2

Users as Innovators

In this chapter I begin by exploring who actually develops novel, commercially successful scientific instruments. Then I explore the actual sources of innovation in two major classes of process equipment used by the electronics industry. In both of these areas, I find that the innovators are most often users.

The discovery that users are innovators in at least some important categories of innovation propels us into the first major question I examine in this book: Who actually develops the vast array of new products, process equipment, and services introduced into the marketplace? The answer is clearly important: An accurate understanding of the source of innovation is fundamental to both innovation research and innovation management.

The Sources of Scientific Instrument Innovations

Scientific instruments are tools used by scientists and others to collect and analyze data. My study of scientific instrument innovations focuses on four important instrument types: the gas chromatograph, the nuclear magnetic resonance spectrometer, the ultraviolet spectrophotometer, and the transmission electron microscope. Each of these instrument types was, and is, very important to science.[1]*

*The gas chromatograph was a revolutionary improvement over previous wet chemistry methods used to identify chemical unknowns. Analyses that formerly took years to do or that could not be done at all prior to the innovation could now often be done in hours with gas chromatography. The nuclear magnetic resonance spectrometer (lately applied to medical research but initially used by chemists) opened an entirely new approach—the analysis of nuclear magnetic moments—to the determination of molecular structures. The ultraviolet spectrometer made analysis of materials by means of their ultraviolet spectra (a very useful research tool) easily achievable. The transmission electron microscope allowed researchers for the first time to create images of objects down to a resolution unit of approximately one angstrom (Å), far better than could be achieved by any optical microscope.

TABLE 2–1. Scientific Instrument Sample Composition

	Improvements			
Instrument Type	*First-of-Type*	*Major*	*Minor*	*Total*
Gas chromatograph	1	11	0	12
Nuclear magnetic resonance spectrometer	1	14	0	15
Ultraviolet absorption spectrophotometer	1	5	0	6
Transmission electron microscope	1	14	63	78
TOTAL	4	44	63	111

My innovation sample for each of the four instrument families included the initial, first-of-type device as it was first commercialized *and* the many commercially successful major and minor "improvement" innovations that enhanced the performance of that basic device over the succeeding 20 or more years.

The sample structure, shown in Table 2–1, might initially seem rather odd. Why focus on the innovations that improved just four types of scientific instrument? After all, many types of scientific instrument exist[2] and perhaps the generalizability of results might be better served by a random sampling from the whole field? Focusing on a few instrument types in depth, however, offers several advantages.

First, by examining successive innovations affecting a given instrument type, variables such as the nature of the market and industry structure, which might affect the sources of innovation we observe, can be controlled for. Second, a sample that follows the evolution of a few products over 20 or more years allows us a longitudinal view of the sources of innovation. Any major changes in the functional sources of innovation that may occur over time should be visible. Finally, an instrument type such as those examined here typically represents a product line from a manufacturing firm's viewpoint. Therefore, patterns of innovation that we observe in our samples are similar to those a manufacturer would have to face and deal with in the real world.

Methods

To guard against enthusiasm coloring my findings, I made my criterion for determining the source of an innovation objectively codable. I defined an *innovator* as the firm or individual that first developed a scientific instrument innovation to a state proved functionally useful, as indicated by the publication of data generated by it in a scientific journal.

My next task was to identify a sample of major and minor improvement innovations for each of the four instruments to be studied. This was done by, first, identifying users and manufacturer personnel expert in each instrument type.[3] Then, to identify major improvement innovations, each expert was asked to identify improvements developed after the basic innovation that provided a significant improvement in instrument performance relative to best preexisting practice.[4] The experts turned out to have quite uniform views. Either almost everyone contacted agreed that an innovation was of major functional utility—in which case it was included—or almost no one did, except the proposer—in which case it was rejected.

Minor improvement innovations were identified for the electron microscope only.[5] To generate a sample of these, the set of experts first listed all the innovations they could think of that had produced *any* improvement to any aspect of electron microscope performance and that had been commercialized. I then augmented this initial list by a scan of the catalogs of microscope manufacturers and microscope accessory and supply houses to identify any innovative features, accessories, specimen preparation equipment, and so on, that met the same criterion.

The samples of first-of-type and major improvement innovations that were identified by these procedures are listed in Table 2–2.

