measured to be 3.8×10^{-7} mole cm^{-3}), u_{Cl}, u_H, and u_{HCl} have been measured to be 1.06×10^{-9}, 2.48×10^{-9}, and 4.5×10^{-9} mole cm^2 sec^{-1} $joule^{-1}$. In drawing Fig. 6, u_{HCl} was assumed to have the value measured for $\bar{u}_{HCl}$ (1.48×10^{-9} mole cm^2 sec^{-1} $joule^{-1}$) while in drawing Fig. 7 the measured value was used.

77. Limiting currents can also be observed in fixed-site membranes if electrolyte depletion takes place in the solution adjacent to the membrane [compare F. Helfferich (*1*), Eq. 8-19 and Eq. 8-20]. These depletion layers may be treated as mobile-site systems [compare Eq. 6 with F. Helfferich (*1*), Eq. 8-118]. In fact the MD system is a good example of classical concentration polarization [K. S. Cole, personal communication; W. Nernst, *Arch. Ges. Physiol.* **122**, 275 (1908); E. Warburg, *Ann. Physik. Chem.* **67**, 493 (1899); A. V. Hill, *J. Physiol. London* **40**, 190 (1910); H. Lullies, *Biol. Rev.* **12**, 338 (1937)].
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Innovation in Undergraduate Teaching

Programed instruction, despite great promise, gains acceptance slowly in undergraduate teaching.

Everard M. Williams

Since World War II, there have been numerous developments in teaching at all levels of education. The most apparent changes are in class size. Lecture classes became increasingly larger in an attempt to alleviate the escalation of instructional costs and, possibly, to free faculty members for research activities. Today, in many institutions, lecturers address a group in one lecture room, while the lecture is relayed by closed-circuit television to other classes in other classrooms. In some of these institutions, the lectures at one hour are recorded on video tapes for reproduction at other hours. These tapes can be replayed as needed. The recorded video tape is of major value because it relieves various scheduling problems such as those which arise because not all students in a course are available at a particular hour, a professor cannot teach two or more different courses at the same hour, or because insufficient classroom space may be available. The term "reproduction" is used here to indicate the general procedure of teaching enlarged student groups within a university by electronic means. When the student group to whom the reproduction is available is enlarged to include students in classes at one or more universities, the term "distribution" is used.

Reproduction and distribution require no restructuring of educational tactics. A basic known instructional technique, such as the lecture or experimental demonstration, is extended by reproduction and distribution to serve more students than could be served by the original lecture itself. The economy inherent in servicing large numbers may at the same time support a more polished and expensive lecture performance or a more elaborate demonstration experiment than would be economically feasible for a small group of students. Although some educators believe that reproduction and distribution adversely affect student motivation, most do not believe that these innovations have a deleterious effect on the educational process. Indeed, extensive test data (*1*) show that the size of a student group in a single class has no effect upon learning.

Elements of Programed Instruction

The "programed" instructional methods are being used extensively at the university level, although probably less widely in science and engineering than in some other fields. A complete programed instructional instrument is made up of the program itself and a device to administer it to the student. When the device is a mechanical construct, it is termed a "teaching machine." The function of a teaching machine is to ensure that the student precisely follows a program without skipping material. If a machine is not used, the administrative control is exercised by a machine-analog arrangement of the program in paper form, such as a book with special page sequencing, or file cards. These latter forms require the cooperation of the student in adhering to the programed plan.

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Teaching programs subject a student to a programed sequence of learning steps. Each step contains the following parts. (i) A small quantity of new material is presented to the student by the machine or other instrument. (ii) The student responds to the new material by answering a question, either of the fill-in-the-blank type, or the true-false or multiple-choice type. (iii) The student is told whether his response is correct or incorrect. (In some types of programing, the correct response may be indicated.)

This short sequence is termed a "frame." The student response is termed a "constructed" response. The last step in the sequence is termed the "reinforcement." After the completion of each frame, the student takes up another frame. A learning sequence in a subject, concept, or skill comprises a series of frames into which the subject has been subdivided.

The strategy of the development of the subject from frame to frame varies according to the type of programing. There are two recognized strategies. In "linear" programing, the sequence development is fixed, that is, the order of the frames remains the same regardless of whether the student constructs correct responses. In "branching" programs, an incorrect constructed response causes the student to be directed to a remedial frame or a series of remedial frames. These frames, in turn, may provide for constructed responses; more incorrect responses may lead to further branching. Because branching programs require advance knowledge of the possible incorrect responses, such programs typically use multiple-choice questions. In a variation of the linear program, a student who makes an incorrect response is referred to a remedial frame in which the correct response is discussed. In this discussion process, additional constructed responses may be required. This method is related to another variation of linear programing termed "multitrack."

