Engineering Education for a Rapidly Changing Technology

by Hans Liepmann

GALCIT, the Graduate Aeronautical Laboratories at the California Institute of Technology, is a system now 50 years old, with which I have been associated for nearly 40 years. Conceived by R. A. Millikan as part of his general scheme to construct a small, very high level technological school, GALCIT was built up by Theodore von Kármán (in the spirit of Felix Klein) to serve as a center for the fusion of science and technology. GALCIT has had an influence on engineering education in the U.S. out of proportion to its size and I will use the experience there as an example from which to extract some principles of engineering education for a rapidly changing technology.

Small Schools — Pro's and Con's

In the 1920's and 1930's the Daniel Guggenheim Fund for the Promotion of Aeronautics made possible the establishment of a set of aeronautical schools in the U.S. The acronym GALCIT, which originally stood for Guggenheim Aeronautical Laboratory at the California Institute of Technology, reflects this origin. The aim of the Guggenheim Fund was clearly directed toward the schooling of engineers for the then rapidly developing aircraft industry. Quoting from C. B. Millikan's write-up in GALCIT's 25th Anniversary brochure of 1953:

> The program of instruction and research which was announced as the GALCIT began its life as outlined in the 1930 Catalogue of the California Institute:
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> 1. A comprehensive series of theoretical courses in aerodynamics and elasticity with the underlying mathematics and mechanics.
> 2. A group of practical courses in airplane design.
> 3. Experimental and theoretical researches on
>   (a) The basic problems of flow in real fluids with regard to the scientific foundations of technical hydro- and aero-dynamics;
>   (b) practical problems in aerodynamics and structures, especially as applied to aeronautics.
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> Far more important than the specific program outlined above was the fundamental concept of modern Applied Mechanics which Kármán brought to the new graduate school and which has ever since dominated its thinking and guided its activities.
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> Modern Applied Mechanics was founded by the German mathematician, Felix Klein, late in the last century. Its aim is the application of methods of pure science to the treatment of engineering problems. Originally it involved the use of the most advanced mathematical techniques in the theoretical analysis of such problems and the application of the physicists' methods to their experimental study. More recently other scientific techniques, especially those of chemistry, have effectively been utilized.

For the times, GALCIT's surprisingly great emphasis on the basic sciences was, on the one hand, necessitated by the discipline: Aeronautical engineering, compared to other engineering disciplines, required far greater attention to fundamentals because ignorance could not be compensated for by large safety factors. On the other hand, these solid science-based foundations provided GALCIT with a marked flexibility, an ability to adjust easily to the rapidly changing technology.

Kármán was well aware of this fact and his insistence on the name "aeronautics" in preference to "aeronautical engineering," and his regret that it was impossible at the time to use the name "applied mechanics," clearly reflect this recognition. This flexibility has proved crucial for the continued success of GALCIT into the present, when standard aeronautical or aerospace engineering is but one part of a host of engineering and applied science problems encountered by its graduates.

Both the California Institute of Technology, with less than 2000 students, and GALCIT, with some 50 graduate students, are very small indeed. This fact presents both an unusual opportunity and unusual challenges. It is certainly far easier to keep a closer interchange between disciplines and between faculty and students in a small university than in a very large one, and it is easier to keep student levels up by selecting a small number from a large sample.

It is far more difficult to staff a small university, since mistakes in faculty appointments stand out, and it is far more difficult to decide on a research and instruction program, because a small set of directions has to be selected — complete coverage of any field being impossible. This selection has to be based, in turn, on a correct evaluation of the importance of developing new technology. This latter choice is obviously the most important and most difficult task in a time of rapidly changing technology. Again, this task is particularly difficult for a small institute, which cannot afford the luxury of safely covering all or most possibilities, a drawback that is fortunately somewhat counterbalanced by the greater flexibility of a small institute or school.

