with various powers to entice co-workers; frequent discussion of results in progress; and cooperative modification of the total research plan as new situations arise. Each such group would require not only a tactful chairman from among the working participants but also a full-time executive officer from the Institute that would be responsible for funding and monitoring the program.

These are some ideas for *supplementing*, not replacing (I stress *not replacing*), the present procedures for supporting medical research in this country through collaborative and coordinated research programs for accelerating the solution of those problems that are too complex to be solved through the uncoordinated efforts of individual investigators.

Project Hindsight

A Defense Department study of the utility of research.

Chalmers W. Sherwin and Raymond S. Isenson

No matter how much science and technology may add to the quality of life, no matter how brilliant and meritorious are its practitioners, and no matter how many individual results that have been of social and economic significance are pointed to with pride, the fact remains that public support of the overall enterprise on the present scale eventually demands satisfactory economic measures of benefit. The question is not whether such measures should be made, it is only how to make them.

We wish to report here on an attempt by the Department of Defense to make such measures. This effort, known as Project Hindsight, is a study of the role that research played in the development of weapon systems between the end of World War II and about 1962 (*1*).

To appreciate the need for Project Hindsight one has merely to examine the budget of the Defense Department. In recent years, the Department has been spending \$300 to \$400 million a year for "research." Of this sum, we estimate that about 25 percent is committed to basic or undirected science, although concentrated in areas generally relevant to the DOD missions, and about 75 percent to applied science more directly related to defined DOD needs. The Department has been spending an additional billion dollars a year for "exploratory development," which includes the more sharply defined applied research, small-component development, and other activities of the sort generally characterized as "technology" (*2*). (This \$1.4-billion expenditure does not include the system development programs which are its main reason for existence.) Questions were constantly being asked, both in the Executive Branch of Government and in Congress: Was this large a sum really needed? What has been the return for the expenditure? Can the Defense Department not depend for more of its science and technology on the private sector or on other Government agencies? These are reasonable questions, but there seemed to be no systematic, quantitative answers. One of the objects of Project Hindsight was to try to provide such answers; that is, to try to measure the payoff to Defense of its own investments in science and technology. A second object was to see whether there were some patterns of management that led more frequently than others to usable results and that might therefore suggest ways in which the management of research could be improved. In particular, we wanted to determine the relative contributions of the defense and non-defense sectors, and, within the defense sector, the relative contributions of in-house laboratories and those of contractors.

Assumptions and Methods

Given these objects, how does one start? Since the challenge was essentially an economic one, the answers would have to be based upon economic benefits. The economic return of a scientific or technical innovation is through its utilization in an end-item—a piece of equipment, a process, or an operational procedure. Therefore in order to assess return one has to measure the value of the end-item made possible by the innovation. As a practical matter, for military hardware the easiest way of measuring economic benefit is by comparing the value of an end-item with that of some predecessor end-item which it partly or wholly replaces.

Our method of analysis was as follows: One begins by comparing a successor item with a predecessor, identifying all the contributions from science and technology which were significant in the improvement in performance or the reduction in cost of the item. One then estimates the portion of the increase in the cost-benefit of the end-item which is attributable to the scientific and technical innovations utilized. (This portion is, of course, very large for defense equipment.) One then calculates what it would cost to obtain enough predecessor equipment to do the job that the successor equipment is now doing, assuming that the same capital resources and management skills were available for the predecessor as for the successor. The difference between this cost and the actual cost of the successor is a measure of the economic benefit assignable to the set of significant contributions from science and technology which were utilized in the successor

Dr. Sherwin, formerly Deputy Director of Defense Research and Engineering for Research and Technology, is now Deputy Assistant Secretary of Commerce for Science and Technology. Colonel Isenson, U.S. Army, is in the Office of the Director of Defense Research and Engineering.

and not in the predecessor. Although this method makes it possible to attach an economic value to the set of identified technical contributions, it has the effect of focusing on recent contributions from science and technology, for, as might be expected, the difference in technological content between the successor and predecessor is found to be predominantly of recent origin. (The time between predecessor and successor in defense equipment is typically 10 to 20 years.) Since the common base extant at the time of the predecessor is largely ignored, the method has built into it a bias against the identification and evaluation of longer-range research. We were aware of this bias from the beginning of the study, but since what we were interested in was the utilization of knowledge generated in the past 15 to 20 years, it seemed not to cast doubt on the soundness of the method (*3*).

