SCIENTIFIC RESEARCH AND INNOVATION

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by

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Like it or not, change is the hallmark of the contemporary world. Generally we like it since we identify change with the idea of progress. In operational terms this reduces to the introduction of new ways of doing things, new products, new processes, new forms of social organizations, new industrial practices -- in short, innnovation in the broad sense of the word.

Clearly, technology -- including product or process directed applied science -- is often an integral part of the process of innovation, but what about that scientific research which has improved understanding of phenomena as its principal goal and new knowledge as its primary product? Does this "phenomena-oriented" research play a central role in the innovative process?

Conventional wisdom, imbued with the idea that innovation usually starts with new understanding, gives a "yes" to this question, but frequently, particularly recently, this "yes" is being questioned. I believe also that the answer is most certainly "yes", but I have come to have considerable respect for the reasons behind the challenges to the conventional wisdom.

In the present paper I discuss the central importance of phenomena-oriented research to innovation, drawing from recent studies on science-technology interactions. These studies show that the demonstration of the role of science in innovation requires focus on the magnitude, variety and importance of the dialogue which takes place between the scientific and technological communities rather than a preoccupation with the role of new scientific research as the fountainhead from which innovation springs.

Invention, Innovation, and Scientific Research

The innovative process includes invention as a step. Invention is the creation of an idea and its reduction to practice; innovation is the bringing of the invention into widespread use.

The body of knowledge which we call science may be characterized by its continuity. Scientific research aims at contributing new knowledge to the already accumulated store. Each contribution in some sense rests on and is related to what has gone before. It also serves to generate or point to future paths of fruitful work. In conjunction with the accumulation of new knowledge, a process of ordering takes place. There is ordering into scientific discipline (with the frequent generation of subdisciplines and hybrid disciplines). There is also ordering in the forms of generalizations -- the laws and theories.

Inventions may be also considered as ordering occurring in the continuum of knowledge. Invention requires the existence of a body of relevant knowledge before the idea can be formed so in this sense invention grows like further scientific knowledge. However, in addition, an invention is an ordered domain that develops simultaneously by projecting outward an external environment of possible utilization. When the question is asked "Why does this happen", we are seeking an ordered domain in the continuum of knowledge, but when we ask "What use could be made of this," we are trying to relate our ordered domain against an external environment also.

Clearly then, there are important cases where innovation and the search for new knowledge can be directly related. This is especially true of radically new technologies, e.g., transistors, synthetic fiber, computers, nuclear energy, for we find that their introduction goes hand in hand with change in scientific theory.

The World War II success story is another part of the conventional wisdom of science and innovation. Certainly, persons doing primarily phenomen-oriented research when the war broke out proceeded to help exploit scientific understanding thus bringing about many important innovations in a short period of time. The WW II story certainly has influenced our ideas about the relationship of science and innovation. Unfortunately for our understanding of the role of science, however, we have given too little consideration to the fact that the vast majority of the scientists involved were working as <u>technologists</u> during the war emergency.

Because of the foregoing and related reasons, it is not surprising that we are tempted to think of innovation as an orderly process, starting with the discovery of new knowledge, moving through applied research, and finally appearing as some manufactured article, system or new structure that is viable in the marketplace or otherwise has a beneficial impact on our society. However, closer examination shows that this "linear" model is atypical and that the prevalence of its acceptance can be detrimental to both the development and use of science.

It is important that the fallacies in the linear model be pointed out since it often leads to the assumption that innovation is a rational process, essentially similar to the other major functions of a firm or organization. The assumption is that it can be analyzed into its component parts and subject to rational control. In other words, it can be planned, programmed and generally managed similar to other activities.

The importance of recognizing the non-rational nature of the innovative process can be seen further through noting that the more novel the inventions, the less the process tends to be orderly and predictable. The addition of a new cake mix flour can be managed rationally. On the other hand, radically new inventions typically will require the organization which adopts it to undergo many major changes, many of which could not be programmed in advance of the discovery.

Some Recent Studies of the Innovative Process

Recently several studies "in depth" of the innovative process have been made which shed considerable light on the contributions of phenomena-oriented research in the innovative process. Dr. Boyer's paper for this panel describes one of the important studies. I will now describe two others briefly, and also mention several others.

The Materials Advisory Board of the National Research Council, National Academy of Sciences recently completed a study (1) of research-engineering interactions. Under the leadership of Dr. Morris Tanenbaum, Director of Research and Development of the Western Electric Corporation, a panel with experience in the support and performance of scientific research and engineering was enlisted. Each participant selected a subject where he believed that interactions between scientific research and engineering had led to a significant technological achievement. He then attempted to document in detail what had occurred.

