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INNOVATION IS NOT A LINEAR PROCESS

Stephen J. Kline

An oversimplified model of the innovation process has led economists to argue whether research or "market pull" is central to industrial innovation. However, an improved model shows the reality—including the role of research—to be much more complex.

Various communities of scholars have very different ideas about the sources of industrial innovation, but each of these ideas seems insufficient to explain the complete phenomena. When this much disparity continues to exist among serious students of a given subject, one ought to suspect that the difficulty rests on lack of clarity in the underlying concepts and hence in the way in which questions are framed. In the case of the sources of industrial innovation, the lack of clarity seems to be based primarily on the *implicit use* of an inappropriate model of industrial innovation processes, specifically, on what Price and Bass (1969) called the "linear model."

The linear model views innovation as "an orderly process, starting with the discovery of new knowledge, moving through various stages of development, and eventually emerging in a final viable form." This model has not been made explicit as a diagramatic model in any publication the writer has been able to find. Indeed, many scholars, including Price and Bass, are quite clear that they see the linear model as far too simple to be adequate. However, the linear model continues to underlie the thinking in many current speeches and much writing. For example, the linear model is implicit in the argument about technical push as opposed to market pull: to have a push or pull implies a process with a beginning and end and some kind of direct connection between them. The common current name for innovation processes—R&D—also implies the linear model: the phrase itself suggests a direct and unique path from research to development and product. This continued use of the linear model very probably arises from the fact that no other model has been available—discussions cannot proceed without talking about something.

Figure 1 shows the words of Price and Bass in schematic form. Several implications will be important in later comparisons. First, Figure 1 shows a unique, linear pathway from science through development to production and finally to marketing. Second, the flow of innovation is visualized as a one-way process. Third, the only initiating step is research, that is, in Price and Bass' words, "new knowledge."

The model of Figure 1 is so oversimple and inadequate that its use must seriously distort thinking about processes of innovation. Probably no student of innovation processes believes Figure 1 is a fully adequate model. The specific nature of the difficulties in thinking caused by its use can be seen far more clearly by comparison with the improved model described in the next section.

The Linked-Chain Model

Based on 30 years of consulting in the aircraft, automotive, paper, petroleum, power plant and other industries, I want to suggest an improved model—the "linked chain" model. In this model five pathways for innovation exist. Historical experience demonstrates that *all five* are important.

The elements of the model, are shown in Figure 2. Each of Figures 3 through 7 elaborates one important pathway for innovation processes among the elements shown in Figure 2. The complete set of elements with the five pathways will be called "R&D."

1. *The "Chain-of-Innovation".*—The first and central pathway in the R&D matrix is shown in Figure 3. The term "innovation" is used in the sense of economics, that is, as the set of actions that leads to actual adoption in practice of a device, machine, process, or system.

The chain-of-innovation most frequently starts with "market finding," that is, with an assessment of what might improve a given product or system, or provide a new product or system that meets an unfulfilled market (use). In the current era, this market finding is usually explicit. Explicitness is not critical; the existence of a market is. This follows from the fact that, if no market (or use) exists for a product, innovation, by definition, will not occur. Innovation (unlike research or invention) is tied from the outset to potential uses and/or potential markets. Innovation does not exist in vacuo. Consequently, innovation implies specific goals (also called design criteria, market conditions, product specifications, etc.). The existence of goals does not imply that innovation is necessarily good or even desirable, it does imply that there has to be some use.

The second element in the chain-of innovation is typically either invention or what I shall label "analytic

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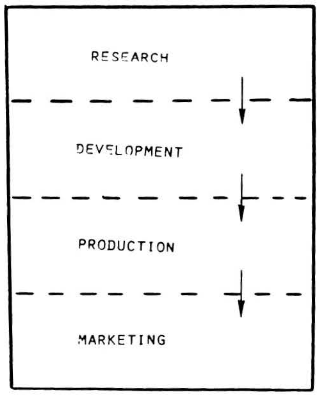

Figure 1.—The conventional "linear model" of the linkage of research to production.

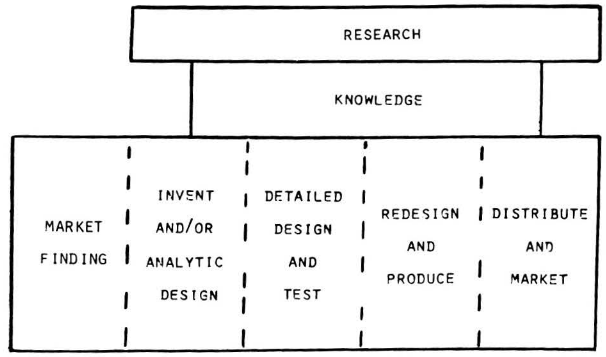

Figure 2.—Elements of the "chain-linked model" for the relationships among research, invention, innovation, and production.

design." The notion of invention is well understood. Invention is clearly defined by the patent office as new design sufficiently different from prior art that it would not have been obvious beforehand to an individual skilled in the relevant art. For the moment, invention needs no further comment. The function of *analytic design* is understood by most engineers, but has no standard name and rarely appears in the literature of economics or discussions of research management. The concept therefore seems to need description and examples; these follow.

