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THE PROCESS OF INNOVATION: A STUDY OF THE ORIGINATION AND DEVELOPMENT OF IDEAS FOR NEW SCIENTIFIC INSTRUMENTS

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Abstract-The process of technical innovation is treated as occurring in three phases: (a) idea generation, (b) problem solving, and (c) implementation and diffusion. Two questions are addressed in a study of the origination and development of 32 new scientific instruments. First, what information led to the origination of ideas for these new products? Second, how was information acquired and used in developing these ideas? Idea generation was assumed to require a synthesis of several pieces of information. Innovators relied on oral communications outside their firm in generating ideas. Conversely, they tended to rely on sources inside their firm and to use first local sources of information (literature and experience), then secondary sources (discussion) and finally primary sources (analysis and experiment) in problem solving. Generation of an idea was found to follow most often from recognition of a need or problem. However, in the minority of cases in which generation of an idea was stimulated by technical information, more recent technology was used in the innovation, and literature and outside consultants were more often used as sources of information during problem solving.

The process of originating, developing, and introducing technical innovations is central to the industrial firm. In a growing industry, innovation can lead to large competitive and sales advantages. In a mature industry, it can lead to diversification and new applications for products. Conversely, it can lead to invasion of traditional markets and replacement of traditional products by other firms. Thus, innovation concerns managers with respect to both the growth and survival of firms, products, and markets.

Major Questions

Two major questions will be addressed in the research reported below. First, what information led to the initiation of innovation; specifically, what information led to the origination and development of new products by industrial organizations? Second, how did information contribute in the development of new products? The term information refers to discrete pieces of technical information which had an important effect on the initiation or on the course of a development. Examples would be a journal article, a discussion, or results of an experiment which generated the solution to a key problem.

A Framework for the Study

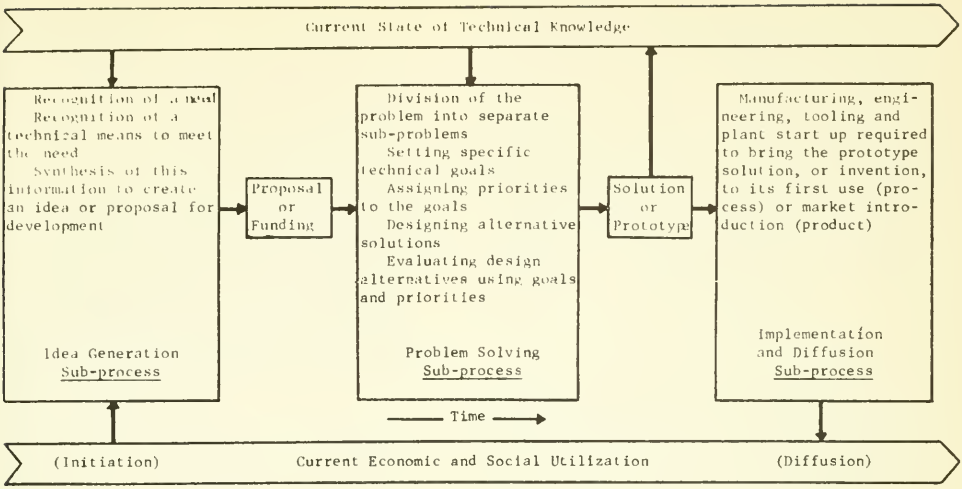
One of the difficulties in attempting to draw conclusions from the many existing studies of technical innovation has been the lack of a coherent framework for organizing and presenting their findings. A model of the process of innovation which suits this purpose was recently suggested by the results of a conference on technology transfer.[1] This model has subsequently been refined and expanded using data from several industries.[2,3]

The process of technical innovation is viewed as being embedded in a diverse environment with political, cultural, and social elements in addition to others. One important element of this environment is the current state of technical knowledge. This is embodied in publication, training, current techniques and devices. The state of technical knowledge is assumed to be continuously changing with time as shown at the top of Figure 1. Another important element of the environment is the degree of economic and social utilization of existing products, processes and systems, and as will be stressed below, factors which lead to recognition of differences between desired and actual performance of these products, etc. The current economic and social usage aspect of the firm's environment is defined by other firms in the industry, potential competitors in other industries and customers and potential customers. Again the degree of use is viewed as changing with time. Other aspects of the environment, for example the competitive structure and rate of growth in a given industry, are not included. This is primarily because the variables to be discussed in terms of the simplified framework below are the sequence, channels and content of communication, and not economic variables.

