The Impact of Scientific and Commercial Values on the Sources of Scientific Instrument Innovation

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ABSTRACT

In previous research, it has been shown that users develop many scientific instrument innovations. In this study we examine the scientific and commercial importance of 62 major improvements to two types of instrument, some developed by users and some by manufacturers. We find that innovations with high scientific importance tend to be developed by users. In contrast, innovations with high commercial value tend to be developed by manufacturers. Some implications are discussed.

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1. Introduction

In previous research, it has been shown that innovation users are the most frequent innovators in some categories of product, and that manufacturers of innovations or suppliers of innovation-related materials are the most frequent innovators in others (von Hippel 1988). The causes of these variations have been explored in terms of appropriability of innovation benefit. Users, manufacturers and suppliers were found to often have differing abilities to appropriate innovation-related benefit from innovations in a given product category, and these variations were found to be correlated with observed variations in the locus of innovation.

In this study we go beneath category-level data and explore variations in innovation-related benefits available to users and manufacturers at the level of individual innovations in scientific instruments. As the reader will see, our ability to explore this matter empirically in scientific instruments is enhanced by the fact that users and manufacturers in this field are seeking to appropriate different kinds of benefit: Users seek scientific value and reputation from innovations, while manufacturers seek commercial value.

The empirical data we will report on is drawn from a study of 62 major improvements to two related types of scientific instrument. For each, we determined the source of each innovation, and also obtained rankings of the scientific and commercial importance. Our major findings are that the ability of users and manufacturers to benefit from particular innovation opportunities *within* the field of scientific instruments do differ significantly, and that innovators are responsive to these differences. Thus users strongly tend ($p<0.0001$) to develop innovations ranked as possessing high scientific importance, while manufacturers strongly tend to develop innovations having high commercial importance ($p<0.01$).

In section 2 we describe the methods used in our empirical study of scientific instrument innovations. In section 3 we report on both our findings regarding the sources of innovation, and on the relationship found between the sources of innovation and an innovation's scientific and commercial importance. In section 4, we consider some implications of these findings.

2.0: Sample and Methods

Our study examines innovation patterns in two related types of scientific instrument, Auger Electron Spectroscopy and X-ray Photoelectron Spectroscopy (Esca). Auger and Esca are used to identify and measure the chemical composition of solid surfaces.[1] Such analyses are important in many fields ranging from the study of metals, catalysis, adhesion and corrosion to studies of the electronic behaviors of materials. The first publications reporting on the potential analytical utility of these methods appeared in the 1950's (Lander 1953; Siegbahn 1954). Instrumentation implementing both methods was first manufactured commercially in 1969, and by 1970 several companies had entered the field. Today Auger and Esca instruments are used in many hundreds of industrial and university labs worldwide. In 1991, the world market for Auger and Esca instruments was approximately $100 million.

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[1] Prior to the development of Auger and Esca, information on the chemical composition of surfaces was typically obtained via indirect methods, such as reflectivity and contact angle measurement, or with methods with low surface specificity, such as multiple internal reflection infrared spectroscopy and x-ray fluorescence. Auger and Esca instrumentation and techniques are a great improvement. They involve placing samples to be analyzed into a vacuum chamber and directing x-ray or electron beams onto the sample surface. Electrons emitted from the sample are collected and analyzed to identify and measure the chemical elements present in the top few atomic layers. (Riggs and Parker 1975; Joshi, Davis and Palmberg 1975)

Our decision to focus this study on Auger and Esca was dictated by two very practical considerations. First, one of the authors (W. Riggs) combines a background in innovation research with extensive prior professional experience in the use and manufacture of both Auger and Esca. Second, the fact that these instruments were developed relatively recently meant that most of the most important contributors to innovation in the field are still professionally active, and able to provide us with rich, first-hand information on their activities.

