SUMMARY

A sample of one hundred and eleven scientific instrument innovations was studied to determine the roles of instrument users and instrument manufacturers in the innovation processes which culminated in the successful commercialization of those instruments. Our key finding was that approximately 80% of the innovations judged by users to offer them a significant increment in functional utility were in fact invented, prototyped and first field-tested by users of the instrument rather than by an instrument manufacturer. The role of the first commercial manufacturer of the innovative instrument in all such cases was restricted, we found, to the performance of product engineering work on the user prototype (work which improved the prototype's reliability, 'manufacturability', and convenience of operation, while leaving its principles of operation intact) and to the manufacture and sale of the resulting innovative product. Thus, this research provides the interesting picture of an industry widely regarded as innovative in which the firms comprising the industry are not in themselves necessarily innovative, but rather – in 80% of the innovations sampled – only provide the product engineering and manufacturing function for innovative instrument users.

We term the innovation pattern observed in scientific instruments a 'user dominated' one and suggest that such a pattern may play a major role in numerous industries.

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the dominant role of users in the scientific instrument innovation process*

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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**,
(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

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** Utterback [1] lists the quantitative findings of eight studies which support this point.

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?

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 this introductory section, we describe our methods of sample selection and collection of data in sect. 2. In sect. 3 we present our findings on the overall pattern characteristic of innovation in scientific instruments, and in sect. 4 we discuss the implications of these. Sections 5 and 6 are given over to the presentation and discussion of more detailed findings bearing on two aspects of the innovation process in scientific instruments, and sect. 7 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

Table 1
Sample composition

Instrument type	Basic innovations	Major improvements	Minor improvements	Total
Gas chromatography	1	11	–	12
Nuclear magnetic resonance spectrometry	1	14	–	15
Ultraviolet absorption spectrophotometry	1	5	–	6
Transmission electron microscopy	1	14	63	78
Total	4	44	63	111

major and minor improvement innovations involving these. The total sample size is 111, distributed as shown in table 1. 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*. Given our sample size of 111 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 [3, 4]. This minimized the risk of choosing to study user need input in an industrial segment where, for some unforeseen reason, such input would turn out not to be salient. Gas–liquid partition chromatography, nuclear magnetic resonance spectrometry, ultraviolet spectrophotometry (absorption, photoelectric type), and transmission electron microscopy 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**.

– 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.

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 [4], Utterback [3], and

* Cf. Project SAPPHO's [2] innovation patterns in the chemical and instrument industries.

** National Research Council of the National Academy of Sciences [5] 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 US 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.

Table 2
Characterization of sample

Instrument type	Annual world-wide sales 1974[a)]	Per unit cost range[a)]	Approx. median unit cost[a)]	Utility measure[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 absorption spectrophotometry	120mm	2.7–26k	6k	21	1941
Transmission electron microscopy	20mm	30–90k	50k	–	1939

a) Source: Estimates by instrument company market research personnel.
b) Instance of use per 100 articles, 1964 (ref. [5], p. 88).

Achilladelis et al. [2]. 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, 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 Spectrophotometer 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.

2.2.1. Major improvement innovations

In setting out to identify major improvement innovations, we took as our base line features which appeared on the initially commercialized unit. Major innovations which were commercialized at a later data 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 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* of users is minimal. From the user's point of view, inputs and outputs affecting him significantly remain undisturbed by the change.

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 contracted 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 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 were collected on *every* major improvement innovation identified by our consensus among experts.

2.2.2. *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.

* 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.

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.

2.2.3. Minor improvement innovations

The criterion for inclusion in our sample of minor innovations (collected for Transmission Electron Microscopy only)* 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 were 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.;

* 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 Transmission Electron Microscopy 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.

(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.

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 collected by interview were written up and sent to the interviewees for verification of accuracy and correction as necessary.

