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# Common Elements and Interconnections

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The American Association for the Advancement of Science is a unique organization. AAAS encompasses more than 135 thousand individuals involved in the investigation of physical, chemical, biological, behavioral, social, economic, and political phenomena and the use of physical, chemical, biological, behavioral, social, economic, and political knowledge to achieve specific ends. An inspection of AAAS activities indicates a strong commitment to expansion of scientific and engineering knowledge and utilization of the capabilities of science, engineering, and technology in resolving societal issues and thus in enhancing the quality of life of this and succeeding generations—commitments not limited by national boundaries. AAAS forums effectively address multidisciplinary matters of concern to scientists and engineers and also societal issues of concern to scientists, engineers, and the general public.

In recent years, I have become increasingly aware of the confusion within the public, and also within the scientific community, as to the nature of science, engineering, and technology and the relation of science, engineering, and technology to society. To me, there are common elements and interconnections within science, engineering, and technology that are attractive and compelling. In this article, I explore these relations and also the relation of science, engineering, and technology to society. In avoiding the constraints of a language that evolved in less scientific and technical times and of terms that have acquired prejudicial and devisive connotations, the wording has to be, at times, both detailed and repetitive.

*Summary.* The major concepts addressed in this article are the synergistic nature of science, engineering, and technology; the benefits and burdens of technology; the resolution of societal issues; and the roles of scientists and engineers in the resolution of societal issues.

My approach is both pragmatic and simplistic. It is not important whether you agree or disagree. It is important that we make the effort to explore relations among science, engineering, and technology and their relations to society. In this simplistic approach, science, engineering, and technological innovations are approached as processes of investigation, each generating a body of knowledge that consists of a data base, an array of methodologies, and an array of concepts.

## Science, Engineering, and Technological Innovation as Processes of Investigation

Science is the process of investigation of physical, chemical, biological, behavioral, social, economic, and political phenomena. Process is used in the collective sense to include everything the investigator does from the selection of the phenomena to be investigated to the assessment of the validity of the results. Process includes the selection of the methodology, the choice of instrumentation, the delineation of protocol, the execution of protocol, the reduction of data, the development of constructs, and the assessment of the certainty or uncertainty of the results. The details of process are dependent on the phenomena and the relative significance of observation, experimentation, and theoretical modeling in the investigation. The legacy of the investigation of phenomena is scientific knowledge consisting of a data base, an array of methodologies, and an array of concepts.

Engineering is the process of investigation of how to solve problems and includes everything the investigator does from the acceptance of the problem to the proof of the validity of the solution. Engineering has been primarily concerned with the use of physical phenomena and to a lesser degree with the use of chemical phenomena. This almost exclusive involvement with physical and chemical phenomena is still evident in the structure of many schools of engineering and in the structure of the National Science Foundation programs in engineering. Engineering is now also concerned with biological phenomena, and subdisciplines such as medical engineering, bioengineering, and genetic engineering have emerged. The legacy of investigations of problem-solving is the body of engineering knowledge consisting of a data base, an array of methodologies, and an array of concepts.

Technology is the process of production and delivery of goods and services. Technological innovation, the activity more parallel to science and engineering, is the process of investigation leading to more effective production and delivery of a good or service, production and delivery of a significantly modified good or service, or production and delivery of a new good or service. Process encompasses everything investigators do from identification of concept to successful production and delivery of the good or

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service. Here again, technology and technological innovation have been involved primarily with the use of physical and chemical phenomena in the production and delivery of goods and services. Today, there is a rapidly expanding involvement with biological phenomena. A legacy of technological innovation is a body of technological knowledge consisting of a data base, an array of methodologies, and an array of concepts. Technological knowledge may also encompass a body of empirical know-how derived over time through an arts-and-crafts approach to the production of goods and services.

It is true that science drives engineering and technological innovation, but it is equally true that both engineering and technology drive science. The three processes, science, engineering, and technological innovation are synergistic. Each is dependent upon the other two; each supports the other two. It is this synergism that so enhances the total capabilities of science, engineering, and technology. The productivity of this synergism is abundantly evident in the events that have and are propelling us into an information society. In rapidly developing areas of new technology at the forefront of scientific knowledge, the distinction between science and engineering diminishes as scientists investigate how to solve problems as well as investigate phenomena and engineers investigate phenomena as well as how to solve problems. Technology, of course, involves not only scientists and engineers but many others working together within an institutional structure essential to the production of goods and services.

