customer with a set of unfamiliar possibilities. The problem of choice in this context involves both the formation of concepts with which to understand the product, and the development of criteria to be used in evaluation. Just as designers faced with a set of alternatives and incomplete information must solve a series of problems to achieve a design, so customers in the face of uncertainty must solve problems related to potential function and use. In this section of the paper, I expand the framework to focus on the nature of problem solving by customers. The ideas developed here build on several recent developments in the literature on innovation and marketing. von Hippel's research has underscored the importance of users as sources of ideas for new products, and has identified subsequent interaction between users and producers as a critical determinant of the success of an innovation. [21] Teubal has argued, further, that the success of an innovation will be influenced by what he calls users' "need determinateness, the extent to which preferences are specified (or need satisfaction is expressed) in terms of product classes, functions and features."[22] Both of these lines of work emphasize the importance of learning in the dynamic interaction between producers and users that occurs as a product evolves. In the words of Teubal, "consumers learn about what they want or need, and producers learn to innovate."

But learning by customers is not simply a matter of finding out which technical features satisfy a set of objective, well known, basic needs. Where products are new, learning focuses on development of the conceptual framework that customers use to evaluate competitive offerings and make purchase decisions. While it is generally recognized in the innovation literature that customer learning depends on experience, the nature and structure of that learning, particularly the character of the interaction with design choices of producers, has not been fully developed. Recent developments in the theory of customer choice in the marketing literature suggest a way of formulating the process of concepts development by users and the interaction with the decisions of producers. [23]

Research on the role of information processing in marketing suggests that customer problem solving is closely related to language and memory and their interaction. The formation of concepts in this context involves the establishment of meaningful connections between the functional and aesthetics of the physical object and words stored in memory. Two aspects of that process are critical. The first is grouping, in which the unfamiliar product is associated with other known product concepts to which it is similar or related. The second is distinguishing, that is, identifying those dimensions of the product that differentiate it from the group in which it has been placed.

The process of grouping and distinguishing can be illustrated with a relatively trivial example. [24] Fig. 2 depicts a set of concepts related to a type of vegetable – asparagus. This set of concepts is hierarchical in nature with the more inclusive, abstract concepts located higher in the order of things. Suppose that a set of customers had never before encountered asparagus. Faced with the problem of evaluating the product, the customers might first group it with other plants simply on the basis of observation. Observation might also provide enough information to permit the customer to make a finer distinction (green vegetable). But further refinement and development of the meaning of asparagus would depend on experience in use. One can imagine further distinctions based on taste, texture and interaction with other foods that would further establish the product's identity within the customer's conceptual framework.

It is important to note that concept develop-

[21] See for example von Hippel [26].

[22] Teubal [24]. See also Teubal et al. [25].

[23] Howard [15] reviews the literature on problem solving by consumers. See especially, Ch. 2–4.

[24] This example is developed at greater length in Howard [15,p. 43].

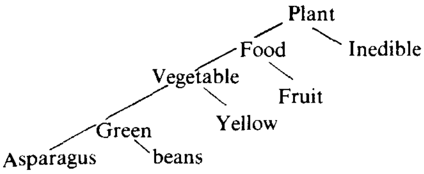

Fig. 2. Conceptual hierarchy related to asparagus. *Source*: [15, p. 43].

ment is based in experience, and that it occurs through a sequence of interactions between the product and the user. Those interactions provide information about the new product's relationship to other products and to the customer's needs. When experience is limited, the customer's search for understanding is dominated by attempts to relate the new product to existing concepts. Grouping of this sort gives way to distinguishing as experience accumulates. Differences between the new product and its conceptual relatives become sharper as the possibilities and potential of the new product become clearer. An accumulation of meaning relating the product's characteristics to customer needs and values is the foundation of a new concept.

The early history of semiconductors illustrates the important role of established and closely related products to the conceptual development of one that is new. The first transistors, for example, were evaluated in the language and context of vacuum tubes. [25] Scientists at Bell Labs thought of the transistor as a substitute for the tube, and subsequent development proceeded in those terms, at least for a while. The transistor's small size was its most distinctive feature, and initial uses were in products like hearing aids where size was critical. It was not until experience with transitors had deepened understanding of the possibilities of semiconductors that new concepts like the integrated circuit emerged. What happened in transistors seems to be a general property of new products: in the early stages, the new product is defined largely in terms of the old; as learning occurs, it develops a meaning and definition of its own.

