The Education of a Scientific Generalist

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THE COMPLEXITIES OF MODERN SCIENCE and modern society have created a need for *scientific generalists,* for men trained in many fields of science. To educate such men efficiently would require modified courses and new ones. However, a good beginning can be made now with courses which are available in many colleges and universities. One such program is set forth here.

General Considerations

The central problem. Scientific and technological advances have made the world we live in complex and hard to understand. We have today large scale division of labor, complex and indirect methods of production and distribution, large communities and large areas held together by common channels of transport and communication, and operation with small margins of safety, requiring close and delicate control. All these complex and delicate activities produce scientific and technological problems of great difficulty.

Science itself shows the same growing complexity. We often hear that "one man can no longer cover a broad enough field" and that "there is too much narrow specialization." And yet these complexities must be met—and resolved. At all levels, decisions must be made which involve consideration of more than a single field.

These difficulties are most pressing in the borderline fields like physical chemistry, chemical physics, biophysics, biochemistry, high polymers, and the application of chemistry, physics, and mathematics to medicine. It is here that both the challenge of the problems and the difficulties arising from over-specialization are greatest. We need a simpler, more unified approach to scientific problems, we need men who can practice science—not a particular science—in a word, we need scientific generalists.

Research teams, aggregations of men of diverse skills working on the various aspects of single problems, have been widely used and have accomplished much. Their use is certain to continue and expand. But the research team must have a leader to unify the group, whether he be director, coordinator, or advisor. This leader must work as a scientific generalist, and we feel he would function better if trained with this in mind.

There is a clear remedy for these complexities, both in education and in science, but its use will involve work and time. We must use the methods of description and model-construction which, in the individual sciences, have made the partial syntheses we call organic chemistry, sensory psychology, and cultural anthropology. We must use these methods on the sciences collectively so that, eventually, one can learn *science,* and not *sciences.*

We suggest that an attempt to unify science may reasonably start from the following ideas:

1. All science began as part of "natural philosophy" and radiated outward. (Even in this modern day, it should be possible to recapture the universalist spirit of the early natural philosophers.)

2. Scientific method is common to all sciences. (The difficulty that almost all scientists have in defining scientific method does not lessen the importance of this fact.)

3. Almost every science is more easily taught by using some of the equipment of the others. (This is generally admitted to be true for mathematics in physics, less generally for chemistry and physics in biology, to name two examples.)

4. Statistics, as the doctrine of planning experiments and observations and of interpreting data, has a common relation to all sciences.

5. Unification will be more easily attained if the logical framework of the individual sciences can be identified and isolated from their factual content.

The isolation of the logical framework of the sciences is a long overdue first step toward a synthesis of science. What is the logical framework of organic chemistry? Or equivalently, what are the characteristic ways in which a good organic chemist thinks and works? There is no place where a student can learn this directly, no place where it is set forth clearly, freed of as many detailed facts as possible. A second step would be the development of courses within individual sciences which really make use of the material and equipment from the other sciences.

A synthesis unifying the sciences is, at best, a long and difficult task. It is a problem that will take time to solve and we do not have a facile answer to it. We shall consider ways in which potential scientific generalists might, as undergraduates, be given the kind of background that would enable them to develop into real scientific generalists. Ours is frankly only an interim proposal; it makes no real synthesis. Yet, since the student will go deeply into parts of many sciences, he will learn something of the habits of mind of the chemist, psychologist, and geologist. These habits, and not subject matter, are what distinguish the sciences—for how else can we distinguish the chemical physicist from the physical chemist, the mathematical biologist from the biomathematician!

Relation to Other Programs

Generalists and scientific generalists. By confining ourselves to scientific generalists, we do not intend to undervalue the need of true generalists, trained in all disciplines, science among them. Science should be able to look to such true generalists for considered judgment about the fields where the greatest speed of development is needed, and then to the scientific generalist for help in attaining that speed. Acting alone, scientists are not competent to plan the training of the true generalists, so that, in spite of the great need of such men, it would be inappropriate for us here to attempt to lay out a program for their training. Nonetheless, some aspects of the scientific generalist's training bear on theirs.

Liberal education. We do not believe that a satisfactory synthesis of the modern world can be achieved without incorporating within it science and the scientific method, which have had a major share in shaping that world, and are still forcing the pace of change. First, however, we must develop some satisfactory synthesis of science by itself, else how can we hope for the greater synthesis of a liberal education, in which science plays so large a part?

