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Technology in Retrospect and Critical Events in Science

A Summary and Critique of Findings by IIT

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and

Critical Events in Science

The following is a summary of the results of research carried out by the Illinois Institute of Technology under a contract with the National Science Foundation and issued in a report entitled "Technology in Retrospect and Critical Events in Science." This report includes the findings with respect to five major innovations that have influenced chemical and engineering industry. The five historically important innovations are 1) Magnetic ferrites, a class of materials widely used in computer memories, in telecommunications, and in small electric motors, which had developed out of a broad base of research activity before and after World War II. 2) The video tape recorder, a device whose origin extends back to basic work in magnetic materials, control systems, and mechanical design, and which culminated from an obvious need created by television and the convergence of research and development shortly thereafter. 3) The oral contraceptive pill, an innovation of great economic and social importance, which resulted from a long history of nonmission-oriented research in physiology, hormones, and chemical synthesis. 4) The electron microscope, an instrument based on knowledge gained from fundamental research in electron physics, wave mechanics, which has had very many applications throughout the scientific and technical world. 5) Matrix isolation, a new and promising technique, already revolutionizing certain chemical processing industries for the study of the mechanism of chemical reactions. Matrix isolation is an example of a scientific technique hardly visible to the non-specialist, yet of great significance because of its contribution to technologies of direct economic importance.

In the summary which follows, only three of these are singled out for discussion, namely, the magnetic ferrites, the video-tape recorder, and the electron microscope. The selection of these cases of innovation and their scientific antecedents conforms with the objective of the research project of the National Science Foundation. In this research it was apparently intended to show the influence of on-going research in scientific institutions frequently without direct contact with the business world. It was decided to attempt to classify the individual research and development events leading to these innovations on the basis of their technical content and motivation, independent of the organization in which they occurred at the time, relative to the innovation, at which they took place. A vast amount of information was available on the three innovations chosen for study, and a selection became necessary. That is, a selection of events which were considered major contributions in the evolution of the appropriate scientific areas and the subsequent technological innovation. The final selection was left to the judgment of the scientists. Although the events selected for the historical evolution represent only the key events, personal and subjective points of view in their selection could not be completely suppressed. Apparently general agreement among the scientists who participated in the project was obtained on what constituted an important event. The origins of the historical antecedents of the innovations were selected by the scientists as those research milestones which are recognized as marking the beginnings of the various distinct lineages of a scientific specialty that contributed to the eventual innovation. The end of the historical evolution was taken as a point at which the first generation of acceptable commercial items appeared, or the most recent date for which information could be obtained if a commercial device had not yet evolved. This discussion shows the long development that leads to the final transfer of technology to a commercial use, and it is for this reason that the developments leading to the three innovations--that is, the magnetic ferrite, the video-tape recorder, and the electron microscope, have been chosen. The report then describes the historical evolution both in a narrative text and in a chart. In these narrative texts, which are summarized in the pages that follow, and in the charts, an event is marked as a point at which a published paper, presentation, or reference to the research is made. In most cases, it appears to represent the culmination of a number of years of effort and much supporting research which is not shown in the chart or discussed in the text. In marking the events, multiple contributors were counted separately, in those cases where they occurred. The general applicability of the results depends, naturally, in a great measure on the representative nature of the sample of the innovations. Before discussing any specific results, it is worth considering some of the general features of the historical evolution and variation among the cases selected.