Samples in hand, I next faced a rather daunting data collection task. I wanted to understand the details of over 100 highly technical innovations and their histories. To accomplish the task I evolved a pattern that has served well during a number of studies. I set aside a summer and, with the aid of National Science Foundation (NSF) funding, recruited several excellent, technically trained MIT master's candidates to work with me. We all worked together in a large office, collecting data through telephone calls, library work, and field trips according to a standard data collection guide. Frequent comparing of notes and joint work (with breaks for noontime volleyball and chess games) kept our data to a high standard of reliability. (Additional discussion of data collection methods will be found in the appendix, along with detailed innovation case histories.)

The Sources of Innovation

As my students and I worked over the summer, we began to see that there was a clear answer to our question regarding the source of innovation in the field of scientific instruments. As can be seen in Table 2–3, it emerged that users were the developers of fully 77% of all the innovations we studied. And, as can be seen in Table 2–4, this pattern was uniformly present in all four instrument families studied.

Some sample members were not clearly independent: Several innovations were sometimes attributed to a single innovating user or manufacturer.[6] But, as is shown in Table 2–5, the finding of user innovation is not affected by this: A subsample that excludes all but the first case, chronologically, in which a particular user or firm plays a role shows the same pattern of innovation as the total sample. Employment of other decision rules in this test (e.g., the exclusion of all but the last case in which a given firm or user plays a role) produces the same outcome.

TABLE 2–2. Sample of Major Scientific Instrument Innovations

First-of-type: Gas chromatograph (GC)	
Major improvement innovations	
Temperature programming	Flame ionization detector
Capillary column	Mass spectrograph detector
Silanization of column support material	Gas sampling valve with loop
Thermal conductivity detector	Process control chromatography
Argon ionization detector	Preparative gas chromatography
Electron capture detector	
First-of-type: Nuclear magnetic resonance (NMR) spectrometer	
Major improvement innovations	
Spinning of NMR sample	Pulsed NMR spectrometer
Fourier transform/pulsed NMR	Heteronuclear spin decoupling
Homonuclear spin decoupling	Frequency synthesizer
Superconducting solenoids	Shim coils
Primas polecaps	T_1rho
Field frequency lock	Electronic integrator
Pulsed field gradient accessory	Proton-enhanced nuclear induction spectroscopy
Multinuclei probe	
First-of-type: Ultraviolet (UV) spectrophotometer	
Major improvement innovations	
Direct-coupled chart recorder	Automatic double beam
Automatic scanning	Double monochrometer
Reflection grating	
First-of-type: Transmission electron microscope (TEM)	
Major improvement innovations	
Pointed filaments	Three-stage magnification
Telefocus electron gun	Scaled-up objective pole piece
Double condenser lens	Goniometer specimen stage
Correction of astigmatism in objective lens	Cold-specimen stage
Well-regulated high-voltage power supplies	High-temperature specimen stage
Well-regulated lens power supply	Biased electron gun
Rubber gasket sealing of vacuum system	Out-of-gap objective lens

Recall that my measure of the source of innovation is based on who *first* developed a later-commercialized scientific instrument innovation. When users were found to be first, I termed them *the* innovators. But is it possible that in such cases manufacturers were also innovators, developing the same innovations independently? It seemed implausible, but I checked.

On the basis of two types of evidence, it appears that users who are first to innovate are indeed *the* innovators. First, most manufacturers who commercialize innovations initially developed by users *say* that their commercial product is based on the earlier, user-developed device. Second, as Table 2–6 shows, 78% of the instruments commercialized by scientific instrument manufacturers display the same underlying technical operating principles as their

TABLE 2–3. Source of Scientific Instrument Innovations by Innovation Significance

Innovation Significance	% User Developed	Innovation Developed by			
		User	Manufacturer	NA	Total
First-of-type	100%	4	0	0	4
Major improvement	82	36	8	0	44
Minor improvement	70	32	14	17	63
TOTAL	77	72	22	17	111

user prototype predecessors. This would be exceedingly unlikely to occur if users and manufacturers were engaged in parallel but independent research efforts.[7]

Three abbreviated case histories can convey a good feeling for the innovation patterns found in scientific instruments. The first is an example of a user-developed major improvement innovation; the second is an example of a manufacturer-developed major innovation; the third is an example of a minor improvement innovation developed by a scientific instrument user.

Case Outline 1. A user-developed major improvement innovation: spinning of a nuclear magnetic resonance sample.