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;

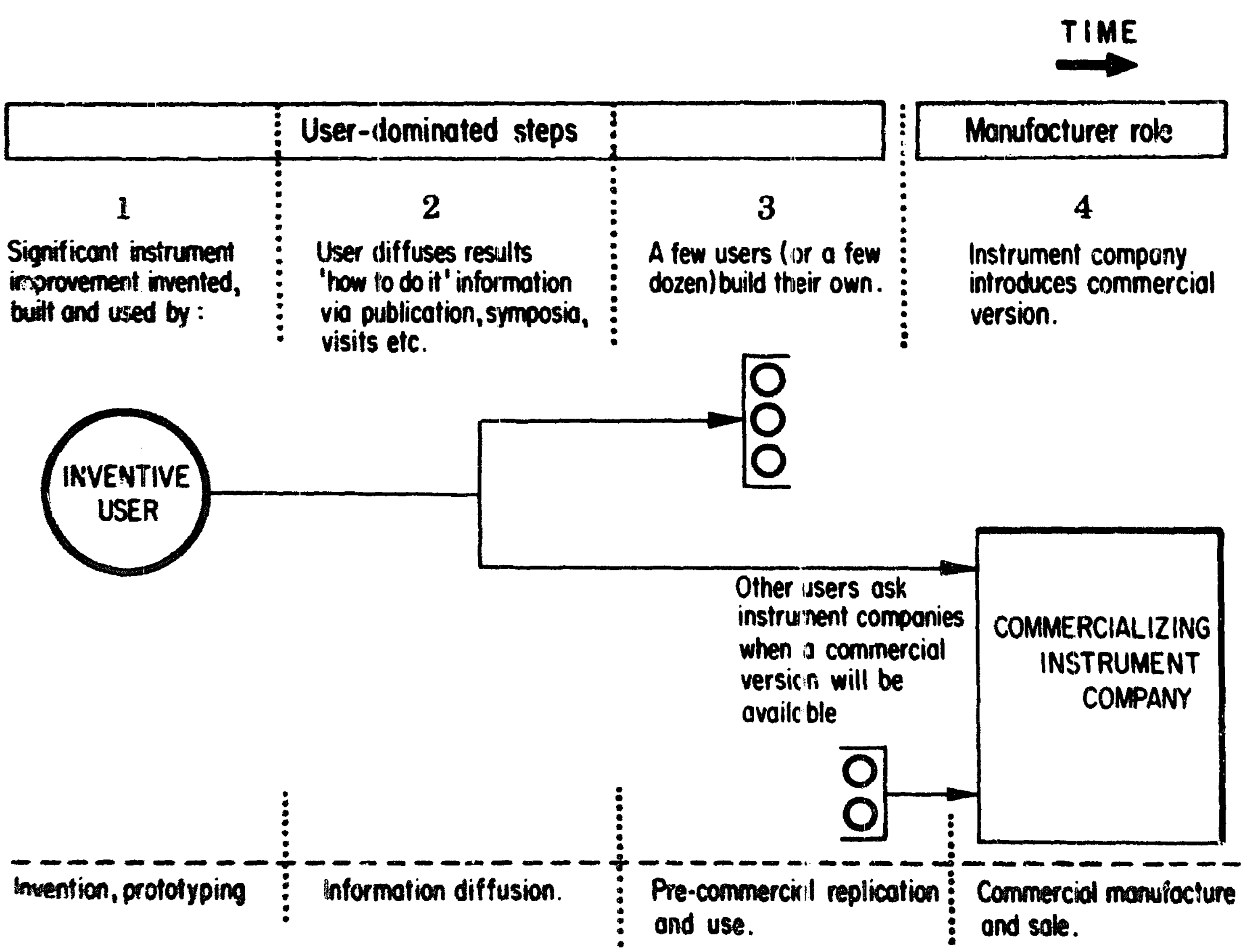

Fig.1. Typical steps in the invention and diffusion of a scientific instrument or instrument improvement.

– 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)*;

– Manufacture, market and sell the innovative product.

The frequency with which this "typical" user-dominated pattern was displayed in our sample of scientific instrument innovations was striking, as table 3 shows.

Interestingly, as table 4 indicates, 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**.