Technical innovation is treated as occurring in three overlapping steps or phases which are (a) idea generation, (b) problem solving, and (c) implementation and diffusion. Idea generation is the origination of a design concept or technical proposal perhaps via synthesis of several pieces of existing information. Problem solving results in an original technical solution (an invention) followed by engineering and market introduction (implementation) of a new product or process. Finally, diffusion is the mechanism of communication and use by which an innovation comes to have a wider social and economic impact.

Generation of an idea and its embodiment in a formal or informal proposal for commitment of resources requires the synthesis of knowledge of both

FIGURE 1: THE PROCESS OF TECHNICAL INNOVATION



a need and a feasible means to meet this need. Usually there are several, perhaps many technological alternatives to meet a given need or to solve a given problem.[4] However, it is also clear that not every need, nor even every urgent need results in innovation. Similarly, it is not difficult to find examples of technical means, even in some cases brilliant solutions to urgent problems which have not been implemented. Thus, the synthesis of both means and need is the critical factor in this sub-process.

Just as several alternatives may be posed to meet a given need there are many alternative ways in which needs are recognized. This includes (a) projections based on historical data, (b) performance comparisons with competing alternatives, (c) demands made by other persons, perhaps customers, and (d) planning.[5] Data from a study of new scientific instruments will be presented in the following section concerning the hypothesis that idea generation is usually initiated by the recognition of a need or technical problem rather than by recognition of exploitable technical information or opportunities.

The problem solving subprocess usually involves a major commitment of resources by the firm, and generally has at least the following five aspects: (1) division of the problem into separable sub-problems, (2) setting the specific technical goals, or criteria to be met for each sub-problem, (3) assigning a priority or ranking to each criterion, perhaps simply as critical vs. desirable, (4) designing alternative solutions, and (5) evaluating design alternatives using the design criteria.[6] The problem of setting goals and priorities will not be discussed below nor will rejected design alternatives be discussed. The sources and development of implemented alternatives are what will be examined in detail.

Implementation refers to the manufacturing engineering, tooling and plant start up required to bring an original solution or invention to its first use or market introduction. While this subprocess generally involves greater expenditure and commitment by the firm than both idea generation and problem solving, the technical uncertainties involved are thought to be less than those in the earlier phases. Once first use or introduction of a process or product occurs the technical process of innovation has ended and an economic process of testing, acceptance and communication begins. Diffusion is considered to be a two or multi-step process.[7] It begins slowly with the product or process being employed by a few influential economic "innovators." These experiments initiate wider communication and use of the innovation.[8] The probability that any firm will adopt a product or technique is believed to be an increasing function of the proportion of firms already using it and the profitability of doing so, but a decreasing function of the size of the investment required.[9] The activities involved in implementation and diffusion will not be examined in detail here.

The idea generation phase is operationally defined to extend from the time of the first communication related to the idea until the time at which a proposal is written, or at which the work is funded, or at which the major effort of at least one person is directed toward work on the idea. The problem solving phase is taken to extend from this point until the time at which a solution or prototype is completed. All activities related to carrying the prototype into use are included in the implementation phase which ends when a new product is first introduced in the market or at which a new process is first used within the firm.

Idea Origination

The first question posed for this study was: what information led to the origination and development of new products by industrial firms? One widely held view is that new alternatives will be sought when present alternatives do not meet expectations.[10] If this is true then information which directs attention toward expectations will be effective in stimulating a search for alternatives.[11] Communication about a specific need or problem, particularly from an important customer or potential customer could be considered to stimulate a search for alternatives in this way. Information about technical possibilities or means probably would be less effective in directing attention toward expectations. Thus, it will be hypothesized that origination of ideas for new products will occur most frequently in response to recognition of need or problem and less frequently in response to recognition of an existing technical possibility or means. (Hypothesis 1.1)

Baker et.al. have reported a study of factors leading to the generation of over 300 ideas created in a divisional laboratory of a large corporation. A major finding from this study is that two pieces of information were associated with each idea. These were recognition of a need, problem or opportunity and recognition of a means or technique by which to satisfy the need, solve the problem or meet the opportunity, as assumed above.[12]

Peters has presented data concerning faculty in four departments at M.I.T. to test the hypothesis that diversity in technical work (and thus in communication) is a major factor leading to the generation of ideas. Sixty-eight ideas were reported which were judged to have commercial potential. Of particular interest here are his findings that faculty who reported such ideas were: a) engaged in both research and development as opposed to being engaged in either activity to the exclusion of the other, and b) more often engaged in consulting than those who did not report having commercially exploitable ideas.[13] Gordon, based on a study of 223 proposals for projects involving social-psychological aspects of disease, also reports that consultation outside the work setting tended to increase idea generation.[14] One might assume that those having more diverse opportunities for communication would be more likely to bring knowledge of needs and means together and create an idea.

