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Patterns of Industrial Innovation

William J. Abernathy
James M. Utterback

A new model suggests how the character of its innovation changes as a successful enterprise matures; and how other companies may change themselves to foster innovation as they grow and prosper.

How does a company's innovation — and its response to innovative ideas — change as the company grows and matures?

Are there circumstances in which a pattern generally associated with successful innovation is in fact more likely to be associated with failure?

Under what circumstances will newly available technology, rather than the market, be the critical stimulus for change?

When is concentration on incremental innovation and productivity gains likely to be of maximum value to a firm? In what situations does this strategy instead cause instability and potential for crisis in an organization?

Intrigued by questions such as these, we have examined how the kinds of innovations attempted by productive units apparently change as these units evolve. Our goal was a model relating patterns of innovation within a unit to that unit's competitive strategy, production capabilities, and organizational characteristics.

This article summarizes our work and presents the basic characteristics of the model to which it has led us. We conclude that a productive unit's capacity for and methods of innovation depend critically on its stage of evolution from a small technology-based enterprise to a major high-volume producer. Many characteristics of innovation and the innovative process correlate with such an historical analysis; and on the basis of our model we can now attempt answers to questions such as those above.

A Spectrum of Innovators

Past studies of innovation imply that any innovating unit sees most of its innovations as new products. But that observation masks an essential difference: what is a product innovation by a small, technology-based unit is often the process equipment adopted by a large unit to improve its high-volume production of a standard product. We argue that these two units — the small, entrepreneurial organization and the larger unit producing standard products in high volume — are at opposite ends of a spectrum, in a sense forming boundary conditions in the evolution of a unit and in the character of its innovation of product and process technologies.

One distinctive pattern of technological innovation is evident in the case of established, high-volume products such as incandescent light bulbs, paper, steel, standard chemicals, and internal-combustion engines, for examples.

The markets for such goods are well defined; the product characteristics are well understood and often standardized; unit profit margins are typically low; production technology is efficient, equipment-intensive, and specialized to a particular product; and competition is primarily on the basis of price. Change is costly in such highly integrated systems because an alteration in any one attribute or process has ramifications for many others.

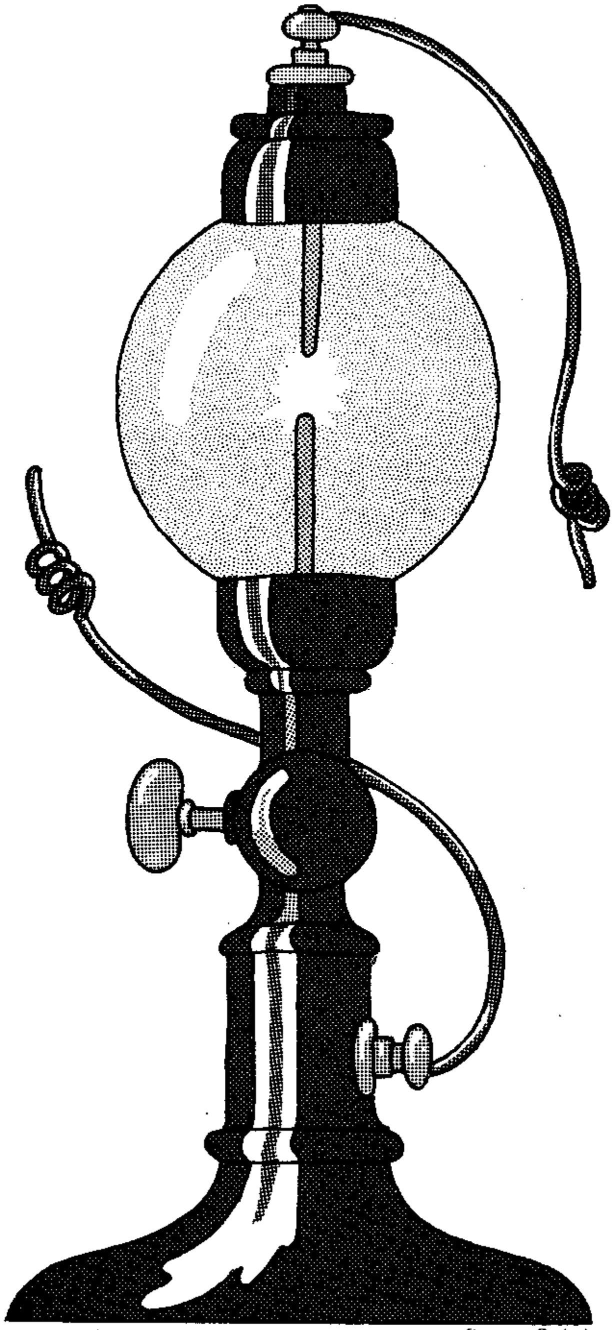
In this environment innovation is typically incremental in nature, and it has a gradual, cumulative effect on productivity. For example, Samuel Hollander has shown that more than half of the reduction in the cost of producing rayon in plants of E. I. du Pont de Nemours and Co. has been the result of gradual process improvements which could not be identified as formal projects or changes. A similar study by John Enos shows that accumulating, incremental developments in petroleum refining processes resulted in productivity gains which often eclipsed the gain from the original innovation. Incremental innovations, such as the use of larger railroad cars and unit trains, have resulted in dramatic reductions in the cost of moving large quantities of materials by rail.