Clearly, the working out of the conceptual definition occurs through use of and experience with the product. Although I have framed the analysis thus far in terms of a single customer, it should be recognized that the development of a new product concept is a market process and thus involves learning and problem solving on the part of the customer group. In this situation communication between customers (e.g. word of mouth) will be important in the diffusion of the product and in the crystallization of concept. Channels of communication, however, may be quite different for different products. Users of semiconductors, for example, often compete with one another and may have an incentive to restrict the flow of information about new products. In this context, communication may be more indirect (e.g. through vendors, journalists, etc.) than the direct word of mouth one might expect to find among consumers of a product like automobiles.

Social processes and patterns of communication thus will influence the speed and pattern of diffusion, but it is important to note that experience with the product (either direct or indirect) is the basis of concept development. Depending on how different the new product is, customer learning is focussed initially on higher order concepts, and those aspects of function that are most distinctive. Subsequent grouping and distinguishing among subsidiary concepts are governed by the problems growing out of the nature of use.

Problem solving on the customer side, thus follows a hierarchy of concept. What the product is, how it meets needs, how it functions in different situations, and so forth, is not defined in one fell swoop. Nor are the different aspects of the product of equal significance. Understanding and insight develop over a period of time as broad categorizations are broken down into related subcategories of concept and refined through experience.

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." Experience with the product, discovery of its possibilities, led to the evolution of concept from "horseless carriage" to the "automobile", with a set of subordinate concepts that gave further definition: speed, mobility, endurance, payload and so forth. Conceptual evolution is evident in the words used to add further distinction to the varieties of automobile. One could not imagine widespread use of words like "roadster" or "touring car" or "coupe" in the 1890s when the "horseless carriage" was first in-

[25] Braun and MacDonald [9].

troduced. These were distinctions and categorizations that rested on years of customer experience, on new habits in transportation and, of course, development of the product itself.

Customer concepts and the hierarchy of design

The conceptual hierarchy of customer choice and the hierarchy of product design interact in complex ways as an industry evolves. It is this interaction that produces the shifting focus and pattern of innovation illustrated in fig. 1. Consider the focus on engine development. Given the importance of grouping and distinguishing in customer choice, it is not surprising that attention focused on the "horse" in the "horseless carriage". The engine was the most immediate and distinctive feature of the new product. Indeed, one can see in photographs of early cars that a good deal of the preceding product (the carriage) was carried over almost intact. There was little distinction in the seats, or the body or even the tires and the frame. The engine gave the new product its character, and provided the greatest source of potential misfit. It was natural that customer learning would focus on engines and their characteristics. Furthermore, the competing core concepts in engines were very different in terms of their performance, and trenchant in their consequences for subsequent development. Thus, the logic of customer concept formation and the logic of design reinforced attention on engine innovation.

Once choices about core concepts in engines were established, innovative effort moved down into subsidiary parameters. Among the variety of possible directions that subsequent development may have taken, the customer concept that came to dominate the market was "basic transportation." As a particular use, basic transportation imposed a set of requirements that strongly influenced technical choices. The key to success was the development of a rugged, durable, reliable vehicle that was easy to maintain, and of course, low cost. The dominance of the Model T in that market lay in the fit between those requirements and its design. But as Abernathy has shown, the Model T was a creative synthesis of design concepts that had developed over time as producers and customers learned about the product, the possibilities of the technology, and their uses.

The example of the Model T illustrates the close interaction between form and context. Not only did the design incorporate features that met the requirements of the context, but it made clear what those requirements were. In effect, the design illuminated the context. In such an early phase of industry development there is much uncertainty about customer needs and preferences and about the characteristics of technology. When a well fitting design emerges and receives market ratification, it clarifies aspects of the customer environment that were vague, and highlights those that are most important in customer choice.

The fact that the Model T endured for many years reflects a stability in customer concepts, and in the hierarchy of design established by initial decisions about basic parameters. This does not imply that technical development came to a stop with the Model T, nor that the customers of 1920 had failed to learn anything in the previous 12 years. The point is that subsequent technical development and customer learning occurred within the framework set out in earlier decisions. What happened was a matter of working out the technical agendas in engines and other major systems. On the customer side one observes stability in the basic concept and in the customer group itself.