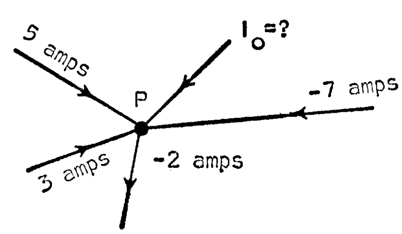
Figure 1 shows an example of a frame from a linear program in which the administrative instrument is a book. The reinforcements are exposed on each page, as needed, by a sliding mask. Successful functioning of the particular format requires the cooperation of the student. This same program could be administered by a machine; machines for administering linear programs are quite simple, since the program mate-

THE ELECTROSTATIC FIELD

electrical	In one definition, a field is defined as a region of space influenced by some physical phenomenon. An electric field, then, is a region in which there are ________________ phenomena.
electric forces	The term electric field is synonymous with electric force field. An electric field, then, is a region in which the characteristic phenomena are ____________.
magnitude and direction	A field is quantitatively and completely described when the relevant physical phenomenon is completely known at every point in the field region. In an electric field, then, the field would be completely described if one knew, for the force, at every point, its ______________.

Fig. 1. Three frames from an elementary program on electrostatic fields. The reinforcements appear in the left-hand column. The student is provided with a sliding mask which covers each reinforcement until the response is written.

Page 57A Let us consider an example. A node P, which forms part of a circuit, is shown in the schematic diagram of Fig. 3-12. The current I_o is unknown, all others are specified. The arrows designate the positive reference direction chosen for each current. If the actual current direction in any instance is opposite to that shown, the current magnitude bears a minus sign in the diagram. One can find the current I_o by adding all the currents, designated as if entering the node (being careful about signs and including all currents), and setting the sum equal to zero. Try it!



If your answer is	Turn to Page
1. -3 amperes	59C
2. 1 ampere	63A
3. 3 amperes	63B
4. Some other answer	65A

Page 63A

You have turned to this page because your answer for the value of the current I_o in Fig. 3-12 on Page 57A was 1 ampere. This answer is incorrect. You probably obtained this answer by adding all the current magnitudes exactly as they appear in the diagram and setting the resultant sum equal to zero. However, note that the wire carrying the two-ampere current has an arrow pointing away from the node while all the other arrows point toward the node. If this suggests to you the reason for your incorrect answer, return to Page 57A and try again. If not, turn to Page 62B for some more help.

Fig. 2. Two branching frames from a program on Kirchhoff's laws for electric circuits. The entire program contains both linear and branching frames. In this particular administrative instrument the branching frames utilize the "scrambled page" format.

rial advances in a steady sequence. A typical machine first exposes at one time all of the frame except the reinforcement. After the student writes his response, it is covered with a transparent shield before the reinforcement is exposed; the shield prevents the student from changing his response. A review of the written records of the student responses provides valuable feedback.

Figure 2 shows two frames from a branching program. The administrative instrument is again a book; for the branching frames there are separate pages, each keyed to a particular response. If the student's response in a frame is correct, the student is referred to a particular page for the next frame; for each incorrect response, there is a corresponding page reference. The term "scrambled text" has been applied to instruments in which the entire program consists of such branching frames, with responses keyed to specific pages.

Figure 3 shows an example of a teaching machine used to administer branching programs. The program material is projected from still-film frames. For each of the multiple-choice responses in a frame there is a designated machine key to be depressed which "calls up" the next frame. If the student makes an excessive number of errors he must return to the start of the program. Such machines are more complex than those used to administer linear programs; a substantial amount of automatic control is involved.

A preprogramed or internally-programed teaching machine may be regarded as a special-purpose digital computer. It is not surprising, therefore, that some of the experimenters in and users of programed instruction have turned to the adaptation of internally-programed digital computers as administrative instruments for programed instruction. The International Business Machines Corporation, for instance, has a library of advanced courses in a central computer; these courses can be administered to students at a number of widely separated locations. A number of experiments on programed teaching with a digital computer have been reported by the University of Illinois. Experiments with a digital computer to teach digital-computer programing have been conducted at Carnegie Institute of Technology.