In the period following their initial development, Auger and Esca instruments were repeatedly improved. The sample of innovations we studied consists of all such improvements that met two criteria: (1) they "offered a major improvement to user laboratory practice" in Auger and Esca and (2), they were produced commercially by equipment manufacturers prior to 1988. Innovations meeting these criteria included improvements to the hardware and software of the instruments themselves; improvements to instrument inputs, such as improved sample handling; and improvements to instrument outputs, such as data analysis software. Innovations that are excluded by the application of these criteria include: (1) innovations developed by users prior to 1988 but not yet commercialized; (2) "technique only" innovations that are useful to practitioners but that have no commercially manufactured embodiment; (3) process innovations that reduce cost or enhance the quality of manufactured instruments, but that do not represent a "major improvement to user laboratory practice".

Our reasons for excluding the three types of innovation just mentioned have to do with being accurate and conservative with regard to testing the hypothesis that is the main focus of this paper. Innovations commercialized more recently than the start of 1988 were excluded in order to insure that we could collect accurate ratings of the scientific and commercial importance of the innovations studied. It seemed to us that expert raters might find it difficult to accurately assess the importance of very new innovations. A side effect of this exclusion is that the proportion of user-developed innovations in our sample will be somewhat reduced. User-developed innovations are often diffused to others in the user community in the form of home-built replications for a number of years before they are first commercialized by a manufacturing firm.

We excluded technique-only and process innovations from our sample in order to be conservative with respect to the hypothesis we are testing. In essence, our hypothesis is that users will tend to develop scientifically important innovations, and that manufacturers will tend to develop commercially important ones. The inclusion of technique-only and process innovations would tend to increase support for this hypothesis. All technique-only innovations we identified were developed by users and would, we judged, be seen as having low commercial importance. (Since there is no commercial embodiment there is nothing to manufacture. An example of a technique-only innovation: The discovery that operating a standard machine in a novel way provides a major performance improvement.). All process innovations we identified (for example: a custom-built automatic tool changer for some machines used in instrument manufacturing) were developed by manufacturers and would, we judged, be seen as having a low scientific value. Excluding these types of innovations has the effect of biasing our sample towards innovations that have *both* scientific and commercial importance. This, in turn, allows a more conservative test of our hypothesis.

Our sample (table 1) of major innovations was identified via a two-step process. First, we reviewed the literature in Auger and Esca and generated a preliminary list of 50 innovations meeting our criteria. Next, we asked experts from the Auger and Esca user and manufacturer communities[2] to review the list

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[2] User experts were selected from among those who had written review articles or books on Auger and/or Esca instrumentation and techniques within the last five years, and so had a broad view of these fields. Manufacturer experts were drawn from the ranks of senior, long-tenure employees in major Auger and Esca manufacturing firms with both science and sales backgrounds.

Table 1: Major improvements to Auger and Esca from 1953 through 1987

First Auger Electron Spectrometer (Auger) (1953, Lander, Bell Labs)

Hardware improvement innovations	Year	Innovator	Affiliation	Type
1. Auger based on 4-grid LEED optics	1967	Weber	U. Minnesota	user
2. First derivative spectra	1968	Harris	GE Labs	user
3. Cylindrical mirror analyzer	1969	Palmberg	Rockwell	user
4. Analysis as a function of depth	1969	Marcus	Rockwell	user
5. Multi-sample carousel	1969	Weber	PHI	mfr
6. Scanning auger microscopy	1970	McDonald	Rockwell	user
7. Simultaneous sputtering and Auger analysis	1972	Palmberg	PHI	mfr
8. Multiplexer	1972	McDonald	PHI	mfr
9. Coaxial electron gun scanning auger	1973	McDonald	PHI	mfr
10. Rastered ion gun	1974	Taylor	Varian	mfr
11. Field emission electron gun	1975	Pocker	WPAFB	user
12. Lanthanum hexaboride electron filament	1976	McDonald	PHI	mfr
13. Microprocessor control of electron column	1976	McDonald	PHI	mfr
14. UHV sample interlock	1977	unknown	VG	mfr
15. Eucentric motion specimen stage	1977	unknown	JEOL	mfr
16. Differentially pumped ion gun	1977	Palmberg	PHI	mfr
17. Full computer control of instrument	1980	McDonald	Perkin-Elmer	mfr
18. Multichannel detector	1980	unknown	VG	mfr
19. Magnetic objective lens	1980	Gerlach	Perkin-Elmer	mfr
20. Multipoint profiling	1981	unknown	Perkin-Elmer	mfr
21. Zalar rotation	1985	Zalar	University	user
Software innovations				
22. Compilation of standard spectra	1972	Palmberg	PHI	mfr
23. Quantitative sensitivity factors	1972	Palmberg	PHI	mfr
Special purpose capability innovations				
24. Specimen fracture attachment	1972	Seah	NPL - UK	user
25. Double-pass cylindrical analyzer	1973	Palmberg	PHI	mfr
26. Esca/Auger two-analyzer instrument	1975	Palmberg	PHI	mfr
27. Esca/SAM double-pass cylindrical analyzer	1977	Palmberg	PHI	mfr
28. Spherical capacitor analyzer for AES	1979	unknown	VG	mfr
29. Spin polarization detector	1982	Landolt	ETH-Zurich	user

