The Dominant Role of Users in the Scientific Instrument Innovation Process

Eric von Hippel

January, 1975 WP 764-75

The research reported on in this paper was supported by the Office of National R&D Assessment, NSF (Grant # DA-44366) and the Office of Experimental R&D Incentives, NSF (Grant # CG-00002). The author gratefully acknowledges intellectual stimulation and assistance rendered by Alan Berger, Allan Chambers, Neal Kaplan, Walter Lehman and Frank Spital, who served as Research Assistants during the project.

1. INTRODUCTION

Quantitative research into the industrial good innovation process has, over the last few years, demonstrated convincingly that:

(1) Approximately three out of four commercially successful industrial good innovation projects are initiated in response to a perception of user need for an innovation, rather than on the basis of a technological opportunity to achieve them.[1]

(2) Accurate understanding of user need is the factor which discriminates most strongly between commercially successful industrial good innovation projects and those which fail.[2]

The studies which produced these findings were designed to test many hypotheses regarding the causes of successful industrial good innovation. Understandably, therefore, they are enticingly scant on detail regarding the 'understanding of user need' hypothesis which showed such an encouraging correlation with innovation success. Among the interesting questions left unanswered are:
How does an innovating firm go about acquiring an 'accurate understanding of user need'? Via an information input from the user? If so, should the manufacturer take the initiative in seeking out such input, or will the user seek him out? And, what does a 'need input' look like? Should one be on the alert for user complaints so vague that only a subtle-minded producer would think of using them as grist for a product specification? Or, perhaps, should one be touring user facilities on the alert for something as concrete as home-made devices which solve user-discerned problems, and which could be profitably copied and sold to other users facing similar problems?

---

1. Jim Utterback, "Innovation in Industry and the Diffusion of Technology" Science 2-15-74 183 pg. 622, Table 2, lists the quantitative findings of eight studies which support this point.
2. Achilladelis et al, Project Sappho. A Study of Success and Failure in Industrial Innovation, Center for the Study of Industrial Innovation, London 1971 Vol 1 Pg. 66.

Answers to questions such as these would be of clear utility to firms interested in producing innovative industrial goods and would also, we feel, be of interest to researchers working towards an improved understanding of the industrial good innovation process. The study which we are reporting on here was designed to forward this work.

Our report is organized into six sections. After our first introductory section, we describe our methods of sample selection and collection of data in section two. In section three we present our findings on the overall pattern characteristic of innovation in scientific instruments, and in section four we discuss the implications of these. Sections five and six are given over to the presentation and discussion of more detailed findings bearing on two aspects of the innovation process in scientific instruments, and section seven is a summing up.

2. METHODS

2.1 The Sample

The sample of industrial good innovations examined in this study consists of four important types or families of scientific instruments and the successful major and minor improvement innovations involving these. The total sample size is 113, distributed as follows:

TABLE 1: SAMPLE COMPOSITION

Instrument Type	Basic Innovation	Major Improvement	Minor Improvement	Total
Gas Liquid Partition Chromatography	1	11	--	12
Nuclear Magnetic Resonance Spectrometry	1	14	--	15
Ultraviolet Spectrophotometry (Absorption, photoelectric type)	1	7	--	8
Transmission Electron Microscopy	1	14	63	78
Total	4	46	63	113

We chose to select our entire sample from a relatively narrow class of industrial goods because previous studies have shown that characteristic patterns in the innovation process vary as a function of the type of good involved. [3] Given our sample size of 113 and the level of detail at which we want to examine 'user input' and 'accurate understanding of user need', discretion dictated the sample's narrow focus. Scientific instruments were selected as the class to be studied primarily because previous research on the innovation process had ascertained that innovation in response to user need was prominent in scientific instruments. [4] This minimized the risk of choosing to study user need input in an industrial segment where, for some unforseen reason, such input would turn out not to be salient.

Gas-liquid partition chromatography (GC), nuclear magnetic resonance spectrometry (NMR), ultraviolet spectrophotometry (absorption, photoelectric type) (UV), and transmission electron microscopy (TEM) were the families of scientific instruments selected for study because:

--These instrument types have great functional value for scientific research as well as for day-to-day industrial uses such as process control. [5]

---

3. See, for example, Project Sappho's (ibid.) comparison of innovation patterns in the chemical and instrument industries.

4. Jim Utterback, "The Process of Innovation: A Study of the Origin and Development of Ideas for New Scientific Instruments," IEEE Transactions on Engineering Management, Nov. 1971, pp.124-131.
Daniel Shimshoni: Aspects of Scientific Entrepreneurship, Unpublished Ph.D. Dissertation Harvard University, Cambridge, Massachusetts, May, 1966.

5. A study by the National Research Council of the National Academy of Sciences (Chemistry: Opportunities and Needs, Printing and Publishing Office, National Academy of Sciences, 2101 Constitution Avenue, Washington, D.C., 1965) found the Gas-Liquid Partition Chromatograph, the Nuclear Magnetic Resonance Spectrometer, and the Ultraviolet Spectrophotometer to be three of the four instruments with the highest incidence of reported use in articles in 'selected representative U.S. chemical journals.' Electron microscopy, of which transmission electron microscopy was the first, and until recently the only type, is the only way one can get a picture of something smaller than 1000 Angstroms in size. As such, it has been and is a key instrument type in fields ranging from genetics to metallurgy.

--First commercialization of all of these instrument types ranges from 1939 to 1954. This time period is recent enough so that some of the participants in the original commercialization processes are currently available to be interviewed. It is long enough ago, however, so that several major improvement innovations have been commercialized for each instrument type.

While neither annual sales of instrument types nor unit prices were used as a criterion for sample selection, the reader may find such data contextually useful and we have included it in Table 2 below.

TABLE 2: Characterization of Sample

strument Type	Annual Worldwide Sales 1974[a]	Per Unit Cost Range[a]	Approx. Median Unit Cost[a]	Utility Measure: Instance of Use Per 100 Articles 1964[b]	Date Type Was First Commercialized
Gas Chromatography	$100mm	3-15k	7k	17	1954
Nuclear Magnetic Resonance Spectrometry	30mm	12-100k	NA	18	1953
Ultraviolet Spectrophotometry (Absorption, photoelectric type)	$120mm	2.7-26k	6k	21	1941
Transmission Electron Micr[illegible]opy	20mm	30-90k	50k	--	1939

a. Source: Estimates by instrument company market research personnel
b. Chemistry: Opportunities and Needs, op. cit., p. 88.

We should emphasize that our sample consists of more than 100 functionally significant improvements within but four instrument 'families.' This sample structure is considerably different from that used by previous studies of innovation in scientific instruments (cf Shimshoni, Utterback and Achilladelis , op cit). While the authors of these studies found it appropriate for their purposes to assemble samples without regard for the instrument family membership involved, we felt it important that we limit our sample to a few instrument families. Our reasoning was that the 'understanding of user need' pattern seen in this kind of a sample would be the one actually experienced by real-world firms. An instrument family or type tends to represent a product line for commercial firms, and clearly, firms tend to be interested in improvement innovations which impact instrument types which they are currently selling - not in a random mix of unrelated improvement innovations. Further, the fact that they are already in the business of selling an instrument type will impact the kind of incremental input they need to 'accurately understand user need' for an improvement innovation, as well as how they go about acquiring that input - and these are precisely the issues which we wish to study here.

There is a negative consequence of our decision to choose a sample limited to a few instrument types. It is that often a single company with an established commercial position in, for example, Nuclear Magnetic Resonance equipment, will be the first company to commercialize several of the improvement innovations in our sample. This raises issues of sample independence which we must deal with in the data analysis.

2.2 Identification of Sample Members

As indicated in Table 1, preceding, our sample of innovations is divided into three categories: 'basic' innovations, 'major improvement' innovations and 'minor improvement' innovations. As will be discussed in detail below, innovations are assigned to one or another of these categories on the basis of the degree of increase in functional utility (basic, major improvement or minor improvement) which its addition to the basic instrument type (Gas-Liquid Partition Chromatograph, Nuclear Magnetic Resonance Spectrometer, Ultraviolet Spectrophotometry and the Transmission Electron Microscope) offers to the instrument user.

Sample selection criteria particular to a single category of innovation are discussed below in the context of that category. Selection criteria common to all three categories are:

--Only the first commercial introduction of an innovation is included in the sample. Later versions of the same innovation introduced by other manufacturers are not included.

--An innovation is included in the sample only if it is 'commercially successful.' Our definition of commercial success is: continued offering of an innovation (or a close functional equivalent) for sale, by at least one commercializing company, from the time of innovation until the present day.