Table 3
Frequency of user-dominated innovative processes by type of instrument

Major improvement innovations affecting	% User dominated	Innovation process dominated by: User	Manufacturer	NA	Total
Gas chromatography	82%	9	2	0	11
Nuclear magnetic resonance	79%	11	3	0	14
Ultraviolet spectrophotometry	100%	5	0	0	5
Transmission electron microscope	79%	11	3	0	14
Total	81%	36	8	0	44

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 indicate 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-dominated pattern we are exploring and code that case as manufacturer dominated.

* Cf. first footnote in sect. 5 for an elaboration of this distinction.

** See sect. 2 for description of basic, major improvement and minor improvement innovations.

Table 4
Frequency of user-dominated innovative processes by type of innovation

Type of innovation	% User dominated	Innovation process dominated by User	Manufacturer	NA	Total
Basic instrument	100%	4	0	0	4
Major improvement	82%	36	8	0	44
Minor improvement (Transmission electron microscope only)	70%	32	14	17	63
Total	77%	72	22	17	111

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 *that* trivial ("You expect *me* to remember who first did *that*?"). Interestingly, on those few occasions when we were able to approach the ultimate in trivia (e.g. specially-shaped tweezers useful for manipulating electron microscope samples), we found that a user was the inventor.

The user-dominated pattern we have described also appears to hold independent of the size – and thus, presumably, of the internal R & D potential – of the commercializing company. Only one out of the ten major improvement innovations in our sample which were first commercialized by companies with annual sales greater than one hundred million dollars (at the time of commercialization) was the result of a manufacturer dominated innovation process. Nine of the ten were the result of user-dominated innovation processes.

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. Of the thirty-four major improvement innovations in our sample which represented additions to established product lines of the companies commercializing them, twenty-four were the result of user-dominated innovation processes and ten the result of manufacturer-dominated processes. *All* of the eight major improvement innovations which represented the commercializing companies' initial entry into a new product line and which we were able to code on this issue (the information was not available in a ninth case) were the result of user-dominated innovation. Indeed, 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. (We here regard Gas Chromatography, Nuclear Magnetic Resonance Spectrometry, Ultraviolet Spectrophotometry, and Transmission Electron Microscopy as "product lines".) 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 type to its established customer base.

As we noted in sect. 2, our data contain 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**. This raises potentially troublesome issues of sample independence. We can easily demonstrate, however, by means of a subsample (table 5)

Table 5
A subsample of cases, which exclude 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.

Major improvement innovations affecting:	% User Dominated	Innovation process dominated by User	Manufacturer	NA	Total
Gas chromatography	86%	6	1	0	7
Nuclear magnetic Resonance spectrometry	100%	5	0	0	5
Ultraviolet spectrophotometry	100%	2	0	0	2
Transmission electron microscopy	83%	5	1	0	6
Total	90%	18	2	0	20

* Specifically, the 111 innovations in our sample were first commercialized by only twenty-six companies as follows: Gas Chromatography; 12 innovations first commercialized by 8 companies. Nuclear Magnetic Resonance Spectrometry; 15 innovations first commercialized by 3 companies. Ultraviolet Absorption Spectrophotometry; 6 innovations, first commercialized by 2 companies. Transmission Electron Microscopy; 15 basic and major improvement innovations, first commercialized by 6 companies plus 63 minor innovations first commercialized by a total of 7 companies.

** Cf. table 8.

Table 6
Presence of homebuilts in the cases of user-dominated innovations, when the time-lag from publication of invention to first commercial model was greater / less than one year

	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

which excludes all but the *first* case, chronologically* 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.

The precommercial diffusion of significant user inventions via "homebuilt" replications of the inventor's prototype design by other users, shown schematically in fig. 1, appears to be a common feature of the scientific instrument innovation process. Literature searches and interviews in our Gas Chromatography and Nuclear Magnetic Resonance Spectrometry samples (we did not collect this particular item of information for our Ultraviolet Spectrophotometry and Transmission Electron Microscopy samples due to time constraints found by those assisting with the data-gathering effort) showed (table 6) that homebuilt 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.

3.2. Sample cases

Abstracts of innovation case histories which display the user-dominated pattern we have observed may serve to give the reader a better feeling for the

* Employment of other decision rules (e.g., "exclude all but the last case in which a given firm or user plays a role") does not produce a significantly different outcome.