Moreover, it seems clear that scientific methods of description and model-building are in many ways the most efficient intellectual techniques yet devised for covering a broad field quickly. Since any satisfactory program of liberal education involves covering an immense mass of material in a limited time, the most efficient techniques must be used. We lay stress in the generalist's education upon these techniques, and in particular upon taking advantage of the efficiency to be gained by using in each science some of the equipment of other sciences. We feel that similar efficiency *could* be gained in history, philosophy, and the "nonscientific" fields by using these techniques. We are not historians or philosophers. We can only say that we think historians and philosophers who are also scientific generalists seem most likely to begin this task.

Finally, we believe that while the scientific generalist's education is not intended primarily as a general liberal education, it may be a temporary approximation to one. The program we outline has room for enough nonscientific courses to meet the going minimum standards of a liberal education as well as the program for a scientific specialist does today. A true generalist would, of course, require a much broader program. In spite of this, a college graduate with an education based upon the generalist's program might well be a better lawyer, businessman, or teacher of high school science than one with a classic liberal education or one with specialized training in a single field.

The Scientific Generalist

What is he? By a generalist—and we shall not bother to specify every time that we mean scientific generalist—we mean a man with training and a working sense in many fields of physical and biological science. His principal interests may be broad or sharply defined, but he is exceptional in his breadth of appreciation. He may be working in pure science, or in the application of science to engineering, business, or industry. He may not be as good a physicist as a student or research man who has been trained principally in physics, or as good a geneticist as the biologist who is trained in genetics, or as good an economist or engineer or psychologist as a specialist in those fields. But he has learned enough of these fields, and of the central tools of mathematics and statistics, to bring to problems of almost any kind the ideas and broad tools of any combination of these many subjects that will speed and improve the work.

We are interested here in the education of a generalist during his four undergraduate years. These four years will not complete his education, any more than four years complete the education of a chemist, a psychologist, or an economist. After these undergraduate years, the budding generalist will go on with further study, presumably in some special field. The aim of the four undergraduate years is to give him a broad foundation and to open his mind to a wide range of scientific fields. Eventually, perhaps, there will be graduate training as a generalist, but until that day comes, specialized graduate study must serve.

Who needs him? First, any research group needs a generalist, whether it is an institutional group in a university or a foundation, or an industrial group working directly on industrial problems. If the problems are broad enough to require a group instead of a few isolated researchers, then there will be a place for a generalist. Many groups who now have generalists or near generalists do not recognize them as such, but think of them in terms of their specialties.

In addition, any first-class administrator or policy-maker in fields related to science must be a generalist to a considerable degree, if only to foresee external influences which might rock the boat. For example, the production of plastics has radically affected almost all enterprises based on the manufacture of small intricate parts. A good administrator needs a generalist's background in appraising the possible effects of going research, estimating its time of fruition, and judging the date and intensity of its ultimate impact on his organization.

What would he do? Many illustrations of the contributions a generalist can make to a research group can be drawn from the recent war. The ability to isolate critical elements, to establish the essentials of the logical framework, to reduce the problem to a few critical issues, is essential in handling problems of military engineering and operations analysis; it is also the ability that the scientist uses every day in his own work. The scientists who were able to carry over and apply their methods of thought to other fields were able to assist largely in the solution of military problems. By working as generalists these scientists distinguished themselves from the specialists, who found themselves baffled and uncomfortable when confronted with unfamiliar and ill-defined issues.

The problems of social engineering and economic engineering are similar to those of military engineering in their need for immediate action, their confusing variety of aspects, the lack of definition of their issues, and, often, the lack of basic knowledge appropriate to their solution. It seems not too much to hope that scientific generalists, amateur and professional, can do much toward developing these fields and solving many pressing problems.

In an engineering group the generalist would naturally be concerned with systems problems. These problems arise whenever parts are made into a balanced whole—balanced so as to serve an end efficiently. It may be weights that are balanced, or sizes, or complexities of component pieces of mechanism, or expense, effort, or research time applied to different phases of the problem.