2.21 Major Improvement Innovations

In setting out to identify major improvement innovations, we took as our base line all features which appeared on the initially commercialized unit. Major innovations which were commercialized at a later date were eligible for inclusion in the sample. In our gas chromatography sample, for example, thirteen such innovations were identified. Capsule descriptions of the utility of two of these may serve to provide the reader with some feeling for what we term 'major functional improvements.'

Name of Innovation	Functional Utility to User
Temperature Programming	Improves speed and resolution of analysis for samples containing components of widely differing boiling points
Argon Ionization Detector	Sensitivity 20-30 times greater than that attainable with thermal conductivity detector

We defined 'major' improvement innovations as those innovations which made a major functional improvement in the instrument from the point of view of the instrument user. Thus, the above-mentioned Argon ionization detector, which improved the sensitivity of the instrument by many fold over previous best practice was judged a significant improvement in functional utility to the user. Transistorization of detector electronics, on the other hand, would not be included in the sample as a significant innovation because the functional impact of the change on the great majority [7] of users is minimal. From the users' point of view, inputs and outputs affecting him significantly remain undisturbed by the change.

7. We say that the impact on the 'great majority' of users is small simply because there might be some few users - say those trying to fit a gas chromatograph into a space satellite, if there are such, to whom the increase in reliability and decrease in size occasioned by a switch from tube electronics to transistorized electronics might be very significant.

The identity of 'major' innovations in a family of instruments was ascertained by consensus among experts -- both users and manufacturers in the field. More quantitative measures of significance were felt impractical given the different parameters impacted by the various innovations (How do you make the functional utility of an improvement in speed commensurate with an improvement in accuracy or with an increase in the range of compounds analysable?). The expert consensus method, while embarked on with some trepidation, turned out to yield remarkably uniform results. Either almost everyone contacted would agree that an innovation was of major functional utility - in which case it was included - or almost no one would - in which case it was rejected.

The experts consulted were, on the manufacturer side, senior scientists and/or R&D managers who had a long-time (approximately 20 years) specialization in the instrument family at issue and whose companies have (or, in the case of electron microscopy, once had) a major share of the market for that instrument family. On the user side, users who were interested in instrumentation and/or had made major contributions to it were identified via publications in the field and suggestions from previously contacted experts.

Data was collected on <u>every</u> major improvement innovation identified by our consensus among experts.

2.22 Basic Instrument Innovations

The basic instrument innovations which we list in Table 1 are basic in the sense that they are the first instruments of a given type to be commercialized. By definition, only four cases of 'basic innovation' are available to us within the sample space of four instrument types which we have allowed ourselves. These are: The first commercial Gas-Liquid Partition Chromatograph; the first Nuclear Magnetic Resonance Spectrometer; the first Ultraviolet Spectrophotometer; and the first Transmission Electron Microscope.

2.23 Minor Improvement Innovations

The criterion for inclusion in our sample of minor innovations (collected for Transmission Electron Microscopy only)[8] was simply that the innovation be of some functional utility to the user in the opinion of experts. This list of minor innovations is probably not exhaustive; it was initiated by asking user and manufacturer experts for a listing of all such innovations they could think of. This list was augmented by our own scanning of the catalogues of microscope manufacturers and of microscope accessory and supply houses for innovative features, accessories, specimen preparation equipment, etc. As in our sample of major improvement innovations, only minor improvements which were not present in an instrument type as initially commercialized were eligible for inclusion in the sample.

2.3 Data Collection Methods

Data was collected under four major headings:

1. Description of the innovation and its functional significance;
2. Innovation work done by the first firm to commercialize the innovation;
3. What, if anything, relating to the innovation (e.g. need input, technology input, etc.) was transferred to the commercializing firm and how, why etc:
4. What was the nature of, focus of, reason for, etc. the innovation-related work done outside the commercializing firm and later transferred to it.

---

8. Our initial plan was to collect a sample of minor improvement innovations for all four of the instrument types which we have been studying -- not just Transmission Electron Microscopy. This plan was abandoned however, when our experience with the TEM sample indicated to us that events surrounding minor innovations were not recalled by participants in them nearly so well as events surrounding major improvement innovations were recalled by the participants in those. The reason for this discrepancy appeared to be that participants in minor innovations generally had no feeling that they were participating in significant events -- they were just doing a typical day's work. Asking them to recall specific aspects of those events perhaps ten years after they had occurred, therefore, was tantamount to asking them to describe details of a casual chat by the water cooler ten years ago-- a bootless exercise.

Our principal data sources were descriptions of instrument innovations in scientific journals and both face-to-face and telephone interviews. Insofar as possible, key individuals directly involved with an innovation, both inside and outside of the initial commercializing firm, were interviewed.

Data from all sources was written up on so-called 'keys'- one for each innovation. Data on these keys collected by interview were written up and sent to the interviewees for correction or verification of accuracy. An example of a completed key (interviewees cited in this key have given permission for its reproduction) is given below:

1. Identification of Innovation

Initial Commercialization of Gas-Liquid Partition Chromatography. This method is distinct from other methods (i.e. frontal analysis and displacement analysis) which are not widely used today.

The device is used for the quantitative and qualitative analysis of unknown chemical mixtures.

It operates by physically separating a chemical mixture into its components. The mixture is passed, in the form of a gas, over a surface containing a partitioning agent, which selectively adsorbs its components. The adsorbing surface is contained in a column. Gas injected into one end of the column as a mixture emerges from the other (having been pushed along by a stream of 'carrier gas') as a sequence of components which pass through a detector.

The method is radically different from previous chemical analysis and is much faster and more accurate.

Good descriptive article: Roy A. Keller "Gas Chromatography" Scientific American, October, 1961.

2. Contribution of first firm to Commercialize Innovation

Perkin-Elmer is the first successful U. S. maker. - Fall of 1954.

Pye, Inc. in England may have produced some GC's prior to or at this same time. (Prior U.S. maker - but not GLPC and not successful). P-E's contribution to the innovation was basically in the engineering (i.e. a rough laboratory device was copied and made acceptable for sale).

P-E experimented with many detectors on this first model and finally settled on a thermistor detector- the idea for using thermistors was picked up from the literature. Also used helium as carrier gas.

Data from Interview at Perkin-Elmer Corp, Norwalk, Conn. with: L.S. Ettre, H. Hausdorff

First Competition Fischer-Gulf, 1956

3. Transfer to First Commercializing Firm

Dr. V.Z. Williams, Vice President of Perkin-Elmer, often traveled to England on Perkin-Elmer business and had contacts among scientists there. (Among other products, Perkin-Elmer sold spectrophotometers to industrial and university scientists). On one of these trips, in 1953, Williams heard of gas-liquid partition-chromatography and suggested to Harry Hausdorff, a young employee of Perkin-Elmer with a background in chemistry, that it might be worth looking into as a commercial possibility.

Hausdorff made a trip to England, visited labs where homebuilt gas chromatography apparatus was in use, attended a lecture at Oxford on gas chromatorgaphy and came back, he recalls, with about twenty journal articles on or related to the subject. (By 1953-54 there were perhaps two dozen home-made GC apparatus in use around the world.) Dr. Hausdorff was convinced of the commercial potential of gas chromatography after his trip but had some difficulty interesting his superiors in the project. (They noted that the device had no optical parts and optics was, after all, Perkin-Elmer's forte.) Eventually Hausdorff prevailed and was given the go ahead to build a commercial device.

Data from Perkin-Elmer interview with L. S. Ettre and H. Hausdorff.

4. Pre-Commercial Events

Liquid-solid chromatography dates back to 1906 when Michael Tswett, A Russian botanist, found he could separate a solution of chlorophyll into fractions by filtering it through a column firmly packed with pulverized calcium carbonate.

Modern gas-liquid partition chromatography can be traced back to a 1941 paper by Martin and Synge which suggested the idea in the course of describing liquid-liquid chromatography--an invention which later won the authors a Nobel prize. No actual device was built in 1941. In 1952, Martin suggested to A.T. James, a young scientist working with him at the Mill Hill Medical Research Labs in England, that he try to build a gas chromatograph along the lines suggested in the 1941 paper. James did, and the device worked. Their initial paper in 1952 described the apparatus and gave some results they had obtained with it ("The Analysis of Fatty Acids and Amines by Gas Chromatography," Biochemistry Journal, 50, 679, 1952). After publication of the article, many scientists in industry and universities began to experiment with the technique. By 1953-54, L. Ettre estimates that there were perhaps two dozen home-made GC devices in use around the world.

L. Ettre tells of an additional route by which information on the promise of GC was transferred to the oil industry. After publication of their first results, Martin and James worked to explore the potential of GC to separate chemical isomers. Oil companies were the best source of isomers of known composition and high purity at that time, and Martin and James asked British Petroleum to send some samples. Denis Desty, a young chemist at British Petroleum brought the samples to Martin and James, looked at their GC work and reported on its potential to his firm.