The Process of Analysis

The most critical step in the analysis was the identification of the key contributions, those which significantly improved the performance or reduced the cost of the successor. The insight of a team of scientists and engineers, working together, and experienced in the system being analyzed, was essential. Each contribution then had to be traced back (again, by scientists and engineers) to a time and place of origin or, as it often turned out, to two or three (usually related) sources. Although we were not sure when we started that a key contribution could be traced back to identifiable people at a definite time, or to an "Event" as it came to be called, we found that almost invariably it could. We shall give some examples shortly.

Research Events are distinguished on the one hand from routine engineering design, and on the other from the broad base of knowledge generally available, or "in the textbooks." An Event is defined as a period of creative effort ending with new, significant knowledge or with the demonstration of the applicability of a new engineering concept. Each Event was written up in a standard format giving considerable detail regarding its significance to the system, its relation to contemporary science and technology, key personnel, and so on.

Having selected the retrospective approach for the reasons described above, we found that it had additional advantages. First, tracing backwards in time from utilization to the originating Event is much easier than the reverse process, for the user of technical information almost invariably knows his sources, whereas the source frequently does not know the ultimate user. A second advantage is that, when one starts with an end-item and tabulates all the significant contributions that have made its improved performance possible, one gets a good perspective on the relative numbers and the importance of the contributions from different sources. Typically, scientists and engineers use the "example argument"; that is, they trace one idea at a time from a source to an application, begging the questions What *other* ideas were important in making the end-item practical? Where did they come from? (For this reason, forward-tracing of ideas does not lead easily to quantitative, economic analysis unless one makes a complete detailed technical analysis of the end-item which brings us right back to the Hindsight approach.) Or even more frequently, enthusiasts point to *anticipated* applications, which are even harder to evaluate since many of the supporting innovations have yet to be created, and whose economic value is almost completely a matter of speculation.

The Systems Studied

The first study in the project, begun in 1964, was an analysis, made by a small group of scientists and engineers working in the Defense Department, of the "Bullpup" air-to-ground tactical guided missile system. The effort was augmented by a contract study performed by Arthur D. Little, Inc. on six additional systems (*4*). These early studies developed the techniques and demonstrated the feasibility of the method of analysis. Then in the summer of 1965, with the support of Harold Brown, then Director of Defense Research and Engineering, a much larger effort was undertaken by teams of Defense Department scientists and engineers working closely with the principal contractors. All told, 20 systems of diverse character were studied, and we estimate that some 40 professional man-years were expended. Counting the initial study group and the Arthur D. Little team, there have been 13 different teams independently analyzing systems for key contributions and tracing them back to their origins. There are now 710 documented Events in the data file. We think it is significant that, in spite of the diversity of end-items studied (for a list see Table 1), and in spite of the fact that 13 different teams made the analyses, the conclusions are of a piece. Indeed, the properties of our sample have not changed substantially since the data base included fewer than 100 Events.

Types of Events and Some Examples

The identified Events are classified according to the intention with which the work that led to them was carried out. *Science Events* are defined as theoretical or experimental studies of new or unexplored natural phenomena. Science Events are divided into two categories: *Undirected Science*, in which the object of the work is the advancement of knowledge, without regard to possible application, and *Applied* or *Directed Science*, in which the object of the work is to produce specific knowledge or an understanding of phenomena which is needed for some particular use or uses. *Technology Events* include the conception or demonstration of the possibility of performing a specific elementary function with the use of new or untried concepts, principles, techniques, or materials; the first demonstration of the possibility of performing a specific elementary function with the use of established concepts, principles, or materials; the measurement of the behavior of materials and equipment as required for design; or the development of new manufacturing techniques.

An example of a series of related technology Events involved the development, starting in 1949, of the titanium-aluminum-vanadium alloy used in the compressor blades of the turbo-fan engine in the C-141 transport aircraft. The high and uniform strength-to-weight ratio, the corrosion and erosion resistance, and the notch-toughness and creep resistance of this material substantially increased the efficiency and reliability and reduced the weight and extended the life of the engine compared to what they would have been had one used the steel blades employed in the turbine engine that drives the propellers on the C-130A aircraft (the predecessor system). The early devel-

Table 1. Systems studied in Project Hindsight.

