Teaching Machines

B. F. Skinner

SCIENCE

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From the experimental study of learning come devices which arrange optimal conditions for self-instruction.

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There are more people in the world than ever before, and a far greater part of them want an education. The demand cannot be met simply by building more schools and training more teachers. Education must become more efficient. To this end curricula must be revised and simplified, and textbooks and classroom techniques improved. In any other field a demand for increased production would have led at once to the invention of labor-saving capital equipment. Education has reached this stage very late, possibly through a misconception of its task. Thanks to the advent of television, however, the so-called audio-visual aids are being reexamined. Film projectors, television sets, phonographs, and tape recorders are finding their way into American schools and colleges.

Audio-visual aids supplement and may even supplant lectures, demonstrations, and textbooks. In doing so they serve one function of the teacher: they present material to the student and, when successful, make it so clear and interesting that the student learns. There is another function to which they contribute little or nothing. It is best seen in the productive interchange between teacher and student in the small classroom or tutorial situation. Much of that interchange has already been sacrificed in American education in order to teach large numbers of students. There is a real danger that it will be wholly obscured if use of equipment designed sim-

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ply to *present* material becomes widespread. The student is becoming more and more a mere passive receiver of instruction.

Pressey's Teaching Machines

There is another kind of capital equipment which will encourage the student to take an active role in the instructional process. The possibility was recognized in the 1920's, when Sidney L. Pressey designed several machines for the automatic testing of intelligence and information. A recent model of one of these is shown in Fig. 1. In using the device the student refers to a numbered item in a multiple-choice test. He presses the button corresponding to his first choice of answer. If he is right, the device moves on to the next item; if he is wrong, the error is tallied, and he must continue to make choices until he is right (1). Such machines, Pressey pointed out (2), could not only test and score, they could *teach*. When an examination is corrected and returned after a delay of many hours or days, the student's behavior is not appreciably modified. The immediate report supplied by a self-scoring device, however, can have an important instructional effect. Pressey also pointed out that such machines would increase efficiency in another way. Even in a small classroom the teacher usually knows that he is moving too slowly for some students and too fast for others. Those who could go faster are penalized, and those who

should go slower are poorly taught and unnecessarily punished by criticism and failure. Machine instruction would permit each student to proceed at his own rate.

The "industrial revolution in education" which Pressey envisioned stubbornly refused to come about. In 1932 he expressed his disappointment (3). "The problems of invention are relatively simple," he wrote. "With a little money and engineering resource, a great deal could easily be done. The writer has found from bitter experience that one person alone can accomplish relatively little and he is regretfully dropping further work on these problems. But he hopes that enough may have been done to stimulate other workers, that this fascinating field may be developed."

Pressey's machines succumbed in part to cultural inertia; the world of education was not ready for them. But they also had limitations which probably contributed to their failure. Pressey was working against a background of psychological theory which had not come to grips with the learning process. The study of human learning was dominated by the "memory drum" and similar devices originally designed to study forgetting. Rate of learning was observed, but little was done to change it. Why the subject of such an experiment bothered to learn at all was of little interest. "Frequency" and "recency" theories of learning, and principles of "massed and spaced practice," concerned the conditions under which responses were remembered.

Pressey's machines were designed against this theoretical background. As versions of the memory drum, they were primarily testing devices. They were to be used after some amount of learning had already taken place elsewhere. By confirming correct responses and by weakening responses which should not have been acquired, a self-testing machine does, indeed, teach; but it is not designed primarily for that purpose. Nevertheless, Pressey seems to have been the first to emphasize the importance of immediate feedback in education and to propose a system in which each student

could move at his own pace. He saw the need for capital equipment in realizing these objectives. Above all he conceived of a machine which (in contrast with the audio-visual aids which were beginning to be developed) permitted the student to play an active role.