In the social sciences, the generalist would provide background in physical science and in scientific inference, and experience in the analysis of data and in use of mathematical methods and techniques, which together seem essential for that rapid development of social science which we all agree is now so urgently needed. The generalist would assist in the construction, interpretation, and modification of mathematical models. He would examine previous findings from a fresh viewpoint. The generalist would be able to assist in the design of experiments—still a fairly weak spot in most of the social sciences. Incidentally, he would assist in the development of statistics by disclosing unsolved problems.

In biological and medical science he would provide efficient interpretation of data and design of experiment, and—what is most important—would suggest physical explanations or mathematical models for known or conjectured facts. The need of such useful and stimulating people is probably better recognized in this field than in any other that we know.

And finally, a student equipped with the undergraduate training of a generalist would have an ideal start toward becoming a consulting statistician, who must work with others on problems in many fields of science and technology. With this foundation, a graduate training in mathematical and theoretical statistics would produce the best beginning of a consulting statistician that we can plan today.

What is his background? Most of the small number of generalists that any institution might train during a year are, we think, going to have the following characteristics: They will be planning, definitely or tentatively, to go on to graduate study in some field. They will have interest and skill in science, fairly general and unspecialized. They will have met and mastered competition in high school (or preparatory school) and will have the self-confidence to attempt an unusual and challenging course in college. They will want to learn, and will be prepared to work hard. After a broad introduction to science, and after they have learned what the various fields of science are really like, and how the practitioners of these fields think and work, they will be able to make an intelligent choice between (1) some single field of science, (2) some borderline field between two or three sciences, and (3) the profession of being a generalist.

Educating the Generalist Now

Principles. There are certain principles that must govern any plan for educating a generalist—an interim plan using present-day courses or the efficient plan of the distant future. Some of these principles are general and will offend no one; others are specific and will bother some administrators and some scientists. Let us list three:

1. The pregeneralist must study many fields of science deeply enough to understand their logical frame-

work and the approaches of their practitioners.

2. With the possible exception of a few tool subjects, the interest of the pregeneralist in factual information is definitely secondary.

3. Skipping prerequisites is to be encouraged.

The idea of skipping prerequisites may seem strange and shocking, but the generalist as such will always be working on problems for which he has not had the normal training. He needs to learn to work well under these adverse circumstances during his college years if he is to prepare for his job realistically. Such flexibility will make administrative complications, and will produce temporary discomfort for many instructors.

Program. We now give an illustrative program, which is specific enough about individual courses to make these principles explicit:

ASSIGNMENT OF 40 SEMESTER COURSES

Biology	4	Statistics	4
Chemistry ... 4 or	5	English	2
Geology	1	Industrial processes	1*
Mathematics	6	Judging	1*
Physics	6	Surveying	1
Psychology	2	Distribution	8 or 7

* If these special courses are not available, the time freed is to be applied to independent work or to distribution.

SUMMER WORK

1st: Summer surveying course listed above.

2nd: Completion of the language requirement of a broad reading knowledge in two important scientific languages (if possible by foreign study this summer).

3rd: Work on a research or development project involving real engineering problems.

INDEPENDENT WORK

Junior Year: Topic involving economic considerations.

Senior Year: Topic involving at least two fields and preferably three.

This program is a definite overload, since it combines 40 semester courses with independent work. But the pregeneralist must be an unusual student, building on high precollege attainment. Any student who does not understand what he has studied will be useless as a generalist, and will have achieved a "smattering of ignorance." Since most schools allow students to limp along with low grades, the pregeneralist's standing must be a full grade higher than that required in other programs.

Besides carrying out his formal program, the pregeneralist should meet regularly with sympathetic and active graduate students and faculty members, for lunch, perhaps, or to drink beer.

The regular courses. We take first the bulk of the program, reserving the special courses in English, industrial processes, and judging for a separate discussion.

The "distribution" courses will have real value for the generalist. History, philosophy, economics, the humanities, and the social sciences come here. Some educators might emphasize the need for a course in social change and cultural lag, others would put the emphasis elsewhere. We cannot plan these distribution courses now; their planning should involve all departments, and should probably not be too rigid.