The correct anticipation of future needs is indeed the key to engineering education; it requires an awareness of both the new directions and results in the sciences, and an acquaintance with and understanding of the needs of industry. The necessary link with industry is not easily handled; *it requires a type of loose interaction sufficiently close to produce a mutual appreciation of problem areas, but not so close as to lead to oscillations in the school's program synchronous with the day-by-day crises in industrial production.*

Consequently, some problems found by engineering education in general are even more pronounced in a small school and some maxims derived from the experience with GALCIT should therefore have general validity.

A school the size of CIT and *a fortiore* GALCIT can never turn out the large number of line engineers required by industry. This has to be left to the large engineering schools with extensive undergraduate programs. GALCIT can only produce a small number of highly trained engineers to fill positions in which their broad background, the exposure to fundamental sciences, and the familiarity with modern tools is important. For the supply of this particular but essential subset of engineers the existence of small, high-level, versatile institutes or schools is, in my opinion and experience, crucial.

INPUTS

Faculty and Teaching. In any school facts and methods can be acquired from reading textbooks and only a minimum of guidance is required from a teacher. The development of an original style of approach to problems, a sort of basic philosophy in judging the importance of technological demands, and in particular access to the interconnections between disciplines, require first-rate instructors in the classroom and even more so in research education. Enthusiastic and forceful teachers sometimes reproduce students in their own image. This tendency, within limits, can be quite fruitful in pure scientific fields. In applied science and engineering, however, the vast majority of graduates should become practitioners of an art in surroundings that seldom resemble the environment of the faculty.

Selecting a faculty capable of remaining abreast of the fundamentals, coupled with an awareness of and interest in industrial problems, is probably the most demanding and difficult problem in engineering education. It is often advocated that teachers in engineering must come from a background in industry. In my opinion — clearly biased by my own upbringing — this is neither a necessary nor a sufficient condition. The background may be hopelessly outdated a few years after leaving industry, and the selection of industrial engineers who leave industry permanently for teaching is often biased toward unsuccessful members of industrial teams. I am *not* insinuating that engineers leaving industry for university appointments cannot become outstanding faculty members, but I do not believe that an industrial background guarantees success.

Often a practitioner of a specific important or fashionable analytical or computing technique appears as the ideal choice for an engineering faculty appointment because of his ability to solve "real" problems. If this competence in a specific technique is not grafted onto a broad interest and knowledge, success will be short-lived, industry will develop the same special capability rapidly, and the university will be left with an analytical technician of very limited use for research and teaching.

The awareness of industrial needs and problems by an engineering faculty, which is obviously a crucial prerequisite, can be brought in differently. Mutual consulting — faculty in industry and industrial engineers in schools — seems to me a necessary requirement. Service of faculty on national committees is another excellent source of inputs of real problems. Of course, the willingness of the faculty to be buffeted by the "real world" is the prime requisite for the success of any industrial contacts.

At GALCIT, two additional contact points with industry have proved important. The operation of a wind tunnel, and later of some water tunnels as well, used extensively by industry on a rental basis, has been a very important link with day-by-day industrial problems spanning a very wide variety of subjects from airplane performance to building aerodynamics and smog control. Indeed, the original GALCIT 10-foot tunnel of the Kármán days has had a beneficial influence on research and instruction that is difficult to overestimate.

The second most recent link with industrial problems that we have found particularly useful is a seminar-like course called "Case Studies in Engineering." This course is aimed at exposing students to the real and often not entirely technical problems in industrial production and consists of a presentation of the steps in the development of a finished product, presented by the engineers who made the decisions and did the actual work. One particular term's study covered the development of the DC-10. Other examples are the Mariner Spacecraft, a Hughes Communications Satellite, and a Lockheed Navy Plane.

In our opinion, such a course demonstrates to the students the intricacies, constraints, and compromises needed for the completion of a whole engineering system; something that is not learned by summer jobs in industry and similar experiences.