Hound Dog, air-to-surface missile
Bullpup, air-to-surface missile
Polaris, submarine-launched ballistic missile
Minuteman I, intercontinental ballistic missile
Minuteman II, intercontinental ballistic missile
Sergeant, tactical ballistic missile
Lance, tactical ballistic missile
Mark 46 Mod 0, acoustical torpedo
Mark 46 Mod 1, acoustical torpedo
M-102, 105-mm howitzer
AN/SPS-48, frequency scan search radar
Mark 56, sea mine
Mark 57, sea mine
Starlight Scope, night vision instrument
C-141, transport aircraft
Navigation Satellite
M-61, nuclear warhead
M-63, nuclear warhead
XM-409, 152-mm artillery round
FADAC, digital computer for field operations

opment of this alloy was the result of the efforts of individuals in two organizations. Some of the basic work was done in 1949 and 1950 at the Armour Research Foundation, supported by the Army and the Air Force, for military applications. At about the same time, further work was performed at the Battelle Memorial Institute funded partly by the Air Force and partly by industry (the Remcru Titanium Corporation). Over the next 10 years, Remcru and others carried the alloy developed for them at Battelle into production, and thus it was available for use in the Pratt and Whitney turbofan engine used in the C-141, where the team identified it. This material is known to have many other military and commercial applications as well.

Another example, also a series of related Events, is the development of the anti-jam radio link that controlled the Bullpup missile, designed (in 1954) and built by the Martin Company. This radio control link was critically dependent upon the principle of correlation detection which emerged in 1942 at the Massachusetts Institute of Technology from Norbert Wiener's theory of correlation, statistical filtering, and prediction. (An applied science Event, since at the time Wiener was working on the problem of anti-aircraft fire control.) Then (1947–1950) Lee, Cheatham, Singleton, and Wiesner of the Research Laboratory for Electronics at M.I.T. applied Wiener's general correlation techniques to the specific case of radar modulation and detection and demonstrated that very large improvements in signal-to-noise ratios were possible. (An applied science Event.) In 1952, J. Alpert of the Martin Corporation picked up the M.I.T results at a technical meeting and, using them as a starting point, developed a practical jam-resistant radio link as a proposed alternative to the guidance system of the Matador missile. (A technology Event). The link was never used for the Matador system, but the concept was available for use in the engineering design of Bullpup in 1954.

Our third example is a series of six related Events. The performance of the SPS-48 radar depends critically upon a high-power hydrogen thyratron not available for the predecessor system, the SP radar of design date 1944. The historical analysis made by the team (mostly from the Naval Research Laboratory) revealed the following sequence. In 1942, K. Germeshausen, working alone, but starting with a knowledge of the work on hydrogen-filled triodes for electronic sweep circuits reported in 1936 by P. Drewell, in Germany, developed the boxed anode structure which made the high voltage thyratron possible. (A technology Event.) Drewell's work was not included as an Event, for it substantially antedated the period of interest. In 1943, to prevent gas "clean-up" due to impurities in the electrodes, the International Nickel Company, working with Germeshausen, developed an electrolytic refining process. (A technology Event.) In 1944 Marsh and Rothstein, of the Army Signal Corps Laboratories, by theoretical calculation of the internal electric field identified the source of the "long path breakdown problem," pointing the direction for the new electrode designs. (An applied science Event.) In 1945, Germeshausen at the M.I.T. Radiation Laboratory, in collaboration with Marsh and Rothstein, conceived and demonstrated the practicality of the titanium hydride reservoir needed to compensate for the residual hydrogen clean-up accompanying very-high-voltage operation. (A technology Event.) In 1951–1955, Martin, Goldberg, and Riley, all of Edgerton, Germeshausen & Grier Company, as a result of a detailed theoretical and experimental study of the hydrogen gas discharge and its effect on tube life, were able to develop a much smaller, more rugged, longer-lived tube. (A technology Event.) Finally, in 1957, the same group developed the high-temperature, metal and ceramic long-life tubes (A technology Event) which were actually used in the SPS-48 radar and which so significantly contributed to its performance and reliability.

The six technology and three applied science Events described above are representative of the type of work identified in the study as the basis of improved system performance, except that if anything these Events have more science content and less practical engineering content than the population of Events as a whole. We hope we can explain below why it is that such practical, even "pedestrian" technical efforts are credited with so big a role in improving weapon systems.

Many Innovations Are Needed

When a weapon system is compared with its predecessor of 10 to 20 years earlier, its ratio of performance to cost and its mean time to failure typically are greater by factors of 2 to 10. Moreover, the operating manpower needed to obtain the same calculated military effectiveness usually drops by a factor of 2 or more. That is, the increase in effectiveness/cost is often 100 percent or more. Yet when one examines the equipment design in detail and tries to determine why this large change has occurred, no one item seems capable of accounting for more than a small fraction of the net change. Thus, for example, if one were forced to use the older steel compressor blades in the C-141 turbo-fan engines, rather than the titanium-aluminum-vanadium alloy mentioned above, the performance of the aircraft would be reduced only slightly, perhaps a percent or so. Still, the C-141 designed in 1964 has a ton-mile cost of only 60 percent that of the turboprop C-130 designed in 1954, which did use steel compressor blades. A careful examination of the C-141 design shows, however, that there are a large number of identifiable significant technical contributions which together explain the improved performance.