Data from Perkin-Elmer interview with L. Ettre and H. Hausdorff and "Past, Present, and Future of Gas Chromatography," A.J.P. Martin address before ISA Information Symposium, Lansing, Michigan, 1957. Also, Ettre: "Chromatography," Anal Chem, Dec., 1971, and Ettre: "The Development of Gas Adsorbtion Chromatography," American Lab, Oct., 1972.

3. RESULTS

3.1 Overview of the Innovation Process in Scientific Instruments

The central fact which emerges from our study of the innovation process in scientific instruments is that it is a user-dominated process. In 81% of all major improvement innovation cases, we find it is the user who:

--Perceives that an advance in instrumentation is required;

--Invents the instrument;

--Builds a prototype;

--Proves the prototype's value by applying it ;

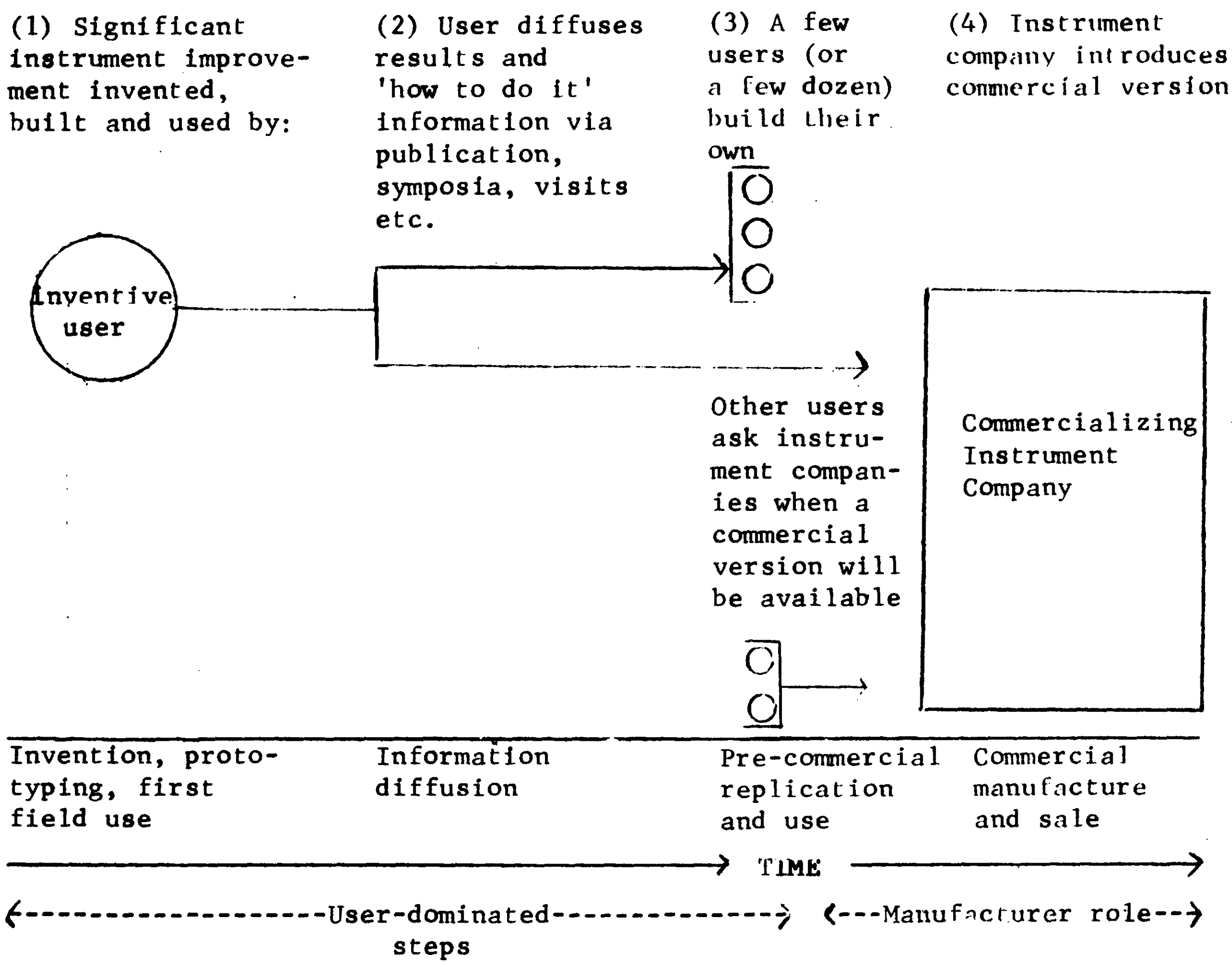
--Diffuses detailed information on the value of his invention and how his prototype device may be replicated, via journals, symposia, informal visits, etc. to user colleagues and instrument companies alike.

Only when all of the above has transpired does the instrument manufacturer enter the innovation process. Typically, the manufacturer's contribution is then to:

--Perform product engineering work on the user's device to improve its reliability, convenience of operation, etc. (While this work may be extensive, it typically affects only the engineering embodiment of the user's invention, not its operating principles);[9]

--Manufacture, market and sell the innovative product.

FIGURE 1: Typical Steps in the Invention and Diffusion of a Scientific Instrument or Instrument Improvement



9. See footnote 31, p. 36 for an elaboration of this distinction.

The frequency with which this 'typical' user-dominant pattern was displayed in our sample of scientific instrument innovations was striking, as the following table shows:

TABLE 3: Innovation process dominated[10] by:

Major Improvement Innovations Affecting:	% User Dominated	User	Manu-facturer	NA	Total
Gas Chromatography (GC)	82%	9	2	0	11
Nuclear Magnetic Resonance (NMR)	79%	11	3	0	14
Ultraviolet Spectro-photometry (UV)	100%	4	0	3	7
Transmission Electron Microscope (TEM)	79%	11	3	0	14
Total	81%	35	8	3	46

Interestingly, this user-dominated pattern appeared typical also for innovations which were more 'basic' than those in our main sample of major improvement innovations and for minor improvement innovations as well.[11]

10. We define the process leading to an ultimately commercialized innovation as 'user dominated' only if a user performed all of the following innovation-related tasks prior to commercial manufacture of the device: invention, reduction to practice, first field use, publication of detailed experimental methods used and results obtained. The data indicates that when a user does one of these tasks, he tends to carry out the entire set. Where he fails to carry out any one of them, however, we take a conservative stand relative to the user-dominant pattern we are exploring and code that case as manufacturer dominated.
11. See 'methods' for description of basic, major improvement and minor improvement innovations.

TABLE 4[12]: Innovation process dominated by:

Type of Innovation	% User Dominated	User	Manu-facturer	NA	Total
Basic Instrument	100%	4	0	0	4
Major Improvement	81%	35	8	3	46
(TEM only) Minor Improvement	70%	32	14	17	63
Total	79%	71	22	20	113

The user-dominated pattern we have described o appears to hold independent of the size - and thus, presumeably, of the internal R&D potential of the commercial company.

---

12. The reader may have noted in Table 4 a trend toward an increasing percentage of 'manufacturer' dominated innovations as those innovations become less significant. Our attention was also attracted by this pattern, and we made several attempts to gather data on innovations far out on the incremental/trivial dimension to see if we could find indications that the trend continued. We were largely frustrated in our efforts because, typically, no one could recall who had first done something <u>that</u> trivial ("You expect <u>me</u> to remember who first did <u>that</u>?). Interestingly, on those few occasions when we were able to approach the ultimate in trivia, we found that a user was the inventor. For example a protracted search for the source(s) of several minor changes in thermal conductivity detectors, (Thermal conductivity detectors are used in GC as well as other applications; in hardware terms, they consist of a hot wire filament mounted inside a chamber through which gas flows. The changes in the detector whose source we were attempting to trace involved minor changes in the geometry of the chamber or filament which resulted in modestly improved detector performance under certain conditions of use), resulted in only one nugget of information, provided by a manufacturer of such detectors: "We used to call that the NIH variation - so somebody in the National Institutes of Health probably specified it." Another example: We found 'Anti-capillary tweezers' advertized in the catalogue of C.W. French, Inc , a firm specializing in supplying the needs of electron microscopists. These tweezers differ from ordinary tweezers primarily by being bent in such a way that an electron microscopist's attempts to manipulate samples a few hundred microns thick is minimally impeded by a tendency for a menicus to form between the tweezers' working surfaces. When we phoned Mr. C. W. French to learn the source of this innovation, we were told that they were the invention of an electron microscope user. That user had told French of the tweezers' design and its advantages in the course of a conversation which took place when both were attending the annual meeting of EMSA (Electron Microscope Society of America).