Let us suppose one is selecting a source of power for a certain task, say, to run a very large air-conditioning system. One might select today any of the following: an electric motor, a gas turbine, a water turbine, a natural gas engine, a gasoline engine, a diesel, a steam turbine, or other possibilities. The decision will be made on the basis of computations concerning the characteristics needed for the task and the cost. In some cases, no commercial unit will fit the need well. Then analytic design of the performance of several of the more likely types of engines might be made. From these analytic designs, one (or at most two) will be selected for further design studies and possible later manufacture. It is emphasized that these analytic designs are not a full set of manufacturing drawings (that is, a detailed design); such drawings would be far too time-consuming and costly at this stage. Rather, analytic design is only a "scoping," that is, calculations setting forth the major features of the machine—for example size, speed, torque characteristics, and so on. If a new machine is needed, the long process of detailed design will come later.

The point that needs emphasis here is not whether a new model is created by invention or an old product is improved or selected via analytic design, but rather two other ideas. First, new models or new products do not flow directly from research; typically they flow from invention or analytic design. Thus research leads to *product* innovation only insofar as it stimulates a *design* via either invention or analytic design. Second, design is qualitatively different from research. A design is the reduction to paper (drawings) of the specific features of a real embodiment of a real machine, system, or device.

The design process is inherently inductive and creative, the process: (i) begins in a human mind; (ii) uses a selection, creates new parts, or makes a choice of process among known ideas and available components and parts; and (iii) reaches a synthesis that satisfies a set of known, present criteria (or goals).

Research is usually investigative and deductive, it may also be analytic. Research may use synthesis and/or induction, but often does not have preset *functional* criteria in the sense of design criteria (see also discussion of Figures 5, 6, 7). Research typically idealizes the processes and reduces the number of variables to produce data or conclusion(s) based on an idealized situation. A design must deal with all the important aspects of a real situation if it is to succeed.

Once an analytic design is believed to meet the criteria adequately, it may be passed along the chain of innovation to another group who: make a detailed design; manufacture prototypes; and perform tests. These processes together are usually called *development*. It needs to be emphasized, however, that development far more often than not demands alterations in the original invention or analytic design. Hence feedback among the steps is usually essential.

In practice, the various steps in development often take considerably more time and money than the basic research. Steiner (1982) says the assembly of a body of knowledge "tends to be the longest, most difficult, and least understood" phase of the total task in developing a new aircraft.

The steps shown in Figure 3 are the longest chain one normally finds, and are typical of heavy industry (such as those in the automotive or power-generation industries). In the production of simpler devices or of devices that are only a small variation from prior models, some steps may be jumped, and the chain will appear shorter. This difference in the number of steps in the chain of innovation is highly dependent on the time required for product development and the costs to the manufacturer and user of failures in service. Hence there is a large variation from one industry to another.

2. *Feedback Links.*—Three types of feedback links essential to effective innovation are shown in Figure 4. The first type of feedback is shown as circles linking the stages along the central chain-of-innovation. The knowledge developed in early stages of work along the central chain-of-innovation is usually critical to success in later stages. For this reason, some companies have a team of people pass through the various stages of a given project until it reaches the market. In some companies, however, the work is passed from one group to another at the interfaces along the chain-of-innovation; in this pattern of work, the feedback shown as circles on Figure 4 are particularly important.

The second type of feedback is shown as thin arrows beneath the chain-of-innovation on Figure 4. They indicate the improvements in a given product that arise from deficiencies discovered in service, for example, a replacement part in a given automobile model. The needed changes may require work in any or all of the prior stages along the chain-of-innovation, and hence arrows to each prior stage are shown.

The third type of feedback is shown as a heavy arrow leading back to market-finding. This arrow indicates assessment of product utility and competitiveness that inevitably is part of the planning and design of later models or new systems.

All these kinds of feedback are normally present in modern industrial practice. Organizations that are repeatedly successful in innovation, such as General Electric and Bell Labs, have typically given much thought to making these feedback links work effectively.

3. *Connections to Research Through Knowledge.*—The third pathway in the R&D matrix is illustrated in Figures 5a and 5b. These connections to research lie outside the processes implied by the linear model, Figure 1. Consequently these processes have been relatively little understood and have seldom entered public discussions of current innovation processes. (An exception is the 1984 paper by W. G. Vincenti.) They are, nevertheless, the normal, common connection between the chain-of-innovation and research. To understand these connections, it is necessary to be clear on the usage intended for the word "science" and its relation to the sectors labeled "research" and "knowledge" in Figure 2.

I take *science* to denote: "The discovery, creation, verification, organization, storage, and dissemination of truth assertions about physical and biological nature." Under this definition, science includes much of the content of the two layers labeled research and knowledge in Figure 2. It also includes such activities as scientific education and the organization and socialization of professional scientists.

Conversely, research as we understand it includes elements beyond science in the sense just defined. While much industrial research is science in the sense of this definition, we shall also need to consider other forms, including systems research, research on processes, and research in organization of production or quality of product. The various forms of research that relate to production lie at two places in the diagram of Figure 2.