TOTAL Auger major improvement innovations = 29

Table 1 (cont): Major improvements to Auger and Esca from 1953 through 1987

First X-ray Photoelectron Spectrometer (Esca) (1954, Siegbahn, Univ. Uppsala)

Hardware improvement innovations	Year	Innovator	Affiliation	Type
1.X-ray monochrometer	1966	Siegbahn	Univ Uppsala	user
2. Electric sector analyzer	1967	Siegbahn	Univ Uppsala	user
3.Multichannel detector	1967	Siegbahn	Univ Uppsala	user
4. High-intensity x-ray source	1968	Helmer	Varian	mfr
5. Computer control of instrument	1969	Helmer	Varian	mfr
6. Rapid sample introduction	1969	Helmer	Varian	mfr
7. Band pass analyzer	1971	Lee	DuPont	mfr
8. Rotating anode x-ray source	1971	Siegbahn	Univ Uppsala	user
9. Dispersion compensation analyzer	1972	Siegbahn	Univ Uppsala	user
10. Ultra-high vacuum Esca	1973	unknown	VG	mfr
11. Multiple anode x-ray source	1975	Fuggle	TU - Munich	user
12. Focussed x-ray source	1980	Kelly	SSI	mfr
13. Automated Esca depth profiling	1981	Riggs	Perkin-Elmer	mfr
14. Direct imaging	1985	Turner	Oxford Univ.	user
Software innovations				
15. Curve fitting	1969	unknown	Varian	mfr
16. Quantitative sensitivity factors	1972	Wagner	Shell Dev.	user
17. S-curve background subtraction	1972	Shirley	Berkeley	user
18. X-ray line deconvolution	1973	Ebel	Univ Vienna	user
19. Satellite subtraction	1974	Larsen	McPherson	mfr
20. Auger parameter	1977	Wagner	Shell Dev.	user
21. Compilation of standard spectra	1977	Riggs, et. al.	Perkin-Elmer	mfr
22. Principle component analysis for Esca	1979	Garenstrom	GM Labs	user
23. Tougaard background correction	1982	Tougaard	University	user
24. Automatic peak identification	1986	unknown	SSI	mfr
Special purpose capability innovations				
25. Hot/cold stages	1967	Siegbahn	Univ Uppsala	user
26. Angle resolved Esca	1971	Fadley	U. Goteborg	user
27. Inert atmosphere sample transfer	1971	Tolman	DuPont	user
28. Gold deposition method for charge corr.	1971	Hnatowich	Brookhaven	user
29. Electron flood gun for charge compensa.	1972	Huchital	Perkin-Elmer	mfr
30. UHV sample preparation chamber	1973	unknown	VG	mfr
31. Esca depth profiling	1974	Riggs	DuPont	mfr
32. UHV sample transfer	1984	unknown	Perkin-Elmer	mfr
33. Element mapping	1987	Smith/Seah	NPL - UK	user

TOTAL Esca major improvement innovations = 33 we had assembled, and to suggest additions and deletions. The result of this procedure was the selection of 29 major improvements Auger, and 33 major improvements to Esca that met our sample selection criteria.