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 then-only manufacturer of nuclear magnetic resonance equipment (Varian Associates, Palo Alto, California) that increased homogeneity of that magnetic field would allow nuclear magnetic resonance equipment to produce more detailed spectra. Felix Bloch, Professor of Physics at Stanford University and the original discoverer of the nuclear magnetic resonance phenomenon, suggested that one could improve

TABLE 2–4. Source of Innovation by Type of Instrument

Major Improvement Innovations	% User Developed	Innovations Developed by			
		User	Manufacturer	NA	Total
Gas chromatograph	82%	9	2	0	11
Nuclear magnetic resonance spectrometer	79	11	3	0	14
Ultraviolet spectrophotometer	100	5	0	0	5
Transmission electron microscope	79	11	3	0	14
TOTAL	81	36	8	0	44

TABLE 2-5. A Subsample, Selected to Assure Independence, Shows Substantially the Same Pattern of User Innovation as Total Sample

Major Improvement Innovations	*% User Developed*	*Innovations Developed by*			
		User	*Manufacturer*	*NA*	*Total*
Gas chromatograph	86%	6	1	0	7
Nuclear magnetic resonance spectrometer	100	5	0	0	5
Ultraviolet spectrophotometer	100	2	0	0	2
Transmission electron microscope	83	5	1	0	6
TOTAL	90	18	2	0	20

the effective homogeneity of the field by rapidly spinning the sample in the field, thus averaging out some inhomogeneities. Two of Bloch's students, 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 the same issue of *Physical Review*.[8]

Varian engineers went to Bloch's laboratory, examined his prototype sample spinner, developed a commercial model, and introduced it into the market by December 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 construct homebuilt spinners prior to that commercialization.

Case Outline 2. A manufacturer-developed major improvement innovation: a well-regulated, high-voltage power supply for transmission electron microscopes.

The first electron microscope and the first few precommercial replications used batteries connected in series to supply the high voltages they required. The major inconvenience associated with this solution can be readily imagined: voltages on the order of 80,000 v were required, and nearly 40,000

TABLE 2–6. Were the Operating Principles of the User's Design Replicated in the First Commercial Device?

Major Improvement Innovations	*%Yes*	*Yes*	*No*	*NA*	*Total*
Gas chromatograph	78%	7	2	0	9
Nuclear magnetic resonance spectrometer	82	9	2	0	11
Ultraviolet spectrophotometer	100	5	0	0	5
Transmission electron microscope	64	7	4	0	11
TOTAL	78	28	8	0	36

single wet-cell batteries had to be connected in series to provide this. A visitor to the laboratory of L. 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 the performance of a high-resolution microscope. This innovative power supply was commercialized in 1941 in RCA's first production microscope.

Case Outline 3. A user-developed minor improvement innovation: the self-cleaning electron beam aperture for electron microscopes.

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 contaminated with carbon. The carbon becomes electrically charged by the electron beam impinging on it; the 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 thus keep the aperture dynamically clean. Some microscope manufacturers had installed electrically heated apertures to perform this job, but these devices could not easily be retrofitted to existing microscopes.

In 1964 a microscope user at Harvard University gave a paper at the 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 that 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. French first offered them for sale in 1964.

The User's Role in Innovation Diffusion

The innovating users in the case histories presented were researchers employed by universities. And, as we see in Table 2–7, this was generally true for my sample of user-developed innovations.

TABLE 2–7. Institutions Employing Innovative Users

Major Improvement Innovations	*University/ Institute*	*Private Manufacturing Firm*	*Self-employed*	*NA*	*Total*
Gas chromatograph	3	3	1	2	9
Nuclear magnetic resonance spectrometer	9	0	0	2	11
Ultraviolet spectrophotometer	4	1	0	0	5
Transmission electron microscope	10	0	0	1	11

Given that the innovating scientific instrument users were university scientists, we might expect them to be very active in speeding the diffusion of their innovations—and they were. First (as required by the mores of science), innovating users (researchers) published their research results *and* the details of any homebuilt apparatus used to attain them. Second, they typically also informed others of their innovations by presentations at conferences and visits to the laboratories of other scientists.