In the case of the C-141, the team from Wright Air Development Center, working with the help of engineers from the Pratt and Whitney Division of United Aircraft and from Lockheed Corporation, analyzed over 80 Events that they judged to be the most significant in accounting for the improved performance of the C-141.

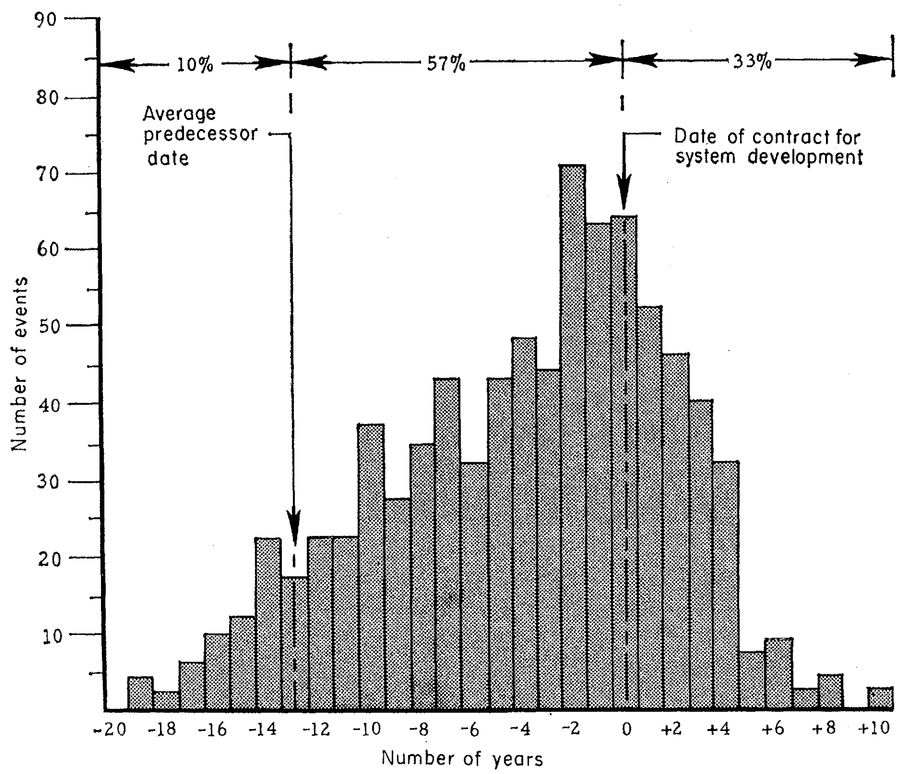

Fig. 1. The time distribution of the Events identified in Project Hindsight with respect to the development-contract dates of the systems in which the Events appear.

Some two or three times as many additional Events were tentatively identified but were not subjected to a detailed historical tracing because the study was terminated when the analysis showed that the Events tended to conform to a uniform pattern with respect to motivation, time to utilization, and so forth.

Our finding in the case of the C-141 was repeated in all the systems we studied—that is, it is the interactions of many mutually reinforcing innovations that appear to account for most of the increase in performance/cost of weapon systems compared to their predecessors.

In the larger systems, 50 to 100 Events were common. Even for small pieces of equipment a number of Events—18 in the case of the night-vision device, for example—were readily identified.

We should, perhaps, note here that an appreciation of the significance of the finding which we have just described is crucial to an understanding of the whole study. All 13 teams arrived at the same conclusion. They simply could not find a dominant invention or discovery which by itself seemed to account for most of the performance/cost increase. Even the invention of the transistor, brilliant though it was, was followed by a long series of other Events in both transistors and components which were necessary before its full benefits could be realized. Incidentally, we classified the series of eight transistor Events occurring at the Bell Telephone Laboratories as applied science since they occurred in a mission-oriented environment and were clearly in support of the mission. Together, the transistor-associated Events did play a dominant role in the FADAC computer and in certain parts of other systems such as the on-board electronics in the Minuteman, the torpedo, and the satellite.

An Important Approximation

At this point we make a zero-order approximation: we will treat all Events as if they were of equal value. Even in a given system, this cannot be true in detail, and it certainly cannot be true when one considers uses in more than one system, such as the sequences of transistor and aluminum-weldment Events, which contributed more frequently and more importantly than others of a much more specialized nature. We are not satisfied with this assumption but see no easy way to avoid it, for much of the value of an Event is derived from its association with other Events and even some of the most elegant contributions that we have identified would have remained unutilized in the absence of a complementary display of creativity in related areas. Within this study, therefore, we have been limited to the mere number of identified Events, and this means that any inferences based upon such counts are reasonably dependable only when they are based upon large numerical ratios.