In the present model, research which is also science (under the definition above) lies primarily in the two top layers of Figure 2. Research is a process, or more precisely, many processes. Research is not in itself knowledge, although it produces knowledge. Knowledge is not and cannot be a process; ***knowledge*** is a property—a kind of quantity that exists and can usually be stored for future use. Processes are actions running through time and cannot be stored. For this reason, Figure 2 shows two layers lying next to the central chain of innovation—research and knowledge. The two layers together constitute a central part of what we usually call "pure science." The layer labeled knowledge is purposely placed between research and the elements in the chain-of-innovation because knowledge intermediates between research and the processes of the central chain-of-innovation. This intermediation must be firmly grasped and constantly remembered if clear understanding is to be obtained concerning the principal connections of research to innovation.

Figure 5a shows the common type of linkages between invention, knowledge, and research. Suppose I am inventing a fuel system for an automobile engine in which I hope to reduce production of pollutants. I shall need to understand the interaction of mixing processes in turbulent flow and droplets of liquid gasoline. Since I lack enough knowledge about that problem to fully analyze the system I am thinking about, I shall do a literature search. I shall find, in this case, that the literature is inadequate for my purposes. Next I shall talk with leading experts. In this case I would find that they also do not have enough information. At this point, a call for potential research is activated. If the research is successful and the results come to hand, some years later, we shall publish the findings, and we and others will begin to use them to design improved fuel systems and in other inventive situations as well.

These processes are illustrated by the links, arrows, and small circles in Figure 5a. The first step is a call on knowledge indicated by line 1 linking the process of invention to the small circle labeled "K" in the knowledge sector. If that provides the necessary data (or theory, or concepts), the information is taken back into the inventive or design process and used. This return link is labeled line 2 in Figure 5a. If I do not find the needed information in any of the various sources of knowledge, then I may activate research; this link is the line labeled 3 from the circle "K" to the circle "R" in

Figure 5a. The return line from research, some years hence, is the line marked 4 in Figure 5a.

A very similar set of connections exists for the processes called detailed design, test, and production. These connections are shown in Figure 5b. In each case, we first call on the cumulated human knowledge to solve problems. In each case, this call on knowledge tends to highlight outstanding problems or gaps in collective human knowledge about physical and biological behavior. Thus, the questions that are thrown up by the processes of invention, analytic design, detailed design, failure in testing, or difficulties in production processes in effect define research problems. These problems are by definition applied, they arise from concern with present or future products for use. However, this does not mean the research generated will necessarily be less long-range, less significant, or less fundamental than what is called "pure" research. A significant fraction of the most important advances in science and in mathematics arose historically from consideration of very practical problems. Four examples make the point clear:

- The first derivation of the Second Law of Thermodynamics in the 1820s by Sadi Carnot was an explicit result of Carnot's recognition that, while steam engines were rapidly changing the societies of Great Britain and Western Europe in fundamental, important ways, no one understood the limits on the efficiency of such engines.
- Edison paid a mathematician to work out the mathematics of the parallel circuit as part of his development of electric lighting systems, because without that theory the system would have been far too expensive, and demanded far too much copper.
- The genesis of the field of mathematics now called "asymptotic perturbation theory" was a paper by Ludwig Prandtl in 1904 in the course of providing a direct solution for important problems in the aerodynamics of wings and other related applications.
- The first work in probability theory was done by the Marquis de Laplace, who was concerned with calculation of odds in gambling games.

These examples make clear that the importance of research is not highly correlated with its "purity." A distinction that is important, however, is whether the research is long-range or short-range, since typically industry is more effective on short-range and universities on long-range problems. See Kline (1972).

It is important to note the types of research connecting the different stages in the chain-of-innovation to research and knowledge. Invention often gives rise to problems in what we usually call long-range science. Detailed design and testing more often give rise to what is often called "systems research," but may also give rise to long-range science. Production (and therefore also design for production) on the physical side gives rise to what is usually called "process research," that is, on the ways that physical processes can be altered to improve the quality of products or the efficiency of production for a given quality of product. Product or process failure gives rise to any or all of these forms of research.

Process research is often the most effective type of research in producing rapid effects on corporate profits.

Process research, whether on the physical or social aspects, or both, is often the most effective type of research in producing rapid effects on corporate profits, because improvements immediately affect competitive position and profit margin. Moreover, process research is the central type of research for any industry concerned with the production of materials.

The physical researches arising from invention, design, testing, production or product failure are typically much like physical or biological science. What is usually called market research is also important, but is a type of work so different, qualitatively, that links to research are not shown in Figure 5b, to avoid confusion.

Finally, in connection with the links shown in Figure 5b, we need to note that any information disclosed by such researches adds to our stock of knowledge, and, provided only that it is disclosed (rather than held as trade secrets), it adds to the cumulative knowledge of the human race and can be used on the next set of problems, as noted in the example about turbulent combustion given above. The example appears to generalize.

4. *Direct Connections between Research and Innovation.*—In addition to the connections shown in Figure 5b, there is an important, direct pathway between scientific research and the chain-of-innovation. However, this pathway is significantly different in two ways from the processes implied by the linear model of Figure 1.