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.

Case Outline 1: A major improvement innovation: spinning of a nuclear magnetic resonance sample (user-dominated innovation process)

Samples placed in a nuclear magnetic resonance spectrometer are subjected to a strong magnetic field. From a theoretical understanding of the nuclear magnetic resonance phenomenon it was known by both nuclear magnetic resonance spectrometer users and personnel of the only manufacturer of nuclear magnetic resonance equipment at that time (Varian, Incorporated, Palo Alto, Ca.) that increased homogeneity of that magnetic field would allow nuclear magnetic resonance equipment to produce more detailed spectra. Felix Bloch, a professor at Stanford University and the original discoverer of the nuclear magnetic resonance 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.

* Readers interested in further material which reflects what we term a 'user-dominated' innovation pattern may wish to refer to Shimshoni [4]. Although Shimshoni focuses his analysis primarily on his hypothesis that "... innovation depends primarily on the mobility of enterprising and talented individuals," his data base is instrument industry innovations and he presents much rich case data and discussion which often includes a description of the role of users in particular instrument innovations.
Although we did not use any data from Shimshoni's work because of our preference for primary sources, in some cases our sample and his overlapped. In such instances, we found his and our data in substantial agreement.

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 breakdown 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 ancillary 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 and Meyers, we find, somewhat counterintuitively, that the locus of almost the entire scientific instrument innovation process is centered in the user. Only "commercial diffusion" is carried out by the manufacturer (fig.2).

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 *manufacturer* starts with an "idea" or "proposal" and that the *manufacturer* must execute stages similar to those described by Marquis and Meyers in fig. 2 in order to arrive at a successful new product. For example, Booz, Allen, and Hamilton suggest that a manufacturer wishing an innovative new product should proceed through the following "stages of new product evolution" [7]:

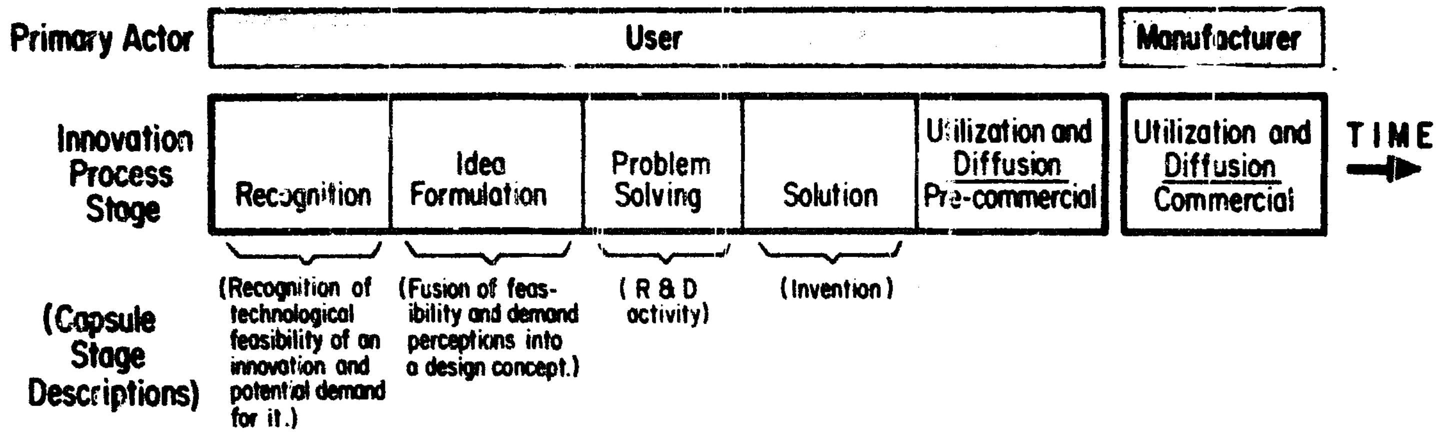

Fig. 2. The primary actor in each innovation process stage* in the scientific instrument innovation process.

> 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.