At the opposite end of the teaching, we rely on close cooperation with the applied mathematics and applied physics options to provide fundamentals in science. This cooperation includes joint faculty appointments. The importance of such cooperation increases with the increasing need for the exposure of engineering students to new developments in applied science: lasers, integrated electronics and optics, and cryogenics, for example, are rapidly becoming routine tools in many technologies. Industrial laser development as well as work on nuclear fusion have, in recent years, attracted a good fraction of our graduates. To be able to work in the "advanced" technology of today, and the unknown advanced technological problems of tomorrow, requires an exposure to fundamental science sufficient to at least permit an overlap with physicists, mathematicians, and chemists. For example, we strongly urge our graduates to take a course in quantum mechanics, as well as courses in solid state physics, modern optics, and, of course, digital electronics and computing. Contrary to public opinion the requirements for modern engineers are for a broad, rather than a narrow, highly specialized, background. *Consequently, the educational policy for a rapidly changing technology should aim for a graduate capable of specializing rapidly rather than being specialized.*

As an illustration from the past and present take, say, jet noise — a very relevant problem. Successful work on its reduction requires a combination of expertise in acoustics and turbulence. The reentry problem of spacecraft requires a combination of shock wave dynamics, and electromagnetic radiation, as well as convective heat transfer and thermodynamics. Chemical laser development leads to combined problems in turbulent mixing, reaction kinetics, and modern optics, coupled with at least rudimentary understanding of quantum mechanical radiation rules.

I may add that close contacts between applied mathematics and engineering is important in *both* directions. Contact with real problems is as important to applied mathematicians as access to new mathematical techniques is to engineers.

It is almost a definition of a real problem that it defies an analytical solution. Consequently, the principal ability that schooling should develop in an engineer or applied scientist is the ability to construct models. Stripping the nonessentials from a real problem to arrive at an approximate solvable model that retains the essential features of the original is the principal art in applied work. The existence of large computers shortens the distance between original and model but does not remove the need for model construction.

It is, of course, impossible to give a universal scheme or method for modeling valid for all cases; in this sense modeling is an art that can be developed fully only on a basis of broad and diversified knowledge coupled with a lot of common sense and intuition based on experience. Hence, modeling cannot be taught as a discipline with set rules but must be expounded by the discussion of examples.

What is surprising is the resistance of students to the use of educated guesses and to the lack of a systematic, foolproof scheme. This quite widespread reluctance to use an intuitive approach, in which not all the steps to the result are visible, is common in modeling, similarity considerations, and dimensional analysis — all of which are very important in solving engineering problems. This reluctance can be broken down only by developing confidence through repeated use which, with some help, leads to the realization that a scientific method need not be pedestrian and that engineering and applied science is an art as well as a trade.

Research. It is evidently easier to teach something you really understand. In a time of rapid changes such understanding, or teaching, requires a continuous education of the faculty. Research is usually the most effective way to keep a faculty competent and aware of recent — and future — problems. A really successful research program in an engineering school anticipates technology. For example, research in compressible fluid flow at GALCIT and elsewhere anticipated the need in the development of high-speed aircraft and jet engines. Research on two-phase fluid flow, which evolved from problems with rockets, proves now to be crucially important for work on reactor safety problems.

Instead of continuing with rows of examples in research, I would rather address two fashionable, and for me rather annoying, arguments faced in applied research.

It is sometimes stated that innovation in engineering requires less originality and ingenuity than innovation in basic science since all the fundamental laws governing engineering problems are known. This is an argument that, transferred to musical performance, would put a violinist at a much higher level than a pianist because the pianist "merely combines existing keys."

The second of the fashionable annoying statements encountered concerns the concept of relevance. I believe that practically every researcher aims at relevance and that research which leads to real understanding of a field is always relevant, if not today, then tomorrow. Wasted research efforts, in my experience, are usually the ones that pretend to be applied by clothing unreal problems in applied language — problems that are sometimes called "dry water."

In this context I cannot help but remember the time, 39 years ago, when I came to the U.S. The then relatively small effort on semiconductor research was considered of academic interest only. The transistor that a few years later resulted from the work is certainly the most important technological innovation of our time. It is almost funny today to read about the 1880 experiences of Werner von Siemens, whose simple theoretical equations leading to a rational way to lay undersea cables were called "scientific humbug" in some English engineering circles.

