Technological Paradigms, Innovative Behavior and the Formation of Dissipative Enterprises

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ABSTRACT. Although many studies have assigned a key role to "technological paradigms" in the development and diffusion of new technologies, which are often pioneered and led by small businesses, the nature of this term has remained somewhat unclear. This paper uses concepts from modern theories of "chaos," information theory and "dissipative structures," to describe the process through which new technological paradigms form and how they evolve. This analysis shows that the development of a new and innovative product or production methods drive existing as well as new firms to search for innovations. The interaction of all firms that are affected by this explorative behavior generates escalating waves of change, and thereby creates "chaos," which is the source of the materials from which new technological structures emerge. These new structures are arrangements of production tasks and activities that link an extended, interindustry group of firms into an interdependent system. This structure constitutes a technological paradigm when it serves as a matrix, or template, through which all firms in the system engage in innovative activity.

Introduction

Although economists have long heralded the central role that innovations have played in technological change and economic growth, no entirely satisfactory general or comprehensive model of the innovative process has as yet been developed.

The literature of the economics of innovation is replete with descriptions of some of the characteristics of the behavior of innovative firms. For example, a number of studies have shown that innovations flow from a process of inquiry — a heuristic pursuit of what has been designated "technological paradigms," or lines of investigation (Dosi, 1982, 1984; Sahal, 1981, 1985; Saviotti and Metcalfe, 1984 ; and Rosenberg, 1976). Such explorations (or "trajectories") are projections from a "knowledge base" (Nelson and Winter, 1982; Winter, 1984; and Dosi, 1988), and tend, as the empirical evidence suggests, to be relatively unique to each firm and largely cumulative (Teece, 1982, 1986; Cooper, 1983; Maidique, 1983; Mowery, 1980, 1983; and Reich, 1985).

Several important, and unresolved, issues in the field of innovation are closely connected with the structural nature of technological paradigms. For example, Dosi (1988, p. 1143) has suggested, based upon empirical analysis, that the nature of paradigmatic trajectories is essentially irreversible, such that any factor-product combination that emerges from the innovative process would be preferable over any of the previous combinations. No theoretical structure has as yet been developed that can account for irreversibility: the extent to which it exists, and how it is related to varying types of technological paradigms.

In addition, Dosi and others have pointed out that the widely noted differences in technological efficiencies not only between firms within a given industry, but between industries — and between nations, for that matter — can be explained in terms of different technological paradigms that have been and are being used in the different situations (Dosi and Soete, 1983; Soete, 1981; Cimoli, 1988; Hay and Morris, 1979; Nelson and Winter, 1982; and Dosi, 1988). Again, no model of innovative search has as yet been developed that is capable of explaining — and understanding the nature of — this phenomenon.

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This paper will present an outline of a model of innovation and technological change that will explain the emergence and development of new technological paradigms.

Many studies have shown that a great deal, if not most, industrial innovation is generated from outpourings of creative effort very largely by clusters or groups of small businesses engaged in intense and very often disorderly, or chaotic, experimentation and exploration (Debresson, 1991). Certainly, most new jobs in the United States, and the development of entire new industries, such as semiconductor and biotechnology, was the result of such activity by small, start-up enterprises. This paper will describe the characteristics of this type of activity, which is typical of many new and entrepreneurial small businesses.

This model will borrow essential concepts from the new and interdisciplinary fields of "dissipative structures," cybernetics, information theory and the more recent work that has been done in "deterministic chaos." As my earlier work (1989) pointed out, the tools from these disciplines are capable of describing the processes and systems undergoing uncertainty, disorder or "chaos," and — most important of all — structural change and evolution. For further descriptions of these concepts, and their use in economic analysis, see Baumol and Benhabib, 1989; Stutzer, 1980; and Jenner, 1966, 1989.