Baker, et.al. reported that seventy-five percent (212) of the ideas studied were stimulated by knowledge of a need, termed a "need event," followed by knowledge of a means, called a "means event" for meeting the need. Twenty-five percent (60) ideas were stimulated by knowledge of a means followed by knowledge of a need met by the means.[15] Myers and Marquis, in a study of successful commercial innovations, report that 75 percent of the original innovations studied (329) were initiated in response to market or production related factors, while in 22 percent (96) of the cases a technical opportunity was the primary initiating factor.[16]

There are certain similarities between the findings reported by Myers and Marquis and those reported by Carter and Williams for British firms for which complete data are given.[17] Sherwin and Isenson document a similar finding for a sample of 710 technical advances incorporated in 20 weapons systems.[18] Sixty-eight percent of these were directed toward filling a need defined by the Department of Defense — 41 percent with respect to a particular system in the advanced development stage, and 27 percent with respect to generic or broadly defined defense needs not related to a particular system. Finally, the Materials Advisory Board concludes from case studies of ten major innovations in materials that in all but one of the cases studied the recognition of an important need was identified in a majority of the events as an important factor in bringing about the research-engineering interaction.[19]

If, as was assumed above, attention directing communication stimulates search for new alternatives, it might be hypothesized that the basic technology used in innovations stimulated by technical possibilities will be of more recent origin than that employed in need stimulated innovations (Hypothesis 1.2). Older technical possibilities probably seldom spontaneously attract one's attention. In contrast, a new discovery or technical possibility might well receive wider communication and attention.

In most industries no single firm commands a majority of the available resources for research. Nor can any one firm anticipate more than a part of the needs or problems which arise in its social and economic environment. Thus it would not be surprising to find that most of the information which stimulated ideas successfully developed and implemented by a firm came from outside that firm. Jewkes, et.al. and Hamberg have identified 88 major innovations which have occurred since 1900.[20,21] A small number (19 cases; 26%) of these originated in large firms, though larger firms did much of the development work. Of the 137 cases studied by Myers and Marquis for which these data are available, most (76 cases; 55%) of the ideas were evoked by information from sources outside the firm. Most of the information which came from outside the firm (45 of the 76 inputs; 59%) was communicated through personal contacts and discussion.[22] Similarly, in a study of DuPont's major product and process innovations from 1920 to 1950 Mueller found that a large number of these (14 of 25 cases; 56%) originated wholly outside that company.[23]

Based on the discussion above one would expect that a) generation of an idea for a new product or process would require synthesis of knowledge about a need or problem and knowledge of a technical means to meet the need or solve the problem; that b) this synthesis would most often occur in response to communication about a need or problem; that c) innovations stimulated by communication about a means or technique would be based on more recent technology than those stimulated by needs; that d) a large proportion of the communication leading to the generation of a new

idea would occur through discussion and consultation, and that e) most of the information related to the generation of an idea would originate outside the innovator's firm or organization.

Problem Solving

The second major question posed above was, "how did information contribute in the development of new products?" In other words, how was information obtained and used in solving problems? Hypotheses concerning the problem solving process will be based on the views of March and Simon and others of the hierarchical ordering of modes of search for information.[24,25,26] Search is expected to proceed from sources easily accessible to ones less so. Ease of access as used here refers to psychological and social factors as well as physical proximity and availability.[27,28,29] Thus one expects that search will normally proceed first through local and easily accessible sources (literature and memory), then through secondary sources (interaction with others) and finally to primary sources (analysis and experimentation). (Hypothesis 2.1)

While this hypothesis is proposed to hold in general, some differences in channel usage between need and means stimulated innovations will be assumed. Means stimulated innovations probably involve more recent technology than those stimulated by needs as hypothesized above. Information on the level or "state of the art" is known to be transmitted by "gatekeepers" who maintain contact with literature and technical colleagues outside their firms.[30] Therefore, one might expect a greater proportion of the information used in developing means stimulated innovations to come from literature and external technical discussion than for those initiated by needs. (Hypothesis 2.2)