In addition to digital computers,

Fig. 3. A teaching machine for administration of branching programs. The top of the machine, access to which requires a key, receives the film-strip program material; there is also a counter which totals the number of incorrect responses. [Photograph by courtesy of U.S. Industries, Inc.]

there are over one hundred types of teaching machines in experimental or other use. Over one thousand instructional programs are available, ranging in length from 1 year (typically, high school courses), to short programs dealing with a single difficult concept. The majority of the machines and programs are on the primary or secondary school level. A number of industries are using programs which range from postgraduate level to detailed training of workers for production-line tasks. There is extensive military use of programed instruction. In comparison with other users the amount of university usage is probably in last place.

Strategy of Programed Instruction

The novelty of programed instruction lies in the combination of short-step-by-short-step instruction with student response and reinforcement in each step in the learning program. Studies in the psychology of learning by B. F. Skinner (*2*), who originated the linear programing method, prove the effectiveness of this step-by-step process.

The machine itself, of course, does not teach. It simply brings the student into contact with the person who composed the material it presents. It is a labor-saving device because it can bring one programer into contact with an infinite number of students. This may suggest mass production, but the effect upon each student is surprisingly like that of a private tutor. The comparison holds in several respects:

(i) There is a constant interchange between program and student.

(ii) The machine insists that a given point is thoroughly understood before the student is allowed to move on.

(iii) The machine presents just that material for which the student is ready.

(iv) The machine helps the student to come up with the right answer.

(v) The machine reinforces the student for every correct response, utilizing the immediate feedback for holding the student's interest.

The "constant interchange" between program and student is particularly significant: "In strengthening behavior, the effect of a reinforcer is on the immediately preceding behavior. Therefore a reinforcer must immediately follow the response to be learned. If the reinforcer is delayed, the desired response may never be learned (although other responses might be)" (*3*).

In a fundamental sense, programed teaching is not new; it is a more precise organization and control of the learning process than provided by conventional texts, lectures, or recitations, either separately or in combination. Programed instruction is based upon what is known about human learning; it is an explicit process, a process followed intuitively by an effective teacher (*4*).

Experimental Objectives at Carnegie Institute of Technology

In 1960 we started experiments to explore the possible contributions of programed instruction as a major component in teaching courses in the undergraduate curriculum of Carnegie's department of electrical engineering. The study started with the hypothesis that any subject can be taught effectively with suitable programs. The problem, then, was (i) to determine some portion of the present tasks of the department's instruction that could be effectively programed; (ii) to determine how to use the programs; (iii) to conduct the programed instruction; and (iv) to test the results.

The first step involved an examination of the several objectives of some typical elementary courses in the undergraduate program to determine which objectives are most easily achieved or, indeed, whether all objectives are equally well pursued with programed instruction. The objectives, as usually stated, include mastery of basic and engineering sciences (hereafter termed subject matter), analytical tools, enhancement of learning skill, and development of skills (including innovative skills) in the solution of problems of analysis and synthesis.

Programed instruction is easily applied to the teaching of subject matter and analytical skills. Any programed experiences in which subject matter is learned will also influence learning skill, but it is questionable if that influence is favorable. It is possible that widespread use of programed materials in the college curriculum will adversely affect the students' capacity to learn in those areas in which no programed materials are available. Conversely, the effect may be favorable since the work done on self-instruction devices is a kind of independent study, with orientation of the student to his own responsibility for completion of work (*5*). As yet, there is insufficient evidence to support either position.

To teach the student a problem-solving skill, a program should guide and advise him in a problem solution but not lead him through the solution. Each step in a solution should first be essayed by the student, then his attempt should be criticized by the program. Of course, realistic problems may usually be attacked along several different paths, and they are likely to have a multitude of possible solutions, one of which is preferable. This multiplicity implies that in order to program a solution for a professional problem, it must be dissected at every step into predictable branching paths. For the time being, the complexities involved may make the use of an instructor in a classroom preferable for teaching problem-solving skills.

Probably the most fruitful field then, for programed instruction is the teaching of fundamental principles, concepts, and analytical skills.

Evaluation Procedures

Tests in instructional use of programed materials in the past have fallen into two categories (i) a test given the student immediately before he is exposed to the program and a test immediately after he completes the program, and (ii) tests which compare the effectiveness of programed instruction with instruction by other methods. The test materials in both cases are closely related to the stimulus-response repertoire of the program. The first procedure tests the effectiveness of the program in teaching its repertoire, and usually simply shows that the repertoire is taught more or less effectively. Tests of the second type have typically shown programed instruction to be as effective as or superior to other methods of instruction. For instance, some tests by A. Roe *et al.* (*6*), showed programed instruction of some freshman-year statistics materials to be superior to instruction by a conventional lecture procedure, except for a case in which the lecture was organized and delivered by an instructor who had prepared the programed material; in this case, the lecture and programed methods produced substantially equal results, a conclusion that suggests that the particular lecturer served as a program administrator.