This paper describes the responses made by managers and entrepreneurs to uncertainty and chaotic conditions by searching for and creating new products and processes. This behavior is at the heart of all creative activity, which has been described as "the act of awakening new thoughts, of rearranging old learning, and of examining assumptions to form new theories, new paradigms, and new awareness" (Boone and Hollingsworth, 1990, p. 3).

Dissipative structures

It has become increasingly clear over at least the last century that the world is not the simple, mechanistic system that is implicitly assumed in the mathematical models used in "classical dynamics" (Devaney, 1989). Many, if not most, processes in the real world are not deterministic, and therefore strictly predictable. For one thing, "irreversible processes," caused by friction and chemical reactions, among other things, occur in every system, tending to cause randomness and decay. Furthermore, it appears that non-linear systems, randomness and "chaos," far from being exceptional, characterize many, perhaps even most, physical systems.

In probing these issues, Nobel laureate Ilya Prigogine and his colleagues have developed a theoretical model of what they term "dissipative structure." This model identifies the processes through which systems are driven to a dynamic state which they term "far from equilibrium." Such a state is created when either an existing system or an unstructured assortment of elements is buffeted by waves of activity, or energy, which drive the components to interact with each other, forming new patterns and relationships. When the interaction arising from this activity generates "positive feedback," i.e., when change in any component in the system feeds back on itself and then generates still further change, the result is typically "chaos," in the sense that no subsequent state or patterns of relationships can be predicted from any previous state.

Chaotic systems that are moving, in Prigogine's terms, "far from equilibrium," are characterized by the appearance of new and temporary structures or patterns, which appear spontaneously and then disappear as new "waves" of change supplant them.

This activity provides the matrix from which a new and stable "structure" appears — the development of a "dissipative structure." Essentially, the parameters of the "chaotic" (or non-linear) system reaches a critical point, a "bifurcation point," where it undergoes an essentially random transformation into a new form. As Prigogine has put it: "a new type of order has appeared." Such a structure exists "far from equilibrium" (Prigogine, 1984, p. 13).

Such structures — which have been commonly observed in a wide variety of physical systems and have been mathematically modeled and computer simulated in many forms — have a number of interesting characteristics. Most important of all, they are capable of eliminating or "dissipating" entropy, which may be roughly translated as "disorder," or destructive processes that tend to build up in all structures.

Another particularly interesting aspect of dissipative structures is the appearance of a rich network of communications channels that link their components. As Prigogine puts it:

> We can speak of a new coherence, of a mechanism of "communication" among molecules. But this type of communication can arise only in far-from-equilibrium conditions. It is quite interesting that such communication seems to be the rule in the world of biology. It may in fact be taken as the very basis of the definition of a biological system (Prigogine, 1984, p. 13).

In order to analyze the factors influencing the appearance of dissipative enterprises, it will necessary to outline a few useful concepts from the two closely related fields of cybernetics and information theory.

Information theory and entropy

Modern information theory, which was developed more than forty years ago by Claude Shannon (Shannon and Weaver, 1949), essentially postulates a close relationship between information and uncertainty. If any message is selected freely from a set containing all messages that describe the state of some system, the amount of information it contains is determined by the uncertainty that is dispelled when it is received.

Uncertainty occurs when an observer does not know in which of several potential states an object exists. If an object could exist in only one state — in other words, it could not change — then no information is conveyed when any message describing it is received.

Uncertainty is represented in terms of the (subjective) likelihood or probability in which each potential state could occur. More specifically, if a system (through variations in its components) could exist in i states, and if p_i is the probability that each state could occur, then the uncertainty as to the status of the system, or entropy of the system, $H(X)$,[1] is given by:

$$H(X) = \sum_i p_i \log_2 1/p_i.$$

When a message arrives describing a system that can assume only one of two equally likely states, the amount of information received is defined by Shannon to be 1 *bit*. Clearly entropy increases as the number of elements in the set of outcomes increases. Furthermore, for any set of n elements, entropy is maximum when $p_1 = p_2 = \ldots = p_n$.