Problem solving, as sharply opposed to idea generation, appears to involve much greater use of information sources inside the firm. Of the 368 cases in Myers and Marquis' study for which data are available on this point a majority of solutions to defined problems (244 cases; 66%) were based on information available inside the firm.[31] Allen reports a slightly higher proportion of 118 alternative solutions considered during problem solving were suggested by external sources (62 cases;52.5%). However, when one looks at the quality of accepted alternatives only, and their sources, this picture changes dramatically. Seven of eight accepted alternatives from internal sources resulted in higher rated solutions, while nine of fourteen accepted alternatives from outside sources resulted in lower rated solutions.[32]

In sum, after information has been synthesized into an idea or design concept, and an organization has committed funds to development, the problem solving process begins. The idea or problem defined earlier must be divided into subproblems amenable to solution. It is hypothesized that in general search for information used in solving subproblems will proceed from local to secondary and then to primary sources of information. For developments stimulated by a technical means a larger proportion of the information used is expected to come from literature and from consultation outside the firm than in those cases stimulated by a need. Finally, most communications during problem solving are expected to come from sources inside the firm.

The Study Sample

Data were gathered to test the hypotheses using the framework outlined above to structure the interviews. The primary sample was a set of innovations from the instrument industry. These were highly rated on the basis of their technical uniqueness, importance, and usefulness by an independent panel of experts. Each primary innovation was matched with two others in the same firm. The first was the most successful product developed by the firm in the past five years in terms of profits and/or sales. The second was a product chosen to be representative of other products developed by the firm, for purposes of comparison.

FINDINGS

What Information Stimulated Ideas?

Work prior to funding of a proposal was generally intermittent, less formal, and involved fewer people than was the case after the committment of funds. It typically involved one or two men part time. These respondents were first asked who had originated the idea and what had stimulated the idea. They were then asked to list the communications which occurred prior to the commitment of funds.

Ideas for four of the thirty-two new instruments in the sample were identified by respondents as being stimulated by information about existing technology. These four and an additional four met the more precise requirement that the first explicitly identified stimulus in the list of communications was about a technical means, or a "means input". The remaining twenty-four cases were classified as need stimulated.

Synthesis of information about both a need and a technical means to meet the need occurred in twenty-seven of the cases prior to funding. In four cases a need was the initial stimulus, but no means was explicitly recognized until after funding. In the one remaining case the stimulus was communication about a technique, and no need has been identified though several have been discussed and rejected since the device was developed.

It can be seen from Table 1 that data for innovations in the most successful and control groups support the hypothesis that innovations will more frequently be stimulated by a need or problem than by a means or technical possibility (H1.1). That this is true for the award winning innovations is doubtful.

The technical award winners appear to differ from the commercially successful and the matched cost innovations. While one can see that the difference found between the award winning and the

most commercially successful innovations is significant, the control group is not significantly different from either of the others. The sample proportion of means stimulated innovations in this group is greater than that for the most successful group and less than that of the award winners, so

TABLE 1

THE NUMBER OF MEANS AND NEED STIMULATED INNOVATIONS FOUND IN EACH GROUP IN THE SAMPLE OF INNOVATIONS

Group in Sample	Means Stimulated	Need Stimulated	Binomial Test*
Award Winners	6	9	p<.304
Most Successful (Profits & Sales)	0	8	p<.004
Control	2	7	p<.090
Total Sample	8	24	p<.004

*p is the probability that the null hypothesis p = q = .50 holds, or that the proportion of need stimulated innovations in the population is not greater than that for means stimulated innovations given the sample results.

The probability of a contrast as extreme as that between the award winners and the most successful group occurring by chance is less than .05 (Fisher exact test with respect to need versus means stimulation). For the award winners versus the controls p = .332, and for the most successful versus the controls p = .265.

this is not a surprising result. One might stretch the point to say that the most successful innovations differ from the norm in one direction while the technically outstanding products differ in the opposite. This is not to say that the award winning products are not also commercially successful. In fact, four of the award winners were also named "most successful" by respondents but were not double counted in the above analysis. Three of these four were classified as need stimulated. In addition, one of the award winners was named as a control for an earlier winner in the same organization. Including each of these five innovations in two groups would not substantially change the results.