Where customer concepts are invariant over time, and where the set of available technologies does not change, one can expect to observe the hierarchical working out of a given technical agenda. Once core concepts have crystallized, once major subsidiary choices have been made, development proceeds along narrowing lines as the design concepts are refined. In effect, items on the technical agenda that were once "open", become "closed". But that process need not persist indefinitely. New technical options, or changes in customer concepts may "re-open" certain items on the technical agenda, and may, in fact, unleash search and learning with renewed vigor.

This was clearly the case in the U.S. auto industry in the 1920s when changes in technology (the closed steel body) and changes in customer groups and customer uses interacted to redefine the product and create new problems in design. The result was a period of ferment in parameters of the product related to ease of operation, smoothness of ride, comfort, convenience and power. The old conceptual hierarchy and the old hierarchy of design was gradually supplanted by the concept of the "rolling living room" (or the "all purpose road cruiser"), and a technical agenda dominated by the search for better suspensions, more powerful and smoothly operating engines, and convenience in operation.

It is in this context that the timing of the development of the automatic transmission makes sense. The automatic shifting of gears was not a major item on the old "basic transportation" technical agenda. But with new customers (less rural, less mechanically sophisticated, less tolerant of inconvenient operation), and new uses (urban travel, intercity travel), the context was quite different; the automatic was the technical solution to a design problem whose time had come.

The "re-opening" of a technical agenda because of changes in context is further illustrated in the case of ion implantation in semiconductors. Although this method of putting impurities into silicon was known in the 1950s, the precision it afforded was not sufficiently desirable to outweigh its problems. Diffusion methods (an alternative doping procedure) provided sufficient accuracy and control; until the late 1960s technical effort in doping had been governed by the diffusion agenda. With the development of new applications of integrated circuits where small size and low power consumption were critical (e.g. hand-held calculators), the question of control and accuracy in doping was "re-opened". Development efforts refocused on ion implantation, and thus established a new technical agenda.

4. The logic of process development

The logic of design problem solving and the formation of customer concepts explains the existence of design hierarchies and the pattern of product development as an industry evolves. But this is only part of the story of overall technical development. Processes of production must also be designed, and the problem of process design are similar to those sketched out for products. It is thus reasonable to expect to observe a hierarchy of design on the process side as well. Process development arises out of a search for solutions to problems of design. It is guided by the logic of problem solving and the development of customer concepts. In these respects the evolution of process design is driven by the same forces that drive product development. It is important to note, however, that by introducing process development explicitly one must confront in a direct way the character of interaction between changes in process and changes in product. The model of Abernathy and Utterback provides a useful point of reference.

In the classic formulation of the A–U model of evolution the transition from the fluid to the specific state is marked by a shift in the relative frequency of product and process innovation. In the fluid stage with learning and search focused on core concepts, the A–U model posits the dominance of product change, supported by a flexible and unspecialized production process. As core concepts appear and establish an agenda of product design, processes can be focused and specialized. Movement toward the specific state entails a diminishing of the rate of product innovation and an acceleration of process development, at least for a time. In the limit, process and product change both decline in frequency and significance.

Where products are complex, where products can be made in different ways, and where some of those processes can accommodate a variety of product designs, the A–U model seems to provide an accurate and useful account of the evolutionary process. There is an important distinction, however, that has not received the kind of attention it warrants. In the A–U model, accelerated process development is conditioned on relative stability in product design concepts. One thus finds in the A–U model that product innovation is much more frequent in the fluid stage of development compared to innovation in processes. But frequency is not the same thing as significance. While it is true that stability in core concepts and major functional product parameters is an essential prelude to a high rate of process innovation, there are two kinds of process change that may grow out of and interact with the development of product design. The two need to be examined separately in gauging the role of process innovation in industry evolution. The first takes the product and its design as given, and introduces new ways of organizing and coordinating production. The second introduces new process capabilities and changes the characteristics of the product. The two are related, and the distinction between them may blur in some instances, but their characteristics and their connection to the product and the market are sufficiently different to warrant separate analysis.