Information diffused by innovators regarding major innovations was rapidly picked up by other scientists or by commercializing firms. In the instance of major improvements to GC or NMR (the two areas where I looked into the matter) one of two types of diffusion occurred within a year after the initial publication by the original innovating user: Either (1) other scientists replicated the homebuilt device and also published papers involving its use (frequently the case) or (2) a commercial version was on the market (seldom the case). Both patterns are shown in Table 2–8.

In sum, we see that the role of the user—depicted schematically in Figure 2–1—was both very rich and central to the scientific instrument innovation process.

TABLE 2–8. When Instrument Manufacturers Did Not Commercialize User Innovations Quickly, Other Users Made Homebuilt Copies

	User time lag > 1 year				*Homebuilts present, time lag 1 year or < 1 year*			
Innovation	*%Yes*	*Yes*	*No*	*NA*	*%Yes*	*Yes*	*No*	*NA*
Gas chromatograph	100%	5	0	0	0%	0	3	1
Nuclear magnetic resonance spectrometer	100	8	0	1	0	0	1	1
TOTAL	100	13	0	1	0	0	4	2

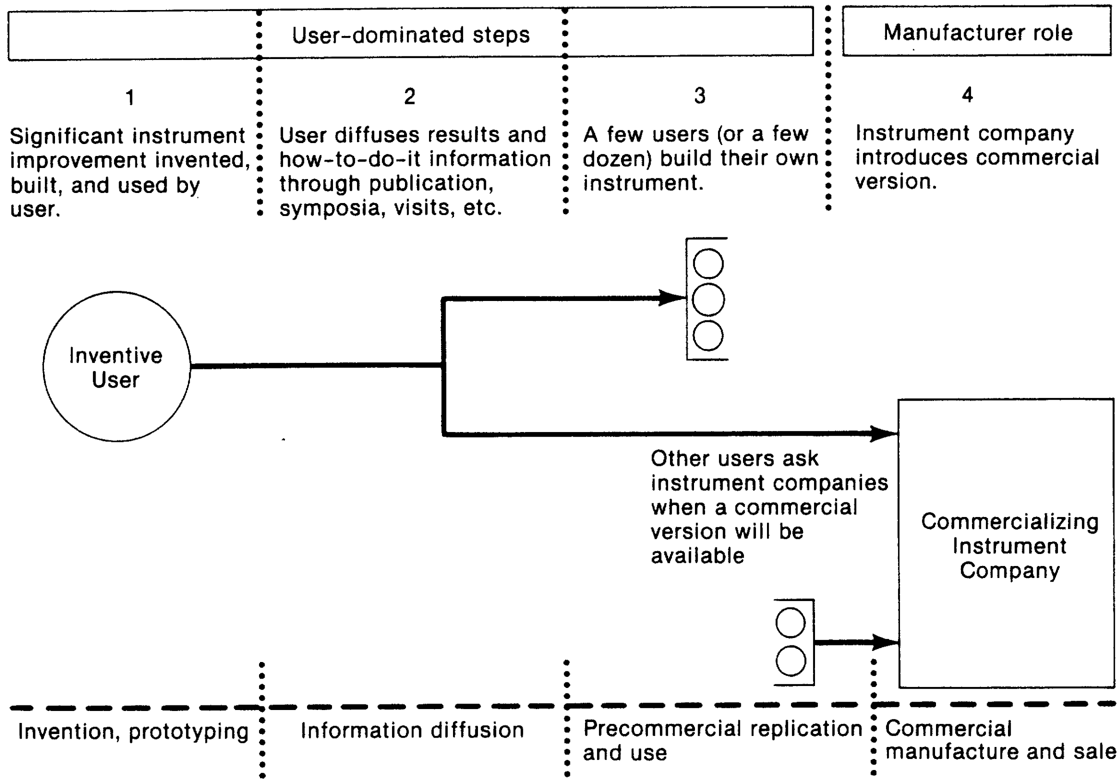

FIGURE 2–1. Typical Steps in the Development and Diffusion of a Scientific Instrument Innovation

Typically the innovative user:

- Perceived that an advance in instrumentation was required.
- Invented the instrument.
- Built a prototype.
- Proved the prototype's value by applying it.
- Diffused detailed information on both the value of the invention and on how the prototype device could be replicated.

In instances coded as user innovation, an instrument manufacturer entered the process only after all of the above events had transpired. Typically, the manufacturer then:

- Performed product engineering work on the user's device to improve its reliability and convenience of operation.
- manufactured, marketed, and sold the innovative product.