Another Kind of Machine

The learning process is now much better understood. Much of what we know has come from studying the behavior of lower organisms, but the results hold surprisingly well for human subjects. The emphasis in this research has not been on proving or disproving theories but on discovering and controlling the variables of which learning is a function. This practical orientation has paid off, for a surprising degree of control has been achieved. By arranging appropriate "contingencies of reinforcement," specific forms of behavior can be set up and brought under the control of specific classes of stimuli. The resulting behavior can be maintained in strength for long periods of time. A technology based on this work has already been put to use in neurology, pharmacology, nutrition, psychophysics, psychiatry, and elsewhere (4).

The analysis is also relevant to education. A student is "taught" in the sense that he is induced to engage in new forms of behavior and in specific forms upon specific occasions. It is not merely a matter of teaching him *what* to do; we are as much concerned with the prob-

ability that appropriate behavior will, indeed, appear at the proper time—an issue which would be classed traditionally under motivation. In education the behavior to be shaped and maintained is usually verbal, and it is to be brought under the control of both verbal and nonverbal stimuli. Fortunately, the special problems raised by verbal behavior can be submitted to a similar analysis (5).

If our current knowledge of the acquisition and maintenance of verbal behavior is to be applied to education, some sort of teaching machine is needed. Contingencies of reinforcement which change the behavior of lower organisms often cannot be arranged by hand; rather elaborate apparatus is needed. The human organism requires even more subtle instrumentation. An appropriate teaching machine will have several important features. The student must *compose* his response rather than select it from a set of alternatives, as in a multiple-choice self-rater. One reason for this is that we want him to recall rather than recognize —to make a response as well as see that it is right. Another reason is that effective multiple-choice material must contain plausible wrong responses, which are out of place in the delicate process of "shaping" behavior because they strengthen unwanted forms. Although it is much easier to build a machine to score multiple-choice answers than to evaluate a composed response, the technical advantage is outweighed by these and other considerations.

A second requirement of a minimal

teaching machine also distinguishes it from earlier versions. In acquiring complex behavior the student must pass through a carefully designed sequence of steps, often of considerable length. Each step must be so small that it can always be taken, yet in taking it the student moves somewhat closer to fully competent behavior. The machine must make sure that these steps are taken in a carefully prescribed order.

Several machines with the required characteristics have been built and tested. Sets of separate presentations or "frames" of visual material are stored on disks, cards, or tapes. One frame is presented at a time, adjacent frames being out of sight. In one type of machine the student composes a response by moving printed figures or letters (6). His setting is compared by the machine with a coded response. If the two correspond, the machine automatically presents the next frame. If they do not, the response is cleared, and another must be composed. The student cannot proceed to a second step until the first has been taken. A machine of this kind is being tested in teaching spelling, arithmetic, and other subjects in the lower grades.