The logic behind process innovation that organizes and coordinates production is derived from the importance of scale, speed and cost in the course of industry evolution. The typical form of evolution in the A–U model – from the fluid to the specific stage – involves a transition from low to higher volume production, and from less to more emphasis on cost. This transition is consistent with stability in customer concepts and a move from choice based on fundamental product performance, to choice based on the price of a standardized design. To the extent that such stability emerges, process development receives powerful incentive to find ways to make the product in higher volumes, more rapidly and at lower cost. Previous research has shown that process design in this context follows a hierarchy of concept and concern. [26] Four levels of activity can be distinguished:

(1) Mechanical analogies to programmed activity: The development of machines to replicate tasks previously performed by people.
(2) Organizing the process: Grouping tasks, defining operations, and flows of material.
(3) Integrating separate operations: Development of equipment, techniques and devices to make processing more continuous.
(4) System creation and improvement: Development of new ways of creating and using information for coordination.

As in the evolution of product, the design of the process follows its own internal logic, but the technical choices and the timing of change are influenced by the choices of product users and designers. Where a well defined product concept has not been established, a focus on integration and organization is not useful and even counterproductive. On the other hand, such a focus can reinforce a prior crystallization of concept, both because it raises the cost of product change, and because by lowering production cost it enhances the attractiveness of the chosen concept.

The second kind of process development – introduction of new process capabilities – also interacts with product design, but in a different way. By their nature, new process capabilities alter the characteristics of the product and its performance. They are often associated with the introduction of new materials, or the ability to process existing materials more effectively (closer tolerances, better finish, and so forth). [27] But new process capabilities may also provide the basis for changes in basic design. Both automobiles and semiconductors provide rich examples of product linked innovation in process.

In the auto case, the introduction of a low priced, high performance V-8 engine in the 1932 Ford, rested on a series of process innovations that materially affected the operating characteristics of the engine. This case illustrates the impact of innovation in casting and machining technologies that influenced the types of materials used, the fineness of tolerances and the weight of the engine. These developments not only affected the cost of the product, but in concert with some changes in design led to much higher levels of performance for given weight and cost. Although in isolation the changes that Ford introduced were not radically novel, in combination, they amounted to a significant departure from existing practice and gave Ford a technological advantage in V-8 engines. In this instance, a significant advance in product performance rested on a cluster of innovations in process capability.

Early development of semiconductors illustrates the impact that change in process capability can have on product design and even product concept. Once again, materials and material processing were at center stage. The first "grown junction" transistors depended on the "art" of crystal growing to achieve material with the right properties and placement of dopants with the right geometry. From the early to the mid 1950s considerable innovative effort focused on achieving greater precision and control over the doping process. Though this work was largely process oriented, it had significant influence on the product. GE developed a process for alloying (rather than growing)

[26] The hierarchy of process development is discussed in Abernathy [1,p. 55].

[27] The interaction of process and product innovation has been an important theme in the history of technological development. Landes, for example, has documented the important connections between iron refining technology and the steam engine in the 18th century; see Landes [16]. Similar stories can be told in material processing industries like oil refining, and synthetic materials. See Freeman [14] for a review of developments in those industries.

indium to germanium, creating the alloy junction transistor. Philco improved on this process with its jet etching technique, which allowed production of very thin germanium wafers with greater precision. All of this led to a very different product, one with superior frequency range, and superior switching (digital) capabilities.

Both the auto and the semiconductor examples illustrate the important influence of process innovation on product design and capabilities. In some instances independent developments in process technology may create capabilities that open up new options and possibilities for parameters of the product. For the most part, however, such changes in process are appropriately viewed as elements of the product design hierarchy. In effect, the search for new process capability grows out of attempts to solve product design problems. In that sense, it is an integral part of working through the product's technical agenda. Indeed there is some evidence to support the conjecture that once the core concepts in a product are established and refinement of associated hierarchies has proceeded down into relatively subsidiary parameters, process innovation becomes more and more the source of significant product advance.

In summary, it is clear that process innovation has significance much beyond its impact on scale and cost. While achievement of volume production and the reduction of cost are important features of evolution in complex product industries, process innovation plays a significant role in competition through its impact on the capabilities of the product.

5. Conclusion and implications

Framing the analysis of innovation in terms of problem solving in an evolutionary context has a number of implications for the management of technology. It is evident from the hierarchical nature of design and the formation of customer concepts, that innovation means different things, and has a different influence on markets and technologies at different points in industry development. Two broad distinctions can be drawn. The first is between movements up and down the hierarchies of design and customer concept. Movements down the hierarchy are associated with refinement or extension of higher order concepts. Innovation of this kind strengthens and reinforces existing commitments. It is conservative in nature; it strengthens and improves the fit between form and context and thus entrenches the established approach.