TABLE 5 : Innovation Process Dominated By

Major Improvement Innovations* segmented by Annual Sales of Commercializing Company at date of Commercialization	% User Dominated	User	Manu-facturer	NA	Total
$ (000,000)					
≤ 1	100%	5[a]	0	0	5
1 ≤ , ≤ 10	50%	1	1	0	2
< 10, ≤ 100	69%	11	5	0	16
< 100, ≤ 1,000	86%	6	1	0	7
< 1,000	100%	3	0	0	3
NA	83%	5	1	0	9

a. Two of the five instances in this category were new companies established by universities to exploit their innovations.

* Data on UV sample not yet incorporated.

Finally, we observe that the pattern of a user-dominated innovation process appears to hold for companies who are established manufacturers of a given product line - manufacturers who 'ought to know' about improvements needed in their present product line and be working on them - as well as for manufacturers for whom a given innovation represents their first entry into a product line new to them.

TABLE 6[14]: Innovation process dominated by:

Major Improvement Innovations which represent:	% User Dominated	User	Manufacturer	NA	Total
A corporation's first entry to a new product line	100%	8	0	1	9
An addition to a corporation's established product line	71%	24	10	0	34
NA		3	0	0	3

14. Note that our sample contained no case in which a manufacturer dominated the innovation process leading to a product's initial entry into a product line. (We here regard GC, NMR, UV, TEM as 'product lines'). It is our (unquantified) impression that users often have to take considerable initiative to bring a company to enter a product line new to it. This is especially interesting when one notes that the degree of novelty involved in entering a new line was usually minimal for companies in our sample. Typically, a company would be introducing a new instrument to its established customer base.

As we noted in the section on 'methods,' our data contains several instances in which more than one major innovation was invented and/or first commercialized by the same instrument firm. Also there are a few cases in which the same innovative user was responsible for the pre-commercial work on more than one major innovation.[15] This raises potentially troublesome issues of sample independence. We can easily demonstrate, however, by means of a subsample which excludes all but the first case, chronologically[16] in which a particular user or firm plays a role, that at least this source of possible sample interdependence is not responsible for the pattern of user-dominated innovation which we have observed.

TABLE 7: A subsample of cases which excludes all but the first chronological case in which a given user and/or firm plays a role, shows substantially the same pattern as did the total sample.

	Innovation Process Dominated by:				
Major Improvement Innovations Affecting:	% User Dominated	User	Manufacturer	NA	Total
Gas Chromatography	86%	6	1	0	7
Nuclear Magnetic Resonance Spectrometry	100%	5	0	0	5
Ultraviolet Spectrophotometry	100%	3	0	0	3
Transmission Electron Microscopy	83%	5	1	0	6
Total	90%	19	2	0	21

The precommercial diffusion of significant user inventions via "homebuilt" replications of the inventor's prototype design by other users, shown schematically in Figure 1, appears to be a common feature of the scientific instrument innovation process. Literature searches and interviews in our GC and NMR samples (we did not collect this particular item of information for our UV and TEM samples due to time constraints found by those assisting with the data-gathering effort) showed that home-built replications of significant user inventions were made and used to produce publishable results in every case where more than a year elapsed between the initial publication of details regarding a significant new invention and the introduction of a commercial model by an instrument firm.

15. cf Table 11, p. 30.

16. Employment of other decision rules (eg: 'exclude all but the last case in which a given firm or user plays a role') does not produce a significantly different outcome.

TABLE 8: In the cases of user-dominated innovations, when the time-lag from publication of invention to first commercial model was:

	Greater than one year, were homebuilts present?				One year or less, were homebuilts present?			
	% Yes	Yes	No	NA	% Yes	Yes	No	NA
Gas Chromatography	100%	5	0	0	0%	0	3	1
Nuclear Magnetic Resonance	100%	8	0	1	0%	0	1	1
Total	100%	13	0	1	0%	0	4	2

3.2 Sample Cases

Abstracts of innovation case histories which display the user-dominant pattern we have observed may serve to give the reader a better feeling for the data we are presenting in this paper. Accordingly, three such abstracts are presented below. The first of these illustrates a user-dominated innovation process leading to a major improvement innovation in the field of Nuclear Magnetic Resonance. The second illustrates a manufacturer-dominated innovation process leading to a major improvement in Transmission Electron Microscopes. The third illustrates a user-dominated innovation process resulting in a minor improvement in Transmission Electron Microscopy. An example of the user-dominated innovation process which lead to commercialization of the basic innovation of Gas-Liquid Partition Chromatography may be found in non-narrative form in the preceding 'Methods' section where an example of a data collection "key" is given.

Case Outline 1: A Major Improvement Innovation: Spinning of a Nuclear Magnetic Resonance Sample (User-Dominant)

Samples placed in a nuclear magnetic resonance spectrometer (NMR) are subjected to a strong magnetic field. From a theoretical understanding of the NMR phenomenon it was known by both NMR users and personnel

of the only manufacturer of NMR equipment at that time (Varian, Incorporated, Palo Alto, Ca.) that increased homogeneity of that magnetic field would allow NMR equipment to produce more detailed spectra. Felix Bloch, a professor at Stanford University and the original discoverer of the NMR phenomena, suggested that one could improve the effective homogeneity of the field by rapidly spinning the sample in the field, thus 'averaging out' some inhomogeneities. Two students of Bloch's, W.A. Anderson and J.T. Arnold, built a prototype spinner and experimentally demonstrated the predicted result. Both Bloch's suggestion and Anderson and Arnold's verification were published in Physical Review, April, 1954.
Varian engineers went to Bloch's lab, examined his prototype sample spinner, developed a commercial model and introduced it into the market by December of 1954. The connection between Bloch and Varian was so good and Varian's commercialization of the improvement so rapid, that there was little time for other users to build homebuilt spinners prior to that commercialization.

Case Outline 2: A Major Improvement Innovation: Well-Regulated High-Voltage Power Supplies for Transmission Electron Microscopes (Manufacturer-Dominated Innovation Process)

The first electron microscope and the first few pre-commercial replications used batteries connected in series to supply the high voltages they required. The major inconvenience associated with this solution can be readily imagined by the reader when we note that voltages on the order of 80,000 volts were required - and that nearly 40,000 single cell batteries must be connected in series to provide this. A visitor to the laboratory of Marton, an early and outstanding experimenter in electron microscopy, recalls an entire room filled with batteries on floor to ceiling racks with a full-time technician employed to maintain them. An elaborate safety interlock system was in operation to insure that no one would walk in, touch something electrically live and depart this mortal sphere. Floating over all was the strong stench of the sulfuric acid contents of the batteries. Clearly, not a happy solution to the high voltage problem.

The first commercial electron microscope, built by Siemens of Germany in 1939, substituted a 'power supply' for the batteries but could not make its output voltage as constant as could be done with batteries. This was a major problem because high stability in the high voltage supply was a well-known prerequisite for achieving high resolution with an electron microscope.

When RCA decided to build an electron microscope, an RCA electrical engineer, Jack Vance, undertook to build a highly stable power supply and by several inventive means, achieved a stability almost good enough to eliminate voltage stability as a constraint on high resolution microscope performance. This innovative power supply was commercialized in 1941 in RCA's first production microscope.

Case Outline 3: A Minor Improvement Innovation: The Self-Cleaning Electron Beam Aperture for Electron Microscopes (User-Dominated Innovation Process)

Part of the electron optics system of an electron microscope is a pinhole-sized aperture through which the electron beam passes. After a period of microscope operation, this aperture tends to get 'dirty' - contaminated with carbon resulting from a break-down of vacuum pump oils, etc. This carbon becomes electrically charged by the electron beam impinging on it and this charge, in turn, distorts the beam and degrades the microscope's optical performance. It was known that by heating the aperture one could boil off carbon deposits as rapidly as they formed and keep the aperture 'dynamically clean.' Some microscope manufacturers had installed electrically heated apertures to perform this job, but these solutions could not easily be retrofitted to existing microscopes.

In 1964, a microscope user at Harvard University gave a paper at EMSA (Electron Microscope Society of America) in which he described his inventive solution to the problem. He simply replaced the conventional aperture with one made of gold foil. The gold foil was so thin that the impinging electron beam made it hot enough to induce dynamic cleaning. Since no external power sources were involved, this design could be easily retrofitted by microscope users.

C.W. French, owner of a business which specializes in selling ancilliary equipment and supplies to electron microscopists, read the paper, talked to the author/inventor and learned how to build the gold foil apertures. He first offered them for sale in 1964.