Ten case histories were generated. They concerned developments in metals, ceramics, and synthetic polymers with structural, electronic and other applications. The authors searched the histories for recurring patterns of events and circumstances which occurred with sufficient frequency to merit their citation and more thorough scrutiny.

The factor which stood out most was that in nine of the ten cases, the explicit recognition of an important need was identified as a major and recurring factor in bringing about the research-engineering interactions. It was rare that basic research by itself produced a technological opportunity which was quickly recognized and developed. Far more frequently an urgent need stimulated a search for a solution through prior basic knowledge. An individual with a well-defined technological need initiated the research-engineering interactions that led to the positive interaction between science and technology.

It was also interesting that in most of the cases the science that led to the technological solution was available <u>before</u> the dialogue began. It was rare that the technological need directly stimulated the generation of the science used to solve the problem.

In the majority of the cases, the fruitful interactions which took place occurred between organizationally independent groups which were also frequently geographically separated. Again it was usually the individual with a need who bridged these gaps.

In only three of the cases did the majority of the research-engineering interaction events involve in any way individuals whose principal interests were in basic research. However, if the attention is restricted only to the research-engineering interactions required to take the innovation through the invention stage, then in more than half of the events interactions with basic research findings or a basic researcher were found to be important.

Recently the Air Force Office of Scientific Research made a study of the benefits accrued to the Air Force through the support of research (primarily in universities) during the last one and one-half decades. These studies, which included information obtained by contacting a large group of persons knowledgeable in depth of that research (e.g., principal investigators), have provided us a large increase in specific information showing how the Air Force has benefited from the AFOSR program. The analysis of these studies, reported elsewhere (2) shows that this science support has been very important to the innovative process engaged in by the Air Force.

We found that the AFOSR has helped colonize many important scientific areas which have turned out to have special relevance to the Air Force, inasmuch as they are generally recognized as underlying important Air Force applications. Colonizing may be described as increasing the chance of important discovery in an area by "raising the temperature" of the world's scientific activity in that field. Through judicious support of phenomen-oriented research and other activities such as symposia, the Air Force research support, amplified by that supported by non-Air Force funds, has affected very significantly the rate of development of important scientific areas -- hypersonic phenomena, hypersonic facilities, magnetic resonance spectroscopy, optimum control theory, visual perception, mass transfer cooling, information theory and many others.

We also found that AFOSR is playing an important role in technical education. At any given time our research program is providing at least partial support for the doctoral research of more than 1,000 graduate students. The over-all importance of this support is quite substantial but hard to measure; however, it can be appreciated by recognizing that these students are among the top strata of the Nation's graduate students and they are receiving their education in areas particularly relevant to the DoD. Many have gone on to work in Air Force contractor or in-house facilities, equipped with knowledge and skills particularly pertinent to their work because of the previous Air Force association.

We also found that we could identify many specific examples where AFOSR supported phenomena-oriented research has provided important support of Air Force weapons acquisition programs at all phases of the research, development, and engineering cycle. We found this input through new or improved manufacturing techniques, design techniques, instrumentation, and weapons systems component concepts, to mention a few cases.

We also found that many scientists supported by AFOSR are consulting for the DoD contractor and in-house research and development activities. In a very real sense, AFOSR support helps these persons achieve and maintain their expertise while they contribute direct practical help to the DoD.

Finally, it is important to note that the AFOSR program has provided research support for scientists who are among the leaders of their respective disciplines and that the research results have often been among the most important in their fields.

There are several other recent studies which I will only mention very briefly. Sumner Myers (3) in a study of five hundred and sixty-seven innovations in the housing, computer and railroad industries, placing particular emphasis on the source and impact of externally generated science data in stimulating technological innovation, concluded that new scientific knowledge seldom starts the process, but rather that successful innovation comes from the synergistic combination of several ideas, many of which are available from unrelated R&D that has not yet been widely applied.

Marquis, et al (4) in studying information flow in various R&D laboratories, have underlined the importance of "technological gatekeepers." These are the persons to whom colleagues turn for technical advice and critiques. They are typically heavy readers <u>and</u> have wide contacts with technical and scientific workers in other organizations including active researchers in universities. Similarly, Rosenbloom and Wolek (5) found the importance of the information obtained from the scientific and technical community outside of their own organization. This conclusion was reached by analyzing the responses of 2,000 scientists and engineers from thirteen establishments of four corporations, and 1,200 members of the IEEE who were requested to furnish information on where and how they received information, from a source other than their immediate circle of colleagues, that proved useful in their work.

Still another fruitful source of information about science-technology interaction is the NAS Report for the U. S. House of Representatives Committee on Science and Astronautics (6).