The modern science of cybernetics provides a set of powerful concepts that describe and analyze the control process in any system or organization. First, there must be a control mechanism capable of performing alterations in critical parameters of the system in order to change its course or behavior in the face of these disturbances. Second, the controller must have feedback information, which identifies the relationship between the actual state of the system (or component of the system) and the goals toward which the system is directed. Finally, a simple and direct relationship exists between the variety of disturbances that threaten an organization and the responses made by the controller. Very roughly, this relationship, known as "the law of requisite variety," demonstrates that the variety of responses made by an organization must be equal to or greater than the entropy of disturbances that threaten it. As Ashby has put it: "only variety can drive down variety" (Ashby, 1964, pp. 122—126; Jenner, 1966, 1989; and Flueckiger, 1976).

Definition of technological paradigm

In order to define the concept of technological paradigm that will be employed in this paper, it is important to first make a distinction between technological *structure* and technological paradigm.

A technological structure describes how a product is produced, the production processes, the tasks and transformations, that are employed to turn inputs into that product. On the other hand, since each firm uses a variety of inputs that are supplied by other firms, complex interindustry effects must be taken into account.

In a broad sense, the technology employed by any production process is contained in the nature of the specific production tasks, the patterns (or "protocols") in which these tasks are organized, and the combinations of machinery, equipment and human activity that generate them. Since these tasks act upon, and anticipate, specific types and forms of inputs, the output of each production process is dependent upon — is "linked" with — the technology employed with that employed by its customers. The entire interdependent system of inputs, outputs, production tasks, as embodied in equipment and human activities, constitutes a technological structure.

A technological paradigm, on the other hand, is a specific type of technological structure that serves as a guide to innovation and change — to creative activity — on an interindustry basis. The nature of how such a paradigm arises and generates this type of activity will be discussed in the remainder of this paper.

Communications channels and markets

The final concept to be introduced is that of a communications channel. Essentially, a communications channel exists whenever a message is sent from a source to a receiver. A "message" will be defined, at least initially, as anything, regardless of form, that is capable of conveying information. (See Abramson, 1962, pp. 10—20.) In a similar sense, a communications channel may be defined as any means whatsoever through which messages may be transmitted.

In general, when a company produces a product and "sends" it into the marketplace, the product may be regarded as a "message" that is sent through a communications channel to the consumer.

In a similar way, the market communications channel may be seen as a means through which the consumers of products communicate with all producers of those products. Essentially, the "message" that is "sent" from the marketplace and "received" by the producer is the preference pattern of the consumers for any given set of products placed on the market by a group of producers. This message is coded into a sales, market share and profit figure for each firm.

Any group of firms that constitutes an industry, including all suppliers intermediate products, are linked through a network of communications channels. Thus, whenever any one of the firms in an industry sends a production/product message into the marketplace, all firms — through changes in profits, sales volumes or market shares — are affected.

In all communications channels largely random elements act to distort or change the messages being transmitted so that the messages that are received may not be the exact form of the messages that were sent. These random elements are termed "noise" in the channel, and are described in terms of the probability that any message sent will be received. One important source of "noise" arises from the introduction of competing products, advertising campaigns, sales promotion, changing tastes, fluctuating income — an almost infinite range of possibilities and permutations.

The initiation of chaotic change

Let us suppose that a new production process is developed and introduced by a firm. This new process consists of a set of tasks (and subtasks) performed in a specific pattern, or *protocol*, by labor and machinery upon a set of inputs.[2] In some cases, only a part of this production protocol is new: either the nature and form of some of the tasks, or some or all of the inputs. In other cases, the entire pattern of production tasks is new. Moreover, we will assume that each production process that uses the new protocol has adapted the new production technique to its own needs — hence, each product "encodes" a slightly different variation of the new process.

Each of the many market messages, however, may not be "understood" or "decoded" correctly. This confusion may result because the nature of the production tasks that produced a given product may not be completely understood or known.