4. IMPLICATION OF THE OVERALL PATTERN OF INNOVATION IN SCIENTIFIC INSTRUMENTS: THE LOCUS OF INNOVATION AS AN INNOVATION PROCESS VARIABLE

We have seen that for both major and minor innovations in the field of scientific instruments, it is almost always the user, not the instrument manufacturer, who recognizes the need, solves the problem via an invention, builds a prototype and proves the prototype's value in use. Furthermore, it is the user who encourages and enables the diffusion of his invention by publishing information on its utility and instructions sufficient for its replication by other users -- and by instrument manufacturers.

If we apply our study finding to the stages of the technical innovation process as described by Marquis, we find, somewhat counterintuitively, that the locus of almost the entire scientific instrument innovation process is centered in the user. Only 'commercial diffusion'[17] is carried out by the manufacturer.

FIGURE 2: Main Locus of Innovation Activity by Stage of Innovation Process in the Scientific Instrument Industry[18]

Primary Actor	User					Manufacturer
Innovation Process Stage	Recognition	Idea Formulation	Problem Solving	Solution	Utilization Pre-Commercial	& Diffusion Commercial
(Capsule Stage Descriptions)	(Recognition of technological feasibility of an innovation and potential demand for it)	(Fusion of feasibility and demand perceptions into a design concept)	(R & D activity)	(Invention)		

This finding appears at odds with most of the prescriptive literature in the new product development process (e.g. the innovation process) directed to manufacturers. That literature characteristically states that the <u>manufacturer</u> starts with an 'idea' or 'proposal' and that the <u>manufacturer</u> must execute stages similar to those described by Marquis in Figure 2 above in order to arrive at a successful new product. For example, Booz, Allen, and Hamilton sug-

---

17. We have divided Marquis' 'utilization and diffusion' stage into precommercial and commercial segments.
18. The names of stages and the capsule descriptions of them used in Figure 2 are taken from Marquis and Meyers, <u>Successful Industrial Innovations</u>, National Science Foundation, May 1969, p.4, Figure 1, "The Process of Technical Innovation."

gests that a manufacturer wishing an innovative new product should proceed through the following 'stages of new product evolution:'

"* Exploration - the search for product ideas to meet company objectives.

* Screening - a quick analysis to determine which ideas are pertinent and merit more detailed study.

* Business Analysis - the expansion of the idea, through creative analysis, into a concrete business recommendation including product features and a program for the product.

* Development - turning the idea-on-paper into a product-in-hand, demonstrable and producible

* Testing - the commercial experiments necessary to verify earlier business judgments.

* Commercialization - launching the product in full-scale production and sale, committing the company's reputation and resources."[19]

As a second illustration from the new product development literature, the Conference Board, in their book, Evaluating New Product Proposals, devotes a chapter to "Early Stage Testing of Industrial Products." In it, they advise evaluation of industrial product concepts before much development work has been done by the firm, apparently assuming that this means that no prototype exists:

> " Just what kinds of idea-pretesting is appropriate or feasible depends on the nature of the product and its market, secrecy requirements and many other factors. If - as many companies recommend - concept testing begins as early as possible, then dealing with abstract ideas poses an especially troublesome dilemma. Naturally, it is easier for the sponsor to present the product idea meaningfully, and for the respondent to react meaningfully to it, if the project is at a more advanced stage where perhaps the respondent can review scale models or prototypes of the product. This is not always possible, but a number of companies have found ways of at least partially overcoming the difficulties of discussing a product that 'exists' only as an idea.
>
> Very early in a development project, concept testing may be carried out to weight potential users' initial reactions to the product idea,

19. Booz, Allen & Hamilton, Inc., Management of New Products, published by Booz, Allen & Hamilton, Inc., New York, 1968. pp. 8-9.

> whether a market need truly exists, or to gain some idea as to what commercial embodiment would have the greatest market appeal. Later, when a model or prototype has been developed, further testing may again be carried out..."[20]

It is perhaps natural to assume that most or all of the innovation process culminating in a new industrial good occurs within the commercializing firm. For many types of industrial goods, the locus of innovation is almost entirely within the firm which first manufactures that good for commercial sale.[21] Our findings that the scientific instrument innovation process doesn't follow such a within-manufacturer pattern does not invalidate that pattern -- it simply indicates, we feel, that other patterns exist.

Some might feel alternatively that the scientific instrument data which we have presented is not evidence of an innovation pattern differing from the within-manufacturer 'norm' and that the Booz, Allen and Hamilton/Conference Board scenarios can be made to fit the scientific instruments data. One might decide, for example, that the user built prototype of an innovative instrument available to an instrument firm simply serves as a new product

---

20. The Conference Board, Evaluating New Product Proposals, Report # 604, The Conference Board, New York, New York, 1973. pp. 63-64.

21. We have preliminary data, for example, which indicates that this would be an accurate description of the process of innovation in basic plastic polymers. Each of the seven basic polymers we have examined to date shows a history of innovation activity located almost entirely within the commercializing firm.
Some additional pressure in the direction of assuming a within-manufacturer innovation process pattern is universal may be exerted unintentionally via product advertising. Very naturally, in the course of marketing an innovation, manufacturing firms will advertise 'their' innovative device. These firms do not mean to imply that they invented, prototyped and field-tested the advertised innovation. But, in the absence of countervailing advertising by other contributors to the innovative process - advertising which they generally have no reason to engage in - it is easy to make the assumption.

'idea' which that firm, in Marquis' terminology, 'recognizes.' It would then follow that the stages coming after 'recognition' in the Marquis model also occur within the manufacturing firm. The 'idea formulation' stage, for example, would consist of the thinking devoted by manufacturer personnel to the commercial embodiment of the user prototype. 'Problem solving' and 'Solution' would be the engineering work leading to realization of the commercial embodiment.

Although one might make the argument outlined above, we ourselves find it rather thin and unproductive to do so: essentially the argument enshrines relatively minor activities within the manufacturer as the "innovation process" and relegates major activities by the user to the status of 'input' to that process. If instead we look at the scientific instrument data afresh, we see something very interesting: an industry regarded as highly innovative in which the firms comprising the industry are not necessarily innovative in and of themselves. Indeed, we might plausibly look at instrument firms as simply the manufacturing function for an innovative set of user/customers. Or, less extremely, we might say that in approximately eight out of ten innovation cases in the instrument industry, the innovation process work is shared by the user and manufacturer. Whatever the view, there are important implications for all those interested in the process:

-- Government, desirous of promoting industrial good innovations as a means of enhancing exports, improving industrial productivity, etc., should consider users as well as manufacturers when designing incentive schemes for innovation.

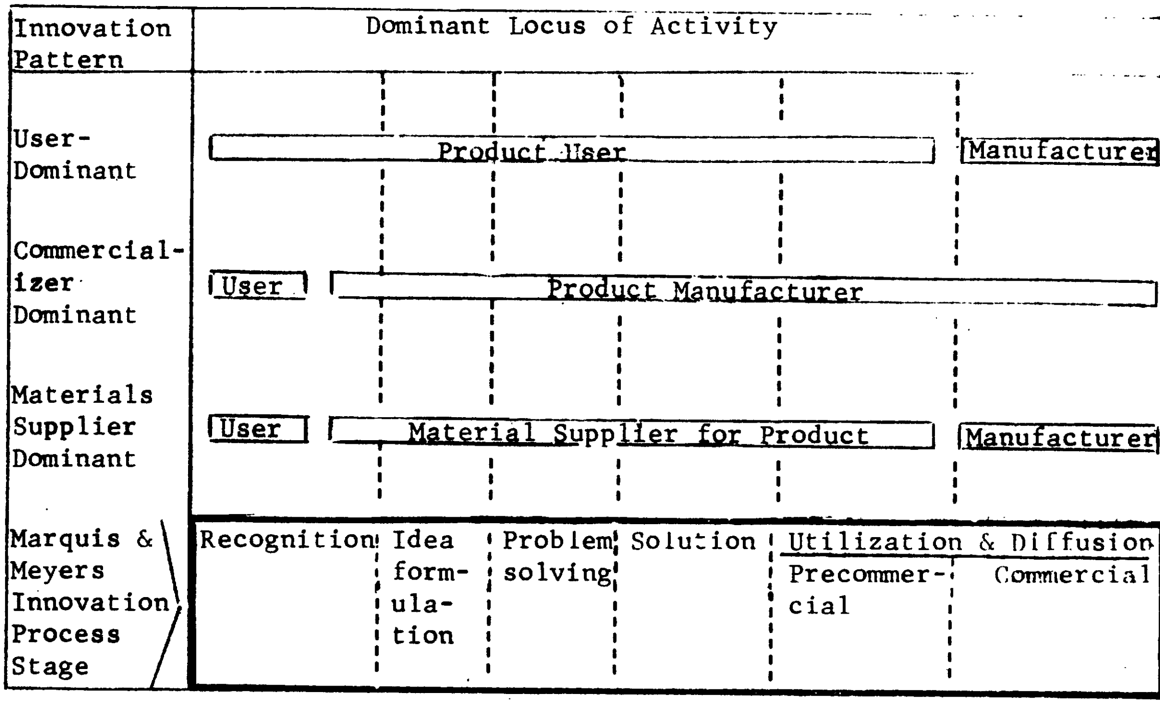
-- Instrument firms, finding that approximately eight out of ten successful instrument innovations come to them from users in the form of field tested prototypes, could optimize their innovation search and development organization for this kind of input

-- Researchers, interested in characterizing the innovation process, can shake their heads sadly at the realization that 'locus of innovation activity' is yet another variable to contend with.