In all these examples, major systems innovations have been followed by countless minor product and systems improvements, and the latter account for more than half of the total ultimate economic gain due to their much greater number. While cost reduction seems to have been the major incentive for most of these innovations, major advances in performance have also resulted from such small engineering and production adjustments.

Such incremental innovation typically results in an increasingly specialized system in which economies of scale in production and the development of mass markets are extremely important. The productive unit loses its flexibility, becoming increasingly dependent on high-volume production to cover its fixed costs and increasingly vulnerable to changed demand and technical obsolescence.

Major new products do not seem to be consistent with this pattern of incremental change. New products which require reorientation of corporate goals or production facilities tend to originate outside organizations devoted to a "specific" production system; or, if originated

Major innovations usually go through countless minor product and systems improvements. . . . Such incremental innovations typically produce a highly specialized system that depends upon economies of scale and mass marketing for success.



Cameron Gerlach

within, to be rejected by them.

A more fluid pattern of product change is associated with the identification of an emerging need or a new way to meet an existing need; it is an entrepreneurial act. Many studies suggest that such new product innovations share common traits. They occur in disproportionate numbers in companies and units located in or near affluent markets with strong science-based universities or other research institutions and entrepreneurially oriented financial institutions. Their competitive advantage over predecessor products is based on superior functional performance rather than lower initial cost, and so these radical innovations tend to offer higher unit profit margins.

When a major product innovation first appears, performance criteria are typically vague and little understood. Because they have a more intimate understanding of performance requirements, users may play a major role in suggesting the ultimate form of the innovation as well as the need *(see "Users as Innovators," by Eric A. von Hippel, January, pp. 30-34)*. For example, Kenneth Knight shows that three-quarters of the computer models which emerged between 1944 and 1950, usually those produced as one or two of a kind, were developed by users.

It is reasonable that the diversity and uncertainty of performance requirements for new products give an advantage in their innovation to small, adaptable organizations with flexible technical approaches and good external communications, and historical evidence supports that hypothesis. For example, John Tilton argues that new enterprises led in the application of semiconductor technology, often transferring into practice technology from more established firms and laboratories. He argues that economies of scale have not been of prime importance because products have changed so rapidly that production technology designed for a particular product is rapidly made obsolete. And R. O. Schlaifer and S. D. Heron have argued that a diverse and responsive group of enterprises struggling against established units to enter the industry contributed greatly to the early advances in jet aircraft engines.