A Summary of the Data

Let us then look at the total data base of 710 Events.

First, we find that 9 percent of the Events are classified as science Events and 91 percent as technology Events. The science Events are distributed as follows: 6.7 percent of all Events were motivated by a DOD need and are therefore classified as applied science; 2 percent were motivated by a commercial or non-defense need and are also applied science. Only 0.3 percent of all Events were classified as undirected science. Of all science Events 76 percent were motivated by a DOD need. If we look at the technology Events, we find that, of all Events, 27 percent were directed at what we call a "generic, DOD-oriented technology," that is, a broad class of defense needs not related to a particular system or system concept—for example, high-power radar components, improved solid propellants, or titanium alloys. Forty-one percent of all Events were motivated by a system or system concept in the early or "advanced development" stage, and 20 percent by systems in the later, or "engineering development," stage. Finally, 3 percent of all Events were motivated by non-DOD end-item need. Of the technology Events 97 percent were motivated by a DOD need. Overall, nearly 95 percent of all Events were directed toward filling a DOD need.

We found that in the great majority of cases the initial recognition of need came from an external group associated with systems design, but that the technical initiative for the solution came primarily from the research-performing group. That is, the need-recognizers made the researchers aware of the nature of the problems but did not dictate the nature of the solutions.

We find that 86 percent of the Events were funded directly by the Department of Defense and an additional 9 percent by defense-oriented industry. Only 3 percent were funded by commercially oriented industry, and only 1 percent by other government agencies. One percent were funded by other sources. It is interesting that, although the non-defense sector had available an estimated 40 percent of all science and technology funds expended in the U.S. during the period covered by the study, only 5 percent of the Events identified by Project Hindsight were funded there. Per dollar of input effort, the non-defense sector produced less than one-tenth as many defense-utilized innovations as did the defense sector.

We tabulated the time distribution of the occurrence of Events for all systems with respect to the engineering design date. The results are shown in Fig. 1. Several significant features can be seen from this figure. The average time interval between predecessor and successor is 13 years, and only 10 percent of the Events utilized in the successor had occurred by the time the predecessor was designed. This demonstrates that it is indeed recent technical activity that accounts for the specific advances to which the improved performance is ascribed. It is significant that many innovations generated after the engineering design date, or contract date, were utilized, some during the system-engineering processes and some even later in the stage called "operational systems development." Despite the very applied nature of the work leading to the innovations, 5 or 10 years often elapsed before an Event was used (see Fig. 1). The median delay for science Events was 9 years, and for technology Events 5 years. One should not, then, be surprised that in a study covering as little as 20 years undirected work should not be found to play a significant role.

Of the research-performing organizations, we found that industry accounted for 47 percent of the Events, DOD in-house laboratories for 39 percent, universities (including contract research centers) for 12 percent, non-DOD federal for 2 percent, and foreign for less than 2 percent. This suggests that, considering their relative funding and size, the in-house laboratories contribute their share of Events.

Implications of the Findings

These then are the principal findings of the study thus far obtained. What inferences can be drawn with respect to the R&D enterprise as a whole and with respect to the science or research components of this enterprise?

The most significant finding is that in the weapon systems we studied, large changes in performance/cost are the synergistic effect of many innovations, most of them quite modest. This finding provides a rationale for most of the other findings. Thus, for example, if many innovations must be skillfully fitted together to produce a large net improvement, it is likely that they are not the result of random efforts directed toward diverse and unrelated goals, but are due to a conscious plan. This at once suggests that the great majority of Events will be technology or applied science Events. It suggests to us that the isolated invention or the random scientific fact is not likely to "fit in" or, therefore, to be utilized. In other words, it tells us once again that recognized need is the key to efficient utilization. But to recognize need one has to have very detailed knowledge of either a class of systems or a specific system so that the critical problems can be addressed. Thus one predicts that actual systems—particularly those in the early stages of design—will be the most frequent sources of the recognized need. One also predicts that, because they are so intimately exposed to system development problems, the in-house laboratories and defense industry will have a very favored position from which to make useful contributions and that non-defense industry will play a small role. In some cases, of course, such as the early transistor developments and aluminum weldment, when its needs happened to coincide almost exactly with defense needs, non-defense industry has been the source of important contributions. For example, the properties needed in solid-state devices for the commercial electronics and communications were just those needed for military electronics and communications, and reliable, tight aluminum welds were as important for beer barrels as they were for missile fuel tanks. In general, however, because of the high performance and reliability requirements and higher allowable cost of defense equipment, one would expect such cases to be rare.