For more advanced students—from junior high school, say, through college —a machine which senses an arrangement of letters or figures is unnecessarily rigid in specifying form of response. Fortunately, such students may be asked to compare their responses with printed material revealed by the machine. In the machine shown in Fig. 2, material is printed in 30 radial frames on a 12-inch disk. The student inserts the disk and closes the machine. He cannot proceed until the machine has been locked, and, once he has begun, the machine cannot be unlocked. All but a corner of one frame is visible through a window. The student writes his response on a paper strip exposed through a second opening. By lifting a lever on the front of the machine, he moves what he has written under a transparent cover and uncovers the correct response in the remaining corner of the frame. If the two responses correspond, he moves the lever horizontally. This movement punches a hole in the paper opposite his response, recording the fact that he called it correct, and alters the machine so that the frame will not appear again when the student works around the disk a second time. Whether the response was correct or not, a second frame appears when the lever is returned to its starting position. The student proceeds in this way until he has responded to all frames. He then
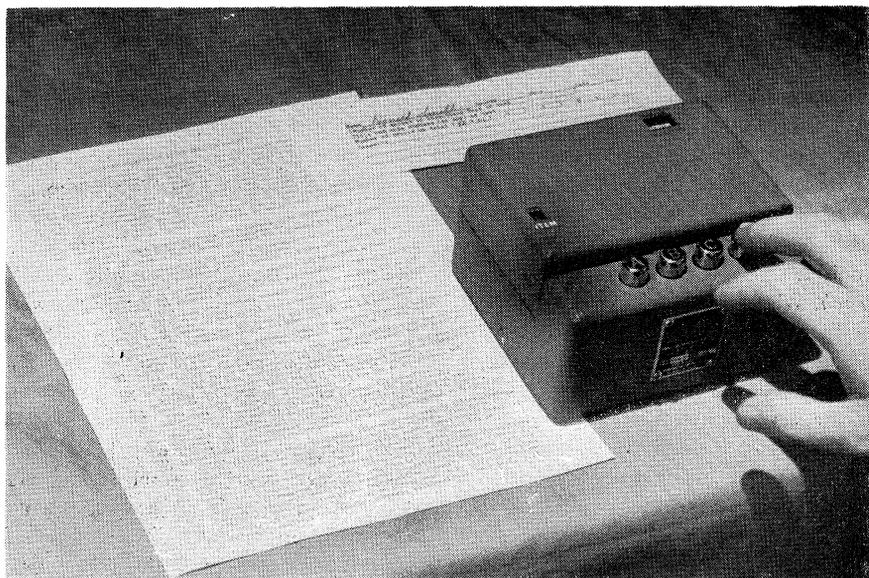
Fig. 1. Pressey's self-testing machine. The device directs the student to a particular item in a multiple-choice test. The student presses the key corresponding to his choice of answer. If his choice is correct, the device advances to the next item. Errors are totaled.

works around the disk a second time, but only those frames appear to which he has not correctly responded. When the disk revolves without stopping, the assignment is finished. (The student is asked to repeat each frame until a correct response is made to allow for the fact that, in telling him that a response is wrong, such a machine tells him what is right.)

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 programmer into contact with an indefinite 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. Unlike lectures, textbooks, and the usual audio-visual aids, the machine induces sustained activity. The student is always alert and busy. (ii) Like a good tutor, the machine insists that a given point be thoroughly understood, either frame by frame or set by set, before the student moves on. Lectures, textbooks, and their mechanized equivalents, on the other hand, proceed without making sure that the student understands and easily leave him behind. (iii) Like a good tutor the machine presents just that material for which the student is ready. It asks him to take only that step which he is at the moment best equipped and most likely to take. (iv) Like a skillful tutor the machine helps the student to come up with the right answer. It does this in part through the orderly construction of the program and in part with techniques of hinting, prompting, suggesting, and so on, derived from an analysis of verbal behavior (5). (v) Lastly, of course, the machine, like the private tutor, reinforces the student for every correct response, using this immediate feedback not only to shape his behavior most efficiently but to maintain it in strength in a manner which the layman would describe as "holding the student's interest."

Programming Material

The success of such a machine depends on the material used in it. The task of programming a given subject is at first sight rather formidable. Many helpful techniques can be derived from a general analysis of the relevant behavioral processes, verbal and nonverbal.

Fig. 2. Student at work on a teaching machine. One frame of material is partly visible in the left-hand window. The student writes his response on a strip of paper exposed at the right. He then lifts a lever with his left hand, advancing his written response under a transparent cover and uncovering the correct response in the upper corner of the frame. If he is right, he moves the lever to the right, punching a hole alongside the response he has called right and altering the machine so that that frame will not appear again when he goes through the series a second time. A new frame appears when the lever is returned to its starting position.

Specific forms of behavior are to be evoked and, through differential reinforcement, brought under the control of specific stimuli.

This is not the place for a systematic review of available techniques, or of the kind of research which may be expected to discover others. However, the machines themselves cannot be adequately described without giving a few examples of programs. We may begin with a set of frames (see Table 1) designed to teach a third- or fourth-grade pupil to spell the word *manufacture*. The six frames are presented in the order shown, and the pupil moves sliders to expose letters in the open squares.