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 [8]]:

> 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

* The names of stages and the capsule descriptions of them used in fig. 2 are taken from Marquis and Meyers [6] with but one alteration: we have divided Marquis and Meyers' "Utilization and Diffusion" state into precommercial and commercial segments.

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 weigh potential users' initial reactions to the product idea, 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 . . .

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*. 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 "idea" which that firm, in Marquis and Meyers' terminology, "recognizes". It would then follow that the stages coming after "recognition" in the Marquis and Meyers model also occur within the manufacturing firm. The "idea

* We have preliminary data, for example, which indicate that this would be an accurate description of the process of innovation in basis 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.

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 scientific instrument industry (given that our sample is indeed representative of that 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 fig. 3, following, we identified cases in the literature appearing to display three clearly different innovation patterns. In one of these the user is

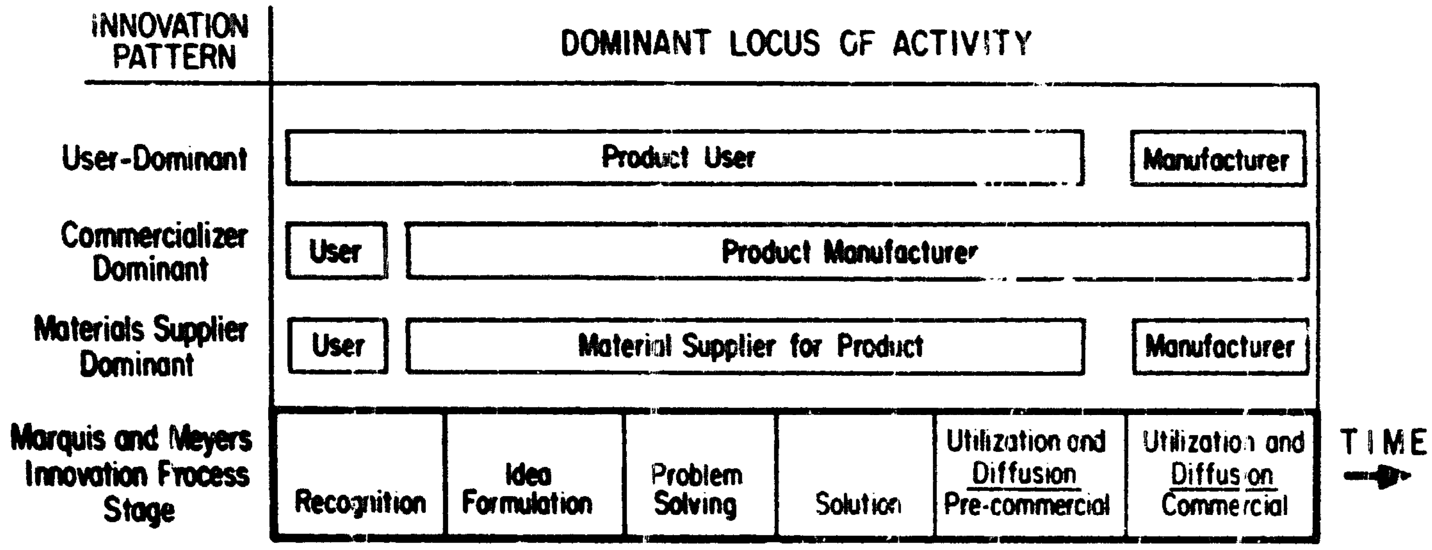

Fig.3. Innovation patterns displayed by some case histories.

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.

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, Project SAPPHO finds*, typical of chemical process innovation. 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).

* SAPPHO (Vol. I, p. 67), ". . . for process innovations, the first successful application is usually within the innovating organization." If (a) the process innovation involved innovative hardware for its execution and if (b) a non-using manufacturer manufactured 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 test tube can play a role in a novel chemical experiment.

Further, we have found that the pattern is at least occasionally present in the innovation of industrial process machinery*.

For examples illustrative of a user-dominated innovation pattern, the reader may refer to case outlines 1 and 3 in subsect. 3.2.

4.2.1. A manufacturer-dominated innovation pattern

Case outline 2 in subsect. 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.