First, the link from scientific research to development seldom can be immediate; it must almost always pass through invention. One cannot develop what has not been designed and built. Design demands the mental creation of a specific product, an embodiment in hardware. Scientific research does not usually produce such an embodiment. Hence an intermediate, inventive step is usually necessary; however, this step is usually omitted in the linear model.

Second, the connection to invention is a two-way street. This applies to the direct link as well as the link through knowledge discussed in connection with Figure 5a.

Figure 6 accordingly shows a two-way arrow connecting research to invention. The two-way arrow indicates not only that long-range science creates opportunities for

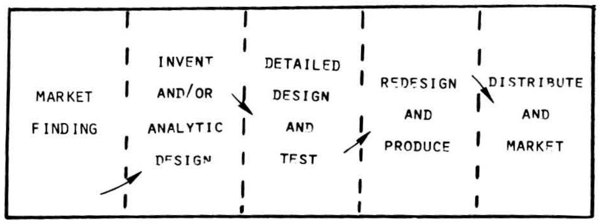

Figure 3.—The central chain-of-innovation in chain-linked model: pathway 1.

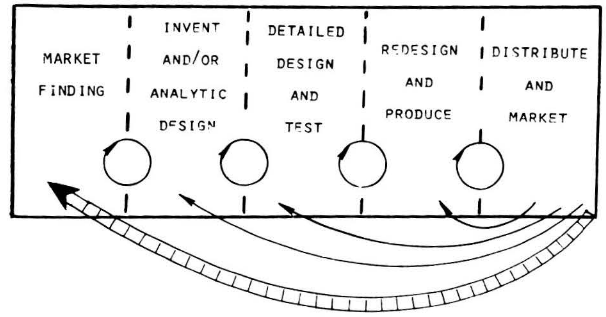

Figure 4.—Feedback links in the chain-of-innovation: chain-linked model: pathway 2.

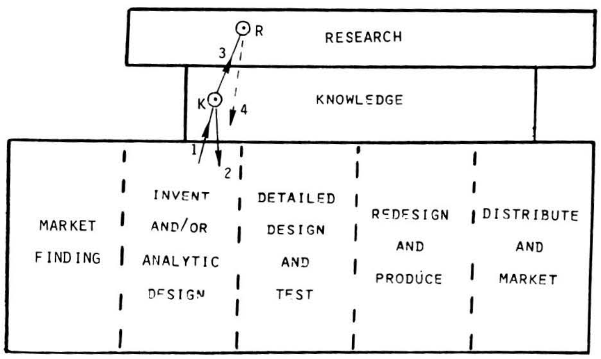

Figure 5a.—Connections of knowledge and research to invention, chain-linked model: pathway 3 (in part).

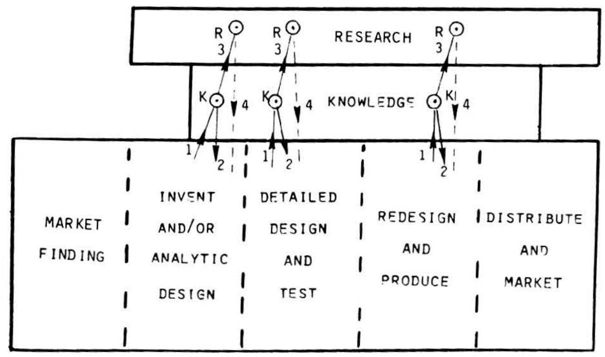

Figure 5b.—Connections of knowledge to the full chain-of-innovation, chain-linked model: pathway 3.

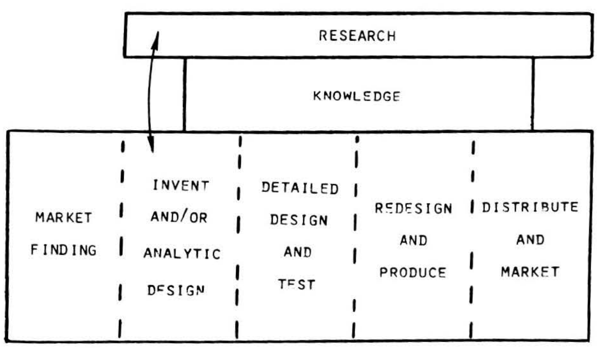

Figure 6.—Direct connections between research and innovation, chain-linked model: pathway 4.

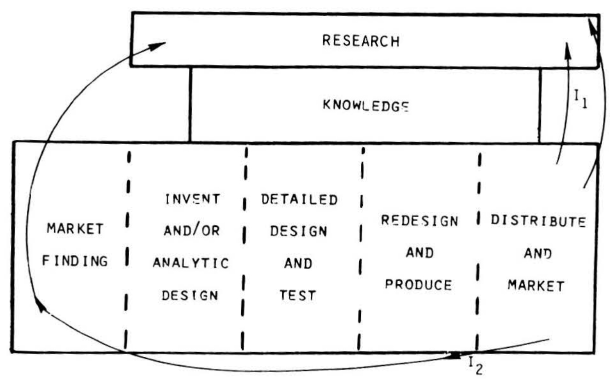

Figure 7.—Connections between market and research, chain-linked model: pathway 5.

new products, but also that perceived needs, or possible market advantages, can stimulate important researches. Such research need not necessarily be any less long-range or fundamental because it arises from a need that was recognized in advance, as already noted.