The word to be learned appears in bold face in frame 1, with an example and a simple definition. The pupil's first task is simply to copy it. When he does so correctly, frame 2 appears. He must now copy selectively: he must identify "fact" as the common part of "manufacture" and "factory." This helps him to spell the word and also to acquire a

separable "atomic" verbal operant (5). In frame 3 another root must be copied selectively from "manual." In frame 4 the pupil must for the first time insert letters without copying. Since he is asked to insert the same letter in two places, a wrong response will be doubly conspicuous, and the chance of failure is thereby minimized. The same principle governs frame 5. In frame 6 the pupil spells the word to complete the sentence used as an example in frame 1. Even a poor student is likely to do this correctly because he has just composed or completed the word five times, has made two important root-responses, and has learned that two letters occur in the word twice. He has probably learned to spell the word without having made a mistake.

Teaching spelling is mainly a process of shaping complex forms of behavior. In other subjects—for example, arithmetic—responses must be brought under the control of appropriate stimuli. Unfortunately the material which has been prepared for teaching arithmetic (7)

Table 1. A set of frames designed to teach a third- or fourth-grade pupil to spell the word *manufacture*.

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1. **Manufacture** means to make or build. *Chair factories manufacture chairs.* Copy the word here:

   □ □ □ □ □ □ □ □ □ □ □

2. Part of the word is like part of the word **factory**. Both parts come from an old word meaning *make* or *build*.

   m a n u □ □ □ □ u r e

3. Part of the word is like part of the word **manual**. Both parts come from an old word for *hand*. Many things used to be made by hand.

   □ □ □ □ f a c t u r e

4. The same letter goes in both spaces:

   m □ n u f □ c t u r e

5. The same letter goes in both spaces:

   m a n □ f a c t □ r e

6. **Chair factories** □ □ □ □ □ □ □ □ □ □ □ chairs.

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does not lend itself to excerpting. The numbers 0 through 9 are generated in relation to objects, quantities, and scales. The operations of addition, subtraction, multiplication, and division are thoroughly developed before the number 10 is reached. In the course of this the pupil composes equations and expressions in a great variety of alternative forms. He completes not only $5 + 4 = \square$, but $\square + 4 = 9$, $5 \square 4 = 9$, and so on, aided in most cases by illustrative materials. No appeal is made to rote memorizing, even in the later acquisition of the tables. The student is expected to arrive at $9 \times 7 = 63$, not by memorizing it as he would memorize a line of poetry, but by putting into practice such principles as that nine times a number is the same as ten times the number minus the number (both of these being "obvious" or already well learned), that the digits in a multiple of nine add to nine, that in composing successive multiples of nine one counts backwards (*nine, eight*een, twenty-*seven*, thirty-*six*, and so on), that nine times a single digit is a number beginning with one less than the digit (nine times *six* is *fif*ty something), and possibly even that the product of two numbers separated by only one number is equal to the square of the separating number minus one (the square of eight already being familiar from a special series of frames concerned with squares).

Programs of this sort run to great length. At five or six frames per word, four grades of spelling may require 20,000 or 25,000 frames, and three or four grades of arithmetic, as many again. If these figures seem large, it is only because we are thinking of the normal contact between teacher and pupil. Admittedly, a teacher cannot supervise

10,000 or 15,000 responses made by each pupil per year. But the pupil's time is not so limited. In any case, surprisingly little time is needed. Fifteen minutes per day on a machine should suffice for each of these programs, the machines being free for other students for the rest of each day. (It is probably because traditional methods are so inefficient that we have been led to suppose that education requires such a prodigious part of a young person's day.)