The "many-innovations-are-needed" concept even gives us insight into the time-distribution curve of Fig. 1. As several of our examples illustrate, later innovations may depend on ones that preceded them. Since one innovation may engender several others, it is reasonable to expect that the rate of accumulation of potentially useful innovations will increase over time (assuming that the level of effort is not reduced).

Because these expectations are in fact borne out by the detailed studies, both individually and in sum, we believe that the picture we present is consistent.

The Case for Directed Effort

We made a crude estimate of the military effectiveness of the successor system in a defined role, divided by its total procurement and operating cost, and made a similar estimate for the predecessor system in the same role. We obtained improvement factors of 1.6:1 for the transport aircraft, 10:1 for the sea mine, and, for the search radar, 40:1 when we require current performance from the old technology and 5:1 when we require the old performance with current technology. We believe that an average improvement factor of 2:1 would be a conservative estimate for the systems we studied. If this same improvement factor were to apply to all the equipment in the total inventory of some $80 billion, we can see that the approximately $10 billion of DOD funds expended in the support of science and technology over the period 1946 to 1962, when most of our Events occurred and which, in fact, financed most of these Events, has been paid back many times over. We believe our study shows, also, that, had the Defense Department merely waited passively for the non-defense sectors of the economy or government to produce the science and technology it needed, our military equipment would be far inferior to what it is today. We believe that the traditional DOD management policy of keeping applied science and technology closely related to the needs of systems and equipment in development (a policy which, of course, is also characteristic of industry) is basically sound if one wants an economic payoff on the 10-year (or shorter) time scale.

Table 2. Educational level of contributors to Project Hindsight Events and of research performers in general.

Highest degree held	Hindsight contributors* (%)	All S&T† (%)	All R&D‡ (%)	All S&T§ (%)	All engineers ‖ (%)
Ph.D.	10.5	3.1	1.2	3.8	
M.S.	22.5	8.6	7.2		63
B.S.	57.0	34.6	47.0		
Some college	6.8	39.5			37
No college	3.2	14.2	44.6		

* Base number, 1725. † S. Warkov and J. Marsh, "The Education and Training of America's Scientists and Engineers: 1962," National Opinion Research Center, University of Chicago, Chicago, Ill., 1965, p. 17. ‡ A. Shapero, R. P. Howell, J. R. Tombaugh, "An Exploratory Study of the Structure and Dynamics of the R&D Industry," Stanford Research Institute, Stanford, Calif., June 1964, p. 31. § "Profiles of Manpower in Science and Technology," NSF 63-23, National Science Foundation, Washington, D.C., 1963, p. 17ff. ‖ "How Many Engineers?" *Engr. Manpower Bull.* No. 5, Engineers' Joint Council, New York, July 1966.

What the Hindsight study has done, therefore, on a scale previously not attempted, is to develop a strong, factual demonstration that recent, mission-oriented science and technology are a good investment in the short term—the 10- to 20-year period. What we have not been able to do is to demonstrate value for recent undirected science. Our observations on why we failed to make this case are discussed in the next section.

The Case for Recent Undirected Science

It is clear that, on the 50-year or more time scale, undirected science has been of immense value. Without basic physical science we could scarcely have had nuclear energy or the electrical industry or modern communications or the modern chemical industry. None of our science Events could have occurred without the use of one or more of the great systematic theories—classical mechanics, thermodynamics, electricity and magnetism, relativity and quantum mechanics. These theories also played an important role in many of the technology Events. If, for example, we were to count the number of times that Newton's laws, Maxwell's equations, or Ohm's law were used in the systems we studied the frequencies of occurrence would be so high that they would completely overshadow any of the recent Events we identified. But, however important science may be, we suspect its primary impact may be brought to bear not so much through the recent, random scraps of new knowledge, as it is through the organized, "packed-down," thoroughly understood and carefully taught *old* science (*5*). Similar conclusions have been reached by others who have considered the question (*6*). Thus when one debates the utility of science the real issue is not the value, but rather the time to utilization. We believe that the Hindsight study has merely reemphasized an old mystery: What *is* the process by which science moves into technology and utilization? It is clearly not the simple, direct sequence taught by the folklore of science.

We feel, however, that entirely aside from the research results themselves—which, of course, go primarily into the "eternal archive," from which they may ultimately contribute to the next great consolidation of science—a laboratory carrying on undirected research, colocated with and skillfully related to an applied research and development organization, more than pays its way.

