

## SOME THOUGHTS

on the

## TRENDS IN ENGINEERING EDUCATION

Barnett F. Dodge  
Chairman, Chem. Eng. Dept.  
Yale University

I propose to discuss two questions which seem to me to be of vital importance to the future of engineering education and on which there is far from unanimous agreement. These are:

1. Should we teach engineering in the undergraduate engineering curriculum? Another way to state this question is as follows: Should the undergraduate curriculum be strictly a "pre-engineering" one including only studies in the basic sciences, in the humanities and social sciences with no introduction to engineering? This would be analogous to the present system of education for the professions of law and of medicine.

Another possibility is a curriculum that is a compromise between one with engineering in it and a strictly pre-engineering one. This is a curriculum which goes beyond what we usually call the basic sciences and include some of what are commonly called the Engineering Sciences. These include thermodynamics, mechanics of solids and of fluids, transfer and rate processes, electrical sciences, and properties of materials. This type of curriculum has become quite popular in recent years.

2. Should there be two parallel programs of graduate study in engineering, one of which is research-oriented and the other design- or systems-oriented? In discussing these two questions I do not intend to limit their application just to Chemical Engineering, but rather I will direct my remarks toward all branches of Engineering.

Let us proceed to consider question No. 1 first. The question is by no means purely academic. It seems to me that the development of courses in "Engineering Science" and "Engineering Physics" and the like is one definite trend in the direction of displacing courses in engineering with courses that have little if any engineering in them. Mr. John Gardner, President of the Carnegie Corp., wrote as follows in "Goals for Americans":

"We are beginning to understand that true professional education takes place at the graduate level. Students headed for graduate professional education should spend their years in a liberal arts program, majoring in one of the scientific or scholarly subjects underlying their future profession.

The trend in all professional education is to emphasize the underlying scientific and scholarly fields and to diminish emphasis on "how to do it" courses. In our rapidly changing technology no student can learn specifically how to do his future job."

The American Society of Civil Engineers held a conference on Civil Engineering education in 1960 and adopted several resolutions, one of which reads as follows:

"THEREFORE BE IT RESOLVED, that this conference favors the growth in universities and colleges of a pre-engineering, undergraduate, degree-eligible program for all engineers, emphasizing humanistic-social studies, mathematics, basic and engineering sciences with at least three-quarters of the program interchangeable among the various engineering curricula; to be followed by a professional or graduate civil engineering curriculum based on the pre-engineering program and leading to the first engineering degree awarded only at the completion of the professional or graduate curriculum."

In spite of what some engineering educators would have us believe, engineering is an art and not a science. Of course the engineer uses as much science as he finds applicable to the problem at hand, but I have never met a real engineering problem that could be solved by science alone. I believe it to be true that most of what we call "theory" is oversimplified compared to an actual situation in practice. In other words, all of our theory has limitations when it comes to the applications, and it must inevitably be mixed with empirical knowledge. Until he is called upon to use his theory the student seldom realizes that nature is never quite as simple as our mathematical equations might lead us to believe. Empiricism is still, and I believe always will be, a valuable part of the engineers "stock in trade." It is very necessary in the solution of practical problems simply because our knowledge of fundamentals is still so incomplete. I wonder how many of the decisions made by most engineers are based purely on a mathematical analysis. Relatively few, I suspect, but admittedly more will be so based in the future.

Engineering and science differ profoundly in their goals though the methods and facts employed by scientists and engineers may be almost the same. Engineering problems--and after all the engineer is primarily a problem solver--vary greatly in the extent to which science can be applied in arriving at an acceptable solution. Some require a very sophisticated approach with the latest and most refined tools of mathematics and the physical sciences while others are of such a nature that science is of almost no help and one must fall back on experience and judgement. Even with problems of the first type, considerable art is involved in such steps as analyzing the problem to break it down into more manageable parts, recognizing what techniques are available and applicable to the solution, making the simplifying assumptions that are almost always essential with a complex situation, using judgement in the selection of data and combining all these and other elements to arrive at a satisfactory result.

