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A PHILOSOPHY OF SCIENCE-ENGINEERING EDUCATION

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The knowledge of the physical sciences, inherited from the past and extended through research of the present, can have little impact on human living unless planned, systematic effort is made toward its utilization in practical applications. It is the function of engineering to create means by which physical science may be utilized for the benefit of society.

Civilization as a whole needs the knowledge, the inspiration, the material products of all lines of effort of all kinds of people. Physicist and poet, engineer and artist, astronomer and historian, biologist and economist—all men who seek knowledge, truth, beauty, and understanding—are adding in equal measure to the welfare of men.

The social scientist cannot hope to see his ideals of a more effective and peaceful social structure come to pass without the tools provided by medicine, public health, science, and industry. Nor is the engineer very effective or useful in a social organization which is unable to provide rudimentary civic orderliness and access to economic resources. Nor do men live happily, even with physical comforts and social and political stability, if they do not have access also to freedom, beauty, inspiration, and love.

It is occasionally claimed that art, music, and literature are beautiful, but that science and engineering are crass, materialistic, earthy, and practical. Who is to say that a symphony or the poems of Omar Khayyam are any "finer" than Newton's Laws of Motion or than the functional beauty of many modern engineering masterpieces such as the Golden Gate Bridge? A symphony may be played by 100 musicians under the baton of a master conductor, or by 50,000 scientists, engineers, and skilled mechanics playing a blueprint score to build a jet airliner. It should not offend those who receive inspiration from art and literature to suggest that others receive just as true and fine an inspirational experience from astronomy, physics, engineering, or social sciences. We should neither envy nor disdain those who have chosen other approaches to knowledge, truth, and beauty than the one we prefer.

Science and technology have become so important a part of the structure of modern American civilization that, like air and water, we have come to take them for granted

and even ignore their intrinsic value. The major objective of scientists and engineers is to make the world a better place in which to live. In an individual, a university, a company, a community, a nation, and in a world community we need knowledge and competence of many types; we need breadth of vision; we need not only intelligence but wisdom, and not only intellectual but also moral responsibility and leadership.

Like the profession of practicing medical doctors, the engineering profession is comprised of "practitioners," who utilize both the science and the art of their professions to obtain immediate answers to problems that face mankind.

Years ago, most engineers were self-taught, practical builders of machinery and instruments, surveyors, and constructors of bridges, roads, and canals. They became engineers after some informal education and on-the-job training and experience. Prospective engineers simply apprenticed themselves to an established engineer or got a mechanical job in a factory or shop, and developed by experience. The early medical doctors similarly were trained, primarily by experience as apprentices; and medical doctors are still required to serve several years as interns to assure adequate integration of medical science and art.

As science and practice in medicine and engineering moved ahead and became more complex, formal education in schools of higher learning became essential in both professions. The physical sciences of physics, chemistry, and mathematics provide the fundamental basis for the practice of engineering, as the biological sciences of biology, biochemistry, bacteriology, etc. provide the fundamental basis for the practice of medicine. In both professions emphasis is placed upon fundamental science, and applied science courses have been developed in universities to enable the future practitioner to integrate the science and the art and thus develop sound skill with the tools and techniques he will use in his profession.

An analogy may be drawn between the human body which is the field of practice of the medical doctor, and the integrated community or industrial plant which is the field of practice of the engineer. By training in surgery and internal medicine, the medical doctor learns to make a sound medical analysis and to prescribe proper treatment. Similarly, by training in engineering methods of analysis and synthesis, the engineer learns to make sound engineering analyses and recommendations on existing plants and to develop sound designs for future enterprises. In this respect the engineer might be considered to have attained a more creative level of accomplishment, since he can use his originality to create entirely new systems, processes, and products that did not exist before, whereas the medical doctor or medical scientist can assist Mother Nature in developing healthier people and can overcome most of their serious ailments, but he cannot create entirely new species. Of course, the human body is infinitely more complex than any engineering installation. Another facetious comparison is that the medical doctor can bury his mistakes, but the engineer has to live with his.

Scientific and engineering developments are worth bragging about

not because they are ingenious, or because they make the inventor a lot of money, but because they save human lives, reduce human suffering, and enable human beings to devote energy to things other than the grim struggle to satisfy the basic human needs for food, warmth, shelter, etc.

The philosophy of science-engineering education is similar to that in many other fields of university education. Stated in simplest form, the objectives are: 1) to learn to think clearly in terms of fundamental principles; 2) to learn to learn by oneself; and 3) to learn to assume responsibilities commensurate with freedoms desired.

Note that memorizing and reciting great masses of factual information are not included in the objectives. A large recognition vocabulary is necessary, but a well classified library makes readily available a storehouse of detailed information far beyond that of the most prodigious memory. The human mind appears to work more efficiently as an imaginative, logical, thinking device when it is not too heavily burdened with masses of details not essential to the problem at hand.