A mission-oriented organization needs highly trained scientists and engineers to help supply what Marquis and Allen (*7*) call "gap-filling science"—the additional knowledge needed to make older, organized knowledge usable—and a very large part of the estimated $100 million a year spent in support of fundamental scientific investigations by Defense goes into research that supports graduate education. Table 2 shows the percentages of individuals with advanced degrees who were identified as contributors to the Events in the Hindsight study, as well as several sets of comparable figures for larger research communities. Advanced degrees are several times more frequent among the Hindsight contributors than among the less select groups. About one-third of the contributions to Project Hindsight Events appear to have depended upon graduate education.

There is, moreover, an important practical need, related to the sociology of science, to carry on some undirected, although generally relevant, research in the mission-oriented research and development organizations themselves. Undirected research serves as a form of postdoctoral training; it provides initial jobs for new Ph.D.'s who are inclined toward basic research but who want a closer look at mission-oriented research before making a career commitment; it provides intellectual stimulation and a link between the research frontier and the applied activities; and it provides a body of in-house expert consultants to help on unusually difficult applied technical problems (*8*).

In the strongest and most productive mission-oriented laboratories undirected research generally amounts to about 15 percent of the total research effort (*9*). If 15 percent of the 30,000 scientists and engineers, military and civilian, who are directly involved in the Defense Department's R&D enterprise were active in undirected but generally relevant science, the cost would be about $150 million a year. This is not a large figure considering the size of the science and technology budget alone of about $1.4 billion a year, and a development, test, and evaluation budget some four times greater still.

What Needs To Be Done Next?

In the original design of Project Hindsight, we recognized that the physical scientists and engineers tracing the historical record might not be sensitive to psychological and other behavioral factors affecting the generation and utilization of scientific and technical knowledge. In order to assure that proper attention would be given to these aspects, Task II of the project was established concurrently with the task that led to the results we have been describing. The second task is directed at understanding the actual processes going on today in the organizations (and in many cases with the same people) involved in the Events identified in Task I.

Within 6 months after the onset of Task I, ten organizations had been identified as being prolific contributors of the science and technology upon which the examined weapon systems were based. Among these organizations were represented industry, the DOD in-house laboratories, and the Atomic Energy Commission. Management scientists from each of the organizations were formed into a team to conduct field studies, each within his own organization, looking into information sources, idea flow, skill development, project selection, relations between research groups, and other such aspects of the R&D process. The field studies were designed by management scientists of Northwestern University and the Sloan School of the Massachusetts Institute of Technology. Participating organizations include Raytheon, Ling-Temco, North American Aviation, Lockheed, United Aircraft, the Army's Picatinny and Redstone arsenals, the Air Force's Wright Air Development Center, the Naval Ordnance Laboratory at White Oak, and the Naval Ordnance Test Station at China Lake. Data are now being collected, and analysis will be initiated in the near future. The findings will be reported by the university groups conducting the research.

It is possible that if systematic retrospective analyses were to be applied to scientific, rather than to engineering accomplishments a great deal more could be learned about the scientific process. Have the randomly directed research efforts so characteristic of much of science in the past played as big a role as they are often thought to do? Or, is it sharply focused effort directed at well-defined, limited goals, which are more frequently the key events in the scientific advance?

Finally, if Project Hindsight tells us anything about science, it is that it is unusual for random, disconnected fragments of scientific knowledge to find application rapidly. It is, rather, the evaluated, compressed, organized, interpreted, and simplified scientific knowledge that we find to be the most effective connection between the undirected research laboratory and the world of practical affairs. If scientists would see their efforts in undirected science used on a more substantial scale in a time period shorter than 20 years, they must put a bigger fraction of their collective, creative efforts into organizing scientific knowledge expressly for use by society.

Summary

Recently developed weapon systems were compared with systems of similar function in use 10 to 20 years earlier. The most significant finding was that the improvement in performance or reduction in cost is largely the synergistic effect of a large number of scientific and technological innovations, of which only about 10 percent had been made at the time the earlier system was designed. The common scientific and technological base of the systems was not analyzed. Of the innovations, or Events, 9 percent were classified as science and 91 percent as technology. Ninety-five percent of all Events were funded by the defense sector. Nearly 95 percent were motivated by a recognized defense need. Only 0.3 percent came from undirected science. The results of the study do not call in question the value of undirected science on the 50-year-or-more time scale. In light of our finding that 5 to 10 years are often required before even a piece of highly applied research is "fitted in" as an effective contributing member of a large assembly of other Events, it is not surprising that "fragments" of undirected science are infrequently utilized on even a 20-year time scale. The most obvious way in which undirected science appears to enter into technology and utilization on a substantial scale seems to be in the compressed, highly organized form of a well-established, clearly expressed general theory, or in the evaluated, ordered knowledge of handbooks, textbooks, and university courses.