4.1 Other Innovation Patterns

We ourselves hope eventually to be able to model shifts in the locus of the innovation process as a function of a few product and industry characteristics and are extending our data gathering into a range of different industries toward that ultimate end. At the moment, however, we can only offer the reader some innovation cases which suggest, but do not prove, that the locus of innovation is in fact an innovation process variable. As is indicated in Figure 3, following, we identified cases in the literature appearing to display three clearly different innovation patterns. In one of these the user is dominant, in one the manufacturer is dominant and in the third pattern the suppliers of material to manufacturers of innovative products appear dominant. We hasten to add that at this point we by no means wish to suggest that the patterns which we will describe are in any sense 'pure types' or represent an exhaustive listing of possible innovation patterns. We merely wish to offer these cases as interesting and suggestive of the possibility that a variety of patterns exist.

FIGURE 3: Innovation Patterns Displayed by Some Case Histories



4.2 A User-Dominated Innovation Pattern

A user-dominated innovation pattern is, as we have discussed, characteristic of scientific instruments used in laboratories and industrial process control. It is also typical of chemical process innovation, Project Sappho finds.[23] On the basis of anecdotal evidence, we suspect that this pattern is also characteristic of medical and dental innovations, (e.g. new dental equipment is usually invented, first used and perhaps discussed in journals by dentists prior to commercial manufacture being undertaken by a dental equipment firm). Further, we

23. It is noted in Sappho (op. cit.) that "...for process innovations, the first successful application is usually within the innovating organization." (Vol. 1, p. 67). If (a) the process innovation involved innovative hardware for its execution and if (b) a non-using manufacturer productized this equipment for commercial sale to other chemical processors, the situation would parallel exactly the innovation pattern which we found in scientific instruments. Conditions (a) and/or (b) do not always hold in the case of chemical process innovations however. With respect to the innovative hardware condition for example: Innovative chemical processes can often be carried out using standard process hardware, just as a standard lab testtube can play a role in a novel chemical experiment.

have found that the patte is at least occasionally present in the innovation of industrial process machinery.[24]

For examples illustrative of a user-dominant innovation pattern, the reader may refer to case outlines 1 and 3 in section 3.2 of this paper.

4.21 A Manufacturer-Dominated Innovation Pattern

Case outline 2 in section 3.2 displays a manufacturer-dominated innovation pattern. Input from the user is restricted to a statement of a need, if that. All other innovation activity is carried out by the manufacturer who first commercializes the innovation.

4.22 A Material Supplier-Dominated Innovation Pattern

Professor Corey of Harvard has written a fascinating book[25] in which he describes an innovation pattern apparently characteristic of suppliers of 'new' materials. Essentially, when suppliers of such materials (e.g. plastic, aluminum, fiberglass) want to incorporate their material into a product but do not want to manufacture the product itself, they will often:

--design the product incorporating the new material;

--help an interested manufacturer with start-up problems;

---

24. An example is provided by a paint manufacturing firm which invented built and field tested a new type of paint mill. After debugging the prototype, it sent engineering drawings to a company specializing in heavy metal fabricating and ordered several for its own use. Later the fabricating company built many more of the innovative paint mills and sold them to other paint companies.
25. E. Raymond Corey, The Development of Markets for New Materials, Division of Research, Graduate School of Business Administration, Harvard University, Boston, Mass., 1956.

--help market the manufacturer's new product to his customers.

The extent to which the materials supplier can be the locus of activity leading to innovative products commercialized by others is made clear in the following two examples from Corey:

(A) Vinyl Floor Tile

> "Bakelite Company, a chemical company producing plastic materials did much of the pioneering work on the chemical technology of using vinyl resin in flooring and on the development of commercial processes for manufacturing various types of vinyl floor products...
>
> Bakelite had experimented with vinyl flooring as early as 1931. In 1933 Bakelite installed vinyl tile in its Vinylite Plastics House at the Chicago World's Fair to demonstrate the product and to get some indication of its wearing qualities. When the flooring was taken up at the close of the Fair, no measurable decrease in its thickness could be noted even though an estimated 20 million people had walked over this surface...
>
> Bakelite Company personnel had attempted before World War II to interest leading linoleum manufacturers such as Armstrong Cork and Congoleum-Nairn in making continuous vinyl flooring. These efforts were to no avail...
>
> The first company to take on the manufacture of continuous vinyl was Delaware Floor Products, Inc., a small concern located in Wilmington, Delaware...
>
> One Bakelite engineer spent almost full time for six months in 1946 to help Delaware Floor Products personnel to iron out the "bugs" in the production process."[26]

(B) Aluminum Trailers for Trucks

> "Alcoa first attempted to promote the use of aluminum in vantype trailers in the late 1920's. In the early stages of market development, Alcoa representatives achieved the greatest success by working with fleet operators and persuading them to specify aluminum when ordering new trailers...
>
> In the development of markets both for aluminum van trailers and for vinyl flooring, the materials producers assumed the burden of extensive technical development work. In the case of the aluminum van

26. Ibid., pp. 18, 21, 22.

> trailer, for example, it was an Alcoa engineer who developed the basic design for the monocoque trailer...
>
> In addition to developing the basic monocoque design, Alcoa engineers assisted fleet operators in designing individual trailers and worked with trailer builders on the techniques of aluminum fabrication. When a fleet operator could be persuaded to specify aluminum in a new trailer, Alcoa prepared design drawings and bills of materials for him. Alcoa personnel then followed closely the construction of this unit by the trailer builder and provided the builder with engineering services during the period of construction." [27]

5. FURTHER FINDINGS AND DISCUSSION

To this point we have restricted our presentation of findings to the overall pattern of the innovation process observed in scientific instruments. In the space remaining, we would like to present further findings and discussion bearing on two aspects of that innovation process. Specifically, we would like to present:[28]

- A further characterization of the 'inventive user';
- An attempt to discern what aspects of the information potentially derivable from a user's prototype

(con't)

---

27. Ibid., pp. 35, 36, 41, 42.

28. Obviously, there are many additional issues which it would be instructive to explore. We are currently addressing some of these in a real-time study of the instrument innovation process now being carried out by Frank Spital, a doctoral candidate at MIT's Sloan School. The real-time feature of this study will allow one to pick up data on issues which one would like to explore, but for which important data is evanescent. For example, it would be very interesting to explore the search and screening strategems used by instrument firms to select out instruments worth commercializing from the range of user prototypes available to them (Or, to state the same issue in terms of an active user: It would be very interesting to explore the search and screening strategems used by user/inventors to select instrument companies to commercialize their prototypes). We have found, however, that the selection process is not very well documented by instrument firms (or users) and that therefore the reliability of retrospective data which might be gathered on this issue is suspect.

instrument (one can find data bearing on both need and on solution technology by studying such a prototype) is actually new and useful information to commercializing firms.

5.1 Characterization of the Innovative User

An instrument firm engulfed by users of its products might well be interested in knowing more about the characteristics of those likely to come up with prototype instruments of commercial potential. It might be modestly useful in this regard to note the organizational affiliations of the inventive users in our sample:

TABLE 8: Inventive Users Were Employed By:

Major Improvement Innovation	University or Institute	Private Manufacturing Firm	Self-Employed	NA	Total
Gas Chromatography	3	3	1	2	9
Nuclear Magnetic Resonance	9	0	0	2	11
Ultraviolet Spectrophotometry	NA	NA	NA	NA	NA
Transmission Electron Microscopy	10	0	0	1	11

We might also note that we feel we can discern two quite different types of reasons why the user-inventors in our sample undertook to develop the basic or major improvement credited to them. Some needed the invention as a day-in, day-out functional tool for their work. They didn't care very much <u>how</u> the tool worked, only that it <u>did</u> work. An example of such a user might be a librarian who builds an information retrieval system of a certain type - because he/she needs it to retrieve information. Others were motivated to invent and reduce the invention to practice because how it performed was a useful means of testing and deepening their understanding of the principles underlying its operation. Thus, a researcher attempting to understand how bits of information are interrelated might also build an information retrieval system - not because he wanted to retrieve information himself or help others to do so, but because he wanted to test an hypothesis. Note that a 'user' inventor so motivated does use his creation although not necessarily for its nominal purpose.