Next come the courses in various fields of science. While specific courses are stated, *it is always permissible to replace any course by a more advanced course in the same field.*

In biology, where we include paleontology, paleobotany, physiological psychology, and the like, there are to be four courses. What shall they be? We do not feel prepared to make really detailed suggestions, and can only point out that it is essential that not all of the courses be at the elementary or near elementary level. It has been suggested by one of our friends (K. W. Cooper) that if four semesters of work in biology were to be given to such students, the most desirable plan might be: (1) cellular biology or general physiology (from the viewpoint of transfer of energy, intermediary metabolism, physiology), (2) comparative anatomy (from the developmental and truly comparative point of view), (3) the problems of genetics (persistence and change of hereditary patterns), and (4) evolution and the evolutionary record. If such a program were available at any institution, we would gladly recommend it as one good set of four courses for the training of a generalist.

The four or five courses in chemistry we propose must give the future generalist a bird's-eye view of a broad field. Hence, we advocate a large amount of skipping around: one or two semester courses in elementary chemistry, one semester in organic chemistry, one semester in physical chemistry, and one semester or none in an advanced elective. To the chemist, the idea of taking one semester of organic chemistry and then jumping to one semester of physical chemistry may seem strange, wild, and unwarranted. But the student generalist wishes to learn how a chemist thinks, how problems are approached, and in what general direction he may learn things once they seem necessary or useful in a particular problem. One semester of organic chemistry (whatever classes of compounds are discussed) and one semester of physical chemistry (whatever branches are included) will do much to orient him and give him a basis on which he can build later as needed. He will know enough physics and mathematics to learn physical chemistry.

Only one course is listed in the field of geology, since paleontology, paleobotany, and the like were included under biology. Just which course is to be taken can safely be left to the choice of the student.

In mathematics there are standard courses available: four semester courses or less in elementary mathematics through calculus and differential equations, one semester in complex variables, and one or more semesters of advanced electives. These courses seem to need little comment.

In physics (where we include astronomy) the situation is also simple, for the courses which should be taken are available at most institutions. Here we suggest: two semester courses in elementary physics, one or two semesters in electricity (circuits and waves), one semester in physical measurements, and one or two semesters of advanced electives. We feel that a knowledge of electrical circuits and the associated knowledge of the uses and behavior of electron tubes would be an essential tool for a generalist in almost all the fields that interested him. The other courses seem to us to require little explanation.

Two courses are proposed in psychology: one semester course in experimental psychology, and one in systematic psychology. Experimental psychology will include laboratory work. Systematic psychology will be a study of psychological problems and theories, with some emphasis on methodology and classic experiments. It will provide a theoretical interpretation for the experimental course. Here the essentials seem to be (1) learning how the psychologist approaches his problems, and (2) acquiring an appreciation of the complications and difficulties which the human observer always introduces into any experiment or study.

In statistics we propose four semester courses, which can probably be found at a few institutions where the training in statistics has been well organized and developed: one or two semester courses in elementary mathematical statistics, one semester in design and analysis of experiment with practical work, and one or two semesters in advanced mathematical statistics, including multivariate methods and the use of order statistics. Because statistics is one of the main tools for applying the quantitative method to any field of science, we feel that four semester courses are by no means too many. We feel that statistics is a distinct field, rather than a branch of mathematics under a new name.

English has been allotted two semester courses in composition. These should be, primarily, courses in exposition. We should prefer to have one a freshman course in "How to Say What You Mean," orally and in writing. The other should be a junior or senior course in writing technical reports, papers, and expository accounts, with emphasis on getting the results and essential spirit across to nontechnical readers.

The proposed inclusion of a course in surveying in this curriculum has led to considerable discussion, and it seems worth while to make very clear what values we hope might be obtained from it, particularly if it were taken just before the beginning of the freshman year. It would provide students with experience in physical measurements for which there are checks (the traverse must "close"), and give them opportunity to observe the customary processes of handling data. It is not essential that the student become a good surveyor, but it is very much to his advantage to learn to recognize a man who is good with tools, and good at measuring.

The special courses. There are two courses that we think should be added to present offerings in order to improve the interim training of the generalist. The first could be given tomorrow at many institutions. The other, here somewhat obscurely entitled "judging," would be very difficult for anyone to teach.

The course in industrial and shop processes should summarize how things are actually made. It could be entirely descriptive, since it is to train generalists, not engineers, and therefore one semester would suffice. It should, for example, describe forging and milling, the function of a turret lathe, the kinds of heat treating used and their effects, what an industrial still looks like, and how it operates—in other words, teach him the unit operations of mechanical, electrical, and chemical engineering. The generalist needs some knowledge of how materials are manipulated.