A Transition from Radical to Evolutionary Innovation

These two patterns of innovation may be taken to represent extreme types — in one case involving incremental change to a rigid, efficient production system specifically designed to produce a standardized product, and in the other case involving radical innovation with product characteristics in flux. They are not in fact rigid, independent categories. Several examples will make it clear that organizations currently considered in the "specific" category — where incremental innovation is now motivated by cost reduction — were at their origin small, "fluid" units intent on new product innovation.

John Tilton's study of developments in the semiconductor industry from 1950 through 1968 indicates that the rate of major innovation has decreased and that the type of innovation shifted. Eight of the 13 product innovations he considers to have been most important during that period occurred within the first seven years, while the industry was making less than 5 per cent of its total 18-year sales. Two types of enterprise can be identified in this early period of the new industry — established units that came into semiconductors from vested positions in vacuum tube markets, and new entries such as Fairchild Semiconductor, I.B.M., and Texas Instruments, Inc. The established units responded to competition from the newcomers by emphasizing process innovations. Meanwhile, the latter sought entry and strength through product innovation. The three very successful new entrants just listed were responsible for half of the major product innovations and only one of the nine process innovations which Dr. Tilton identified in that 18-year period, while three principal established units (divisions of General Electric, Philco, and R.C.A.) made only one-quarter of the product innovations but three of the nine major process innovations in the same period. In this case process innovation did not prove to be an effective competitive stance; by 1966 the three established units together held only 18 per cent of the market while the three new units held 42 per cent. Since 1968, however, the basis of competition in the industry has changed; as costs and productivity have become more important, the rate of major product innovation has decreased, and effective process innovation has become an important factor in competitive success. For example, by 1973 Texas Instruments which had been a flexible, new entrant in the industry two decades earlier and had contributed no major process innovations prior to 1968, was planning a single machine that would produce 4 per cent of world requirements for its integrated-circuit unit.

Like the transistor in the electronics industry, the DC-3 stands out as a major change in the aircraft and airlines industries. Almarin Phillips has shown that the DC-3 was in fact a cumulation of prior innovations. It was not the largest, or fastest, or longest-range aircraft; it was the most economical large, fast plane able to fly long distances. All the features which made this design so completely successful had been introduced and proven in prior aircraft. And the DC-3 was essentially the first commercial product of an entering firm (the C-1 and DC-2 were produced by Douglas only in small numbers).

Just as the transistor put the electronics industry on a new plateau, so the DC-3 changed the character of innovation in the aircraft industry for the next 15 years. No major innovations were introduced into commercial aircraft design from 1936 until new jet-powered aircraft appeared in the 1950s. Instead, there were simply many refinements to the DC-3 concept — stretching the design and adding appointments; and during the period of these incremental changes airline operating cost per passenger-mile dropped an additional 50 per cent.

The Unit of Analysis

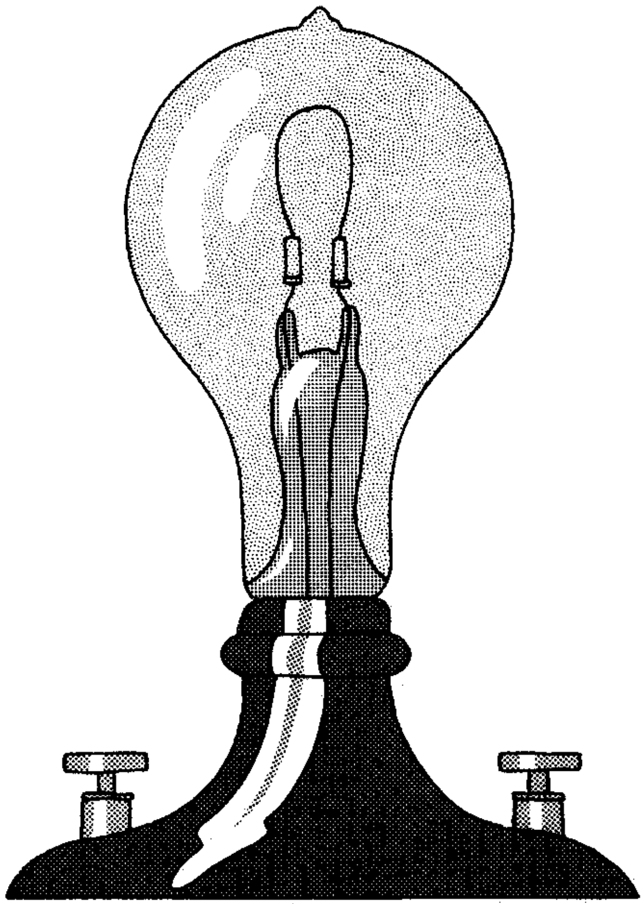
As we show in this article, innovation within an established industry is often limited to incremental improvements of both products and processes. Major product change is often introduced from outside an established industry and is viewed as disruptive; its source is typically the start-up of a new, small firm, invasion of markets by leading firms in other industries, or government sponsorship of change either as an initial purchaser or through direct regulation.