In summary, I believe that these studies show that:

1. Innovation rarely proceeds by the linear process with the discovery of a new knowledge being the starting point of the innovative process.

2. However, <u>very frequently</u>, interaction with new knowledge or with persons actively engaged in the search for new knowledge is an <u>essential</u> part of the innovative process.

3. Furthermore, very frequently these interactions are made possible by a great deal of freedom and flexibility in the process -- across organizational, geographical, discipline lines -- and they utilize information the need for which could not be anticipated and therefore not programmed. In short, the innovation typically follows a non-rational process.

4. The interactions with new knowledge can often be described in terms of a communication between the technological community and scientific community. The entrepreneurs in the innovative process are members of the former community. Those persons intimately familiar with the scientific understanding needed are members of the latter community.

5. The innovative process requires that members of both the technology community and the scientific community be open to engaging in the dialogue.

6. Persons in technological organizations who are in intimate communication with the scientific community play a key role in the innovative process -- the "technological gatekeeper."

Description of the Innovative Process

In a real sense the innovation process defies generalization, since there apparently is no one model, or even small set of models, useful in classifying the various cases of innovation which have been studied. However, it is useful to liken the process to a complex feedback-type information processing system(7).

Innovation should be regarded as a total process consisting of a number of factors acting together in a collective cooperative way. In other words, it is not generally possible to understand innovation just as a novel invention, the development of a new gadget, the design of a new system, the creation of a new market, or the devising of new ways of raising the required capital.

As the innovative process is considered as an adaptive system consisting of many parts which depend on individually creative acts and collectively creative acts of people, and particularly as the individual science-technology interactions are brought into focus, the vital importance of the search for new knowledge is seen. At the same time that the importance of entrepreneurship, market development and other factors are being brought into focus, it is seen that innovation is increasingly bound up with research and education.

Whether or not one attempts to develop models demonstrating the role of research in the innovative process, I believe that it is essential to recognize both the existence and the continuing importance of the scientific and technical communities as separate entities. It is helpful, both in describing the role of the search for new knowledge as part of the innovative process and in discussing the support of a science-dependent organization through scientific research, to divide research and development activities into two broad categories -- phenomena-oriented science and technology -- as illustrated in Figure 1. In technology creative efforts are primarily concerned with synthesis, that is, integration of previously existing knowledge components into operational capability -- for example, systems, devices, processes, methods, and materials. In contrast, phenomena-oriented science is more heavily concerned with the origins of the knowledge components themselves.

As new phenomena are understood, this new knowledge is made available to the scientific and technological communities in many ways. However, it is important to note that the new information becomes known by the peer group in the world scientific community much sooner than it is known by other groups, particularly those associated primarily with technology utilization. Thus new science may forge ahead, relatively independent of an ambient technology.

Similarly, technology usually feeds upon technology, in the presence of an ambient science. Technology events are usually initiated within technology. This means that usually it is difficult to establish a unique correlation between a technology advance and one within phenomena-oriented science.

Thus the gross picture is that technology usually feeds upon technology and phenomena-oriented science usually feeds upon phenomena-oriented science. However, at the same time it is absolutely essential to emphasize the magnitude, vitality, and effectiveness of the varied dialogue between the two communities.

The nature of this interface is dynamic, varying greatly among different science-technology pairs and with time for a given technology. Industries such as communications, computers, and instruments are much more closely coupled to science than are the railroad and agricultural equipment industries, for example, and transistor technology was much more closely coupled to solid state physics fifteen years ago than it is today.

Thus it is clear that any study, such as the Department of Defense Project Hindsight, which concentrates on isolating the points of origin of technological events, will usually reveal them to lie within technology. It is equally clear, however, that it is invalid to conclude from this finding that research taking place in the scientific community and therefore not related rather directly to the technology concerned was of little help to the innovation which occurred. On the contrary, the studies referenced in this paper and others like it make it abundantly clear that this research is a highly essential part of the innovative process.

It is unfortunate that some have quoted (8) the first interim report of Project Hindsight concerning the small identified contribution of university research to weapons system development, without critical commentary with regard to the applicability of the Project Hindsight methodology for evaluating the contribution of such research. It is important that we continue to attempt to further understand and communicate the real nature and importance of the role of phenomena-oriented research in the innovative process in order to prevent non-objective backlash against the support of research by industry and the Federal Government. It is also essential that we use this understanding to optimize the effectiveness of the industry and mission-oriented

Federal agencies in benefiting from scientific research.