References and Notes

1. For a more detailed account see C. W. Sherwin and R. S. Isenson, "First Interim Report on Project Hindsight" Summary, 30 June 1966; revised 13 Oct. 1966, No. AD 642-400, Clearinghouse for Federal Scientific and Technical Information, Springfield, Va.
2. The total expenditure for research, development, technology, and engineering, 1946–1963, was approximately $44 billion. Of this, $10 billion went for scientific and technical investigations; the remainder went for prototype and engineering development of weapons and other end-item equipment and for test and evaluation. Although Project Hindsight considered almost exclusively the physical and engineering sciences (and technologies) the dollar figures include expenditures for life and behavioral sciences. Records do not permit a more detailed breakdown.
3. We believe, in any case, that the method is probably capable of being used in a sequence of historical steps to pick up the earlier contributions in a sort of historical integration process. Alternatively, one could take larger historical steps; for example, one might compare a military radio in 1966 with one in 1916. A step of this size, though possible, would be much more formidable, because almost everything—components, modulation techniques, spectrum utilization, in this example—is different, and the history of an older item would be more difficult to reconstruct. Moreover, because of the greatly changed background conditions even our crude measures of relative economic value would be much less reliable.
4. "Management Factors Affecting Research and Exploratory Development," Arthur D. Little, Inc., April 1965. No. AD 618-321, Clearinghouse for Federal Scientific and Technical Information, Springfield, Va.
5. Thus, for example, in the development of the "field-enhanced, low density, transmission secondary emission films" used in the SEC Vidicon, G. W. Goetze of Westinghouse relied heavily on H. Bruining's *Physics and Applications of Secondary Electron Emission* (Pergamon, New York, 1954), which summarized what was known about secondary emission in transmission starting with the work of Leonard in 1900 and terminating with that of S. Wecker in 1941. Similarly, in the design of the broadband wave guides essential for the operation of the SPS-48 frequency scan radar a handbook composed of numerical tables based upon Bethe and Marshak's 1942 calculation of wave guide transmission was used, and for the signal-detection "strategy" of the same radar Marcum's handbook of charts and graphs presenting in convenient form the signal-detection probabilities based upon earlier analytical work of North and others was used. Thus there is evidence that the processing through handbooks and reviews is an important stage between the generation of new science and its application. We found one instance in which the development of instruments intended for undirected science played a role in Project Hindsight Events: some work on image-intensifiers for use in astronomy was used in the development of the night-vision device.
6. It seems to take about a generation for research results to reach this stage, as D. J. de Solla Price has observed [*Technol. Culture* **6**, 533 (1965)]. Price describes the process as one in which technology seems to arise directly from the established trunk and main branches of the tree of science, rather than from its growing twigs. Occasionally, says Price, "A single new piece of science gives rise quickly and directly to technological repercussions. When it does, the effect is brilliant and startling, and the incident becomes glamorized and mythologized, but the main advance of technology follows well behind the moving frontier of science." Jacob Schmookler has reached similar conclusions [*Invention and Economic Growth*, Harv. Univ. Press, Cambridge, Mass., 1966]. In a set of 934 important inventions in four different fields, Schmookler observes, "there was no single instance of a scientific discovery acting as a stimulus, and . . . in most cases either the inventions contained no identifiable scientific component, or the science they embody is at least 20 years old." He also observes that, in almost every instance when a stimulus to an invention was identified, it was a "technological problem conceived by the inventor in economic terms." Another study of this question, a detailed analysis of the process by which ten recently developed materials proceeded from the research stage into engineering, has recently been made by the special committee of the Materials Advisory Board of the National Research Council ("Report of the Ad Hoc Committee on Principles of Research-Engineering Interaction," MAB-222-M, National Academy of Sciences–National Research Council, Washington, D.C., July 1966. No. AD 636-529, Clearinghouse for Federal Scientific and Technical Information, Springfield, Va.).
7. D. G. Marquis and T. J. Allen, *Amer. Psychologist* **21**, 1052 (1966).
8. J. Morton, *Intern. Sci. Technol.* No. 29, 82 (May 1964).
9. R. S. Isenson, *IEEE Inst. Electron. Elect. Engrs. Trans. Eng. Management*, *EM*-12 113 (1965).