Such tests of the effectiveness of programed instruction are valid (*7*) only when the questions are not keyed directly to the programed material; that is, the items used in the criterion test should be independent of the frames of the program. The test must evaluate the student's general understanding of the material and not his ability to respond to familiar stimuli. Success demonstrated by limited criterion tests which were overly closely associated with the programed repertoire has been termed "administrative success" (*8*).

To illustrate this point concerning criterion tests, we describe some earlier tests at Carnegie of a short program on capacitors and capacitance. This particular program comprised frames treating the definition of capacitance, a discussion of capacitors, stored energy, the charging of a capacitor from a d-c source in series with a resistor (Fig. 4a), and a variation of this circuit (Fig. 4b). This program was reported to have been tested widely and found to be "highly successful" on the basis of a test which was administered after the students had completed the program and which was keyed somewhat closely with the frames of the program. In our sophomore electrical engineering course one section worked with the program and an-

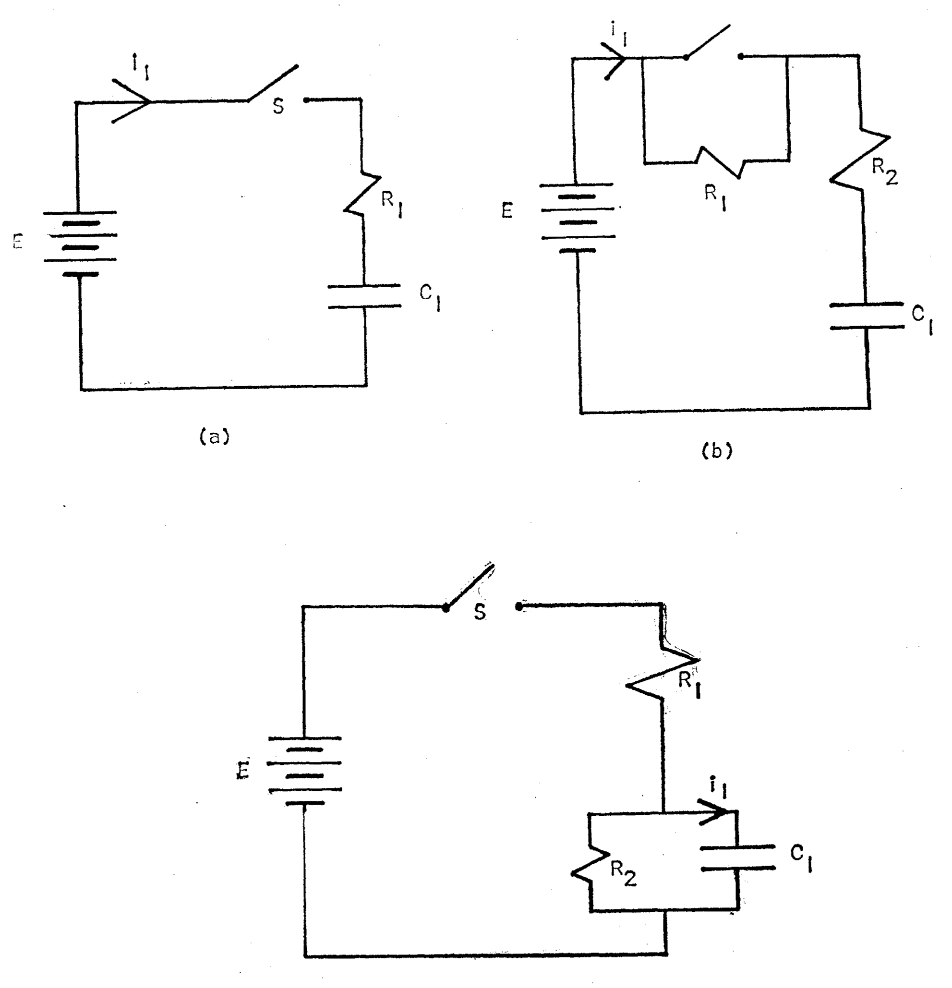


Fig. 4. The first two diagrams, (a) and (b), are the circuits treated in the program on capacitors and capacitance; (c) is the circuit used in the criterion test cited.