These circumstances mean that the standard units of analysis of industry — firm and product type — are of little use in understanding innovation. Technological change causes these terms to change their meaning, and the very shape of the production process is altered.

Thus the questions raised in this article require that a product line and its associated production process be taken together as the unit of analysis. This we term a "productive unit." For a simple firm or a firm devoted to a single product, the productive unit and the firm would be one and the same. In the case of a diversified firm, a productive unit would usually report to a single operating manager and normally be a separate operating division. The extreme of a highly fragmented production process might mean that several separate firms taken together would be a productive unit.

For example, analysis of change in the textile industry requires that productive units in the chemical, plastics, paper, and equipment industries be included. Analysis involving the electronics industry requires a review of the changing role of component, circuit, and software producers as they become more crucial to change in the final assembled product. Major change at one level works its way up and down the chain, because of the interdependence of product and process change within and among productive units. Knowledge of the production process as a system of linked productive units is a prerequisite to understanding innovation in an industrial context. — *W.J.A., J.M.U.*

The electric light bulb also has a history of a long series of evolutionary improvements which started with a few major innovations and ended in a highly standardized commodity-like product. By 1909 the initial tungsten filament and vacuum bulb innovations were in place; from then until 1955 there came a series of incremental changes — better metal alloys for the filament, the use of "getters" to assist in exhausting the bulb, coiling the filaments, "frosting" the glass, and many more. In the same period the price of a 60-watt bulb decreased (even with no inflation adjustment) from $1.60 to 20 cents each, the lumens output increased by 175 per cent, the direct labor content was reduced more than an order of magnitude, from 3 to 0.18 minutes per bulb, and the production process evolved from a flexible job-shop configuration, in-



volving more than 11 separate operations and a heavy reliance on the skills of manual labor, to a single machine attended by a few workers.

Product and process evolved in a similar fashion in the automobile industry. During a four-year period before Henry Ford produced the renowned Model T, his company developed, produced, and sold five different engines, ranging from two to six cylinders. These were made in a factory that was flexibly organized much as a job shop, relying on trade craftsmen working with general-purpose machine tools not nearly so advanced as the best then available. Each engine tested a new concept. Out of this experience came a dominant design — the Model T; and within 15 years 2 million engines of this single basic design were being produced each year (about 15 million all told) in a facility then recognized as the most efficient and highly integrated in the world. During that 15-year period there were incremental — but no fundamental — innovations in the Ford product.

In yet another case, Robert Buzzell and Robert Nourse, tracing innovations in processed foods, show that new products such as soluble coffees, frozen vegetables, dry pet foods, cold breakfast cereals, canned foods, and precooked rice came first from individuals and small organizations where research was in progress or which relied heavily upon information from users. As each product won acceptance, its productive unit increased in size and concentrated its innovation on improving manufacturing, marketing, and distribution methods which extended rather than replaced the basic technologies. The major source of the latter ideas is now each firm's own research and development organization.