Note that, since our sample selection criteria did not constrain our experts with respect to how many users a "major" innovation must affect, some of the innovations included in the sample were of value to essentially the total user community while others were of interest to only a subset. (For example, an innovation enabling users to examine the surfaces of materials that have been freshly fractured under vacuum is of major importance to only some users.) Also note that, as specified in our sample selection criteria, all selected innovations were commercially manufactured. However, some have been superceded by later improvements and so not all have remained in production.

Information presented in this paper was collected from several sources. Semistructured interviews were conducted (face-to-face and via telephone) with those who had developed and/or had first-hand knowledge of the development of the innovations in our sample. Additional information was collected from scientific publications, and from manufacturers' published product literature. All information from interviews that we report has been cross-checked with two or more experts to insure accuracy.

3.0: Findings

In this section we first report on patterns that we found in the sources of innovation in Auger and Esca. Then we report on the way that we identified the scientific and commercial importance of each innovation in our sample. Finally, we compare the identity of the developer (user or manufacturer) with the importance rankings and discuss the relationship found.

3.1: The Sources of Innovation

We explored the history of each innovation in our Auger and Esca samples, and found that approximately half of these innovations had been developed by instrument users and half by instrument manufacturers (table 2). "Users" are practicing scientists who utilize Esca and/or Auger in their research, and who are not employed by manufacturers of Auger or Esca equipment. (Fifteen of the innovating users in our sample were employed by a university, 10 by an industrial laboratory, and 4 by a government laboratory.) "Manufacturers" are employees of firms that manufacture Auger and/or Esca systems and/or related accessories and components.

Table 2: Source of Auger and Esca Innovations[a]

	The first practical instrument was developed by:			
	Instrument User		Instrument Manufacturer	
	Number	%	Number	%
Esca	19	56%	15	44%
Auger	10	33%	20	67%
Total	29	45%	35	55%

[a] Some users and some manufacturers (see table 1) developed more than one of the innovations in our sample. These relatively prolific innovators did not greatly affect the pattern we found regarding the sources of innovation, however. A subset of our sample consisting of only the first innovation by any innovator shows 52% user innovations and 48% manufacturer innovations.

An innovation was coded as user-developed in table 2 if a user built a working device and published findings derived from its use *before* any manufacturer brought that innovation to market. Otherwise, it was coded as manufacturer-developed. Priority with respect to these events was determined by comparing the date of the first publication in the scientific literature by users with the date of first market introduction by a manufacturer. Market introduction was deemed to have occurred on the date when any of the following events first took place: (a) a public exhibition of the innovation by a manufacturer, as at a trade fair; (b) an announcement of commercial availability published in the trade literature; (c) first shipment to a customer. (First shipment sometimes occurs prior to a general product announcement when a manufacturer accepts an initial order on a "special product" basis.)

3.2: Differences Between Innovations Developed by Users and Manufacturers

It has been shown that innovators innovate because it pays (Schmookler 1966, Mansfield 1968). In the field of scientific instruments, users and manufacturers are motivated by different types of benefit. Scientists find reward in a sense of accomplishment and in the evaluation of peers as to the scientific importance of their achievements (Merton 1957). In contrast, scientific instrument manufacturers are profit-making firms, and are presumably motivated by expectations of profit.

This distinction appears to us to be stable during the period under study. We have found that user-innovators in our sample almost never sought to benefit financially from their instrument innovations. Indeed, personnel in PHI, the firm with the largest share of both the Auger and Esca market, could recall only one instance in which they were asked for or offered financial rewards to a scientist whose innovation they commercialized: They gave a scientist-innovator from a country with a non-convertible currency, "a few thousand dollars worth" of equipment that he needed but could not purchase. Scientific instrument manufacturers' focus on the commercial value of innovations also appears to be stable, albeit not quite as exclusive: Such firms employ scientists who are not immune to the rewards to be had from publishing, and sometimes they do publish. However, the firms we studied are aware of the importance of priority in publication to their scientist customers. They do not seek to compete with them, and do take pains to acknowledge their priority as appropriate.