5. *Direct Connections between Products and Research.*—The fifth and final pathway in the R&D matrix is from market to long-range research. This pathway can be seen as a direct connection, or as tracing back through market-finding, as shown by the two arrows on Figure 7 marked I_1 and I_2. Today many government agencies and large corporations continually ask the question, "What areas of long-range research are likely to potentiate inventions and hence new products, or to suggest advances in the quality or performance of old products?" Thus market factors or military needs can stimulate long-range research. An example is the development in the Bell system of the transistor (as a result of known long-range system needs for a solid-state amplifier). Current emphasis in some government agencies and in the auto companies on long-range research in turbulent combustion is motivated by well-known design and performance problems in jet engines and auto engines, respectively. Numerous other examples exist.

A second important, qualitatively different link also exists between market products and research. The production of new instruments, tools, and processes has in many instances made possible new forms of research. Galileo's foundation work in astronomy became possible only after the telescope became available. Pasteur's discovery of microbes awaited the microscope. In the past decade, the procedures and equipment for radioactive dating have allowed major advances in understanding the evolutionary origins of homo sapiens. Many other examples are given by de Solla Price (1984), who sees the development of such new instruments and processes as often "determining what was discovered."

Even this paper by de Solla Price does not put the case strongly enough. Most of what we now call "advances in science" depend as much on modern sociotechnical systems as on prior science. A large fraction of the work requires modern tools, components, computers, techniques, etc. In some cases it also requires the infrastructure of the large laboratory. Indeed, the modern research laboratory would be impossible without modern sociotechnical systems—both the technical and the social parts.

For these reasons, the dependence of science on technology is shown as a separate link marked "S" on Figure 7. The Support For Science link (S) follows the same route as the Initiation of Science link (I_1) in Figure 7, but the two links represent qualitatively different functions.

The new science, accumulated with the aid of the link S, will, after some time, aid in further technological innovation. Thus science and technology continuously assist each other through multiple links along the chain-of-innovation. The linear model of Figure 1 creates not one but many significant distortions of the reality.

I do not want to leave the impression that the link from market is the only major source of long-range research. Long-range research, as science, has always had two major, identifiable sources and motivations: the desire to solve problems in the real world (market); and the state of science itself, the questions thrown up by the existing state of data, concepts, theories, discussion and debate. Often these operate simultaneously. Few large scale human activities are singly motivated.

To sum up this portion of the discussion, all five pathways are important; no one pathway describes all the sources of innovation or all the necessary functions for successful R&D in industrial societies. Moreover, we should not overlook the fact that important innovations need individuals with vision, knowledge, influence, and much persistence—individuals Schon appropriately calls "champions" (1969). Unless the institutional culture at least condones such champions, important innovations will rarely, if ever, occur. This point is elaborated very effectively by Peters and Waterman (1982).

Some Implications of the Chain-Linked Model

1. *The Bases of Innovation.*—While research in the physical and biological sciences has had an enormous impact on human societies and human life styles, we have seen that research is not the ***direct*** source of innovations, and that much innovation proceeds with little or no input from current research. This seeming paradox is easily resolved, once we see clearly the relation of research and knowledge to innovation, as illustrated in the chain-linked model of R&D processes.

Referring again to Figure 5b, we observe that the primary input, and the first line of reference, for innovation processes everywhere along central chain-of-innovation is not research but the ***totality of cumulated human knowledge***. Moreover, the relation between research and the totality of cumulated human knowledge is an integral one. Each bit of research adds a tiny increment to the totality of human knowledge. To put this in a metaphor, the totality of human knowledge is like the total stock of human housing, and research is like this year's addition to our housing. No one would expect us to replace all our housing this year. However, the linear model of Figure 1 implies that we replace our cumulated knowledge with this year's research output whenever we begin innovation. This implication is probably the most important cause of confusion resulting from implicit use of the linear model of Figure 1 to think about innovation. Some further comment is therefore appropriate.

Any modern technical person beginning a task in innovation will not turn first to research. On the contrary, one turns first to the current state of the art, then to personal knowledge about the governing principles of the field. After that, one goes to the literature, consults colleagues, calls in leading experts. Only when all that does not suffice does one start research. Even then, many innovation projects we now attempt routinely would be not only unfeasible but would be literally unthinkable without the vast accumulated storehouse of knowledge attained by several centuries of work by many, many workers in the appropriate fields of research.

Over the past two centuries, this cumulation of knowledge about physical and biological nature has provided the human race with an increase of many orders of magnitude in insight into physical and biological nature. Furthermore, we have used this increased and increasing knowledge to vastly improve our stock of tools, instruments, machines, and processes and to build increasingly powerful sociotechnical systems. The result is an accelerated increase in the capability of human sociotechnical systems that began about 1830, and is still continuing. This acceleration has been documented quantitatively by Lienhard (1979) and also by Kline (1977), using somewhat different methods. In many instances, this power of human systems has increased more than a million times during this period, and the process does not yet seem to have ended or to be slowing down in an overall sense.