The Sources of Semiconductor and Printed Circuit Board Assembly Process Innovations

The study of scientific instruments I have just reviewed showed user innovation as typical in that field. But is this pattern unique to scientific instruments? After all, university scientists, the typical innovators in that field, are clearly not typical of the users of most products, processes, or services.

TABLE 2–9. Sample Composition

	Innovations Implemented by	
	Novel Equipment	*Novel Technique Only*
Semiconductor		
Initial practice	5	6
Major improvements	16	3
Minor improvements	11	0
PC board assembly		
Initial practice	2	2
Major improvements	6	0
Minor improvements	9	0
TOTAL	49	11

To explore this matter, I decided to conduct a second study in other, more "normal" fields, before suggesting that users-as-innovators might be a generally significant phenomenon. In this study, I examined innovations affecting two types of processes: the manufacture of silicon-based semiconductors and the assembly of printed circuit (PC) boards.*

Methods

Semiconductors and PC boards are, in common with most products, manufactured by means of a series of process steps. Thus, the process of manufacturing silicon-based semiconductors may start with a crystal-growing process step, followed by a step in which the crystal is sliced into thin circular wafers, and so forth.

My sample in this study consisted of the successive innovations that first established and then improved several such manufacturing process steps (see Table 2–9). Since the machinery used for a manufacturing process step often represents a product line for an equipment manufacturer, the resulting sample structure is similar to that used in the study of scientific instruments, and it shares its advantages.

The 60 innovations included in this study (listed in Table 2–10) were identified by means of a process involving several steps. I began by studying process flow sheets to identify the major process steps used to manufacture semiconductors and assemble printed circuit boards. Next, I selected some of these process steps[9] and identified the method used in the initial commercial practice of each (i.e., the first method used by any firm to manufacture products for sale rather

*Most electronic products today use printed circuit boards to link the electronic components they contain (integrated circuits, resistors, capacitors, etc.) into functioning circuits. The PC board itself resembles a plastic board or card. It is typically rectangular, it is less than 1⁄16-in. thick, and it measures a few inches on each side. Electronic components are mounted on one or both board surfaces, and thin metal paths that run on the surface of the board and/or within it interconnect the components into the desired electronic circuitry. Board manufacture here includes the manufacture of the basic board, component insertion, interconnection, and testing.

TABLE 2–10. Innovations Identified for Silicon Semiconductor and for Printed Circuit Board Subassembly Processing[a]

Major Process Step	*Initial Commercial Practice*	*Major Improvement*
Silicon semiconductor products		
1. Growth of single-silicon crystal[b]	Crystal puller	Resistance-heated crystal puller Dislocation-free crystal puller[c] Automatic diameter control
2. Wafer slicing	High-precision saws[d]	ID saw
3. Wafer polishing	Optical polishing equipment and technique[d]	Chemical/mechanical polishing (SiO_2)[d] Chemical/mechanical polishing (Cupric salts)[d]
4. Epitaxial processing (optional process step)	Pancake reactor	Horizontal reactor Barrel reactor
5. Oxidation	Not examined	
6. Resist coating	Wafer spinner	High acceleration wafer spinner 11 minor improvement innovations
7. Mask alignment and wafer exposure	Mask aligner	Split field optics aligner Automated mask aligner
8. Oxide etching	Not examined	
9. Silicon junction fabrication	Grown junction[c]	Diffused junction furnace Ion implantation accelerator
10. Metalization	Not examined	
11. Scribing and dicing	Jig and fixture[c]	Mechanical scriber and dicer Laser scriber and dicer
12. Mounting	Not examined	
13. Wire bonding	Solder bonding	Thermocompression bonding Ultrasonic bonding
14. Encapsulation	Not examined	
15. Mask graphics	Handcut rubylith patterns[c]	Optical-pattern generator Electron beam pattern generator
16. Mask reduction	Two-stage step and repeat reduction process	Not examined
Electronic subassembly manufacture		
1. Circuit fabrication	PC board[d] Wire wrapping (optional)	Not examined[d] Automated wire wrapping (optional)
2. Component insertion	Hand component insertion[c]	Single-component-per-station component insertion X–y table component insertion Numerically controlled-driven x–y-table component insertion Sequenced component insertion
3. Mass soldering	Dip solder[c]	Wave solder 9 minor improvement innovations
4. Assembly	Not examined	

[a]*Source*: Eric von Hippel, "The Dominant Role of the User in Semiconductor and Electronic Subassembly Process Innovation," *IEEE Transactions on Engineering Management* EM-24, no. 2 (May 1977), 64–65 © 1977 IEEE.