A simple technique used in programming material at the high-school or college level, by means of the machine shown in Fig. 2, is exemplified in teaching a student to recite a poem. The first line is presented with several unimportant letters omitted. The student must read the line "meaningfully" and supply the missing letters. The second, third, and fourth frames present succeeding lines in the same way. In the fifth frame the first line reappears with other letters also missing. Since the student has recently read the line, he can complete it correctly. He does the same for the second, third, and fourth lines. Subsequent frames are increasingly incomplete, and eventually—say, after 20 or 24 frames—the student reproduces all four lines without external help, and quite possibly without having made a wrong response. The technique is similar to that used in teaching spelling: responses are first controlled by a text, but this is slowly reduced (colloquially, "vanished") until the responses can be emitted without a text, each member in a series of responses being now under the "intraverbal" control of other members.

"Vanishing" can be used in teaching other types of verbal behavior. When a

student describes the geography of part of the world or the anatomy of part of the body, or names plants and animals from specimens or pictures, verbal responses are controlled by nonverbal stimuli. In setting up such behavior the student is first asked to report features of a fully labeled map, picture, or object, and the labels are then vanished. In teaching a map, for example, the machine asks the student to describe spatial relations among cities, countries, rivers, and so on, as shown on a fully labeled map. He is then asked to do the same with a map in which the names are incomplete or, possibly, lacking. Eventually he is asked to report the same relations with no map at all. If the material has been well programmed, he can do so correctly. Instruction is sometimes concerned not so much with imparting a new repertoire of verbal responses as with getting the student to describe something accurately in any available terms. The machine can "make sure the student understands" a graph, diagram, chart, or picture by asking him to identify and explain its features —correcting him, of course, whenever he is wrong.

In addition to charts, maps, graphs, models, and so on, the student may have access to auditory material. In learning to take dictation in a foreign language, for example, he selects a short passage on an indexing phonograph according to instructions given by the machine. He listens to the passage as often as necessary and then transcribes it. The machine then reveals the correct text. The student may listen to the passage again to discover the sources of any error. The indexing phonograph may also be used with the machine to teach other language skills, as well as telegraphic code, music, speech, parts of literary and dramatic appreciation, and other subjects.

A typical program combines many of these functions. The set of frames shown in Table 2 is designed to induce the student of high-school physics to talk intelligently, and to some extent technically, about the emission of light from an incandescent source. In using the machine the student will write a word or phrase to complete a given item and then uncover the corresponding word or phrase shown here in the column at the right. The reader who wishes to get the "feel" of the material should cover the right-hand column with a card, uncovering each line only after he has completed the corresponding item.

Several programming techniques are exemplified by the set of frames in

Table 2. Part of a program in high-school physics. The machine presents one item at a time. The student completes the item and then uncovers the corresponding word or phrase shown at the right.