We have not attempted to code our sample of users according to the motivational distinction outlined above because motivations are hard to judge and often change over time: A biologist might start out to improve gas chromatography apparatus in order to forward his work in membranes but later get fascinated by the process itself and continue to explore it for its own sake.

5.12 Multiple Significant Innovations by the Same Individual

The search process of instrument companies for user invented prototypes of commercial interest would be eased if the same non-instrument firm employees tended to come up with more than one such prototype. We went through our data and did find a few such cases as shown in Table 11 below.

TABLE 11: Multiple Significant Innovations by the Same Individual

Major Improvement Innovations Affecting:	Total Major Innovations by Users	Instances of more than one major Innovation Invented by the same non-instrument firm employee
Gas Chromatography	9	2 by one user
Nuclear Magnetic Resonance	11	3 by one user
Transmission Electron Microscopy	11	4 by one user
Total	31	9

Those individuals who are responsible for more than one significant innovation in an instrument type are not unknown quantities to instrument a user prototype will in effect be saying: 'We already knew what you needed, but didn't know how to build a suitable device. Thanks for the design help." A firm using both the need and solution content of the user prototype will be saying in effect: 'You need that? OK. I'll build some to your design.')

6.1 Frequency with which Technical Solution Content of User Prototype was Utilized by Commercializing Firm

Clearly, we cannot directly ask personnel of commercializing firms 'which aspects of Dr. X's user prototype conveyed novel information to you when you looked it over in 1953,' because retrospectively-gathered data is notoriously unreliable, unless substantiated by memos or other forms of contemporaneously generated evidence.[30] We can, however, reliably note whether the solution content of a user prototype was exploited by a commercializing firm by looking at physical artifacts: Does the commercialized instrument display the same technological solution to the new problem as did its user prototype predecessor? As we indicated earlier in this article when we described the product manufacturer's role in the innovation process as product engineering work which "...typically affects only the engineering embodiment of the user's

---

30. See, for example, J.J. Levine and G. Murphy "The Learning and Forgetting of Controversial Material," J. Abnormal and Social Psychology, 38, 1943, pp. 505-517. In this study Levine and Murphy observed that only 30-40% of "ideas" learned over a four week training period were correctly reproduced by the subjects upon testing five weeks after this training period was concluded. (The study additionally noted a differential rate of learning and forgetting as a function of the 'controversial nature of the material learned. For both controversial and non-controversial material, however, the rate of forgetting was in the range noted above).
A study by A.G. Dietze and G.E. Jones, "Functional Memory of Secondary School Pupils for a Short Article Which They Read A Single Time," J. Educ. Psychology, 22, 1931, pp. 586-698, 667-676 shows a 60% recollection rate immediately after the reading dropping to 30% after 100 days.

invention, not its operating principles," the answer to the question is 'yes,' the operating principle portion of the solution content of the user prototype is typically used.[31]

TABLE 12: In those cases where a user prototype precedes a commercialized innovation, was the solution used by the prototype substantially replicated in the commercial device?

Major Innovations	% Yes	Yes	No	NA	Total
Gas Chromatography	78%	7	2	0	9
Nuclear Magnetic Resonance	82%	9	2	0	11
Ultraviolet Spectrophotometry	100%	4	0	3	7
Transmission Electron Microscopy	64%	7	4	0	11
Total	77%	27	8	3	38

Interestingly, in all cases where an instrument firm did not utilize the operating principles of a preceding user prototype in its commercial version, the operating principle involved lay within the purview of mechanical or electrical engineering.

31. The coding of this question involves some existence of technical judgement by the codes as no clear definitional boundary exists between the 'operating principles' of an invention and its 'engineering embodiment: Perhaps we can best convey a feeling for the two categories via an illustration. If we may refer to the example provided by Bloch's sample spinning innovation described on p. 17-18 of this paper: The concept of achieving an effective increase in magnetic field homogeneity via the 'operating principle' of microscopically spinning the sample can have many 'engineering embodiments' by which one achieves the desired spin. Thus one company's embodiment may use an electric motor to spin a sample holder mounted on ball bearings: Another might, in effect, make the sample holder into the rotor of a miniature air turbine, achieving both support and spin by means of a carefully designed flow of air around the holder.
One should note that our distinction between the operating principle(s) of an innovation and its engineering embodiment is not a function of the presence or absence of any absolute level of inventiveness or creativity displayed. Rather, it is a relative measure which distinguishes between the overall outlines of the technical solution content of a given innovation and its detailed engineering execution. (Were we to attempt to establish some absolute level of innovation as our measure, we would find that the most creative aspects of some of our sample of innovations of major functional utility only rose to the 'creatvity level' of the 'engineering embodiment' aspects of other innovations. The consequence would be an obscuration of the finding which we perceive as interesting here: Users are responsible for the operating principles--the 'overall outlines' of the technical solution content of 77% of instrument innovations judged to be of major functional utility).

6.2 Use of Implicit Need Content of User Prototype by Commercializing Firm

Unfortunately, no similar, retrospectively reliable evidence exists regarding the novelty and usefulness of the user need content which a user prototype makes available to a commercializing firm. Did the firm know of the need prior to the user prototype's availability? Hardware and publications typically can shed no light on this matter. Intriguing comments from interviews, however, seemed to indicate that the user need content of a user prototype sometimes was not novel to the commercializing firm. A sample of the comments:

--'we knew improved sensitivity was important, and we were always looking for ways to get it.'

--'everyone working in NMR knew that if you would make the magnetic field more homogeneous, you could improve the instrument's resolution.'

6.21 Dimensions of Merit

Comments such as the above implied to us that sometimes the fresh user need input involved in a user prototype instrument was not necessary to attain an innovation presumeably accurately responsive to user need.

Seeking to understand why this might be the case, we hypothesized a concept which we call 'dimensions of merit' which suggests that fresh user need input is not required for some types of innovations but is necessary for others. What we mean by the 'dimension of merit' as opposed to a 'unit of merit' can be seen in the following example. Suppose that an aircraft manufacturer requires an electrical generator for use in a new airplane he is designing. His purchase order to a manufacturer of generators might specify, among other things, that:

(1) the electrical output of the generator must be 440 Hertz (cycles per second) and

(2) the generator must be as reliable as possible - with a minimum acceptable reliability of x mean failures per thousand hours.

Note that when the generator manufacturer has met the 440 Hertz requirement of specification #1, he has exhausted the information content of that specification. There is no implication that, if the generator manufacturer finds he can build a generator next year capable of 441 Hertz, the aircraft manufacturer would be pleased to buy it - and, in fact, he surely wouldn't. Specifications of type 2, however, contain information about a dimension along which improvement is desired by the user. At the time of the order, the generator manufacturer will produce a product as reliable as he then can - given the state of the technology at the time and other constraints in the specification package given him by the aircraft manufacturer, such as cost. If later an opportunity presents itself to improve reliability further - as a consequence of the availibility of a certain type of transistor, for example - the generator manufacturer has the need data from the user already in hand to proceed with the innovation. He needs no new specific need input.[32]

32. Note that although the argument presented here would say that the innovation of a transistorized aircraft generator was in fact a response to a previous user need input, the immediate stimulus would be the new technological opportunity represented by the availability of transistors. Previous studies, therefore, might well have recorded the innovation as 'technology stimulated.'

Figure 4: Dimensions of Merit vs. Points of Merit

An aircraft generator specification contains information regarding:

DIMENSIONS OF MERIT such as:

'the generator will be as: light
cheap
reliable
small as possible'

POINTS OF MERIT such as:

The generator output will be 440 Hertz

The generator will be a face mounted against a circular flange of design X

The generator will operate in: air pressure as low as X pounds per square inch

temperature as low as Y degrees Centigrade

Is there any evidence to support our hypothesized 'dimensions of merit' concept? While there is evidence that aspects of user need for industrial good innovations are sometimes expressed in dimensional terms,[33] there is not yet any data on a possible correlated reduction in the amount of new need input used by firms which commercialize inno-

33. The expression of new product attributes in dimensional terms is common currency in the fields of Marketing Research and Technological Forecasting. Also, Tom Allen has found that aerospace engineers engaged in technical problem-solving expressed aspects of the customer's solution specification in dimensional form. He called these "critical dimensions" in Frischmuth and Allen, "A Model for the Description and Evolution of Technical Problem Solving," IEEE Transactions on Engineering Management, May, 1969). Also, engineers working on a complicated set of specifications will sometimes express the relationship between some of these by means of a mathematical equation. The solution to this formula is sometimes called a 'figure of merit' with an acceptable solution to the problem being defined in part as achieving a particular value for that figure of merit.

vations accurately responsive to user need.[34] Certainly the concept appears congruent with common sense, however. One suspects, for example, that computer manufacturers know that a cycle time as fast as possible and a cost per calculation as low as the state of technology will allow is desired by the user. Few would suggest that computer manufacturers stop and rest on their laurels after each cost-reducing speed-increasing innovation until a user approaches them with a new need input suggesting that still faster and cheaper is desirable. Similarly, one would not expect plastics manufacturers to stop improving plastics along such dimensions of merit as impact strength, and flame resistance in the absence of new need inputs received after each incremental improvement.