Given these ideas, it is instructive to consider an example—the jet engine. Its design and manufacture would be equally unthinkable without these powerful systems, including special manufacturing processes, advanced materials, and skilled, cooperating workmen. The same remarks apply to many modern systems, such as automobiles, air-conditioners, petroleum refineries, computers, steel mills, electric power systems and the appliances they power, and so on. In all these cases and many more, it would be infeasible and unthinkable to design these systems without the foundations of the total cumulated human knowledge of mechanics, electromagnetism, thermodynamics, quantum mechanics, etc. Furthermore, it would be equally infeasible and unthinkable to manufacture or operate them without the cumulated power of modern sociotechnical systems.

It is the combination of the increased understanding and the increased power of human sociotechnical systems of many kinds that we now bring to bear on innovation, and that has accelerated the processes of change.

The ideas expressed in this section were directly borne out in project "HINDSIGHT." In that project, the input of research was traced back 20 years, but this time period was found to be seriously insufficient; many of the inputs traced back much further in time to the foundations of the underlying subjects, as was later shown in project "TRACES." This is precisely what must be expected from the discussion of this section.

What, then, is the message about research and innovation? First, research is critical. It is the primary tool we use to create our storehouse of cumulated knowledge, but it is the cumulated knowledge and the systems built from that knowledge that provide the primary *direct* inputs to current innovation. It is only when that storehouse of knowledge and current systems is insufficient that we turn to the much more expensive and *much slower* process of research for direct solutions to problems in innovation.

I emphasize the words "much slower" because the matter of time scales is very important. Since we cannot expect the output of this year's research to add a major fraction to our total stock of cumulated knowledge, we should not expect current research to affect this year's innovation greatly. On the other hand, we should expect this decade's research to affect the results of innovation in the 1990s and beyond very strongly. That is what history tells us, and that is what many observers have documented. The time scale of completion of innovation based on new research is about a decade. See, for example Steiner (1982); see also Kline (1972).

This distinction is far from trivial. The failure to understand the distinction between cumulated human knowledge and power of human sociotechnical systems and the output of this year's research has caused serious troubles in U.S. R&D systems. More than one large corporation, apparently acting on the implications of the linear model, established large research laboratories in the expectation that they would produce important innovations over short time spans. When this development did not occur within a few years, the laboratories were dismantled.

2. *Undervaluation of Process and System Research.*—As already noted, systems research is the major component of research associated with the development step in the central chain-of-innovation of Figures 3–7; process research plays a similar role for production activity. To be concrete, a very large portion of the work in the space program has been systems research, including validation of components and coordination of very complex activities. The only kind of effective research that bears directly on any industry producing materials, rather than products, is process research.

However, the linear model of R&D shown in Figure 1 has no place for either system or process research; the model excludes them by implication. As a result, system and process researches appear to have had less attention within the total U.S. R&D system than they deserve, in several ways. First, they have not often been explicitly discussed or considered in national discussions about "science policy." Hence, research funding has not favored these areas, and the science policy advice to the Congress has not made sufficiently clear the complete patterns of innovation and the associated needs. As a result, university research, which does what can be funded, has neglected process and systems research relative to the other areas. This neglect has, in turn, reduced the numbers of new, educated, technical workers who appreciate the value of these areas and are trained in them.

Since systems research is essential to reliable performance of products and any gain in process research effectiveness is quite rapidly reflected on the bottom line of corporate financial statements, we should expect corporate managers to continue these activities—as indeed they have. As one reviewer of this paper pointed out, most of the advances in the process and materials industries in the past century are direct results of research on and cumulated knowledge concerning process functions. Despite this fact, appreciable distortion of the system does seem to have occurred from use of the linear model of Figure 1. An important and rather clear example of this neglect that has become apparent in the last few years is the neglect of the U.S. machine-tool industry, which is fundamental to advances in processes in most other industries. Few universities have offered classes or done research in this area. Innovation appears to have slowed to the point of national concern, as a recent report sponsored by the National Academy of Engineering makes clear.

Reconsideration of policy regarding research funding and education in process and systems research seems needed.

3. *The Role of Invention.*—Invention is an important initiating activity in the central chain-of-innovation. Jewkes et al. (1968), in a study of many cases, conclude that invention was still an important source of innovation in the decade following World War II. Burton Klein, a long-time student of the subject, not only agrees, but reaches a much stronger conclusion. Klein (1977) says,

> *Where do the discoveries come from to make new S-shaped curves? Assuming that the industry has already reached the stage of slow history, the advances will seldom come from major firms in the industry. In fact, of some fifty inventions—most of which were included in the Jewkes, Sawers, and Stillerman study—that resulted in new S-shaped curves in relatively static industries, I could find no case in which the advance in question came from a major firm in the industry. In some cases (Bessemer Steel, the electric steel process, jet engines, the Polaroid Land Camera), the inventions came from newly established firms. In others (the Diesel locomotive, synthetic fibers, computerized machine tools), the inventions came from firms in other industries or from universities. In other words, as long as organizations remain highly dynamic, they can produce a series of important advances—for example, as have been produced by Bell Telephone Laboratories. But once firms in an industry become static, the discoveries will come from newcomers. Evidently the process of going from a dynamic to a static organization is highly irreversible, for otherwise firms that had remained static for a period of years could have made major discoveries.*

Thus Klein sees individual inventors as playing a critical role in industries that have reached a stage of "slow history," which he defines as the upper part of a major S-curve of growth. It is important to note that Klein does not make this assertion about all industries; he specifically notes that some large organizations, for example Bell Labs, have continued to make important innovative advances for long periods of time. This is true of a number of institutions, including General Electric, Hewlett-Packard, and 3M, for example.