Sentence to be completed	Word to be supplied
1. The important parts of a flashlight are the battery and the bulb. When we "turn on" a flashlight, we close a switch which connects the battery with the ——.	bulb
2. When we turn on a flashlight, an electric current flows through the fine wire in the —— and causes it to grow hot.	bulb
3. When the hot wire glows brightly, we say that it gives off or sends out heat and ——.	light
4. The fine wire in the bulb is called a filament. The bulb "lights up" when the filament is heated by the passage of a(n) —— current.	electric
5. When a weak battery produces little current, the fine wire, or ——, does not get very hot.	filament
6. A filament which is *less* hot sends out or gives off —— light.	less
7. "Emit" means "send out." The amount of light sent out, or "emitted," by a filament depends on how —— the filament is.	hot
8. The higher the temperature of the filament the —— the light emitted by it.	brighter, stronger
9. If a flashlight battery is weak, the —— in the bulb may still glow, but with only a dull red color.	filament
10. The light from a very hot filament is colored yellow or white. The light from a filament which is not very hot is colored ——.	red
11. A blacksmith or other metal worker sometimes makes sure that a bar of iron is heated to a "cherry red" before hammering it into shape. He uses the —— of the light emitted by the bar to tell how hot it is.	color
12. Both the color and the amount of light depend on the —— of the emitting filament or bar.	temperature
13. An object which emits light because it is hot is called "incandescent." A flashlight bulb is an incandescent source of ——.	light
14. A neon tube emits light but remains cool. It is, therefore, not an incandescent —— of light.	source
15. A candle flame is hot. It is a(n) —— source of light.	incandescent
16. The hot wick of a candle gives off small pieces or particles of carbon which burn in the flame. Before or while burning, the hot particles send out, or ——, light.	emit
17. A long candlewick produces a flame in which oxygen does not reach all the carbon particles. Without oxygen the particles cannot burn. Particles which do not burn rise above the flame as ——.	smoke
18. We can show that there are particles of carbon in a candle flame, even when it is not smoking, by holding a piece of metal in the flame. The metal cools some of the particles before they burn, and the unburned carbon —— collect on the metal as soot.	particles
19. The particles of carbon in soot or smoke no longer emit light because they are —— than when they were in the flame.	cooler, colder
20. The reddish part of a candle flame has the same color as the filament in a flashlight with a weak battery. We might guess that the yellow or white parts of a candle flame are —— than the reddish part.	hotter
21. "Putting out" an incandescent electric light means turning off the current so that the filament grows too —— to emit light.	cold, cool
22. Setting fire to the wick of an oil lamp is called —— the lamp.	lighting
23. The sun is our principal —— of light, as well as of heat.	source
24. The sun is not only very bright but very hot. It is a powerful —— source of light.	incandescent
25. Light is a form of energy. In "emitting light" an object changes, or "converts," one form of —— into another.	energy
26. The electrical energy supplied by the battery in a flashlight is converted to —— and ——.	heat, light; light, heat
27. If we leave a flashlight on, all the energy stored in the battery will finally be changed or —— into heat and light.	converted
28. The light from a candle flame comes from the —— released by chemical changes as the candle burns.	energy
29. A nearly "dead" battery may make a flashlight bulb warm to the touch, but the filament may still not be hot enough to emit light—in other words, the filament will not be —— at that temperature.	incandescent
30. Objects, such as a filament, carbon particles, or iron bars, become incandescent when heated to about 800 degrees Celsius. At that temperature they begin to —— ——.	emit light
31. When raised to any temperature above 800 degrees Celsius, an object such as an iron bar will emit light. Although the bar may melt or vaporize, its particles will be —— no matter how hot they get.	incandescent
32. About 800 degrees Celsius is the lower limit of the temperature at which particles emit light. There is no upper limit of the —— at which emission of light occurs.	temperature
33. Sunlight is —— by very hot gases near the surface of the sun.	emitted
34. Complex changes similar to an atomic explosion generate the great heat which explains the —— of light by the sun.	emission
35. Below about —— degrees Celsius an object is not an incandescent source of light.	800

Table 2. Technical terms are introduced slowly. For example, the familiar term "fine wire" in frame 2 is followed by a definition of the technical term "filament" in frame 4; "filament" is then asked for in the presence of the nonscientific synonym in frame 5 and without the synonym in frame 9. In the same way "glow," "give off light," and "send out light" in early frames are followed by a definition of "emit" with a synonym in frame 7. Various inflected forms of "emit" then follow, and "emit" itself is asked for with a synonym in frame 16. It is asked for without a synonym but in a helpful phrase in frame 30, and "emitted" and "emission" are asked for without help in frames 33 and 34. The relation between temperature and amount and color of light is developed in several frames before a formal statement using the word "temperature" is asked for in frame 12. "Incandescent" is defined and used in frame 13, is used again in frame 14, and is asked for in frame 15, the student receiving a thematic prompt from the recurring phrase "incandescent source of light." A formal prompt is supplied by "candle." In frame 25 the new response "energy" is easily evoked by the words "form of . . . ." because the expression "form of energy" is used earlier in the frame. "Energy" appears again in the next two frames and is finally asked for, without aid, in frame 28. Frames 30 through 35 discuss the limiting temperatures of incandescent objects, while reviewing several kinds of sources. The figure 800 is used in three frames. Two intervening frames then permit some time to pass before the response "800" is asked for.