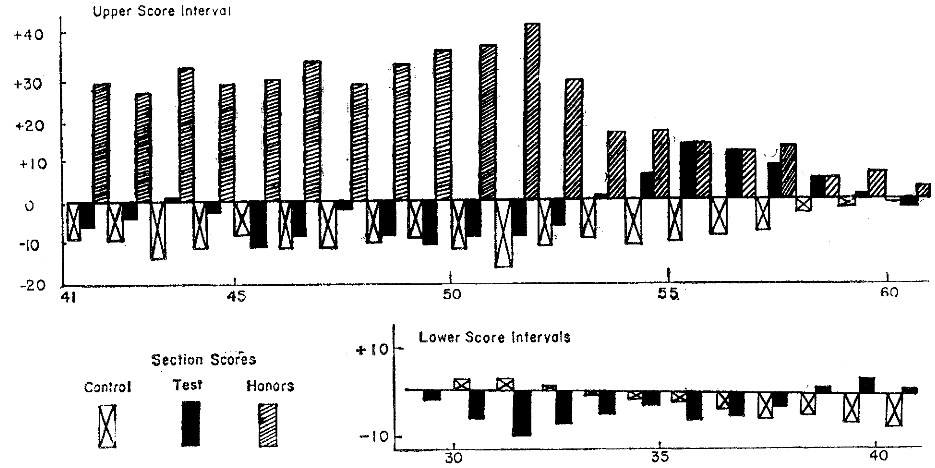


Fig. 5. Results of the overall criterion test of the one-semester programed teaching experiment in elementary electric circuit theory. To prepare this chart, the percentage of the students scoring in each score interval or higher was computed for the honors section, test section, and three control sections. The percentages for the total group established the zero line on the chart. The percentages for the three groups separately are then plotted (vertical bars) with respect to the total group.

other worked without it. The control section used a conventional text, a recitation discussion, and a homework problem, with approximately the same amount of total time, for the average student, as that taken by the program. (The conventional text was also available to the program users, since it was their text for the overall course.)

The test which we used to evaluate this short program was a problem based upon the circuit of Fig. 4c; the students were asked to calculate the capacitor current as a function of time. This problem had not been treated in the program, in the control section, or in the regular text. In this problem the student should apply Kirchhoff's laws to the circuit and solve the resulting first-degree differential equation. This procedure would qualify as a generalization of desired programed behavior and would be an appropriate exercise of the skills that the student should have acquired at this level of his development. The control and test section scores on the test were 85 percent and 15 percent, respectively. No student in the test section attempted to use Kirchhoff's laws in his solution; the program failed to teach this response. (The much simpler attack comprising simplification of the circuit by application of Thevenin's theorem was beyond the student's preparation and was therefore also not attempted.)

The cause of the student failure with this program is not lack of subject-matter coverage but rather the manner of coverage. From frame to frame the strategy of the analysis in the program is not disclosed to the student; instead, the student blindly follows the program's lead. He acquires very precisely the stimulus-response repertoire practiced, and a test administered after the program is completed and which is closely related to this repertoire would demonstrate substantial program success. The fault of the program for the purpose of instruction in the behavior desired in our experiment lies not in the programing technique but in the organization of the subject matter by the program writer. This particular organization, incidentally, characterizes a number of conventional texts on the same subject; however, the conventional text does not limit the student's learning process to a predetermined track as completely as does a program. Thus, a poor text may be tolerable in instructional use but a poor program, that is, a program which is technically well programed and scientifically accurate but defective in its disclosure of subject structure and method, may be disastrous.

Tactics of Instruction

Since there were no suitable programs available for our particular courses, it was necessary to prepare them. The course selected for a first major experiment was an introductory course in electric circuits (*8*, *9*). The programs were administered by paper texts and comprised mixtures of linear and branching frames.

A commonly quoted figure for the cost of writing, testing, and refining programed materials is $2000 per hour of student time. Although our costs were slightly below this amount, it is a useful figure; a programing effort should not probably be started without support at or close to this level.