On the basis of the above, we hypothesize that users will be motivated to develop scientific instrument innovations on the basis of their anticipated scientific importance, and manufacturers will be motivated to develop innovations on the basis of their expected commercial importance.

We sought to test this hypothesis in our sample by asking five experts drawn from the user and the manufacturer communities to rank each innovation in our sample in terms of scientific and commercial importance on a scale of 1 - 5.[3] Each expert was asked to rate each of the innovations on a five point scale for commercial importance and for scientific importance. Given the unreliability of retrospective data, we had no realistic expectation of determining what the expectations of potential innovators would have been on these matters at the time of the innovations. Therefore, we did not ask our experts to judge what these importances would have seemed to have been at the time of the innovations. Instead, we asked them for their judgments as to what these importances had turned out to be over time, and assume that innovators expectations on these matters were a (somewhat) accurate predictor of actual outcomes.

After the ratings were complete, each expert was asked to describe what he had in mind with respect to the "scientific importance" and "commercial importance" of the innovations he ranked on these variables. Four of the five

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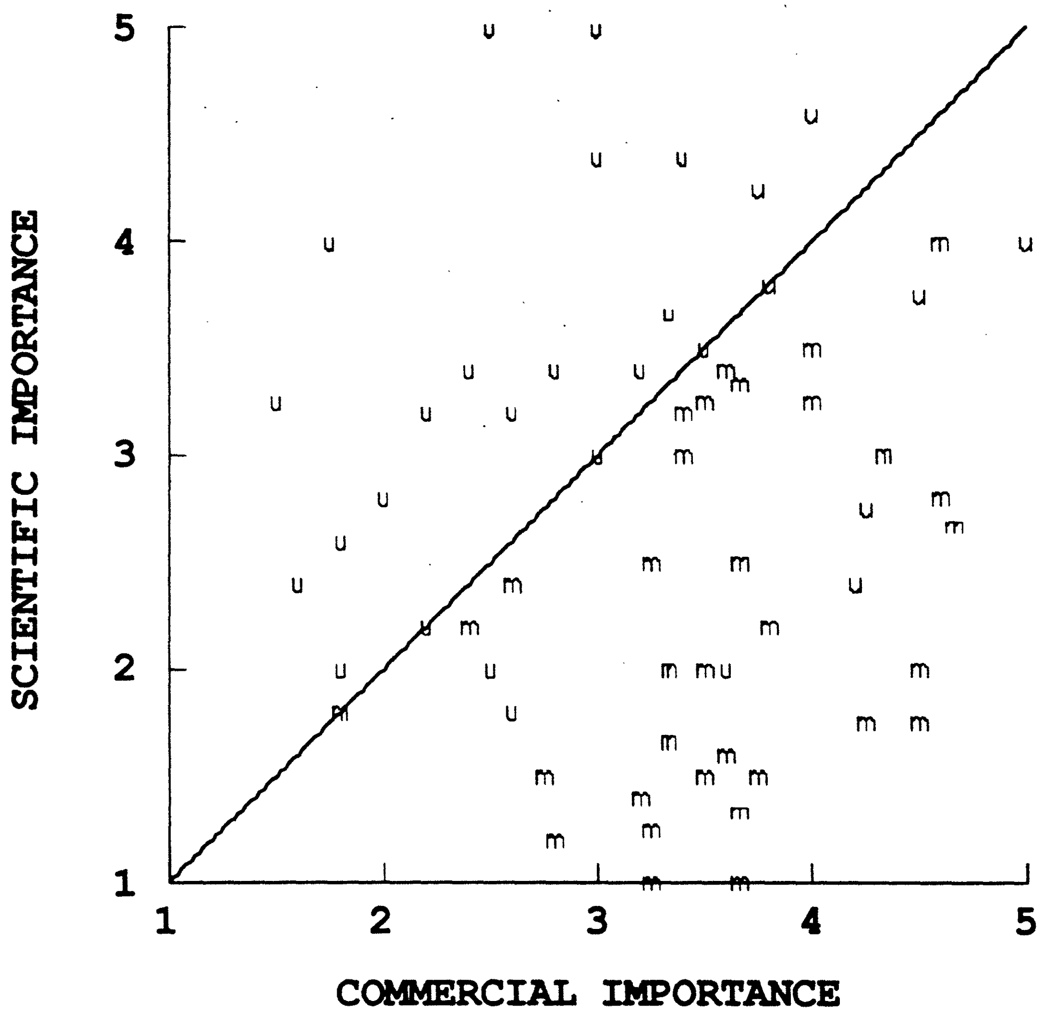
[3]These rankings were collected as follows: We contacted 6 experts (drawn from the group identified as described in footnote 2) by telephone to determine their willingness to complete a questionnaire on innovations in Esca and Auger. Five of the 6 contacted agreed. The panel consisted of two representatives of commercial instrument companies and three scientist-users of Auger/ Esca instrumentation. The manufacturer representatives were from different firms, and were positioned to know how their firm would view the value of various possible product innovations. One of them was a marketing executive, and the other the entrepreneur-founder and President of one of the firms in the field. Both hold Ph.D. degrees in physics. The three user respondents were Ph.D. chemists and physicists from a university, a government laboratory and a basic research laboratory of a large chemical company.