The present storehouse of knowledge is so vast, and it is expanding so rapidly, that there is a strong trend toward increased specialization in fields of study. A large university may list 3000 courses of study in its catalog. It would require 40 years to attend all of these courses. In the 40 years there would probably be added hundreds of more courses. Therefore, the tendency is to know more and more about less and less; the ultimate in this direction appears to be to know everything about an infinitesimal field of knowledge.

If we are to avoid a morass of confusion, duplication, and mediocrity, we must present knowledge in brief, understandable form in terms of fundamental principles. We must learn to think clearly and logically in terms of these fundamental principles. Mathematics is a very useful universal language in which most principles, of the physical sciences at least, may be expressed most concisely. An understanding of algebra and the simpler aspects of calculus and differential equations is adequate to permit progress to be made in mastering large fields of engineering knowledge. Simple scientific truths and principles stated in mathematical language are our best means of reducing our great storehouse of knowledge to a manageable size.

The science-engineering curriculum permits attaining a higher level of ability along this line, so the engineer can communicate with and work with the scientist at the endless frontiers of research and development. A common core of basic engineering subjects is retained, and some 20% of the time is devoted to social-humanistic courses. However, greater depth in the physical sciences and mathematics and greater flexibility are provided for by the elimination of the engineering major dealing with applications in a specified field such as electrical, chemical, civil, and mechanical engineering. The more flexible program permits selecting a sequence of courses oriented to the interests of the mature, imaginative student, and thus enables him to attain his goal more directly with the assurance that he

is well equipped to continue to "learn by himself" as he progresses toward full professional responsibility.

The use of symbols for the chemical elements and physical laws and equations is an analogous, simplified language. It might be noted that the improved thinking and communications permitted by the languages of physics, chemistry, and mathematics are available only to those who have learned these languages. All other people are mystified and a little afraid of these strange languages. In advancing civilization these scientific languages appear to have taken the place that was occupied by the classical languages in man's struggle for individual freedoms in the days of the Renaissance.

Philosophers, psychologists, businessmen, engineers, and military men have all made intensive studies of, and have arrived at similar procedures for, logical thinking. There is good agreement that the following are the most important steps involved in logical thinking in any field of knowledge: 1) visualize; 2) set objective; 3) make plans, assumptions; 4) work out plan; 5) complete; and 6) generalize.

1). The step *visualize* includes gathering together all pertinent information and sorting it out so it can be reviewed at will.

2). Setting the *objective* is essential to define the problem on which we wish to think logically and to solve. It selects from the large number of possible problems that might be selected from the mass of information we collected under item 1 and permits us to concentrate on a specific problem.

3.) All possible *plans* for attaining the objective should be stated and, if time is limited, the most promising plans selected for working up in detail. In developing a workable plan, it is usually necessary to make certain simplifying *assumptions.* Such assumptions must be carefully written down for clarity in thinking and for communication to others.

4). *Working* out the *plan* requires utilizing all the skills, knowledge, and resources available to attain the objective. This may be very time consuming.

5). *Complete* means to finish the job by making recommendations for action and following up to assure action has been taken. This usually involves communicating to others by means of written reports or by oral instructions.

6). *Generalize* includes the review of the actions taken under items 1 to 5 and drawing generalizations or fundamental principles from the results. This is most important in the learning process.

The engineering method of teaching by problem-solving attempts to instill in the student this habit of logical thinking, with the objective of developing the ability to make sound, intuitive judgments in complex problems without the detailed working out of plans listed as item 4. As a child learns to crawl, then walk, and then run, so the student gradually acquires skill and confidence in the use of the "steps in logical thinking" in more and more complex situations. As he "learns to learn by himself," he develops broad flexibility and a desire to attack new problems by logical thinking in terms of fundamentals. Developing intuitive judgment appears

to result from 90% perspiration and 10% inspiration, since most outstanding engineers, particularly those who have developed intuitive judgment to a high level and are successful in management of our large corporations in technological fields, have undergone intensive experiences, starting with emphasis upon items 3, 4, and 5 and gradually becoming skilled in items 1, 2, and 6. Their experiences appear comparable to those of the highly skilled medical surgeon who spends long hours on minor details of surgery until they are thoroughly mastered, and then apparently performs miracles in difficult and delicate operations with no apparent effort. This is also comparable to the experiences of the outstanding leaders in all of the arts and professions, such as artists, musicians, sculptors, writers, poets, etc. The internship, the apprenticeship, and the self-disciplinary training period are long and arduous, but they appear essential to attain outstanding results.

The essential, fundamental principles or tools that the science-engineer uses in carrying on his work are: 1) material balances; 2) energy balances; 3) equilibria; 4) rate processes, such as physical kinetics (mass, momentum, and energy transfer) and chemical kinetics; 5) economic balances; and 6) human values.