At the same time, the status of invention and inventors has been very low in the U.S. when compared with that of research workers, at least since World War II. A researcher is seen as a man in a white coat, working in a laboratory, and producing important results. An inventor is seen as a crank who disturbs the social equilibrium and produces little, if anything, that is useful. This relative status has been clearly reflected in *Research Management*.

A word count of the titles of all articles in *Research Management* for the period 1975–80 reveals that the word "research" occurs 297 times; "development," 204 times; "invention," 3 times; and "inventors" 4 times. Such a title count is only a rough measure of status, but the count is so lopsided that the low status of invention is quite clear.

Will inventors continue to play an important role in the future? All the 30-odd commentators on the first draft of this paper who discussed the issue believed that they would. The writer has had the privilege of reading ten patent applications by M. R. Showalter, an independent analytic innovator (inventor), all on the subject of lubrication and friction reduction. I am as sure as one can be at an early stage that these patents will have a major impact on automotive engines, machine tools, and many other applications. They solve some very old problems and create new advances. Moreover, they were not anticipated by engineers in the industries involved; the patent searches showed remarkably little earlier work on these problems, despite the fact that most of the solutions are clever adaptations of knowledge created by research and clearly recorded in texts and Handbooks, such as Fuller (1956) and the Standard Handbook of Lubrication Engineering (1969).

Showalter has also filed patents that involve ideas on mixing in turbulent fluids. In my opinion, Showalter's ideas on mixing are far ahead of the research community at this time, and turbulent fluid mechanics has been one of my special areas of expertise for more than two decades. I expect to see other important ideas emerge from Showalter's work. The day of the independent innovator is certainly not passed. We should expect to continue to see important innovations created by able, independent, technically trained individuals, since they sometimes bring the detachment about a problem that is lacking in the current common wisdom.

Moreover, invention is not a low-brow activity. It is very demanding, intellectual work. In addition, successful invention requires careful attention to details of hardware, manufacturing techniques, and cost control that long-range research often does not. Successful invention in the late 20th century will often demand more theoretical knowledge than in earlier times, but that does not alter the preceding remarks in this section; rather, it reinforces them.

4. *The Role of "Design"* —In order to understand innovation in industrial societies, it is important to realize that much analytical design and also detailed design is institutionalized invention. A large fraction of engineers get paid to create the new. The engineering groups in some companies and industries have been very innovative, repeatedly, for long periods of time; see for example Mowery (1981) or Peters and Waterman (1982).

There is an extensive literature created by "engineering designers" on creativity and innovation. See for example, Mann (1965). This literature has discussed models of innovation that look very much like the chain-linked model for a long time. However, these models usually exclude economic considerations, are often rather complex in details, and typically are couched in jargon that only engineers understand. Hence they were not discussed in the introductory section of this paper. This "design" literature does strongly reinforce the ideas expressed in the chain-linked model, and it certainly verifies the point that much engineering design, both analytic and detailed, is institutionalized innovation.

5. *Invention and Analytic Design.*—In reality invention and analytic design often interact strongly. Moreover, they should probably interact more than has been typical, particularly in the heavy industries. When a good theory exists, it is obvious that an analytic investigation of a proposed design will be much faster and much cheaper than construction and testing. The widespread availability of the digital computer makes available powerful methods for solution of differential equations, and this amplifies the applicability of this remark greatly. A very high fraction of all design configurations are too complex in detail for ready construction of closed-form analytic solutions, but a considerably larger fraction are straightforward applications for digital computation.

It thus becomes possible to manipulate invention in the computer and also to search for near-optimal solutions in ways that were not possible up to a decade or so ago. It is this fact that makes possible the reinvention of many machines in improved configurations. The lubrication patent applications mentioned above are an example of precisely this kind of work. Much more of this type of work remains to be done. However, it demands a clear conception of the proper role of invention and of the combined use of analytic design and invention as the initiating step in the chain-of-innovation.

In sum, invention and/or analytic design is the direct, first step in the chain-of-innovation, not research. Generally, research contributes to important innovation only when it stimulates invention. If research is to become important in production, it is counterproductive to assign a low status to invention.

For the purposes of this discussion, we therefore need to note three things. First, we must expect important innovation not only from institutions but also from individuals who are largely outside the formal system, and should arrange the system to make both possible. That is why Figures 3–7 show both analytic design and invention as primary, common initiating steps in the central chain-of-innovation.

Second, the linear model of Figure 1 omits analytic and detailed design as sources of innovation and replaces them with research. If we believe that replacement, we shall be seriously misled about the nature of innovation and also about the appropriate roles for science and engineering and the relationship between them.