[b]Float zone refining and dislocation-free float zone refining offer an alternate silicon single crystal growing technology.

[c]This process innovation was embodied primarily in operator technique rather than in novel process equipment.

[d]The process machinery used in the initial commercial practice of this process step was commercially available and being used in other industries. Innovation work needed in these instances consisted simply of identifying the equipment as appropriate for the process step contemplated and/or redefining the process step specifications until they fitted the capabilities of that equipment.

TABLE 2–11. Sources of Process Machinery Innovations

	Innovation Developed by					
	% User	User	Manu-facturer	Joint User/ Manu-facturer	NA	Total
Semiconductor process						
Initial practice	100%	5	0	0	0	5
Major improvements	71	10	2	2	2	16
Minor improvements	56	5	3	1	2	11
PC board assembly						
Initial practice	100	2	0	0	0	2
Major improvements	40	2	2	1	1	6
Minor improvements	63	5	2	1	1	9
TOTAL	67	29	9	5	6	49

than for laboratory purposes). Then, using the same process of polling experts described earlier in the context of the scientific instrument study, I identified the major improvements that had been made to each process step over the following years. (A *major improvement* was defined as a change in equipment or technique that provided a significant improvement in process step performance relative to best preinnovation practice.) Finally (again following methods described earlier), I identified an exhaustive sample of minor process step improvements affecting one semiconductor and one PC board assembly process step. (*Minor improvement* innovations were defined as those that gave the user any improvement in any dimension important in processing such as cost reduction, increased speed, quality, consistency, and so on.[10])

As in the scientific instrument study, I defined an innovator as the firm or individual that first developed a sampled innovation to a state *proved* functionally useful. Here, proof of functional usefulness was documented use of the innovation in commercial production. All of the innovations selected for study were commercially successful, with commercial success being defined as near-universal adoption by process users in the few years following the innovation's debut. (Today, of course, many of the innovations have been supplanted by later improvements.)

Data collection methods used in this study are precisely the same as those used in the study of scientific instruments that were described earlier in this chapter.

The Sources of Innovation

As Table 2–11 shows, users developed all of the process machinery innovations involved in the initial commercial practice of a process step and more than 60% of the major and minor improvements to that machinery. (Conventional wisdom suggests that user-developed innovations are rare. But even if

TABLE 2–12. Process Innovations That Do Not Require Novel Equipment

	Innovations Implemented Through		
	Commercial Equipment[a]	*Technique Only*[b]	*Developed by*
Semiconductor process			
Initial practice	2	3	100% User
Major improvements	0	3	100% User
PC board assembly			
Initial practice	1	1	100% User
Major improvements	0	0	—
TOTAL	3	7	

[a]Identified in Table 2–10 by the superscript "d."
[b]Identified in Table 2–10 by the superscript "c."

we allow H_0 to be that users will develop 50% of the sampled innovations, $p <$ .02, our sample would yield the 67% user-developed innovations reported in Table 2–11.) Clearly, user innovation is not a phenomenon restricted to scientific instruments only.

In this second study we see a modest amount of joint user/manufacturer innovation activity (coded as user/manufacturer in Table 2-11). Also, we see users active in two types of innovations that I have not discussed before.

First, from Table 2-12 note that users developed all of the technique-only process innovations in the sample. (Such an innovation does not require any novel equipment for implementation. Rather, it involves modifying the way in which existing equipment is operated in order to make an improvement.)

Second, users were found to be the developers of all (three only) multistep process concepts I examined in this study. These are the important process concepts that underlie single process steps and give them meaning. For example, in the semiconductor industry the process steps listed as 5–10 in Table 2–10 are all steps in a photolithographic process that are intended to implement a larger process concept known as the planar process of semiconductor manufacture.