6.22 Complexities of Describing A Dimension of Merit

If one wants to, one can define a dimension of merit so general that any innovation can be said to be subsumed by it. For example, the dimensions of merit: "chemists desire that the process of analysis of chemical unknowns be made easier, more accurate, and less expensive," would probably embrace every innovation in GC, NMR, and UV examined by this study. The problem is not to invent a dimension of merit. Rather, one should seek out dimensions which commercializing firms use and which they feel reflect a dimension of user need

34. Unfortunately, we cannot develop the required evidence by means of the retrospective data base used in the present study. Although a particular innovation in our data might appear to us to be clearly responsive to a user dimension of merit and thus we hypothesize, require no new user need input for its accomplishment, we have no way of assuring ourselves on the basis of retrospective data that no new need input was, in fact, present. Some anecdotal support for the dimension of merit hypothesis, however, can perhaps be designed from the interview data collected for this study as follows: Interviewees would sometimes spontaneously describe the utility of a particular innovation in terms of a step along a dimension of merit.

accurately enough to allow them to innovate without a need for fresh user input. Such a dimension will probably not be as simple as we perhaps implied when we suggested that 'reliability' might be a dimension of merit applicable to an aircraft generator. To suppliers of and users of aircraft generators, the term 'reliability' probably embraces complex subcriteria such as:

-- frequent failures at known intervals are preferable to infrequent failures at unknown intervals
-- a 'graceful,' gradual failure is preferable to an abrupt one

6.23 Further Points Regarding 'Dimension of Merit'

--Incremental improvements along a dimension of merit may be of progressively less utility to the user. Extension of the mean time between failure of an aircraft generator, for example, to a period longer than the expected life of the aircraft it serves is probably of limited interest to the user. Similarly, successive halvings of the hardware cost of a computer of a given power will be of progressively less interest to computer users if other elements of total cost per calculation such as software, remain unchanged.

--A dimension of merit, once identified, is traversed incrementally only because technological or other constraints (eg. social constraints prevent the elimination of rush hour) prevent one from moving immediately to the desired end point.

--Some dimensions of merit are special to a particular context and need be ascertained by examining user need within that context, while others are general from context to context and can be assumed. Thus, an innovator must understand NMR and what a user needs it for before he can derive 'increased homogeneity of magnetic field' as a demension of merit. He need know nothing about NMR, however, to understand that the general dimension of merit, 'decreased cost' applies.

6.24 Operational Implications of Dimensions of Merit

If further research indicates that the 'dimensions of merit' hypothesis has some validity, the concept may provide firms with a tool to better understand the type and amount of need information which they need if they are to accurately understand users' needs in their particular marketplaces. For example, if one is a member of an industry in which the major thrust of innovative effort is devoted to progress along dimensions of merit, one's R&D program needs little input from the user. Arthur Bennes of Lockheed Electronics, implied this way true for his specialized market segment when he said:

> 'The defense market is better defined than the commercial market. We always know that we can sell another 10 dB of subclutter visibility, but we are not always sure what the consumer will buy as far as a commercial product is concerned.'[35]

Conversely, if one is in an industry where innovation is dominated by points of merit, a constant flow of new need data is all. Consumer good innovation often rests on points of merit. If a breakfast cereal of a given sweetness is a hit, one cannot assume that increasing or decreasing the sweetness will be better still. Further,

35. Hillier,"Venture Activities in the Large Corporation,"IEEE Transactions on Engineering Management, June, 1968, p. 69.

even if it happens that one has identified an important new parameter and that more or less sweetness would be desirable, there are no technological barriers preventing movement on the sweetness dimension. One can immediately move to the newly identified ideal point - thus exhausting the innovation-orienting potential of the nascent sweetness dimension.

Isolation from user and new need input while preoccupied with moving down a dimension of merit can be dangerous. One might easily miss signs that the marginal utility to users of further improvement on that dimension is dropping, and continue emphasizing it after one should perhaps be moving on to other things.

Aside from the improved understanding of the 'structure' of user need which it may allow, the operational utility a firm may derive from an awareness of 'dimensions of merit' is very much a function of the cost of acquiring user need information: If the cost of information is high the potential utility is high and vice-versa. This is because the effect of describing a user need partially in terms of dimensions of merit is to reduce the amount of new input required by a firm keeping current on that need. If the dollar cost of acquiring that increment of user need information accurately is high,[36] so is the saving obtained by eliminating the need to acquire it through recasting one's understanding of the user need in terms of dimensions of merit. If, on the other hand, accurate user need input flows in as an almost costless by-product of customer contact, monitoring of competitors, scanning of literature, etc., which would continue independent of the user need information garnered, the savings obtainable are small.

---

36. What the firm requires is new accurate information. The total cost of its acquisition is the cost of obtaining the raw data plus the cost of processing to obtain/assure accuracy and relevance.

7. SUMMARY

Previous research into the industrial good innovation process has indicated that accurate understanding of user need on the part of innovating firms is key to a commercially successful outcome.[37] Our present study has undertaken to examine precisely how such accurate understanding is achieved in the instance of innovating scientific instrument firms.

We have found that scientific instrument firms face an information-laden marketplace. Innovative instrument users are continually filling conferences and journals with detailed descriptions of innovative <u>solutions</u> to their self-perceived needs which they have prototyped and field-tested themselves. This information is available to the instrument manufacturer as a means by which he may accurately understand user needs; and/or as a ready, costless[38], source of technical solutions to those needs.

We have found that the instrument manufacturer typically <u>does</u> utilize information from this source, and that commercially successful, new-to-the-marketplace scientific instrument innovations are derived from home-made prototype instruments built by users.

As we studied the extensive user contribution to the instrument innovation process - a contribution which typically includes perception of the need, invention of a solution, reduction to practice, first field use and the dissemination of information on both the design of the instrument and results obtainable with it - and compared it with the instrument firms' usual contribution of product engineering, manufacture and sale, we began wondering whether the conventional innovation process model offered an adequate description of such data. The conventional model describes the

37. cf. references cited on page 1 of this paper.
38. Users almost never patent their homebuilt instrumentation, and will usually allow instrument company personnel to come to their laboratories to examine it without attempting to exact a price.

commercializer of an innovative product as the main locus of the innovation process culminating in that product, while our data shows an innovation process whose main locus of activity is the product user, approximately 80% of the time. We have suggested that scientific instrumentation is not the only industry for which this user-dominated pattern is typical.

Once one becomes used to seeing the locus of innovation activity as an innovation process variable, still other patterns may be found typical of other industries. As an example, we have offered anecdotes in which suppliers of new materials are seen playing central roles in the innovation process leading to innovative industrial goods which they themselves will not manufacture.

The results and lack of results of the study we have reported on here lead us to suggest two research directions as being exciting and worth further work:

(1) We feel that the finding that the locus of innovation activity is not necessarily found within the commercializing firm, but rather may vary from industry to industry and very possibly also within a single industry is worth further exploration. An effort to map who carries out what role in the innovation process in various industries and structures might allow us to eventually model and understand the 'locus of innovation'. Such understanding would surely benefit those trying to manage the innovation process at the firm, industry or government level: knowing where innovation occurs would seem to be a minimum prerequisite for exerting effective control.

(2) In this study we keenly felt our inability to explore certain issues of interest within the context of the scientific instrument industry, due to limitations inherent in retrospectively-gathered data. We have been unable to 'see' messages about and perceptions of user needs which were not documented contemporaneously. More narrowly, we have been unable to test our

hypotheses regarding the impact of 'dimensions of merit' on the accurate understanding of user need by instrument firm. Also, we have not been able to determine how instrument firms choose out some user prototypes for commercialization from the many available (or do users with prototypes choose firms?) Better understanding of such issues should make it possible to make operationally useful suggestions regarding the scientific instrument innovation process.