## Scientific, Engineering, and Technological Knowledge

It is the combined body of knowledge derived from the processes of investigation that are science, engineering, and technological innovation that has become a resource of unprecedented value in local, regional, and world affairs. There is no term in the English language to encompass this conglomerate of knowledge, and it may be incorrectly referred to as scientific knowledge. To do so has escalated the erection of barriers to free exchange of true scientific and engineering knowledge among scientists and engineers throughout the world.

The integrated body of scientific, engineering, and technological knowledge is (i) the basis for the investigations of phenomena, problem-solving, and innovation in the production and delivery of goods and services; (ii) in part the basis of our perception of the universe; of physical, chemical, biological, social, economic, and political environments throughout the world; of ourselves; and of relations with others including relations among nations; and (iii) the basis of technological innovation, the production and delivery of goods and services, and the effective use of the products of technology.

The first role, the basis of the expansion of knowledge, ensures the enhancement of the future capabilities of science, engineering, and technology. The second role, the basis of perceptions, provides a background for assessments, negotiations, and decision-making and is a significant component of what is becoming known as the new liberal arts. The third role, the support of technology, promises to gratify, at least in part, the desire for the benefits of the products of technology and the contribution of technology to the economy. This is a promise viewed with cautious optimism by those who fear the negative impacts of technology on the environment and on the quality of life.

## Benefits and Burdens of Technology

Society is not home free with the benefits of goods and services and the benefits of economic development. Every technological change, be it by transfer or by innovation and regardless of how great the positive impact on society, also has a negative impact. This is a statement with no proof. I have for some years challenged audiences to cite examples of technological change for which it is not true. The most apt reply so far was proposed by a West Point cadet who suggested the flyswatter.

Some consequences of technological change may be surprising. For example, the great success of medical technology in saving lives and enhancing the quality of life is intensifying many social issues. There is simply so many more of us to consume and to pollute. To recognize this is in no way to imply that efforts in medical innovation should be diminished. It does imply that issues related to high density populations must be addressed simultaneously.

The subset of society that derives the benefits may not be the subset that bears the burdens of technological change. The time frame of the benefits may be quite different from the time frame of the negative impacts. And the magnitude of the benefits and the magnitude of the burdens of technology may be quite different. The sweet-bitter characteristic of technological change is not a unique characteristic of technological change; it is a characteristic of change—of all social, economic, and political change. The goal of technological transfer and technological innovation is to bring about change. The great challenge is to use technological change selectively to enhance the quality of life and to disperse more equably the benefits and burdens of technological change throughout society. This challenge has the potential to unite the endeavors of those in science, engineering, and technology with the goals and endeavors of all society, including, of course, scientists and engineers.

## Medicine, Agriculture, and Education

Many endeavors such as medicine, agriculture, and education are in part science, in part engineering, and in part technology. I find it very illuminating to think of them in that way. For example, investigating the chemistry of the brain and its relation to how we learn and remember is science. The endeavor to solving problems of communication and of the development of curricula and curriculum materials is engineering. The schools themselves are institutions of technology delivering services that enable students to expand their knowledge and understanding of the universe and of the past and present aspirations, achievements, and failures of the peoples on the earth. The schools have the institutional structure and problems characteristic of institutions of technology—physical plant, management, work force, product design, and quality control. Viewed in this way, we could compare the productivity of our schools with the productivity of other institutions of technology.

Is it possible that the forces that determine the competitive position of automobiles and other products of technology in world markets are related to the forces that determine the position of children in worldwide testing? If so, should we seek fundamental causes of both with the expectation that the strategies that enhance the position of our technological products in the marketplace may also enhance the achievements of children in the classroom? Do we expect a higher level of commitment and diligence on the part of children in their efforts to extend their knowledge and understanding than we expect of their elders in continuing to extend their knowledge and understanding?

## The Resolution of Societal Issues

Some societal issues, such as the perceived potential of products of our technological society such as the chlorofluoroalkanes to diminish the ozone content of the stratosphere and permit more ultraviolet energy to reach the surface of the earth and the perceived potential of the combustion of fossil fuels to increase the carbon dioxide content of the atmosphere and elevate the temperature of the earth, are truly world issues. Other issues, such as malnutrition, disease, acid rain, waste disposal, natural catastrophies, poverty, unemployment, discrimination, and child abuse manifest themselves locally and regionally and can sometimes be resolved locally and regionally. In the sense that the problems are ubiquitous, they also are world issues.