The answers to the question, "When was the basic technology used in the product developed?" can be used to test the hypothesis that newer technology will be employed in means than in need stimulated innovations. Technical information used in means stimulated innovations ranged from 0 to 10 years old and its mean age was 2.0 years. The technology employed in need stimulated innovations ranged from 0 to 56 years old with a mean age of 12.2 years. It is unlikely that this difference could be the result of chance as can be seen from Table 2. (Hypothesis 1.2)

TABLE 2

TIME LAG (YEARS) IN THE IMPLEMENTATION OF THE BASIC TECHNOLOGY USED IN MEANS AND NEED STIMULATED INNOVATIONS

Age of the Basic Technology	Means Stimulated Innovations	Need Stimulated Innovations
0 to 5 years	6	7
6 or more years	1	12

Fisher exact probability that this difference could occur by chance is less than .01

Description of Information Inputs Prior to Funding

From Table 3 it can be seen that most of the communication prior to funding came from outside the organizations which actually produced the new products, that the most frequent source of information was discussion with a contact outside the organization, and that the most frequent function of the information was definition of technical or economic requirements. Some interesting differences can be seen by comparing all "stimulating inputs" (all means inputs and need inputs) with other communication inputs prior to funding. The stimulating inputs were mostly from sources outside the firm (66.1%) as opposed to all other information (52.2%).

The stimulating inputs were often initiated by someone other than the person who developed the innovation (52.5%) as opposed to all other information (39.7%). The stimulating inputs more often came from discussion inside and outside the firm (57.6%) than did all other information (36.3%), while many of the stimulating inputs came from the literature (15.2%) as did all other information prior to funding (17.0%). Not shown in Table 3 is the fact that need inputs were most often initiated by someone other than the person who initiated the idea for the innovation (63.4%) while means inputs were most often initiated by the innovator himself (58.5%). Means inputs came mainly from three sources: discussion outside the firm (31.0%), literature (24.2%), and analysis and experiment (24.2%); while the overwhelming majority of need inputs (73.4%) came from discussion, most from outside the firm (56.7%). While both types of stimuli came most frequently from outside discussion, the source was most often a customer or potential customer for need inputs and most often a vendor or other source of technical information for means inputs.

TABLE 3

COMPARISON OF COMMUNICATION EVENTS PRIOR TO AND FOLLOWING FUNDING

	Stimulating Inputs		Other Inputs Before Funding		All Inputs Prior to Funding		All Inputs Following Funding		Total	
	Freq	%	Freq	%	Freq	%	Freq	%	Freq	%
Source of Communication										
Internal	20	33.9	42	47.8	62	42.2	92	64.4	154	53.1
External	39	66.1	46	52.2	85	57.8	51	35.6	136	46.9
Initiation of Communication										
Self	28	47.5	53	60.3	81	55.1	123	86.0	204	70.3
Other in firm	15	25.4	18	20.3	33	22.4	13	9.1	46	15.8
Outside of firm	12	20.4	8	9.1	20	13.6	5	3.5	25	8.6
Other (no data)	4	6.7	9	10.2	13	8.9	2	1.4	15	5.2
Channel of Communication										
Literature	9	15.2	15	17.0	24	16.3	12	8.4	36	12.7
Experience	6	10.2	4	4.6	10	6.8	11	7.7	21	7.2
Discussion (external)	26	44.0	24	27.3	50	34.0	31	21.7	81	27.8
Discussion (internal)	8	13.6	8	9.1	16	10.9	14	9.8	30	10.3
Analysis & Experiment	8	13.6	25	28.4	33	22.4	74	51.8	107	36.8
Other (or no data)	2	3.4	12	13.6	14	9.5	1	.6	15	5.2
TOTALS	59	100.0	88	100.0	147	100.0	143	100.0	290	100.0

Comparison of Information Inputs Prior to and Following Funding

A number of differences can be seen from Table 3 between all information inputs prior to funding and all inputs following funding. Information came most often from sources outside the firm prior to funding and from sources inside the firm following funding. This finding is even more pronounced when one recalls that information inputs classed as stimulating events more often came from outside the firm than did all inputs prior to funding. The creative effort involved in the 32 innovations occurred mainly prior to initiation of formal work. This was strongly confirmed during the interviews. Respondents often described the work after funding as "straight-forward engineering" or "design" work. Communication following funding was much more often initiated by the innovator (86.0% of all inputs) as opposed to others inside or outside the firm. Finally, the inputs following funding were more often from analysis and experiment (51.8%) and less often from discussion (31.5%) than was the case before.

TABLE 4

ANALYSIS OF TRANSITIONS IN CHANNEL USAGE PRIOR TO AND FOLLOWING FUNDING

Source of Initial Input (i) in Each Pair Prior to Funding	Source of Subsequent Input (i + 1) in Each Pair: Literature and Experience	Discussion	Analysis and Experiment
Literature and experience	9	10	7
Discussion	10	28	11
Analysis and experiment	6	9	8

The probability that the distribution above could occur by chance is less than .70 (Signs test).