Next, the firm faces the problem of translating the new production code into its particular production system. Each firm's production methods may be to some extent unique, adapted to its characteristics, such as location, access to raw materials, labor conditions — and, ultimately, past experience. Therefore, in many cases, even where a competitor produces a very similar product, production protocols need to be adapted to fit the characteristics of a specific company. The problem is obviously greater in cases where the new production protocols are first introduced in a product that is quite unlike that produced by the firm.

In many cases, there will exist more than one possible way to introduce the new production process into the firm's existing system, although only one of the variants, we will assume, is "better" than any others, in the sense that it will yield higher benefits at lower costs.

From a variety of sources, each firm must evaluate each of the alternative tasks which it might consider using in its production process. Some of this information, of course, is obtained merely by estimating the change in sales (or other relevant variable) that results when other firms introduce the new techniques or materials. In most cases, however, it must learn from experience by actually trying out the new protocol in its own production system: i.e., it must engage in a "trial and error" process.

Frequently when a new product is introduced to the market, often many variants are introduced by competing firms, and frequently parallel changes are made by producers of complementary products, or those that provide inputs and productive factors into the various production processes. As these changes are introduced, and as consumers make choices among these changes, the result is fluctuation in sales, profits or market share, which increases the level of entropy faced by all firms.

In a trial and error process, the firm decides to adopt one of the production protocols into its production systems. In many cases this change causes a change in output, which effects the other tasks and stages in the production system to which this output is an input. In other cases, the new protocol might only result in a change in costs, not in output. Changes in costs, however, would cause (or be caused by) a change either in the rate of production of output, or the use of new production protocols in the production system.

The introduction of uncertainty

In general, management encounters uncertainty in its production system whenever the possibility of alternatives to any of the components that constitute a production stage — or any of the couplings between them — are considered. These possibilities might actually have been implemented in other, similar or dissimilar, production systems, or might be no more than hypothetical considerations.

More generally, alternatives may arise because management considers (perhaps imagines) the effect of changing some aspect — such as deformation or other alteration — upon the shape, configuration or materials used in the construction of one or more of the components that constitute the stage. In other cases, management may consider the possibility of coupling a new component, including new labor tasks or activities, to existing components, and thereby creating a new structural form.

These possibilities may be generated through the receipt of external "messages" originating in the economy or marketplace. For example, the introduction of new products by competitors, or a decrease in the price of existing competitive products — resulting in a decline or fluctuation in sales, or a drop in market share — might signal to management that new and improved techniques have been introduced by competitors. These techniques imply that new components, new materials, or changes on existing components (and linkages between them) have been introduced. If the change introduced by competition adversely affects the business, it will then be driven to search for — and consider — the structure of these changes. (Of course, a business might be continually involved with consideration of new alternatives as a part of its research and development program, undertaken perhaps to gain a competitive advantage.)

If the enterprise is surprised to learn that a competitor has introduced something new — a new product, a new production technique which results in lower costs, for example — and does not know how this variation was accomplished, its level of uncertainty, or entropy, increases. If it has literally no idea — and cannot even imagine how the change could have been accomplished, all possibilities are open, equally probable, and its entropy is, of course, highest. The enterprise literally has no idea where to begin to look, to experiment, to search for responses. In such a situation, the firm is clearly driven to search vigorously for information, much of it from trial-and-error experimentation, if it hopes to gain control of its market.[3]

Interindustry transmission of entropy

The general principles through which the firm's ability to control its output and production system — and which define the general characteristic pattern of its search for new technology and products — may be used to describe the competitive interactions of firms within an industry, as we have defined the concept.

The input/output flows that connect firms within an industry — and throughout the economy — as well as the interrelationships between demand curves — i.e., the marginal substitutability and complementarity among their products by consumers — constitute a network of feedback linkages between these firms.