responded to this open-ended question, and their responses showed a high degree of consistency on the matter. All viewed commercial importance as meaning impact on manufacturers' sales, and all viewed scientific importance as having to do with the enabling of scientific advance. Representative quotes from the experts may help to convey the flavor of their responses.

> Scientific Importance means: "...contributes to enabling scientific advance"; "...opens up access to new levels of scientific information"; "...number and quality of publications resulting from an innovation"; "...whether the innovation furthered understanding...". Commercial importance means: "...the effect on manufacturers' product sales"; "...what sells instruments"; "...recognition that it would be useful"; "...extent used on a routine basis to solve problems."

The results of this procedure are shown on figure 1 in the form of a scatter diagram. As can be seen from figure 1 and table 3, we did find that, as hypothesized, users did show a significant tendency to develop innovations ranked as high in scientific importance, and manufacturers did show a significant tendency to develop those ranked as high in commercial importance. A test of the significance of the tendency for users rather than manufacturers to innovate when scientific importance is rated high shows the pattern to be significant at $p< 0.0001$ (Mann-Whitney U test). Testing the tendency for manufacturers rather than users to innovate when the commercial importance of an innovation is rated high confirms that this is also the case, with the null hypothesis rejected at $p< 0.01$ (Mann-Whitney U test).

Figure 1: Scatter plot of ratings of innovations on scientific and commercial importance



u = user innovation

m = manufacturer innovation

Table 3: The scientific and commercial importance of each innovation sampled compared with the source of innovation (user vs mfr)

Ratio of Innovation Importances	Innovation developed by: User	Manufacturer	Total
Comml Value > Scientific Value	7	34	41
Comml Value= Scientific Value	4	1	5
Comml Value< Scientific Value	18	0	18
Total	29	35	64

In table 3 we show this same finding in terms of the proportion of user and manufacturer innovations below and above the 45 degree line shown in figure 1. (Although the data in table 3 are shown in terms of "greater than, equal to and less than" for convenience, the reader should keep in mind that our measures of scientific vs commercial importance are not commensurable, and that we are referring to ratios.)

Note that, while the kinds of benefit sought by users and manufacturers have remained constant during the period we have studied, the amount of benefit that each type of innovator might expect from innovating has probably changed. On the user side, the level of scientific novelty and excitement associated with the field has certainly declined over time. And, on the manufacturer side, growth in the market and changes in industry structure have occurred that must affect firms' expectations of appropriable commercial benefit.

Such changes in level might change the frequency of innovation over time and/or the proportion of user vs manufacturer innovation. They would not, however, affect the validity of the test just reported.