The shift from radical to evolutionary product innovation is a common thread in these examples. It is related to the development of a dominant product design, and it is accompanied by heightened price competition and increased emphasis on process innovation. Small-scale units that are flexible and highly reliant on manual labor and craft skills utilizing general-purpose equipment develop into units that rely on automated, equipment-intensive, high-volume processes. We conclude that changes in innovative pattern, production process, and scale and kind of production capacity all occur together in a consistent, predictable way.

Though many observers emphasize new-product innovation, process and incremental innovations may have equal or even greater commercial importance. A high rate of productivity improvement is associated with process improvement in every case we have studied. The cost of incandescent light bulbs, for example, has fallen more than 80 per cent since their introduction. Airline operating costs were cut by half through the development and improvement of the DC-3. Semiconductor prices have been falling by 20 to 30 per cent with each doubling of cumulative production. The introduction of the Model T Ford resulted in a price reduction from $3,000 to less than $1,000 (in 1958 dollars). Similar dramatic reductions have been achieved in the costs of computer core memory and television picture tubes.

Managing Technological Innovation

If it is true that the nature and goals of an industrial unit's innovations change as that unit matures from pioneering to large-scale producer, what does this imply for the management of technology?

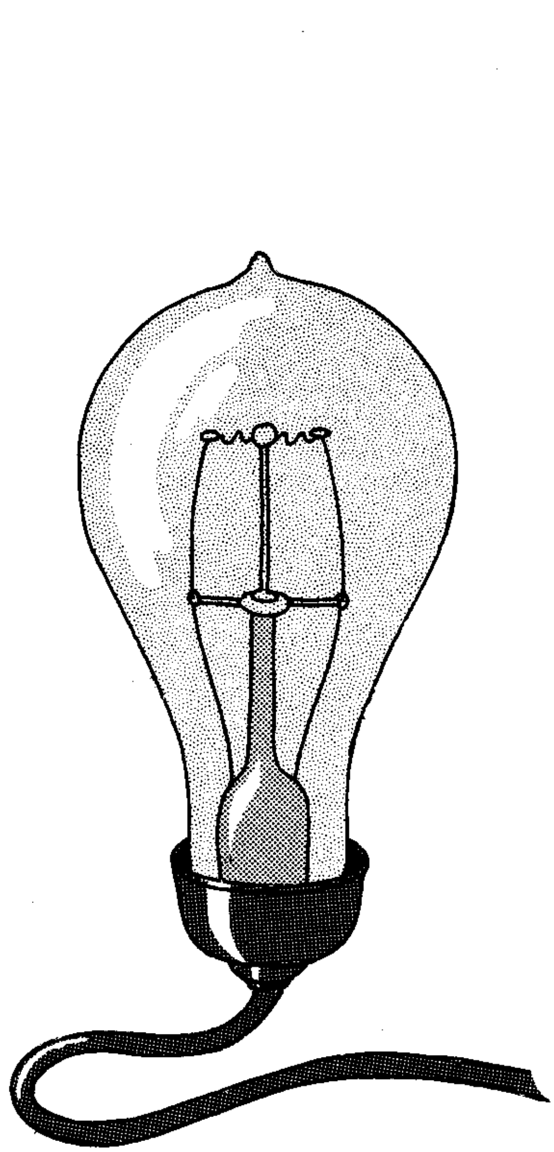
We believe that some significant managerial concepts emerge from our analysis — or model, if you will — of the characteristics of innovation as production processes and primary competitive issues differ. As a unit moves toward large-scale production, the goals of its innovations change from ill-defined and uncertain targets to well-articulated design objectives. In the early stages there is a proliferation of product performance requirements and design criteria which frequently cannot be stated quantitatively, and their relative importance or ranking may be quite unstable. It is precisely under such conditions, where performance requirements are ambiguous, that users are most likely to produce an innovation and where manufacturers are least likely to do so. One way of viewing regulatory constraints such as those governing auto emissions or safety is that they add new performance dimensions to be resolved by the engineer — and so may lead to more innovative design improvements. They are also likely to open market opportunities for innovative change of the kind characteristic of fluid enterprises in areas such as instrumentation, components, process equipment, and so on.