Students. The selection of the small number of entering students from a large sample is obviously a problem. Contrary to public opinion, to make this selection independent of incidentals like financial means, race, or sex is far easier than prejudging performance. Grades and tests measure the "voltage," but the requirement for performance is power — voltage times current; and the "current" is only partly evaluable from personal references. The history of past educational opportunities too can only partly be assessed and it is unavoidable that mistakes occur. The difficulties in selection are enhanced by the undergraduate background of the GALCIT students, which varies from civil and mechanical engineering to physics and mathematics, and by the variety in the universities and industrial positions from which they apply.

A small fraction of the incoming class has traditionally come from the military academies. I fully realize that the presence of officers on university campuses is considered a controversial subject in some quarters. To me, the contact between civilian and military engineering students is extremely helpful in developing mutual understanding and respect. In some curious ways, it contributes to the civilian education as well; for example, destroyer-trained engineering officers demonstrate an unbelievable ability to find and make do with scrap materials in their experiments!

For historical reasons the armed services in the U.S. have always played an important role in supporting research — indeed, often some very fundamental and not military oriented research. To have the technological interface between the military and civilian research establishment handled well requires, obviously, very competent officers who are aware of the sensibilities and idiosyncracies of the civilian research establishment.

Admissions to GALCIT are handled by the faculty, not by special administrators, and in borderline or particularly unusual cases we have arranged for personal interviews. A similar process is, of course, impossible for a large engineering school, which has to devise more formal schemes of admission to insure the best overall selection. A small school can handle fluctuations from the mean more easily and accommodate the occasional "oddball" who does not fit any established rules of admission.

In the vast field of engineering education, Caltech and GALCIT are of course singularities, but here — as in the theory of complex variables — the singularities determine the function.

OUTPUTS

Graduates. Since its beginning GALCIT has produced some 1100 graduates, and detailed statistics have been kept of their careers. The most important results to be drawn from these statistics are:

1. Even during the depth of the crisis in the aerospace industry, graduates had no difficulty in finding industrial jobs. This is certainly due to their breadth in both training and outlook and it is reflected in the shift from employment in conventional aerospace to other industries. The dividing line between "aerospace" and other industry is today, of course, not sharply drawn but the diffusion of the graduates into very diversified industrial employment is evident.
2. The percentage of graduates who took academic positions has been nearly constant at between 16 and 18 percent except in the post-Sputnik years, when every university increased its space program and an unusually large fraction of graduates was seduced into academia.

One emerging technological field is doubtless energy engineering in all its forms, from fusion and fission reactors to coal combustion and the development of efficient power distribution, communication, and transportation systems. For these fascinating fields, the need for an engi-

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neering education, broad rather than specialized in training and outlook, is obvious.

PhD's. A few words should be added concerning PhD's in engineering: The first rather common misconception on PhD's is that they must be highly specialized, very theoretical, and lacking in common sense. This prejudice probably stems from reading the titles of PhD theses, which almost always sound very specialized and which often sound (and sometimes are) silly. In this connection, I remember having been told that a quite famous paper by H. Bateman, "The decay of a simple eddy," gave the United States Congress a few happy minutes because its colloquial interpretation is indeed quite silly.

To realize the ability to penetrate a particular subject to the limit of the state of the art, the experience of both the frustration and exhilaration in trying for new understanding are (or should be) the factors of lasting value in PhD research. The ability to penetrate a new subject rapidly is, after all, one of the outstanding requirements for leading engineers today where fields, techniques and products are changing continuously.

The second misconception is the belief in the lack of appreciation of engineering PhD's in industry. In our experience, this is not true at all; in fact, we have not been able to supply the demand. In cases where I have found such a prejudice, it was based on experiences with narrow specialists who wanted to do their PhD research over and over again. Actually the years spent in the work toward the PhD degree can and should be used for broadening and not for specialization. Of course this presupposes students with a sufficient intellectual curiosity and a faculty that appreciates and actively stimulates the trend. Evidently a reasonable selection process should eliminate PhD candidates who do not live up to these standards. Since no foolproof selection process has ever been found, a few PhD candidates will slip through who act strictly according to the motto posted as a joke in some university offices: Take a PhD. It beats working anytime! □