Unwanted responses are eliminated with special techniques. If, for example, the second sentence in frame 24 were simply "It is a(n) —— source of light," the two "very's" would frequently lead the student to fill the blank with "strong" or a synonym thereof. This is prevented by inserting the word "powerful" to make a synonym redundant. Similarly, in frame 3 the words "heat and" preempt the response "heat," which would otherwise correctly fill the blank.

The net effect of such material is more than the acquisition of facts and terms. Beginning with a largely unverbalized acquaintance with flashlights, candles, and so on, the student is induced to talk about familiar events, together with a few new facts, with a fairly technical vocabulary. He applies the same terms to facts which he may never before have seen to be similar. The emission of light
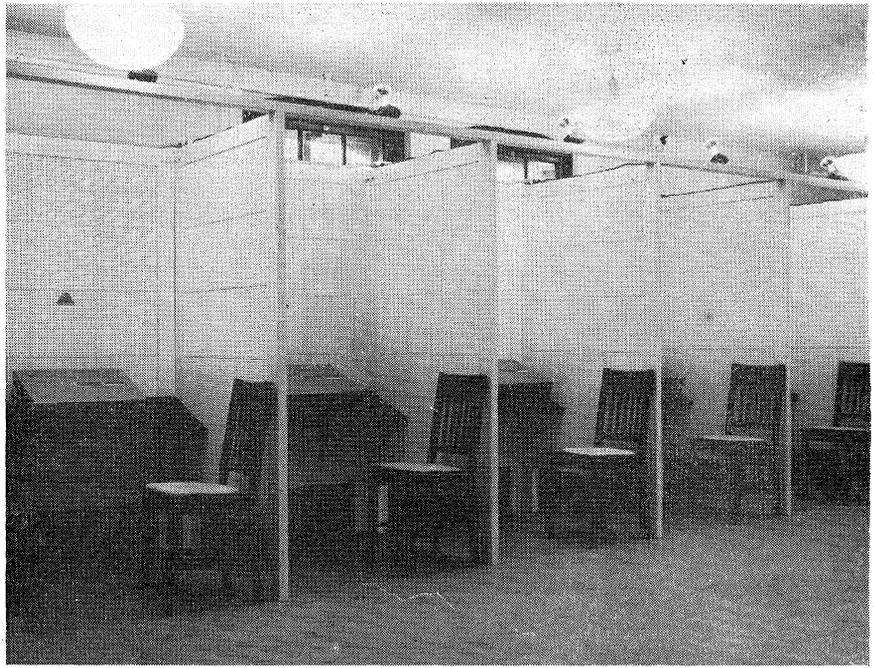

Fig. 3. Self-instruction room in Sever Hall at Harvard. Ten booths contain teaching machines, some equipped with indexing phonographs.

from an incandescent source takes shape as a topic or field of inquiry. An understanding of the subject emerges which is often quite surprising in view of the fragmentation required in item building.

It is not easy to construct such a program. Where a confusing or elliptical passage in a textbook is forgivable because it can be clarified by the teacher, machine material must be self-contained and wholly adequate. There are other reasons why textbooks, lecture outlines, and film scripts are of little help in preparing a program. They are usually not logical or developmental arrangements of material but stratagems which the authors have found successful under existing classroom conditions. The examples they give are more often chosen to hold the student's interest than to clarify terms and principles. In composing material for the machine, the programmer may go directly to the point.

A first step is to define the field. A second is to collect technical terms, facts, laws, principles, and cases. These must then be arranged in a plausible developmental order—linear if possible, branching if necessary. A mechanical arrangement, such as a card filing system, helps. The material is distributed among the frames of a program to achieve an arbitrary density. In the final composition of an item, techniques for strengthening asked-for responses and for transferring control from one variable to another are chosen from a list according to a given schedule in order

to prevent the establishment of irrelevant verbal tendencies appropriate to a single technique. When one set of frames has been composed, its terms and facts are seeded mechanically among succeeding sets, where they will again be referred to in composing later items to make sure that the earlier repertoire remains active. Thus, the technical terms, facts, and examples in Table 2 have been distributed for reuse in succeeding sets on reflection, absorption, and transmission, where they are incorporated into items dealing mainly with other matters. Sets of frames for explicit review can, of course, be constructed. Further research will presumably discover other, possibly more effective, techniques. Meanwhile, it must be admitted that a considerable measure of art is needed in composing a successful program.