It is interesting that in the lineage charts the historic evolutions are classified with respect to type, time, type of innovation, socio-economic effect, and the contributing disciplines. For example, with respect to the videotape recorder, the date of innovation is given as 1956. The time period for the last 50 percent of the events leading to the innovation, events as defined above, is given as 1927 to 1956, a period roughly of thirty years. The socio-economic effect is considered large, and the major disciplines that have contributed to the innovation are listed as physics, chemistry, mathematics, ceramics, and electrical engineering. In the case of magnetic ferrites, the innovation date is about the same, 1955, but the period over which the last fifty percent of events were spread is only 14 years, that is 1946 to 1959. The disciplines are the same as those that contributed to the video tape recorder. In the case of electron microscopes, the innovation is dated 1940, fifty percent of the events leading to it occurred in the thirty year period from 1910 to 1940, and the disciplines contributing, again, are physics, mathematics and electrical engineering. Nevertheless, a significant diversity of scientific and engineering research becomes apparent when one considers the areas of specialization, rather than the major disciplines, that contributed to the innovation. Each of the historical descriptions delineate the lines of activity which are recognizable as technical specialties in the various professions, such as hormone research, electron sources, magnetic materials. In discussing the innovations, at least 25 areas of specialization were identified. Certain areas, of course, appear in more than one historical evolution, but there are at least distinct fields that have contributed highly selected and important events relevant to innovation. This the scientists say, means that many of the elements of the technological lineages were and will be utilized not only for the application considered here, but for other purposes as well. It also means that each of the fields has multiple descendants in the various technological and commercially useable fields. However, in the interest of simplicity, the authors of the historical tracings have reduced the number of such lineages by combining closely related areas. This the scientific and engineering specialties identified in the charts can be considered as a minimum. In any given chart, which shows the historical evolution, development of certain areas of specialization is obvious. It is not surprising, for example, to see magnetic theory and the development of magnetic materials in association with the development of magnetic recording techniques. However, it is difficult to imagine that prior to the inception of the video tape recorder, one could have predicted that control theory, a mathematical design concept for improving the response of mechanical and electrical systems, and the theories of frequency modulation would be required to converge in the near future to achieve a successful videotape recorder. Equally unpredictable, the scientists say, was the merger of the relatively mundane development of cathode ray tubes with the newly developed quantum theory and with the dualistic concept of nature to stimulate the electronic analogy of the microscope. Nor can one usefully speculate, so say the scientists, on the altered course of events had one of the many pieces of the research puzzle been missing. In all cases, the existence of a diverse fund of knowledge was clearly essential to the development of that innovation at that time and at that place. This last statement clearly shows, shall we say, the basic objective of the analysis of the scientists. They seem to be bent on finding that a basic knowledge and a continuous forward movement in the development of basic knowledge is the best guarantee that multiple innovations will emerge. This of course, is contrary to the objective research and development departments in industry are generally following, namely the confinement to the specific knowledge applicable to a particular industrial field. The scientists go on to elaborate the 341 distinct key research and development events which were judged to be important to the evaluation and testing of the innovations surveyed by them. A very large number of research events of lesser significance to the innovation were also part of the total picture, but apparently were not documented in the report. Of these lesser events, approximately 70 percent were non-mission oriented, that is, not oriented towards a particular objective. 20 percent were mission oriented, and 10 percent were classified as development and application. This relatively small percentage of development events was due in part to the fact that these tracings concentrated on the events leading to the first clearly identifiable commercialization and did not consider product improvement and further product evolution. However, in this context, the scientists say, it demonstrates the diverse and large background of research on which innovation is based. The inclusion of all of the instrument development and advance in skills and crafts and peripheral research which underlie the events as identifiable, serves further to increase diversity and amount of activity which could be shown as necessary to innovation. This means that the scientists, if they had

had room enough expert knowledge at their disposal, probably would have had to include the basic mathematics developed in antiquity and would prove that without this, the final evolution of either matrix isolation or magnetic ferrites would have been impossible. They noted that several areas of specialization, such as magnetic theory, and electron physics, are common to several innovations. In particular, distinct events were shown to have contributed to more than one innovation. While they were not part of the study, one knows that other innovations, such as the transistor and the synthetic fiber have utilized research events which are documented in this IIT report. This illustrates, in the view of the scientists, an important point, namely that while this study consists only of five or three historical evolutions, it is not fully evident that it exhausts all the antecedents of these innovations. "Knowledge developed by research has multiple application, and is utilized repeatedly, not only for direct innovation, but also for the continuous development of new areas of science and technology."

The role of the various kinds of institutions which were engaged in research and development and contributed major events to the innovation are also described in the study. The percentage of contributions from universities, research institutes, government labor-stories, and industries were calculated for each of the three categories of research, namely mission research, non-mission research, and development and application research. The proportion of non-mission research events originating at universities was approximately 75 percent of all such research and was of course much larger than one would expect in the mission-oriented research and the development and application research.

Typically, the National Science Foundation has found, universities have been receiving between 50 and 60 percent of the basic research funds over the past 20 years, and they therefore contributed a much larger percentage to the basic, or non-mission oriented, research than the other groups. The research institutes of the government contributed 16 percent, and those of industry 14 percent to basic non-mission research.

The scientists also addressed themselves to the question as to whether the research and development done outside the United States has been a factor in the innovations described. The relative influence of foreign efforts in research and development was on the decrease in the period after the forties. The continued growth of research funds in this country relative to foreign efforts is clearly reflected in the specific historical evolutions. For example, the national trend in the research and development events show that they reached their peak insofar as non-mission research is concerned, in the sixties, while the foreign non-mission research reached their peak in the thirties. The mission-oriented research in the United States reached its peak in the fifties, while the foreign non-mission research stayed at a plateau throughout this period. And in development and application research in the United States, research peaked also in the fifties, while abroad it reached its peak before the forties. The overall impression one gains from the contribution, both of foreign and United States research activities, shows that the bulk of research and development specifically identified in the three cases took place after 1940. This, in the view of the scientists, is indicative of the accelerated activity in the transition from research to innovation which is evident in these historical descriptions. Although the authors had gone far back in history to establish the initial events and the subsequent scientific lineages, more than 30 percent of all events contributing to innovation occurred in the post-1940 period. This, the scientists feel, is due to at least two factors; one, most of the innovations studies here occurred between 1950 and 1960, and therefore, the research efforts contributing to the innovation must have proceeded this decade. Furthermore, there was a marked increase in all research and development activity which took place after World War II, thanks to new budget allocations.