This is the very essence of engineering and, to me, it is unthinkable that the student of engineering should not be exposed to it early in his career. The earlier in his career that he is introduced to the methodology of engineering, the more likely is he to become really interested in the field and enthusiastic over the opportunities that it offers. Some say "teach the engineering student only the fundamentals and leave the application to on-the-job training or at least to graduate work." This is one of the surest ways I know of to turn the student away from engineering. If he is exposed only to courses in mathematics and science he naturally gets the idea that this is all there is to engineering. Why undertake graduate work in engineering if science is the whole basis of engineering? Not having much conception of the real nature of engineering, he will naturally turn toward advanced courses in math and pure science especially since the various media of publicity make no distinction between the scientist and the engineer and describe most of the great engineering achievements of the past decade or two as wonders of science. Unless we give our students a concept of what professional engineering work is like, we may expect to lose many of them to science. They can only acquire this point of view by doing something in college which at least bears some resemblance to engineering.

The student of science is accustomed to thinking of problems as having single, rather precise, answers. This is the type of problem he meets in his courses in math and science. Very few engineering problems are of this type. They have multiple answers and much of the work of the engineer consists in selecting the one best suited for the particular situation. To give the student early in his career a real grasp and understanding of this simple fact, is a potent reason why at least an introduction to real engineering problems should be in the undergraduate curriculum.

It is quite generally agreed by those who have given much thought to the subject that design is the characteristic function of the engineer. This means design in its broadest sense---the creation of something new in response to a social need. It takes many forms---the design of a new or improved machine, a better process, a new material, a new combination of various elements into a system designed to yield a product with maximum economy just to mention a few examples. If this is true, it seems inconceivable to me that we should not give the student an opportunity to practice this art early in his career.

I find that many undergraduates feel abused if a problem isn't so clearly stated that the method of solution is almost obvious, or if some data which they feel they need are missing, or if the problem doesn't have a clear cut single answer. But this is precisely the kind of problem he is likely to meet in professional practice and we should prepare him for it. One reason that he resents this type of problem is because in so many of his courses in science he has been conditioned to problems which are precisely stated and which do have unique solutions. The design problem offers a quite different experience and this is why it is so important. It is also important because it can demonstrate to the student of engineering that some of the science and math he has been learning can be put to practical use and this is an important motivating factor.

Let us return for a moment to the question of a pre-engineering course analogous to the pre-medical or pre-law courses. The analogy is not a very good one because of the great difference in these professions. The doctor and the lawyer generally deal directly with the public and their accomplishments are open for all to see and well understand. The situation is quite different in the case of the engineer. He seldom deals directly with the public and his part in an end result is never clear. A college student who has only had an introduction to math and the basic physical sciences can begin to practice the art of engineering in a limited way i.e. at least by his sophomore year. This is probably not true of the law or the medical student. Apparently more maturity is required before one can accomplish anything in a professional way.

I agree that graduate work is becoming more and more important in the study of engineering and that one of the important objectives of the undergraduate course is preparation for graduate work. This is used by some educators as a reason for omitting engineering -- that is, design-- from the undergraduate curriculum. I must insist that an undergraduate course with no engineering in it is hardly good preparation for graduate work in engineering. It may be desirable for a career in research but this is not engineering. Engineers frequently engage in research, and I mean to make a distinction between research and development, but usually for the purpose of developing data or correlations for use in design. When they do this they are acting as scientists rather than engineers and the only essential difference between research by a scientist and that by an engineer is the objective. I think it is an excellent thing for every engineering student to have some research experience if only for the purpose of giving him a real feeling for what is involved in establishing a simple fact. But let's not delude ourselves into thinking that research commonly undertaken by students of engineering, is truly engineering.

I think that engineering educators themselves are partly to blame for the flight of good students away from engineering and into the basic sciences. They themselves have been emphasizing science at the expense of engineering by introducing more and more courses into the curriculum which are mostly science and math with very little engineering even though they often carry engineering labels. Good students can see through this decept- and rightly conclude that if engineering is only a degraded and diluted form of science, why not do it right and become first-class, instead of second-class scientists.

Instead of trying to blur the distinction between the scientist and the engineer and helping to create the impression that the engineer is really only a second-class scientist, I suggest we reverse this trend and take every occasion to emphasize the difference between the two, at the same time showing how each has his own contribution to make and that each depends on the other.