Since the experts who provided our ratings of commercial and scientific importance were widely knowledgeable in the field, is it possible that they had a source bias? That is, is it possible that they ranked a given innovation as of high scientific importance because they knew that a respected scientist developed it? One way to test for this type of bias would be to examine the importance ratings given to the multiple innovations developed by a single innovator. If the reputation of scientist-innovators were strongly biasing the scientific importance ratings of their innovations, the scientific importance ratings given to the innovations developed by a single innovator would tend to be similar. (Of course, this pattern would also appear if the scientific importance of the innovations by a single innovator were similar in fact.) Our current sample allows only an informal test of this matter, as there are only three user-innovators in the sample responsible for more than one innovation (one developed 7, and two developed two each). However, we can observe that the 7 innovations of the most prolific and highly-regarded user-innovator in the field, Kai Siegbahn, (a Nobel laureate) have been assigned very different importance ratings ranging from 5.0 to 1.8. This is the kind of pattern we would expect to see if this particular type of source bias was *not* strong among our raters.

4.0: Discussion

In a previous study, von Hippel (1976) found that scientific instruments were sometimes developed by users (77%) and sometimes by manufacturers (23%)[4]. However, no exploration was done as to whether those instruments developed by users differed in some way from those developed by manufacturers: the data at the level of individual innovations simply wasn't there. In this study we have developed data on innovation-related benefits available to users and manufacturers at the level of individual innovations. And, we have found that user and manufacturer innovations are not perfect substitutes in that they are characterized by different levels of scientific and commercial importance.

On the face of it, one might expect a close link between the scientific and commercial importances of instrument innovations. After all, an innovation with high scientific importance might well be of interest to many purchasers - and thus of high commercial importance as well. A detailed look at some of the innovations in our sample shows why this is sometimes not so.

Innovations in our sample that had high scientific importance tended to be those that made it possible for users to obtain qualitatively new types of information. Innovations having high scientific importance and <u>low</u> commercial importance were applicable only to specialized areas (e.g., of potential interest to only a few purchasers); and/or, the manufacturer had only a limited ability to appropriate benefit by commercializing them. An example of the first type is the spin polarization detector for Auger spectrometers developed by Landolt. This device makes it possible to image and analyze magnetic domains with sub-microscopic dimensions - a capability of great interest to only a few users. An example of the second type is a software-embodied innovation which exists both as commercial software and as user-developed software in the public domain. When this is the case, the existence of the public domain version limits a

[4] The innovations explored in this earlier study involved improvements to four types of scientific instrument: the Gas Chromatograph, the Nuclear Magnetic Resonance Spectrometer, the Ultraviolet Spectrophotometer, and the Transmission Electron Microscope.

manufacturer's ability to appropriate benefit from the commercial version.

Innovations in our sample that had high commercial and low scientific importance typically had to do with automating the instrument to increase ease of use and/or with increasing its speed of operation. Many users found such improvements worth buying. On the other hand, these innovations seldom made it possible to collect a qualitatively new type of data, and so their scientific importance was typically judged to be low.

The data we have displayed in figure 1 and table 3 show a strong tendency for users to develop innovations having significant scientific importance, and for manufacturers to develop innovations having significant commercial importance. This pattern does not contain any information regarding possible interactions between user and manufacturer decision-making: It is compatible both with a pattern of innovation decision-making in which each type of innovator focuses on its type of importance only, and with a pattern involving some sort of *interdependence* between user and manufacturer decision-making with respect to innovation.

We have not yet explored this matter in depth. However, on an anecdotal basis some of our interviewees have informed us that at least one form of coordination between user and manufacturer decisions on this matter does exist. Sometimes, a user will tell a manufacturer about an innovation opportunity that is attractive from both the scientific and commercial point of view, and invite the manufacturer to develop that innovation. The reward to the user under these circumstances is often receipt of the first machine produced that embodies the innovation. The user thus gains lead time that allows him to reap the (priority-based) scientific innovation benefits associated with the innovation even as the manufacturer reaps the commercial benefits.

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