Finally, the linear model seriously misleads us on the role of inventors. The linear model omits invention and replaces its role with research. It seems likely that this substitution is part of the reason for the present low status of invention and inventors.

6. *Technological Push versus Market Pull.*—The linear model of Figure 1 has inspired a long and inconclusive literature in economics discussing the relevant importance of technology (or science) push versus market pull (or "needs") in innovation. If the chain-linked model of Figures 2–7 is appropriate, the question is essentially irrelevant and should be dropped. Figures 2–7 suggest several sources as initiators of the chain-of-innovation, and all of them include important examples. All need to be continued; no single one is *the* major source.

Moreover, if, as indicated on Figure 4, feedbacks are crucial and the loop back from market to need-finding is essential to innovation (as opposed to long-range research), then questions of cause and effect are basically irrelevant. In looped processes, every cause becomes in due time an effect, and every effect becomes in due time a cause. The distinction between pushes and pulls loses essentially all meaning.

The Role Of Science

The preceding sections point to the importance of invention and design processes as initiators of the central chain-of-innovation and suggest a somewhat different role for research than has often been invoked by direct or implicit use of the linear model of Figure 1. It is therefore important to be clear about the implications for the role of science.

Research, including the forms of research we call science, have been and remain critical with regard to innovation processes, in two ways.

First, the knowledge cumulated by research, which is to say largely by science, is the foundation beneath the entire structure of modern industrial innovation and the more powerful sociotechnical systems we now employ. As has been stressed repeatedly, the total cumulated knowledge about how physical and biological nature do function is a principal ingredient in innovation. Moreover, when it comes to establishing truth assertions about nature, the processes we have come to call "science" are far more powerful than any methods previously devised by humans—so much more powerful that, to paraphrase Lombardi, "There isn't anything in second place."

Second, the knowledge and methods of science are used continuously in innovation whenever a question arises within any step in the processes along the central chain-of-innovation. If we don't have the information in our heads, we go to the literature of science and related fields. If that fails, we use "scientific" methods to do some form of research to solve the problems. The methods of science and technology largely overlap, even though their goals are different. It is precisely this continuous linking of scientific knowledge and the methods of science to the processes in the central chain-of-innovation that suggests use of the word "linked" in the name given to the model of Figures 2–7.

Since World War II, the U.S. government has put considerable funds into support of science. Has that support been an economically supportable proposition? The reconsiderations in this paper suggest the answer is an unambiguous, "Yes!" By and large, where we have kept our research active, maintained strong industry-university links, stimulated bright students to enter the field, we have progressed well and maintained strong industrial positions. Where we have let our research and education lapse, we have suffered relative declines in innovation and have tended to lose position with respect to the international competition over the long haul.

However, it is clear that science and research in all forms is only one necessary condition among a variety of sufficient conditions that initiate and drive innovative processes. We should also keep in mind that technology supports science in critical ways and always has, as noted in the discussion of pathway 5 above.

Some Remaining Questions

This paper suggests a considerable revision in the model and hence in our views of the processes of innovation. It therefore raises a number of policy questions:

- Do we need to change our patterns of engineering education in order to improve our processes of innovation? If so, in what ways?
- Can we formalize the processes of analytic invention and coordinate them with analytic design to create more effective procedures for establishing near-optimal designs of both existing and new devices and systems?
- What are the appropriate roles for industrial, governmental, and educational institutions in fostering innovation, given the model of Figures 2–7, and what should the relationships among these institutions be?
- How can we recognize and make more effective the important role of individual inventors in the ongoing process of improving of the efficacy of sociotechnical systems?
- How can we improve understanding of innovation processes among economists, government officials, and leaders of business?

The frequent use, usually implicit, of a linear, single-pathway model connecting research to production has often distorted our thinking about processes of innovation and thereby sometimes distorted governmental policy and industrial decisions. The more important distortions seem to include the following:

- Failure to recognize clearly the distinction between "total cumulated knowledge" and "the output of this year's research" as the knowledge base used in innovation processes.
- Failure to recognize that the initiating steps in the central chain-of-innovation are analytic design and/or invention, and that research affects production only as it stimulates inventions or changes in process.
- Frequent devaluation of invention, of process research, and of system research with respect to their importance in the total R&D matrix.

These conclusions raise questions with regard to a number of policy issues and institutional arrangements that have persisted since World War II in the U.S. systems of R&D. These issues appear in need of separate, further study and possible reconsideration. □

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Flaws in Engineering Education

For the most part, we do not teach our engineers to innovate or invent. We teach them how to analyze and do research. We do not even give engineering students a clear picture of the importance of invention and innovation; rather most of the time we stress analysis and practice, and for graduate students, research. We imply the model of Figure 1. As Peters and Waterman (1982) document, large, rigid bureaucracies reinforce these educational experiences. Nor do we teach engineers, or any other students, that sociotechnical systems are the physical foundations of all human societies and that innovation in such systems is a part of our evolutionary and cultural heritage. Students in the social sciences and humanities, who sometimes later run industrial organizations, seem to be told that the whole process is the result of a mystery labeled "Science." In short, we have not been running some parts of our technological system well. We have not even been inculcating appropriate attitudes.—**S.J.K.**