If a firm in sector m, X_m, introduces any type of change in its output, ΔX_m, which is preferred over previous inputs by enough firms to cover its average production costs, a growing ripple of changes spreads throughout the economy. For one thing, all firms that use ΔX_m do so because it enhances their competitiveness, perhaps by lowering costs or improving the consumer acceptability of — and demand for — their final products. This, of course, disrupts demand for all outputs (and inputs) which are displaced by the new product variant.

The change in sales constitutes feedback from the market that is received by each firm, including X_m. Those firms that suffer a decline in demand experience a correlated increase in uncertainty, or entropy, about what their responses should be.

Since each firm will adjust to declines in the demand for its products in some way, by decreasing its production of these products, or by experimenting with new production variants of its own, the result is to alter its demand for inputs from other firms. This activity sends ripples of changes in demand for all firms that produce intermediate products as well as for all firms whose final products are linked through substitutability and complementarity.

The existence of such feedback effects results in dynamic interactive changes that are essentially nonlinear in nature. Such systems are characterized as chaotic, are inherently unpredictable, and, as recent research has discovered, constitute the crucible, as it were, out of which creative changes occur.

A new paradigm emerges

All firms that are affected by the high and possibly rising levels of turbulence are forced to find ways of reducing the high levels of entropy they are encountering. As we have seen, this requires them to search for and develop new production techniques — new production tasks, protocols and inputs — which, when implemented, result in reduced entropy. At some point, a new technology emerges — one that is interindustry in nature — which serves to force the system to develop a relatively stable, although nevertheless evolutionary, structure. The system is "relatively stable" in the sense that a "trajectory" of changes in this technology will consist largely of incremental improvements or variations in the existing structure of tasks and inter- and intra-firm linkages, and not new structures which would increase turbulence in the market. These changes will tend to be incremental because any firm that introduces an innovation not in accordance with the newly-emerged paradigm will encounter increased fluctuations, and higher entropy, in its sales and market share, which will serve to drive it back to the new and now dominant technological paradigm.

The new interindustry technology emerges out of the rich variety of new products, both intermediate and final, which in turn are generated by a large number of new production tasks and protocols (as embodied in new equipment, skills and machines) that all firms affected by the change are adopting. If the chaotic conditions are to be reduced, at some point all firms undergoing technological search activity produce a unique combination of final and intermediate outputs that causes results in a *simultaneous reduction in entropy for all firms in the group*, although the differential effects might vary widely among the firms. A new paradigm has been discovered.

The emergence of the new technological paradigm, however, serves as a magnet, drawing other, often small, firms to adopt the production technologies that the initial firms in the paradigm had developed. New firms might copy the same tasks and protocols as the older firms, or they might introduce new variations on them. In either case, all firms — including the initial ones — that constitute the paradigm find their entropy increasing, and are therefore compelled to renew their search behavior. Since this activity essentially is launched from an existing and successful production technology, as embodied in the new paradigm, all changes are henceforth incremental alternations on the existing technological paradigm.

In this process, each incremental change — or sequencing of changes — that is made on each production task or protocol affects the output of existing tasks and protocols in such a way that the firm's entropy is reduced. Each such change must fit into — couple with — the pattern of existing tasks harmoniously, and tends to reduce uncertainty associated with the linkage between any tasks in the protocol. In this sense, therefore, each change is determined by the existing tasks and protocols. Therefore, any change in a production protocol that reduces entropy constitutes an *autocatalytic* agent or guide for the development and introduction of the next task that is introduced — either to replace the initial task, or to augment or supplement it. A technological paradigm, therefore, serves as a template, or framework, through which this process of autocatalytic innovation is "guided."