I am strongly urging that we stop squeezing all the engineering out of the curriculum in order to put in more science. I would like to start some elementary design in the first or at least the second year and continue through the undergraduate years and on into the graduate study. Such courses I am convinced, can be made just as interesting and challenging, perhaps more so, than any pure science course. Furthermore they will go a long way toward giving the student an insight into what the practice of engineering involves and, I hope, arousing enthusiasm for the possibilities for service that the profession offers. In addition -- and I am sure this will be considered heresy in some quarters -- my own experience has convinced me that the best way to gain an understanding of scientific principles is to have to apply them to solve a practical problem - in other words, to study engineering.

Unfortunately, I think that some engineering teachers are really more interested in the science content of the courses they teach than they are in the engineering aspects. In fact I have been a little shocked to find that some engineering teachers I know are not really interested in what I, at least, consider to be engineering. One reason for this is simply the plain fact that they have never done any real engineering. I have the feeling that some engineering teachers are not only uninterested in design but actually look down on it as a second-class endeavor not worthy of their best efforts. This is cause for considerable concern when one considers that design is generally recognized as the most characteristic activity of the engineer.

I think we need to attract into the teaching profession more men who have had experience in the practice of engineering and in some cases it should be engineering of a very up-to-date and sophisticated character. Perhaps we can begin by bringing in young engineers with 5-10 years of practical experience on a part-time basis. I would like to see this avenue explored more fully. I would agree that some of the members of the engineering faculty should be scientists rather than engineers but scientists with an interest in application and who are willing to work with engineers. This is becoming increasingly important now that science is developing so rapidly and the science that the engineering student learned in college is likely to become obsolescent in 5 to 10 years. I am concerned, however, with maintaining a good balance between the applied scientists and the engineers on our engineering faculties.

I certainly wouldn't quarrel with the idea that the modern engineer needs as much science as it is possible to acquire and not just superficial knowledge but knowledge in depth. But there is a limit to the amount that the average engineering student can absorb and really understand without

being given the opportunity to use some of it in the solution of a practical -- as distinct from a purely artificial -- problem. All through the student's academic career, I think the science and math courses should be paralleled by courses, or at least one course, that offers the opportunity of applying them. At this point I should like to emphasize again that few real engineering problems - and I am using the word "problem" in the broad sense of a situation calling for an action, a question demanding an answer which may or may not be quantitative - can be satisfactorily solved with the tools of science alone. These must usually be combined with empirical information and especially with economic balance among various alternatives. The balance may be of a rather crude, semi-quantitative type or it may be of a highly sophisticated character requiring an electronic computer to solve. This points up one of the most important differences between the engineer and the scientist. The former is continually preoccupied with costs and economic balances and the latter almost never is. This makes a profound difference in their attitude and approach to problems.

There are, in my view, four areas that should be included in all engineering curricula. These are:

1. Humanities
2. Basic Science
3. Engineering Science
4. Design

I am not concerned with No. 1 in this discussion. Let us accept without argument that something like 20-25% of the time of the undergraduate course should be devoted to this area. In passing, let me say that I think there is considerable room for improvement in the way in which this time is used, but that is another story.

No. 2 needs no discussion and I will merely say that I think the proportion in the curriculum should lie between 25 and 35 percent.

Area No. 3 builds directly on No. 2 and is essentially an extension of it to develop tools that the engineer can directly use. Perhaps an example or two is needed here to clarify the point. The student learns the basic principles of thermodynamics both in physics and in physical chemistry but anyone who has taught thermodynamics as an engineering science knows how far the student is from being able to use these principles. They need to be amplified and illustrated in many ways before the student can expect to have any facility in their use. This is the reason why engineering teachers give courses in this subject. I should like to choose one other example and this time from the field of chemical engineering. In his physical chemistry course the student learns the basic principles on which the unit operation of distillation depends but here again these need to be supplemented and illustrated in much greater depth before he is in any position to use them in the solution of an engineering problem. This area might occupy from 25 to 35 percent of the curriculum.

I would like to emphasize again that mere knowledge of the "tools of engineering" does not constitute an ability to practice it. Admittedly, the student will do most of his learning about how to apply these tools after he graduates but I firmly believe that he should have some introduction to this art in school. This brings us to a consideration of the fourth area in my list.