The Role of the Time Factor in the Transition from Research to Innovation

According to the scientists working for the National Science Foundation, the conversion of scientific knowledge into technology is an important part of the innovation process. The individual historical descriptions show that the elements of knowledge required and the detailed transfer mechanism differed among the innovations. Ranging on the one hand from a publication in a professional journal to communication in a multi-disciplinary laboratory on the other hand. A simplified view of the time-history of historical events leading to the three innovations may be shown by a bar chart which contains three major elements. One, the duration of the phase from origin to innovation, second, the period from 'conception' to innovation, and third, the time at which theknowledge from 75 percent of the events of all three research classifications had been acquired. The 75 percent level represents a point at which the majority of the research events had already occurred, but at which a significant fraction of the research and development critical to the innovations remained to be done. The 'conception' was interpreted as having occurred when a clear concept of the device or of the process or of the effect which was the objective of the research was apparent. However, no discrete innovation time could be set for the magnetic ferrites, since these products were produced sporadically over a period of years. The various times at which products were developed late in the ferrite history were used to calculate the arithmetic mean (1955) which was arbitrarily employed in the scientists' historical tracing as the date of innovation. The longest period of development is that recorded for the matrix isolation. This, as was reported earlier, is an innovation of an experimental process, and its early progress may have been controlled by the growth of interest in scientific applications, rather than by the potential commercial usage. The scientists might have expected that the increase in the scale of scientific technology, together with advancing knowledge and more rapid communication, should have served to shorten the time between the conception and innovation, certainly for the recently occurring innovations. The time between conception and innovation ranges from 14 years for the matrix isolation to 6 years for the video tape recorder. The limited data available do not warrant a conclusion concerning changes in the development period and the influence of the increasing research and development budgets.

Another view of the relationship between the types of research events can be obtained by plotting them against time, backwards, from the date of innovation. If we show non-mission research, mission research, and development and application research by decades of time prior to innovation, then we find that the non-mission events reach their peak between the 20th and 30th year prior to innovation. The scientists attributed this behavior to the rate at which new knowledge becomes an integral part of and a tool of mission-oriented research and development. The period of 20 to 30 years corresponds roughly to the educational cycle, the time necessary for producing a new scientist endowed with a new body of knowledge, and tends to confirm the fact that most inventors rely heavily on information created in the previous generation. Both mission-oriented research and development research contribute equally through the average historical evolution, but mission-oriented research increases in the last two decades before the innovation, whereas the major developmental inputs occur in the final ten years. The interval between years 10 and 20 contain the World War II period for the three historical cases, and therefore the level of activity in this interval is somewhat lower than might have been expected in a normal history. The pattern displayed in the individual historical evolutions strongly resemble the composite, which suggests that the relative roles of the three categories of research and development activity tend to be invariant with the bounds of accuracy of the study. It also suggests that time-histories of current research and development programs having breadth comparable to the innovations treated in the study might be used to guide the required activity levels of non-mission, mission-oriented and development efforts. This criterion of course helps the scientists who are concerned with justifying a long-term budget commitment. Other figures also support the scientists' view that it takes a long time-span over which research, especially non-mission research, accumulates knowledge leading towards innovation. Or to put it another way, the long term value of good research is clearly demonstrable and even though the linear chain of events often encountered in the historical tracing is sometimes frustratingly long, the ultimate necessity for particular bits of knowledge justify this slow progress. They come to the conclusion that "the average time from conception to innovation is approximately nine years for all five cases considered, including the three described in detail. Ten years prior to innovation, that is, shortly before conception, approximately 90% of the non-mission research is found to have been accomplished. Insofar as one can generalize from these time-spans to other cases of transitions from research to innovation, the bulk of non-mission research is completed without insight into the conception and innovation to which it will ultimately contribute. Here again, one notes a bias of the scientists who wish to bring out the fact that basic research must be carried on without tying it to a conception, let alone to an innovation, to which it may ultimately contribute. From the previous discussion it follows that, in the views of the scientists, if the history of an innovation is traced only within the confines of its development, that is the period after conception, and before innovation, the resulting picture is incomplete. Innovation and development are often based on science which is thirty years old or older, some 45% of non-mission research having been completed at the 30 year level. Furthermore, assuming that the date of innovation as defined in this study and the design decision reference point used here are roughly comparable, then approximately 80 percent of the development work remains to be done at year 15. The 80 percent of non-mission research already done is completely excluded from consideration, in an analysis limited to that short time scale. Although non-mission research and mission-oriented research play a diminishing role in terms of total activity during the several years just preceding the innovation, it is apparent from the tracings that the interplay between the effort in these phases is important and sometimes even crucial during the terminal period. The tracing of the ferrites provides a striking example of this. During the decade 1950 to 1960, non-mission research in the form of theoretical and experimental studies of electromagnetic resonance properties of materials was interwoven with mission-oriented studies of specific ferrite materials and with development and application research of ferrites in connection with computer memory storage devices, high frequency ferrite cores, etc. The large amount of interplay between areas of technical specialty and discrete research events in the ten or twenty years prior to innovation, together with the importance of techniques and instrumentation, strongly suggests the need for overlap between the experienced researcher and the inexperienced engineer, and therefore the need for interchange between the industrial research and the academic communities.