The manner in which societal issues are perceived and the steps undertaken to resolve or ameliorate them are significantly dependent on the available body of scientific, engineering, and technological knowledge. Even so, the scientific, engineering, and technological community, a subset of the public, cannot resolve societal issues. Such issues relate to the quality of life; value judgments are called for and value judgments are the prerogative of the public and surrogates of the public, elected officials and those appointed, either directly or indirectly, by elected officials. Only society can resolve societal issues. Judgments appropriate to one society are not necessarily appropriate to another society nor are they necessarily appropriate to the same society at a later time. The values of society are a continuously evolving characteristic of the culture. The priorities of a society must reflect these values and, at the same time, be responsive to social, economic, and political pressures as well as the availability of renewable and nonrenewable resources. In response to these pressures, priorities may undergo rapid change.

It is essential that decision-makers understand the probable consequences of each available option (including the option to do nothing) sufficiently to make decisions that are consistent with the values of the society. This is as true for positions taken in regard to social, economic, and political negotiations and actions as for positions taken in regard to technological changes involving physical, chemical, and biological phenomena. With increasing reliance on referendums in decision-making at the state and local level and the increasing use of initiatives to bring issues directly to the voter, more individuals are involved in making decisions about such sophisticated topics as land use, resource conservation, waste disposal, the use of nuclear energy, and disarmament.

The roles of scientists and engineers are to identify issues, assess the nature and the magnitude of the issues, identify areas requiring further investigation, propose technological options, assess the probable positive impacts and the probable burdens of each option, and communicate these assessments to the public or the surrogates of the public in such a manner that the assessments can be understood. These can be challenging tasks. There are no generally accepted quality of life indicators, and the practice of using economic indicators is at best a very inadequate substitute—particularly if the data base cannot be disaggregated to monitor identifiable subsets of society in successive time intervals. Economic indicators are valid components of the assessment of the quality of life but in themselves are not sufficient to assess the quality of life. Once the decision is made to implement a particular option, scientists and engineers may have large roles in its implementation and the monitoring of the consequences of the actions taken.

There are great variations in the utilization of physical, chemical, biological, behavioral, social, economic, and political knowledge in the resolution of societal issues. The approach to resolution through negotiation is highly dependent on knowledge and understanding of social, economic, and political structures and priorities of the local communities, states, regions, and nations involved as well as understanding of the relation of proposed solutions to the structures and priorities. The resolution of issues such as child abuse or discrimination in access to education and employment are sought in behavioral, social, economic, and political phenomena. Even though the resolution of issues such as toxic waste and generation of adequate electrical power are sought through the utilization of physical, chemical, and biological phenomena, there are also a host of behavioral, social, economic, and political issues that must be resolved. One of the effective measures in the resolution of the electrical power issue has been self-imposed conservation of electrical energy by the public.

If the social, economic, and political issues are not resolved, it may become increasingly difficult to implement technological options or to use effectively those that have been implemented. Traditionally, the focus has been upon the utilization of physical and chemical phenomena to resolve societal issues; it is not at all clear how adequate has been the incorporation of a more comprehensive body of knowledge in resolving these issues. The current federal R&D budget strongly supports the investigation and use of physical phenomena.

## Responsibilities of Scientists and Engineers

Scientists and engineers are united by responsibilities that are uniquely the responsibilities of scientists and engineers. Five such responsibilities are identified below, all of which are addressed with varying degrees of focus and diligence by AAAS: (i) to ensure the integrity of scientific and engineering knowledge, (ii) to facilitate the identification and resolution of barriers to communication among scientists and engineers and to assess to scientific and engineering knowledge, (iii) to maintain the distinction between the roles of a scientist or an engineer as an expert witness and as an advocate, (iv) to endeavor to enable all individuals to extend their knowledge and understanding of physical, chemical, biological, behavioral, social, economic, and political phenomena, of engineering, and of technology throughout their lifetimes, and (v) to ensure freedom from discrimination in education and in employment opportunities related to science, engineering, and technology.

*The integrity of knowledge.* Any misadventure in the processes of investigation, for whatever reason, compromises the integrity of the knowledge generated and initiates the diversion of resources into nonproductive endeavors. Fraud, the deliberate corruption of process, is antiethical to the standards and practices of the scientific and engineering professions; its detection attracts wide public attention and seriously diminishes public confidence in scientific and engineering knowledge and also diminishes public confidence in scientists and engineers.

As serious as fraud is, its occurrence can, in time, be detected; I am much more concerned about inadvertent misadventures, which I believe are much more prevalent and pose a more insidious threat to the integrity of process and consequently to the integrity of knowledge. The sophistication of modern methodologies, of instrumentation, and of computer capabilities enhances our productivity and also allows the opportunities for misadventure to proliferate. The probability of misadventure is also increased by the movement of scientists and engineers into rapidly developing interdisciplinary fields and into the investigation of increasingly complex systems utilizing a wide variety of methodologies and concepts, some of which may be new to a number of investigators. It is probably more difficult to ensure the integrity of scientific and engineering knowledge today than it has ever been. To test, reevaluate, and revise constitute the ultimate safeguard, but the necessity to identify a high incidence of essentially random misadventures is to be avoided through high professional standards in teaching and in research supervision.