This area is the only real engineering part of the curriculum. Without it the course should not carry the label of engineering. It should probably constitute from 15-20% of the curriculum. It should consist of problems or projects for which no single answer exists and which demands some kind of original thinking. In chemical engineering, the only field about which I can speak with any authority, it usually takes the form of a choice between

several processes or courses of action, based on an economic criterion. Naturally the problems will initially be very simple and then gradually increase in scope and difficulty.

Admittedly we should not even attempt in the 4-year undergraduate course, and probably not even in the graduate courses, to turn out professional engineers but it does seem to me that we should teach them the engineering approach to problems and try to arouse an interest in professional work. I fear that some of us seem to lose sight of the fact that we are supposed to be educating engineers and not scientists. Whereas work of a truly professional character must be deferred until after graduation we cannot begin too soon to inculcate the habits of thought and the attitudes of the engineer. Some of these are:

1. The willingness to accept a rather vague assignment and to go ahead and define the problem himself.
2. The courage to go ahead and make a decision when the available information on which it has to be based, is quite incomplete.
3. A questioning attitude toward facts and formulae.
4. Recognition that few engineering problems have a single solution and that one needs to learn how to exercise judgement in selecting the best one.

Such attitudes of mind can only be acquired by tackling problems of a type that will call them into play. If they are not acquired early in the student's academic career, contrary habits will be formed which are very difficult to change.

The problem with a single numerical answer has two great advantages for the teacher over the design-type. It is much easier to make up and also easier to judge and grade but it does not help much to develop judgement; in fact it tends to discourage it.

Let me now turn to the other question which I said at the very beginning I intended to discuss. It is not unrelated to the first one. As I see it, the common pattern for graduate work in engineering consists of more textbook-type courses but of course more advanced plus sometimes a brief introduction to research leading to a master's degree and then further research leading to the doctorate. The main objective is to train men for careers in research, or teaching. For this it is well suited and conforms to the general theme I have been developing, which applied to this case simply says that the best way to train men for research is to have them do some research. But I submit that a large proportion of our engineers in industry are not doing research but are engaged in other kinds of professional activity. My point is simply this: that for those students who are more interested in these other activities, for example design, development, production, systems analysis, technical service, etc. another type of graduate education would seem to be more suited to their needs. In other words we need two distinct types of graduate programs, one of which is research-oriented and the other directed more toward professional engineering or design.

The program of the first or research-oriented type would consist of advanced courses in applied mathematics and engineering sciences followed by a research problem. As at present it would be desirable to have two levels of degrees, a master's and a doctor's degree. The main difference between them would be the amount of time spent on research. In the case of the master's degree one could only offer a brief introduction to the technique of doing research and little in the way of results of value could

be expected. In the case of the doctor's degree the research would be more thorough and should lead to publishable results.

In the case of the profession-oriented or design-type of graduate program, the first part of the program would be quite similar to that of the previous type, namely advanced courses in applied math and the engineering sciences, but in place of research the student would undertake one or more projects involving engineering design or planning or analysis of systems with a view of optimization. Again there might well be two degrees corresponding to the two levels of accomplishment.

The names of the degrees for these two parallel programs naturally should be different. For the first type, which is the one commonly offered by most of our universities and institutes of technology, we might retain the present names of Master of Science (MS) and Doctor of Philosophy (Ph.D.). For the second type I would suggest the designations of Master of Engineering (ME) and Doctor of Engineering (DE). Some schools now offer these four degrees but in most if not all of these cases with which I am familiar the difference between the programs leading to the MS and to the ME or those leading to the Ph.D and the DE are quite trivial. I think it is time that we recognize that there are these two different interests among students of engineering and provide these two avenues of training with a real difference between them.

One of the difficult problems involved in administering the second type of graduate program is that of securing competent teachers. They must be men who have had actual design or systems-engineering experience in industry or government. By contract, competent teachers for the research oriented type of programs need never to have worked outside the walls of an academic institution though I am sure they would be better teachers for some experience in industry.

I have discussed two points related to engineering education which are somewhat controversial and have tried to give you one man's thoughts based on many years experience in the field of education and some years of industrial experience. I offer these mainly for the purpose of stimulating discussion and not to "lay down the law" on what should be done. In fact I am going to confess that I still have an open mind on these questions and am as perplexed as anyone about what is our best course.