The utilization of all the above tools to give an integrated result is professional engineering when applied to problems falling within the broad province of engineering.

The above fundamental principles, or tools, are very simply stated. The *balances*, items 1, 2, and 5 merely state:

Input=output + accumulation (inventory change)

The usual concept of *equilibria* (item 3) is that of dynamic equilibria, *i.e.*, the steady state attained when opposing tendencies are just balanced. This applies to all forms of physical equilibria. Statics, thermodynamics, and statistical mechanics are very powerful tools in this field.

The rate processes (item 4) are based upon the simple concept:

$$\text{Rate} = \frac{1}{\text{resistance}} \text{ x driving force}$$

This rate concept applies to the flow of an electric current along a wire, to the flow of water through an irrigation system, to the flow of heat through a nuclear reactor, to the speed of a train or an airplane, to the rates of chemical reactions, etc.

Just as a skilled surgeon can perform miracles with a scalpel, which is not much different from the simple knife I carry in my pocket, so the engineer can perform miracles with the above simple engineering tools in the analysis and synthesis of problems involved in the utilization of science. In the past few centuries, by observation of almost countless experimental facts coupled with inductive thinking, man has established many laws, theories, and fundamental principles. The scientists have expressed many of these principles in differential equations, which then enable the scientists to use deductive thinking to plan further experiments and to advance knowledge. Similar quantitative deductive thinking by the science-engineer based on these fundamental principles permits him to solve problems involved in the applications of

science, but introduces the additional difficulty of applying boundary conditions to the equations which are dictated by the complex physical situations encountered in engineering applications. This involves a very high order of ability by individuals motivated by the utilization of science for the needs of man, as contrasted to the scientist who is more interested in the search for truth for its own sake. Practice without theory soon ends in sterility; while theory without practice is tempted to lose its way in metaphysical futility. It is the team of scientist and engineer that should be unbeatable.

Down through the ages, the job of the technologist, the engineer, and the applied scientist has been to develop methods of satisfying human needs. The people who have the need will work to acquire the device or service. They will pay for it. Hence, somebody makes some money. There is nothing wrong in making money, and it is vital to our way of life; but it is wrong to put the importance of the medium of exchange through which a need is met above the importance of the need itself. The engineer's contributions to society should be expressed in terms of human needs, and it should be clearly recognized that the engineer's emphasis on *economics* is merely as a convenient unit of measure of human needs. Although the engineer is not primarily interested in "*value judgments*" of "good" or "bad," he should be alert to such judgments as may affect matters in his field. It is the breadth of possible applications of fundamental concepts that assures versatility in the thinking of the science-engineer.

The objective of undergraduate engineering is not to give the student all the answers, but rather the methods of observation and thinking which will lead him to the answers. While our students gain facility in the application of scientific and engineering principles through intensive and extensive problem work, we recognize that these problems are packaged and delivered to the student with little effort on his part. Major emphasis in textbook problems is on items 3 and 4 of the steps in logical thinking, *i.e.*, on detailed planning and solving of well defined problems. Not infrequently this leads to the belief by the student that the engineering solution of a problem is more difficult than its recognition and definition. The converse is the fact. The problems encountered in industry are usually broad and unstated, and frequently indefinite and intermingled. The analysis of these more or less confused situations and their resolution into one or more discrete problems is almost invariably more demanding than the pertinent engineering solutions. The power to do this work rests on a mastery of principles rather than on a great proficiency in engineering calculations. While the latter is a necessary tool, it is only a tool. It is merely the servant of the ability to isolate and state the problem, *i.e.*, items 1 and 2 in the steps in logical thinking. It is the over-all ability not only to find the problems, but also to solve them, which is highly rewarded. This over-all ability is usually the result of a fruitful industrial experience built on a strong foundation of scientific knowledge. This strong foundation can be acquired best in

college. It is only engineering efficiency for the colleges to give the strongest possible background in the quantitative application of fundamental principles, since such quantitative thinking is very difficult to "learn by oneself." It requires long hours of arduous work, which is more effectively done in the friendly, competitive college atmosphere with the guidance and inspiration of an experienced faculty. The fruitful industrial experience can be acquired only in industry and must be learned by oneself. The ability to draw sound conclusions from insufficient data is a most important criterion of the successful engineer.

There is one thing the young engineer must understand. When he completes his academic training, he has not received his education, he has merely been equipped with a few tools with which to obtain it. He has reached the threshold of his professional education and is headed in the right direction. The remainder of his professional life will be spent in getting his education. From about 35 to 55 years of age is the period of greatest productivity. Certainly up to age 35 the young engineer should concentrate on gaining knowledge that broadens his capacities (learning by himself).