The stimulus for innovation changes as a unit matures. In the initial fluid stage, market needs are ill-defined and can be stated only with broad uncertainty; and the relevant technologies are as yet little explored. So there are two sources of ambiguity about the relevance of any particular program of research and development — target uncertainty and technical uncertainty. Confronted with both types of uncertainty, the decision-maker has little incentive for major investments in formal research and development.

As the enterprise develops, however, uncertainty about markets and appropriate targets is reduced, and larger research and development investments are justified. At some point before the increasing specialization of the unit makes the cost of implementing technological innovations prohibitively high and before increasing cost competition erodes profits with which to fund large indirect expenses, the benefits of research and development efforts would reach a maximum. Technological opportunities for improvements and additions to existing product lines will then be clear, and a strong commitment to research and development will be characteristic of productive units in the middle stages of development. Such firms will be seen as "science based" because they invest heavily in formal research and engineering departments, with emphasis on process innovation and product differentiation through functional improvements.

Although data on research and development expenditures are not readily available on the basis of productive units, divisions, or lines of business, an informal review of the activities of corporations with large investments in research and development shows that they tend to support business lines that fall neither near the fluid nor the specific conditions but are in the technologically-active middle range. Such productive units tend to be large, to be integrated, and to have a large share of their markets.

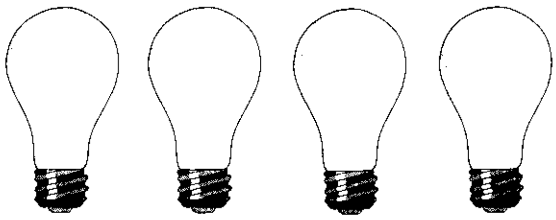
A small, fluid entrepreneurial unit requires general-purpose process equipment which is typically purchased.

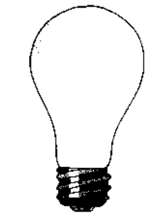


As it develops, such a unit is expected to originate some process-equipment innovations for its own use; and when it is fully matured its entire processes are likely to be designed as integrated systems specific to particular products. Since the mature firm is now fully specialized, all its major process innovations are likely to originate outside the unit.

But note that the supplier companies will now see themselves as making product — not process — innovations. From a different perspective, George Stigler finds stages of development — similar to those we describe — in firms that supply production-process equipment. They differ in the market structure they face, in the specialization of their production processes, and in the responsibilities they must accept in innovating to satisfy their own needs for process technology and materials.

The organization's methods of coordination and control change with the increasing standardization of its products and production processes. As task uncertainty confronts a productive unit early in its development, the unit must emphasize its capacity to process information





by investing in vertical and laterial information systems and in liaison and project groups. Later, these may be extended to the creation of formal planning groups, organizational manifestations of movement from a product-oriented to a transitional state; controls for regulating process functions and management controls such as job procedures, job descriptions, and systems analyses are also extended to become a more pervasive feature of the production network.

As a productive unit achieves standardized products and confronts only incremental change, one would expect it to deal with complexity by reducing the need for information processing. The level at which technological change takes place helps to determine the extent to which organizational dislocations take place. Each of these hypotheses helps to explain the firm's impetus to divide into homogeneous productive units as its products and process technology evolve.

The hypothesized changes in control and coordination imply that the structure of the organization will also change as it matures, becoming more formal and having a greater number of levels of authority. The evidence is strong that such structural change is a characteristic of many enterprises and of units within them.

Fostering Innovation by Understanding Transition

Assuming the validity of this model for the development of the innovative capacities of a productive unit, how can it be applied to further our capacity for new products and to improve our productivity?