4.2.2. A material supplier-dominated innovation pattern

Professor Corey of Harvard has written a fascinating book [9] 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;
– 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* [10]
>
> 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 . . .

* 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.

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 processes

(B) Aluminum trailers for trucks [11]
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 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.

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*:

– A further characterization of the "inventive user";

– An attempt to discern what aspects of the information potentially derivable from a user's prototype 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 inventive 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 7).

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 develope 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 *how* the tool worked, only that it *did* 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

Table 7
Employment of inventive users

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	4	1	0	0	5
Transmission electron microscopy	10	0	0	1	11

* 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 study issues characterized by data too evanescent for retrospective examination.)

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 on membranes but later get fascinated by the process itself and continue to explore it for its own sake.

5.2. 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 8.

Those individuals who are responsible for more than one significant innovation in an instrument type are not unknown quantities to instruments firms who sell that type of instrument. Two out of the four individuals identified in table 8 had firmly established consulting relations with a single company.

Table 8
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
Ultraviolet spectrophotometry	5	2 by one user
Transmission electron microscopy	11	4 by one user
Total	36	11

6. NON-REDUNDANT INFORMATION CONTENT OF USER PROTOTYPES

We introduced this paper with the observation that prior research into the innovation process had highlighted a strong correlation between innovation success and "accurate understanding of user need" on the part of the innovating firm. We further noted that prior research did not shed much light on how such "accurate understanding of user need" was obtained by innovating manufacturers and that the present study would explore this issue further in the particular context of scientific instrument innovations. On the basis of the broad brush findings we have set forth so far, we can see that scientific instrument companies typically are *not* constrained to accurately perceive user need as such. Instead, they have available to them a hardware *solution* to a need which a user has – hopefully accurately – perceived himself as having. The fact that a hardware solution (a user prototype) is typically available to the commercializing firm, however, does not mean that that firm will find all the information derivable from that prototype either novel or useful. Therefore, while a commercializing firm *can* derive data on both user need and on solution technology from a prototype instrument, it does not necessarily follow that the firm *will* use both – or either. (A firm utilizing the user *need content only*, will in effect respond to a user prototype by saying: "We didn't know that you needed something to do that. Now that we see the need, we'll sit down and design a solution better that the one used in your prototype." A firm using only the *solution content* of 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. We'll build some to your design.")
During the course of our retrospective data gathering work, we tried to explore this issue and determine the frequency with which the need and/or the solution content of a user prototype did in fact convey novel information to a commercializing firm participating in a user-dominated innovation process. Unfortunately, we found that we could not succeed in answering this question reliably insofar as the novelty of *need* input was concerned. Retrospectively gathered interview data is notoriously unreliable unless buttressed by memos or other forms of "hard" evidence generated contemporaneously with the events being discussed and, in the case of novelty of need input to a commercializing firm, we were unable to find any such supporting documentation. When we sought to determine the novelty of the *solution* content of a user prototype to a commercializing firm, however, we had better luck. We

Table 9
In those cases where a user prototype precedes a commercialized innovation, was the technical 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%	5	0	0	5
Transmission electron microscopy	64%	7	4	0	11
Total	78%	28	8	0	36

were able to buttress the recollection of our interviewees regarding the novelty and utility of the *solution* content of a user prototype by looking at contemporaneously generated hardware and publications and asking: Does the commercialized instrument display the same technological solution to the new problem as did its user prototype predecessor? When this test supported our interviewees' recollection regarding the novelty and utility of user prototype solution content to the commercializing firm, we felt able to use the data (table 9).

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 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*. Interestingly, in all cases where an instrument firm did not utilize the operating principles of a preceding user prototype in its com-

* The coding of this question involves some existence of technical judgment by the coder 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 in subsect. 3.2 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.

mercial version, the operating principle involved lay within the purview of mechanical or electrical engineering rather than chemistry or physics.

7. SUGGESTIONS FOR FURTHER RESEARCH

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. For example, we have been unable to "see" messages about and perceptions of user needs which were not documented contemporaneously. Also, we have not been able to determine how instrument firms select 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, and we suggest that real time, rather than retrospective, research designs are most appropriate for addressing many of them.

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