The Scientific Research Activity of a Mission-Oriented Organization

I believe that the above considerations make it abundantly clear that any organization dependent on a science-based technology is in turn highly dependent on the scientific community. The fact that many of these organizations -- both industrial and federal -- devote very substantial attention to their dialogue with the scientific community is an affirmation of this statement.

There is a significant body of experience of mission-oriented agencies and industrial corporations (some of which is described in the literature (9))with the conduct and support of scientific research activities. I believe that this type of activity will not only continue to be viable, but will grow in amount and effectiveness, providing sufficient attention is given to making certain that these activities serve their proper role and the performance of this role is as effective as possible.

In view of the limited time available, I will restrict my remarks to just the scientific research activities of mission-oriented agencies. However, I have been continually impressed with the extent to which the industry picture -- particularly large industries -- is analogous.

AFOSR and similar science-support activities can perform an important interface function when they incorporate an intimate involvement with both the university scientific community and the agency. For example, AFOSR has good ability to attract the interest of the world's top scientific talent, since it is a science-oriented organization with a well-established reputation in the scientific community as a good research agency with which to work. At the same time the AFOSR staff members have the organizational position, and a growing body of experience and techniques for carrying on an effective dialogue with the Air Force technology community.

In providing this interface, AFOSR engages in two types of activities. The first main function is to support high-quality scientific research chosen because of its importance to the development of science and its relevance to defense. We pursue this support in a manner calculated to colonize scientific activities of special importance to the Air Force. The selection of these areas may be motivated either by seeking to pioneer new fields of science holding out high promise for generating the new knowledge from which new technologies or new operational possibilities may evolve or it may be motivated by helping various development or other user groups solve certain difficult classes of important problems by providing a fuller understanding of the phenomena behind them.

The second main function is to help communication between the scientific community and the Air Force. This is a two-way communication -- needs to the research program and scientific information to the user. The AFOSR project scientists play the key role in this communication or coupling activity. In addition, part of what we purchase through contracts and grants is primarily designed to provide communication. This part refers not only to the symposia we sponsor, but to the connecting-type research which allows us to keep abreast of a variety of scientific areas largely supported by other agencies, but nevertheless important to the Air Force because of rapidly emerging scientific developments.

AFOSR and similar organizations face two special continuing challenges described briefly below. One is selection of the areas in which to sponsor research -- the "planning function." The other is constructive support of the dialogue between the scientific and technological communities -- the "coupling function."

Scientific importance, in terms of the scientific interest in the field, its stage of development, and the qualifications of the researchers, must always be the prime consideration in selecting research. In addition, relevance and other considerations must be taken into account and research managers continue to search out additional means to improve their effectiveness in doing so. However, research managers properly approach this "planning" with caution and humility because of their respect for history which makes it clear that really new ideas and startling developments of technology typically contain very important elements of surprise (10). Some of the considerations followed have been described elsewhere (11).

A great deal of sustained attention is being devoted to coupling science and technology. A sampling of some recent literature reveals the extent and nature of this attention (12).

The fact that new knowledge originating in phenomena-oriented research often has implicit in it important new opportunities for exploitation suggests that when these can be recognized on the research side, great advantages, particularly in timing, can be realized. This appears to be an important area for increased attention by phenomena-oriented research activities toward the end that the initiative can be successfully taken by the scientist more frequently, even though there is some serious question of the value of a solution looking for a problem in the over-all scheme of things.

It is clear that the technological community has an important continuing responsibility in the coupling process. Pierce (13) has put this very well in his recent article discussing "When is research the answer?" In part, he says "The effective application of understanding and invention requires the effective and interrelated carrying out of many functions other than research, including development, trial, production, distribution, and continual evaluation and improvement. Good research may -- or may not -- find use through various fortuitous mechanisms of society."