Movements up the hierarchy are associated with departure from existing approaches, and the setting out of a new agenda for subsidiary parameters. Such innovation is most dramatic when it involves core concepts, but it may occur within lower order concepts and yet have significant impact. Within the last several years for example, several new concepts in materials, fuel delivery and combustion control have had an important influence on the internal combustion engine based on gasoline. The core concept has not changed, but the new designs have altered performance and upset established systems of production. Movements up the hierarchy destroy the value of established commitments and competence, and call forth new skills and resources.

The second distinction is between hierarchies and associated skills and resources linked to product and process technology, and those linked to customers and markets. The importance of that distinction lies in the fact that a given innovation need not affect the two hierarchies in the same way. What may be a movement down the design hierarchy, may open up new channels of distribution and draw in new customers with different uses and needs. Conversely, an innovation that departs from previous design concepts, may be applied to an unchanging set of customers with unchanging conceptual hierarchy.

The appearance of a particular mix of refinement and departure in technology and market linkages is not arbitrary or whimsical. Indeed, particular combinations of refinement and departure are characteristic of particular stages of industry evolution. [28] The "fluid to specific" pattern of evolution in the A–U model involves a transition from a phase of innovation marked by new core concepts in both technology and market, to one marked by refinement of existing designs applied to existing customers and uses. Said another way, the transition is from an "architectural" phase

[28] The four phases of innovation and their connection to industry evolution are discussed in Abernathy et al [2,Ch. 9]; a more detailed examination of these issues can be found Abernathy and Clark [5].

where fundamental characteristics are defined, to a "regular" phase where the established technical and market linkages are strengthened.

Innovation that refines existing designs, but opens up new channels of distribution or that draws in new customers, defines what has been called the "niche creating" phase of development. It tends to appear when competitors seek ways of extending the sales and growth of a relatively well defined technology. The fourth pattern of market-technology interaction occurs with an innovation that departs from existing concepts but is applied to existing markets. Such revolutionary changes mark a reversal in the classic pattern of evolution and may be a prelude to the redefinition of the product and the eventual reemergence of an "architectural" period of activity.

Innovation plays a role in the competition that characterizes each of these phases, but that role varies significantly. The most dramatic and epochal (in the sense of opening a new era of development) influence of innovation appears in the guise of "revolution" and the laying down of new "architecture." While less dramatic the process of refinement of technology, the movement down the design hierarchy, has a significance that can be overlooked or misperceived. The "regular" phase of innovation, for example, takes as given a set of core concepts in basic functional domains, but enhances their value and appeal in the market through changes in both product and process. This is the phase of evolution associated with rapid advances in process and consequent declines in cost. The importance of such learning effects is well known and their competitive significance well documented.

But the problem solving that underlies cost reducing innovation is not the only kind of problem solving or learning going on. We have already noted the important influence of process change on product performance, but there is another effect as well. Movement down the hierarchy implies increased understanding about the characteristics of the technology, and in particular, its possibilities. This insight into the potential of the technology enhances the versatility of particular designs in meeting existing customer needs. In effect, variation in the details of secondary parameters (made possible by insight into how they work) become the source of variation in product performance, thus limiting the need for variation in higher order concepts. [29] When linked to insight about customers and their needs, innovation that enhances performance and versatility can be the source of competitive advantage.

It is clear from this discussion that innovation has a rich and varied influence on competition. Moreover, it is also clear that effective innovation requires different managerial skills in different contexts. Each of the phases of development involves the search for solutions to problems, but the nature of the problems, the nature of solutions and the nature of the search process are quite different. The implication is that the environment for innovation, the set of skills, incentives, and organizational context required for effective action, will differ as well. Where fresh insight and bold creativity may be required in laying down an "architecture," stability, consistency and planning may be the essentials in the "regular" phase movement down the hierarchy. Where timing and responsiveness to markets may be the key to success in creating niches, the key to fostering a "revolution" may be superior technical talent.

As evolution proceeds, the focus of innovative effort shifts, and the managerial requirements shift as well. For a given company, enduring the full gamut of evolutionary change has proved a very difficult task. The problem is compounded when a company has different products at different stages of evolution. Effectively managing across and within different design hierarchies and different customers and uses, poses a significant set of problems for both practice and research. This paper has identified the beginnings of a framework for studying those issues, and the examples from automobiles and semiconductors suggest that a focus on problem solving and learning in design and marketing may be a fruitful direction for further work.

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