We predict that units in different stages of evolution will respond to differing stimuli and undertake different types of innovation. This idea can readily be extended to the question of barriers to innovation; and probably to patterns of success and failure in innovation for units in different situations. The unmet conditions for transition can be viewed as specific barriers which must be overcome if transition is to take place.

We would expect new, fluid units to view as barriers any factors that impede product standardization and market aggregation, while firms in the opposite category tend to rank uncertainty over government regulation or vulnerability of existing investments as more important disruptive factors. Those who would promote innovation and productivity in U.S. industry may find this suggestive. *(See "Why Innovations Fail," by Sumner Myers and Eldon Sweezy, March/April, pp. 40-46.)*

We believe the most useful insights provided by the model apply to production processes in which features of the products can be varied. The most interesting applications are to situations where product innovation is competitively important and difficult to manage; the model helps to identify the full range of other issues with which the firm is simultaneously confronted in a period of growth and change.

Consistency of Management Action

Many examples of unsuccessful innovations point to a common explanation of failure: certain conditions necessary to support a sought-after technical advance were not present. In such cases our model may be helpful because it describes conditions that normally support advances at each stage of development; accordingly, if we can compare existing conditions with those prescribed by the model we may discover how to increase innovative success. For example, we may ask of the model such questions as these about different, apparently independent, managerial actions:

☐ Can a firm increase the variety and diversity of its product line while simultaneously realizing the highest possible level of efficiency?

☐ Is a high rate of product innovation consistent with an effort to substantially reduce costs through extensive backward integration?

Design as a Milestone of Change

The milestone in all the examples of transition in the accompanying article is a dominant new product, synthesized from individual technological innovations introduced independently in prior products. This dominant design has the effect of enforcing standardization so that production economies can be sought. Then effective competition begins to take place on the basis of cost as well as of product performance.

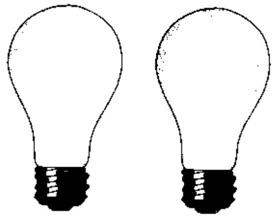
Similar product design milestones can be identified in other product lines: sealed refrigeration units for home refrigerators and freezers, effective can-sealing technology in the food canning industry and the standardized diesel locomotive in the locomotive and railroad industry. In each case the milestone signals a significant transformation, affecting the type of innovation which follows it, the source of information, and the size, scope, and use of formal research and development.

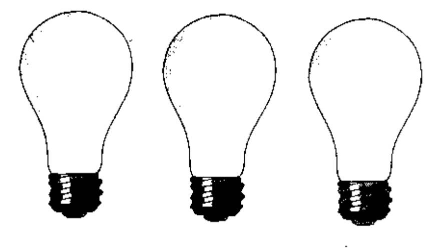
In an earlier article in this series, George R. White *(see his "Management Criteria for Effective Innovation," February, pp. 14-23)* contends that dominant designs can be recognized in the early stages of their development. His analysis suggests that dominant designs will more likely display one or more of the following qualities:

☐ Technologies which lift fundamental technical constraints limiting the prior art while not imposing stringent new constraints.

☐ Designs which enhance the value of potential innovations in other elements of a product or process.

☐ Products which assure expansion into new markets. — *W.J.A., J.M.U.*





☐ Is government policy to maintain diversified markets for technologically active industries consistent with a policy that seeks a high rate of effective product innovation?
☐ Would a firm's action to restructure its work environment for employees so that tasks are more challenging and less repetitive be compatible with a policy of mechanization designed to reduce the need for labor?
☐ Can the government stimulate productivity by forcing a young industry to standardize its products before a dominant design has been realized?

The model prompts an answer of "no" to each of these questions; each question suggests actions which the model tells us are mutually inconsistent. We believe that as these ideas are further developed they can be equally effective in helping to answer many far more subtle questions about the environment for innovation, productivity, and growth.

Further Readings

For readers who wish to explore this subject in greater detail, the authors recommend:

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When Transition Is [illegible] — or Even Absent

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