It is clear that the sources of turbulence in a group of firms affected by technological change — the search for and adoption of new production techniques — are paradoxically also the source of the development of the chaos-reducing new paradigm. In a deeper sense, this analysis assumes that all potential production techniques differ in their ability to reduce entropy, and thus provide what amounts to a "trajectory" of changes leading to the emergence of relative stability for all firms in the group. If this were not true — and all possible changes had no differential effects on entropy — then no trajectory would emerge, firms would be sooner or later forced to cease the search and leave the industry. As the exodus of firms occurs, and as technological change subsides, entropy (i.e., "chaos") declines until an equilibrium is reached, in which case perhaps one or a few firms remain (Jenner, 1966).

Technological paradigm reconsidered

This analysis suggests that technological paradigms perform critical roles in transforming the nonlinear turbulence that characterize technologically dynamic industries. Moreover, the technological paradigm that emerges from this turbulent exploratory process serves as a pattern that binds together a series of production tasks and products which defines a technologically evolving group of firms, each of which constitutes a kind of "dissipative structure," and which are technologically interrelated. All firms in this group, which we may designate a "dissipative group," experience lower levels of entropy than any other such grouping producing the final output of the group. In addition, each task, subtask, protocol, stage, and linkage between firms that constitute this chain of relationships is capable of further refinement which leads to further reductions in entropy for the whole group. In this way, the paradigm serves as a template for change; it serves as a matrix that is particularly suitable for small, entrepreneurial businesses, since these firms are more flexible, more willing to take risks, and tend to be quicker to enter and to leave new industries than larger, more established firms.

Conclusion

This analysis shows that the development of a technological paradigm is an interindustry, as well as intra-industry and intra-firm, activity, where mutually interactive and complementary innovations constitute components of a process of change. The constituent enterprises that form this system are what I have called dissipative enterprises (Jenner, 1989), which parallel the processes described by Prigogine as "dissipative structures." Once formed, moreover, this group of dissipative enterprises, guided by the paradigmatic matrix, always moves toward lower entropy. Since dissipative enterprises through their internal dynamic processes are uniquely capable of dissipating entropy, it is clear that paradigms, once developed, are fundamentally irreversible.

It is clear from the above analysis that paradigms are formed from the dynamic innovative activity in which enterprises engage. Since this activity is guided by the effect of information flows on the firm's perception of entropy, technological paradigms may be said to precipitate out of the new information generated by the "chaos" of the search behavior. Therefore, it is evident that paradigms essentially must arise from a particular context or environment — each paradigm represents a means to which a firm or a group of firm adapts to its surroundings. For any type or class of product, any differences between environments must necessarily result in differences in technological paradigms. Such differences might be found in market and technological communications patterns in alternative environments, or in the preference patterns of the consumers, for example. In other words, technological paradigms ought to be different in different contexts.

Finally, this analysis suggests that anything that hinders the free flow of information between firms may prolong the period of turbulence, or hinder the formation of new paradigms.

Summary

This paper presented a model of interindustry exploration of new technological production techniques, termed "protocols," in which the input/output relations between firms creates feedback and nonlinearity among all firms affected. Nonlinearity tends to generate "chaotic" market conditions, and constitutes a major force driving firms, particularly small businesses, into still further exploration of technological alternatives — thereby causing greater turbulence in the market conditions all firms face. The attempts of firms to reduce the uncertainty — the "entropy" — they perceive in their markets, however, generates the great variety of alternatives that ultimately generate a technological paradigm, which consists of a structure in which a pattern of production techniques, and products, form an input-output pattern in which the uncertainty for all firms in the group is simultaneously reduced. Furthermore, this paradigm provides a matrix through which all firms in the group are able to engage in a sequence of continual and incremental improvements, each of which reduces entropy for the initiating firm, but for all firms in the group.

Notes

[1] Uncertainty is referred to as "entropy," since it closely parallels the use of this term in statistical mechanics.

[2] The term "protocol" refers to a permutation, or sequencing, of activities and tasks, and is commonly used in cybernetics to describe the activity of a generalized, or "theoretical" machine.

[3] The behavioral consequences of increasing entropy are that the search for information, or messages that reduce entropy, becomes more and more random.

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