Source of Initial Input (i) in Each Pair Following Funding	Source of Subsequent Input (i + 1) in Each Pair		
Literature and experience	2	6	6
Discussion	3	8	12
Analysis and experiment	2	8	17

The probability that the distribution above could occur by chance is less than .08 (Signs test).

TABLE 5

COMPARISON OF THE USE OF COMMUNICATION CHANNELS DURING PROBLEM SOLVING FOR MEANS VS. NEED STIMULATED INNOVATIONS

Channel of Communication Used	Means Stimulated Innovations	Need Stimulated Innovations	
Prior to Funding			
Literature and technical consultation outside organization	15	34	$X^2 = 1.214$
Other sources	17	66	$p = .270$
Following Funding			
Literature and technical consultation outside the organization	14	26	$X^2 = 4.012$
Other sources	18	84	$p = .045$
In Total			
Literature and technical consultation outside the organization	29	60	$X^2 = 5.528$
Other sources	35	150	$p = .019$

How Was Information Used In Problem Solving?

Since several parts of a development project might be undertaken at once, the work following funding was further divided into sub-problems. Each respondent was asked about information inputs and order of communication with respect to each sub-problem, rather than entire development projects, as the unit of analysis. Seventy-eight sub-problems were identified and discussed in total.

The data presented in Table 4 will be used to test the hypothesis that during problem solving search for information will proceed from available information (literature-memory) to secondary sources (discussion) and to primary sources (analysis-experiment) (H2.1). An analysis of the lower part of Table 4 with respect to this hypothesis will reveal that data reported above the diagonal supports the hypothesis, while data below the diagonal contradicts it. In other words, a transition in channel usage from literature or experience to discussion would be reported in the upper right hand part of the table, and a transition in the reverse direction would be reported in the lower left hand part. Summing the data for inputs within subproblems following funding one can see that there are 24 changes in the predicted direction and 13 which are in the reverse direction. These data support the hypothesis above.

It is interesting to compare these results with those in the upper part of Table 4 for information inputs prior to funding. There is no indication that the hypothesis would hold for this less structured phase, nor was this expected to be the case. In sum, search for information appears to be more highly ordered following funding than before, and search appears to proceed in a heirarchical order from local to secondary and then to primary sources of information in the problem solving process.

The hypothesis that channel usage would differ after funding for means stimulated innovations as opposed to need stimulated ones can be examined using the data presented in Table 5. This hypothesis (H2.2) was based on the expectation that means stimulated innovations would involve more recent technical information than those stimulated by needs.

One may speculate that means-stimulated innovations require a greater amount of consultation outside the organization and use of technical literature to acquire recent information than do those stimulated by needs. The data presented support the hypothesis that a greater proportion of communication inputs for means stimulated innovations came from the literature and technical contacts outside the organization (other than customers) than was the case for need stimulated innovations.

SUMMARY

The model of the process of innovation presented above has allowed analysis of several interesting differences with respect to the way in which communication in different phases and from different environments affects this process. With respect to phases in the process it was concluded that: (a) information inputs come most often from outside the firm during idea generation, but that during problem solving internal sources are more heavily used (b) oral sources account for the majority of communications in both phases; and (c) search for information proceeds in a more definitely structured pattern during problem solving than in the earlier idea generation phase. With respect to inputs from different environments it was concluded that: (a) generation of a new idea was most often stimulated by recognition of a need or problem followed by recognition of a technical means to meet the need or solve the problem; but that (b) in the minority of cases stimulated by technical

information the technology employed was more recent, and literature and technical consultation outside the firm was the source of more of the information used than was the case for the need stimulated innovations. Generalization of these results is limited by the small number of cases studied and the fact that the study was limited to a single industry and region.

Several interpretations can be given to the results reported. On one hand attention to needs and problems may inhibit attention to technical opportunities and result in fewer novel or important ideas. On the other hand it may be that formulation and communication of needs and problems will encourage innovation in promising directions. The weight of the evidence presented seems to favor the latter interpretation.

Management of a firm interested in stimulating the creation and development of ideas for new products can gain several insights from these findings. First, integration of market and economic information with technical information, and analysis and communication of needs and problems appear to be critical in generating ideas for new products. Second, while communication patterns and requirements vary considerably between the idea generation and problem solving phases, technical consultation outside the firm appears to be important both in discovering needs and problems and in obtaining and applying the most current technical information. Consideration of these points should improve both the direction and the outcome of research and development efforts.

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