*Barriers to communication.* Barriers to the transfer of scientific, engineering, and technological knowledge diminish the utilization of this knowledge as a base for further investigations, for new perceptions, and for the support of technology, including the effective use of the products of technology. Such barriers are worldwide societal issues. Current electronic capabilities have the potential to enable all the peoples of the world to transfer information at the speed of light. The barriers to access are the cost of information services and the sequestering of new knowledge to protect perceived short-term personal, institutional, and national advantages. Scientists and engineers have the responsibility to ensure that serious issues raised by these barriers are addressed as long-term societal issues, with a full assessment of total costs and total benefits associated with the various options for resolving them.

*Experts and advocates.* The roles of scientists and engineers as experts and as advocates are both honorable, but they are different. Confusion about that difference on the part of scientists and engineers as well as by lawyers and the general public has diminished the credibility of scientists and engineers as participants in the resolution of societal issues.

To be an expert, the individual must have attained and demonstrated competence in the area of expertise, and the individual is obligated to delineate, without prejudice, what is known and to what degree of certainty it is known, what is not known, and what is probably knowable utilizing current methodologies.

The role of the advocate is to advance or defend a particular position or option through the selective presentation of information to support a position or option. Scientists or engineers choose the role of advocate when they make a value judgment in favor of a particular option and support that option over others. This is their right as citizens. On this particular issue they have chosen the role of advocate and waive the role of expert.

Circumstances can cast a scientist or an engineer in the role of advocate though it is not his or her intent to be such. For example, in the adversarial structure of our courts, a scientist or engineer called as an expert witness by one of the contending parties is constrained to present information that is consistent with the arguments of that side of the case, even though the witness knows that there is equally valid information that would be supportive of the other side of the case. This, in my opinion, is demeaning and destructive to the expert witness and, in the long run, destructive to the credibility of our courts. A scientist or engineer called by the court as an expert witness for the court is not constrained to support any argument and can, in fact, serve as an expert witness.

*Lifelong education.* It is highly probable that most of what an individual knows and understands about science, engineering, and technology 10 or 15 years after terminating the formal academic experience has been acquired subsequent to the formal academic experience. This follows from the rapid expansion of scientific, engineering, and technological knowledge. It is also highly probable that how much an individual knows and understands 10 to 15 years later is highly dependent on the nature of the formal academic experience.

The education of an individual is the consequence of how that individual responds to a great multiplicity of enabling experiences—some provided for the individual and some created by the individual. The great challenge is to enable all individuals to continue to extend their knowledge and understanding of science, engineering, and technology throughout their lives. It is frequently the new developments in science, engineering, and technology that are most relevant to the resolution of societal issues.

It has been my experience that in endeavoring to communicate with legislators, lawyers, business personnel, and journalists, who may have little background in science, it is comparatively easy to bring them up to speed in recent scientific advances if the individual understands the nature of scientific knowledge and the nature of the process of investigation that generates knowledge. In particular, it is essential that the individual understands the uncertainty associated with scientific knowledge and has some concept of probability. Without the understanding, it is very difficult, if not impossible, to use scientific knowledge as a basis for decision-making.

The schools, the museums, and the mass media are in the business of providing enabling experiences. If the public is to keep pace with science, engineering, and technology, scientists and engineers must use their knowledge and understanding of the nature of the changes taking place to assist others to ensure that appropriate enabling experiences are made available to the public.

*Discrimination.* For society to derive the benefits of the creativity and productivity of the physically handicapped, minorities, and women in the scientific, engineering, and technological professions, it is essential that scientists and engineers be vigilant in ensuring freedom from discrimination in access to education and in employment opportunities related to science, engineering, and technology.

## Conclusion

The coherence of the scientific disciplines, the synergism of science, engineering, and technology, the congruity of responsibilities of scientists, engineers, and the public in resolving societal issues constitutes a tremendous potential to expand knowledge, to protect and improve the quality of the environment, and to enhance the quality of life of all the peoples of the earth. I suggest that the great deterrents to the utilization of that potential are limited commitment to enabling all students, those who do not become scientists and engineers as well as those who do, to have access to meaningful experiences with mathematics and science in the schools and limited commitment to enabling all individuals to extend their knowledge and understanding of science, engineering, and technology throughout their lives.