I did not explicitly collect a sample of this important type of innovation, but I did note three in the course of collecting data on the single-step innovations I was studying. The first of these was the planar process for manufacturing semiconductors just mentioned. It was developed by Fairchild Semiconductor, a process user.The product/process concept of building semiconductors on a silicon substrate rather than on germanium also affected many process steps, and it was developed by Bell Laboratories and Texas Instruments, both users of the process. Finally, the basic product/process concept of mounting electronic components on a plastic board that had electrical circuits printed on it (the basic concept of the PC board) was developed by the U.S. Signal Corps, a user, in 1948 as part of an effort to miniaturize military electronics.

TABLE 2–13. Patterns in Transfer of User Innovations to First Commercializing Equipment Manufacturers[a]

	How Frequently Observed		*Lag Between User Innovation and First Commercial Equipment Sale*	
Pattern Observed	*%*	*(n)*	*Mean Years*	*SD*
Multiple user/ manufacturer interactions	46%	11	3.7	1.3
No transfer found	25	6	1.8	0.4
User equipment order	21	5	1.0	1.3
User becomes manufacturer	8	2	4.0	0.0

[a]Total user-developed process machine innovations = 29; transfer pattern data NA = 5.

Diffusion of Innovations

Unlike the situation in scientific instrument innovations, users of process equipment innovations do not necessarily have an incentive to transfer what they know to an equipment manufacturer. In fact they might have an incentive to hide what they know to achieve a competitive advantage. (I will consider this matter in depth in chapter 6.) Therefore, it would be interesting to know how equipment manufacturers learned of the user process innovations I studied, and I looked into the matter.[11]

Details of the transfer process were typically not well documented or recalled by interviewees. However, I determined that the transfer of user-developed process equipment innovations to the first equipment manufacturing firm to produce them as a commercial product fell into one of four general patterns (see Table 2–13).

In order of the frequency with which these were observed:

1. Multiple interactions between the staffs of user firms and manufacturer firms made it impossible to isolate *the* events surrounding transfer. In these instances, several user firms had homemade versions of the innovation in-house at the time of transfer, and it was clear that a great deal of information was being passed around. A typical interviewee comment: "Everyone was talking about *x* user design at the time."
2. No transfer identified. Although a user was first to develop the equipment used commercially (and was coded as the innovator on this basis), no transfer process was identifiable retrospectively.
3. A user (not necessarily the initial innovating user) transferred the design of the innovation along with a purchase order for units produced to that design. The user's intent in these instances was to obtain an outside source of supply for the novel equipment.
4. An equipment user (not necessarily the innovating user) also adopted the role of equipment manufacturer and began to produce the innovation for sale to other user firms.

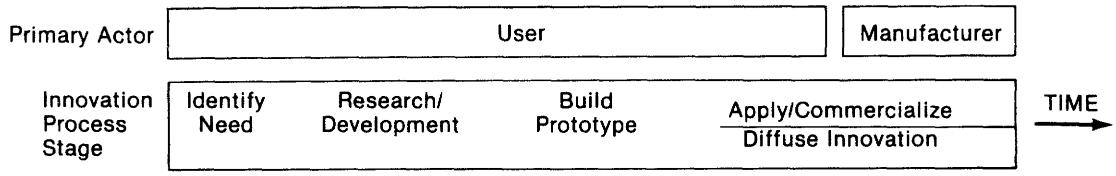

FIGURE 2–2. Steps Observed in the User Development of an Innovation

The User-Dominated Innovation Process

We have now found three innovation categories in which it is typically the product user, not the product manufacturer, who recognizes the need, solves the problem through an invention, builds a prototype, and proves the prototype's value in use. If we apply this finding to "stages" of the technical innovation process, we find—somewhat counterintuitively—that the locus of almost the entire innovation process is centered on the user. As is shown schematically in Figure 2–2, only commercial diffusion is carried out by the manufacturer.

This finding is at odds with conventional wisdom and with most of the prescriptive literature in the new product development process directed to manufacturers. That literature characteristically assumes that the *manufacturer* must find a need and fill it by executing the new product development stages in Figure 2–2.

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. First, as we will see in chapter 3, the manufacturer *is* the usual innovator in many product and process categories. Second, a manufacturer's association with an innovation is usually much more public than that of users and others, and this can inadvertently reinforce the presumption (sometimes false) of manufacturer-as-innovator. Thus, very naturally, in the course of marketing an innovation, manufacturing firms may 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 innovating users or other contributors to the innovative process (advertising they generally have no reason to engage in), it is easy to make the assumption.