Somewhere in the curriculum, probably in the senior year, there should be a course in judging, guessing, and the scientific method. This course is needed not only by the generalist, but by many other scientists. We have no way now to encourage or require a man to bring his education and intelligence to bear on estimation and prediction problems for which he has inadequate information. As a result, scientists often become stuffy and narrow in their views. To meet this need, we propose a course in educated, intelligent guessing. It would be principally a laboratory course, in which essentially impossible problems were put to the student, who would be required to supply answers and estimates of their trustworthiness, on the basis of the inadequate data given plus what he knows about the world. The time limits for these answers would vary. Some problems would be done by individuals; others by groups. There would be discussion periods after solutions were submitted. The main difficulty with this course would be finding an instructor equipped to teach it.

None of these four special courses is essential to the training of a generalist, but all of them would be extremely helpful. We believe their value to other students as well as to generalists would make them worth adding to the offerings of most colleges.

Another generally useful course which we would place next in importance for the pregeneralist is one in "intellectual techniques." This should supply the student with tools which would help him to ingest and digest a large amount of material in a limited time. It should include rapid and effective reading, quick ways of using a library, and what is known about efficient methods of study and learning. Such a course should come in the freshman year if possible. Some of us feel that introductory psychology is a good facsimile, others feel that it does not concentrate enough on the tool aspect to meet the need.

Installing the program. Before any new program can be introduced into an American college or university without objection it must be shown to fill certain needs. For the next decade colleges will ask: Does this program meet the distribution requirements? Does this program fit into the scheme of departmental concentration or majoring?

Distribution requirements vary from institution to institution, and are in the process of changing at many institutions. We have compared the proposed program with the distribution requirements at Harvard and at Princeton, since we are most familiar with these universities. There the distribution requirements would easily be met. It seems reasonable to conclude that this program would be consistent with the distribution requirements of a substantial number of institutions.

Next, there must be a home for the pregeneralist. Some department must be prepared to accept his widely distributed work as concentration in that department. Or a new interdepartmental program must be set up! Fnding a home may be difficult.

There will be difficulty with individual scientific departments wherever such a program is proposed; each such department has a natural desire to have these very good students concentrate in its department.

Finally, there will be objections from administrators about any program requiring students to take courses without the usual prerequisites.

These difficulties of installation, however, are merely details, and such a program can be started.

The point of view we have tried to expound might be summarized thus: Science is complex; yet it must become manageable. It can be managed better with the help of a few scientists with training in many sciences. A few such scientific generalists can be trained tomorrow with the courses at hand. To make science more manageable, we must perform a new and difficult synthesis on a higher level of organization.

Photoproduction of Molecular Hydrogen by *Rhodospirillum rubrum*

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THE PHOTOSYNTHETIC, nonsulfur purple bacterium, *Rhodospirillum rubrum* (strain SI)[2] will grow anaerobically upon illumination in a synthetic medium consisting of pure organic substrates, mineral salts including ammonium chloride, and a trace of biotin (*3*).[3] The organic substrate can be any of a large variety of compounds. Substrates more oxidized than carbohydrate are decomposed with a net production of CO_2 during growth. Aside from CO_2 and cell material, no other products have been observed in appreciable quantity. However, *R. rubrum* grown photosynthetically on certain oxidized substrates, with glutamate or aspartate instead of ammonia as a nitrogen source, exhibits in addition to CO_2 evolution a vigorous production of hydrogen.

In a preliminary survey, the only compounds so far found to be effective in evoking hydrogen production in growing cultures are malic, fumaric, and succinic acids. Of several dozen substrates tested at pH 6.6 with resting cells derived from hydrogen-producing cultures, only malic, fumaric, oxaloacetic, and pyruvic acids are effective. The magnitude of the hydrogen evolution from malic acid is of the order of one mole per mole of added substrate. Succinic acid has been tested with resting cells using pH values

[1] Predoctoral fellow of the American Cancer Society, recommended by the Committee on Growth of the National Research Council, 1947–1949. Present address, Department of Microbiology, Western Reserve University Medical School, Cleveland, Ohio.

[2] Original culture obtained through the courtesy of Prof. C. B. van Niel, Hopkins Marine Station, Pacific Grove. California.

[3] Hutner studied growth under aerobic conditions only. However, it appears that anaerobic growth requirements are similar.