In the pattern of student use of texts, references, recitations, lectures, and homework exercises, what is the role to be assigned to the programed material? When a conventional text is assigned in a course, it is assumed that it is an imperfect teacher; at least, the student is expected not only to study the text but also to attend lectures or recitations which also treat the text subject matter, and the student often performs homework exercises as well. A programed text is certainly more than a substitute for a conventional text; if the program is as efficient as it ought to be, the material treated by the program should not need lecture, recitation, or homework reinforcement. If the objective of a course is subject matter and analytical skill only, the lecture and recitation could be omitted, as they have, in fact, been in some experimental use of programs on the university level. In our recent experiment we combined the program with class time in order to further develop problem-solving skills. Presumably the use of the program in home study would permit less class time in the course, since no portion of class time should be required for basic science instruction; however, we hesitated to lose instructor-to-student contact at this early stage. Moreover, the course selected for an experiment included a problem-solving laboratory, and much of the recitation time could be occupied with student discussion of laboratory experiences. In fact, the experimental class was conducted in this way. Because it was not necessary to repeat the material covered by the program, classroom atmosphere was relaxed and there was ample time for thorough discussion.

The students were distributed in five sections: an honors section, a test section (with the programed material), and the remaining three sections were controls. A comprehensive 2-hour test at the end of the semester was used to compare the students' subject matter and analytical skill inventory in the course areas. The results are shown in Fig. 5. The scores of the upper 25 percent of the students in the test section were very close to those of the honors section and substantially better than those of the control sections. In fact, the scores of most of the test-section students compare favorably with the control sections except in the very lowest scoring intervals, in which the test-section students were distinctly poorer. (There is some evidence that the poorest students in the test section had not taken the programs very seriously and had generally procrastinated in their course work.)

The experimental results must be regarded as less than conclusive because of the small student numbers involved. Furthermore, the Hawthorne effect may have been operative, that is, the students in the experimental group may have been motivated to try harder merely because they were receiving special treatment. For use in program improvement, more data will be sought in further tests on the extent and details of student use of the programs.

The experiments described demonstrate some success for teaching tactics which combine instructors in the classroom with home study from programed texts. Although the preparation of the programed material was formidably expensive, this expense was largely capital investment, that is, it is amortized with widespread or repeated use. The cost of program preparation per student hour is substantially lower than that of movies. We suspect that one reason more funds are being expended upon preparation of instructional films rather than instructional programs is that the films fit in more readily with established instructional arrangements and thus gain ready acceptance. However, the potential for gainful reconfiguration of instructional schemes when programed materials are used suggests that such materials may have the greater promise for over-all learning improvement.

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Peter Debye—An Appreciation

F. A. Long

Peter Debye came to Cornell University in the winter of 1939–40 to give the Baker lectures in chemistry. He was then 55 years old, a Nobel laureate who was universally considered one of the scientific greats of the 20th century. I was a freshly appointed assistant professor at the time and had no knowledge of the complex circumstances that brought Debye to the United States, but I do recall the sense of satisfaction that pervaded the chemistry faculty when the word was passed around that Debye was in fact coming. I also recall the enthusiasm which greeted his lectures. Those lectures were lively, vigorous, and filled with that sense of intellectual excitement which I came to realize was a Debye hallmark. The young faculty members at Cornell were all delighted when we were told that the department was trying to persuade Debye to stay on as professor and chairman of the chemistry department; we were overjoyed when he accepted.

Debye was to stay at Cornell, first as professor and then as a very active emeritus professor, for 26 years—much the longest time he had ever spent at any one university. His influence on the Cornell chemistry department and indeed on chemistry in the United States was profound. But in recalling some of the things that made Debye the very great man he was, I find myself thinking of Debye in very personal terms, what he was like as a person and of how others reacted to him.

The most characteristic aspect of Debye was his unflagging enthusiasm for science. Nothing pleased Debye more than hearing and talking about what he called a "good idea." He was a very friendly man and always welcomed visitors, but he particularly welcomed visiting scientists who wished to talk science. He was also a very courteous man and was quite prepared to talk on the visitors' terms. But, given a proper opening, he would delightedly talk on his own research or, more specifically, on his latest "idea." It was then that his face would light up, his smile would broaden, and the equations would stream from his chalk or pen.

Debye was remarkably sensitive to the level of understanding of his audience. He could successfully explain scientific ideas to school children, to colleagues, to graduate students, and to business executives. And as he explained, he invariably also communicated his personal enthusiasm for science.

Although one automatically thinks of Debye as a theorist (the Debye theory of dielectrics; the Debye-Huckel theory; the Debye law of specific heat; and so on), his approach to problems was not fundamentally a mathematical one. He was a model-builder. In discussing a new theory his first question usually was, "What is your picture?" One of my warmest memories of his particular approach concerns a colloquium lecture when he was giving the development of the now famous equation for light-scattering by solutions. Having presented most of the development, he then said, "Now you see we have almost everything, but our equation is dimensionally incorrect.

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This tribute was written after the death of Professor Debye on 2 November 1966.