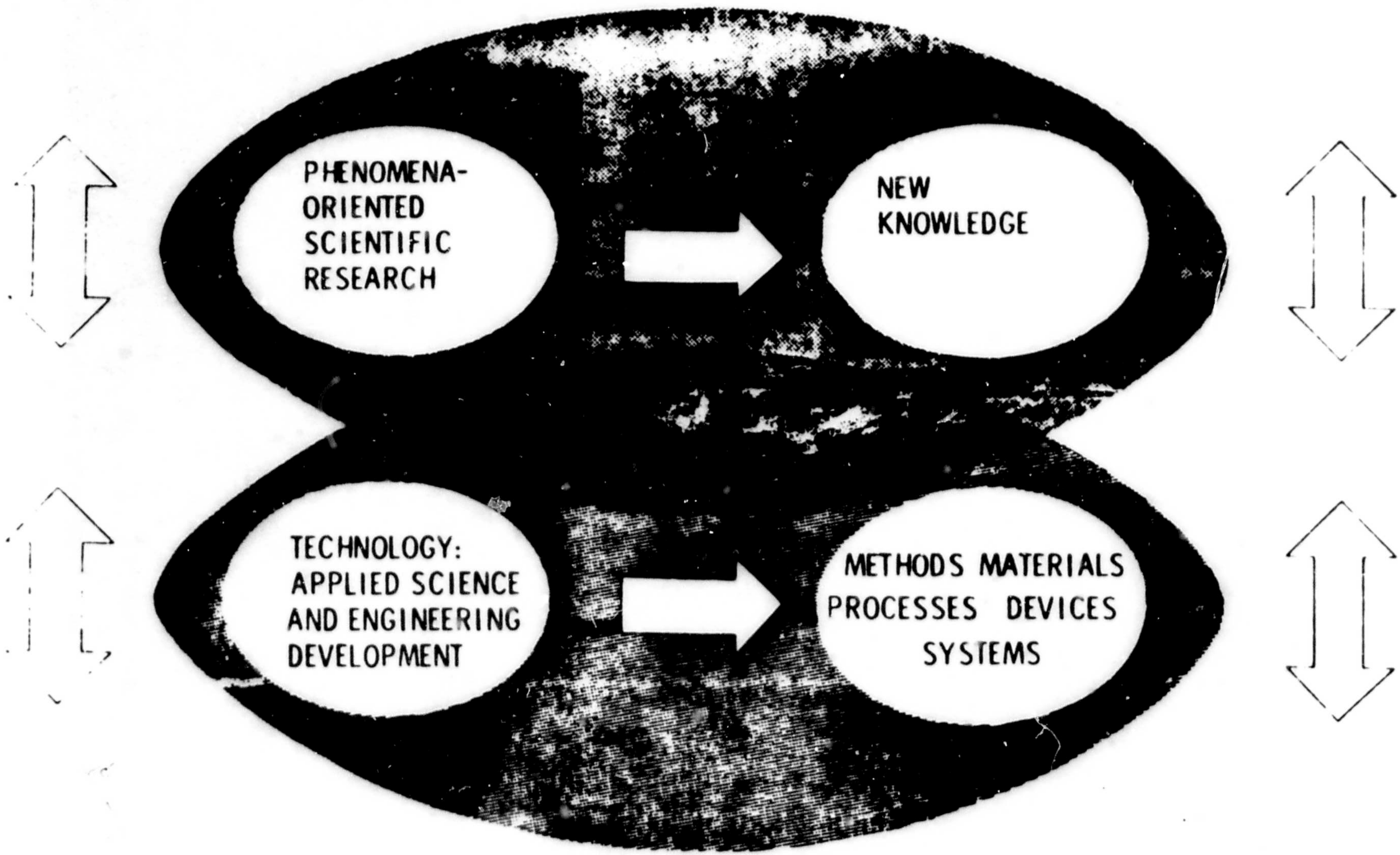
Conclusions

I believe that it is most certainly true that scientific research is a very important part of the innovative process. However, we need to give continued attention to the understanding and articulation of this process in order to receive adequate support for the required research and to assure that its impact is optimized.

I believe that the managers of the scientific research activities of both mission-oriented agencies and of industry have in general evolved adequate means of choosing the fields of long-range research which is relevant to their organizations. However, it is clear that we need to continue to develop improved planning methods in order to increase the credence of others in this process as well as to increase the quality of the choices made as the leveling off of the budgets continue to force a higher degree of selectivity.

Further, I believe on the whole that the scientific and technological communities are effectively coupled although there are certainly areas where significant improvement can be made on the part of both communities.

It is particularly essential that high priority be given to the maintenance of highly viable university-industry and university-Federal Government interfaces. This requires the active participation of many persons in all three communities, and special studies on these matters are already underway.


PHENOMENA-
ORIENTED
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RESEARCH
NEW
KNOWLEDGE
TECHNOLOGY:
APPLIED SCIENCE
AND ENGINEERING
DEVELOPMENT
METHODS MATERIALS
PROCESSES DEVICES
SYSTEMS

Figure 1

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13. ABSTRACT

The author examines the innovative process as exemplified in technological progress as directly related to the ordering process of the generation of new knowledge through scientific research. Inventions are seen as ordering occurring in the continuum of knowledge. A number of case surveys were both conducted in AFOSR and analyzed, together with outside studies. Innovation is found to be a non-linear process usually resulting from a high degree of interaction with new knowledge or with persons actively engaged in research. The research dependency of a mission-oriented organization is examined, with improved planning methods found to be of value in increasing the effectiveness of the research process.