Of course, some might feel that the data presented in this chapter are *not* evidence of user innovation and that the within-manufacturer "norm" applies. 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 "need" that the firm (in the terminology of Figure 2–2) "identifies." It would then follow that the succeeding stages in Figure 2–2 also occur within the manufacturing firm. The "research and development" stage, for example, might consist of the engineering work manufacturer personnel devote to converting the user prototype into a commercial product.

Although one might make the argument outlined above, I myself 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 and process equipment data afresh, we see something very interesting: Product categories marked by a great deal of innovation in which the firms manufacturing the products are not necessarily innovative in and of themselves. Indeed, we might plausibly look at the manufacturers of these products as typically only providing the manufacturing function for an innovative set of user/customers.

This finding that nonmanufacturers may be the innovators in some industries certainly opens the way to an interesting new view of the innovation process. After all, accurate knowledge of who the innovator *is* is essential to much innovation research and practice.

Notes

1. National Research Council of the National Academy of Sciences, *Chemistry: Opportunities and Needs* (Washington, D.C.: National Academy of Sciences, 1965), 88.

2. U.S. Department of Commerce, Bureau of the Census, *Current Industrial Reports: Selected Instruments and Related Products* (MA38–B (80)–1 January 1982 SIC Code 38112) (Washington, D.C.: U.S. Government Printing Office, 1982).

3. 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. The users consulted were interested in instrumentation and/or had made major contributions to it (as evidenced in scientific review articles of each field).

4. This decision rule excluded "me-too" innovations from the sample, including those that duplicated the successful performance increase of a previous innovation but by different technical means.

5. Much of the improvement in performance of a product or process can be the cumulative result of many minor, incremental innovations (see Samuel Hollander, *The Sources of Increased Efficiency: A Study of Du Pont Rayon Plants* [Cambridge, Mass.: MIT Press, 1965], 196; Kenneth E. Knight, "A Study of Technological Innovation: The Evolution of Digital Computers" [PhD diss., Carnegie Institute of Technology, Pittsburgh, Penn., 1963]). Therefore, I had wanted to identify samples of minor improvement innovations for all four types of scientific instruments being studied. As work proceeded, however, I only carried out this plan in the instance of the transmission electron microscope. Unfortunately, experience showed that participants could not recall events surrounding minor innovations very well or very reliably. The events had not seemed very significant at the time—indeed, they were not, they were minor—and the details had faded with time.

6. The community of users and manufacturers associated with each of the four instrument types I studied was small in the early days of each type. Therefore, as is reasonable, my data contain several instances in which more than one major innovation was invented by the same user or first commercialized by the same instrument firm. With respect to a single user developing more than one innovation: 2 GC innovations were developed by a single user, as were 3 NMR innovations, 2 UV innovations,

and 4 TEM innovations. With respect to a single manufacturing firm being first to commercialize more than one sample innovation, the 111 innovations in my sample were first commercialized by only 26 companies: 12 GC innovations, first commercialized by 8 companies; 15 NMR innovations, first commercialized by 3 companies; 6 UV innovations, first commercialized by 2 companies; 15 TEM basic and major improvement innovations, first commercialized by 6 companies; and 63 TEM minor innovations, first commercialized by a total of 7 companies.

7. 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 I can best convey a feeling for the two categories by an illustration using Felix Bloch's sample spinning innovation described later in this chapter. The *concept* of achieving an effective increase in magnetic field homogeneity through 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.

8. F. Bloch, "Line-Narrowing by Macroscopic Motion," *Physical Review* 94, no. 2 (15 April 1954): 496–97; W. A. Anderson and J. T. Arnold, "A Line-Narrowing Experiment," *Physical Review* 94, no. 2 (15 April 1954): 497–98.

9. I originally planned to study all 21 major process steps identified in Table 2–10. Because of time limitations, however, only 14 were completed. These were not chosen for study randomly, but were chosen by no conscious system.

10. Innovations that offered major or minor increments in functional utility to users relative to previous best practice were identified independently for each process step studied (i.e., major improvements in component insertion equipment were identified by comparison with other component insertion equipment innovations only). This was done because improvements in the different types of equipment typically had an impact on various dimensions (precision, speed, reliability, and so on) not easily made commensurable.

11. Eric von Hippel, "Transferring Process Equipment Innovations from User-Innovators to Equipment Manufacturing Firms," *R&D Management* 8, no. 1 (October 1977): 13–22.