Whether good programming is to remain an art or to become a scientific technology, it is reassuring to know that there is a final authority—the student. An unexpected advantage of machine instruction has proved to be the feedback to the *programmer*. In the elementary school machine, provision is made for discovering which frames commonly yield wrong responses, and in the high-school and college machine the paper strips bearing written answers are available for analysis. A trial run of the first version of a program quickly reveals frames which need to be altered, or sequences which need to be lengthened. One or two revisions in the light of a

few dozen responses work a great improvement. No comparable feedback is available to the lecturer, textbook writer, or maker of films. Although one text or film may seem to be better than another, it is usually impossible to say, for example, that a given sentence on a given page or a particular sequence in a film is causing trouble.

Difficult as programming is, it has its compensations. It is a salutary thing to try to guarantee a right response at every step in the presentation of a subject matter. The programmer will usually find that he has been accustomed to leave much to the student—that he has frequently omitted essential steps and neglected to invoke relevant points. The responses made to his material may reveal surprising ambiguities. Unless he is lucky, he may find that he still has something to learn about his subject. He will almost certainly find that he needs to learn a great deal more about the behavioral changes he is trying to induce in the student. This effect of the machine in confronting the programmer with the full scope of his task may in itself produce a considerable improvement in education.

Composing a set of frames can be an exciting exercise in the analysis of knowledge. The enterprise has obvious bearings on scientific methodology. There are hopeful signs that the epistemological implications will induce experts to help in composing programs. The expert may be interested for another reason. We can scarcely ask a topflight mathematician to write a primer in second-grade arithmetic if it is to be used by the average teacher in the average classroom. But a carefully controlled machine presentation and the resulting immediacy of contact between programmer and student offer a very different prospect, which may be enough to induce those who know most about the subject to give some thought to the nature of arithmetical behavior and to the various forms in which such behavior should be set up and tested.

Can Material Be Too Easy?

The traditional teacher may view these programs with concern. He may be particularly alarmed by the effort to maximize success and minimize failure. He has found that students do not pay attention unless they are worried about the consequences of their work. The customary procedure has been to maintain the necessary anxiety by inducing errors.

In recitation, the student who obviously knows the answer is not too often asked; a test item which is correctly answered by everyone is discarded as nondiscriminating; problems at the end of a section in a textbook in mathematics generally include one or two very difficult items; and so on. (The teacher-turned-programmer may be surprised to find this attitude affecting the construction of items. For example, he may find it difficult to allow an item to stand which "gives the point away." Yet if we can solve the motivational problem with other means, what is more effective than giving a point away?) Making sure that the student knows he doesn't know is a technique concerned with motivation, not with the learning process. Machines solve the problem of motivation in other ways. There is no evidence that what is easily learned is more readily forgotten. If this should prove to be the case, retention may be guaranteed by subsequent material constructed for an equally painless review.

The standard defense of "hard" material is that we want to teach more than subject matter. The student is to be challenged and taught to "think." The argument is sometimes little more than a rationalization for a confusing presentation, but it is doubtless true that lectures and texts are often inadequate and misleading by design. But to what end? What sort of "thinking" does the student learn in struggling through difficult material? It is true that those who learn under difficult conditions are better students, but are they better because they have surmounted difficulties or do they surmount them because they are better? In the guise of teaching thinking we set difficult and confusing situations and claim credit for the students who deal with them successfully.

The trouble with deliberately making education difficult in order to teach thinking is (i) that we must remain content with the students thus selected, even though we know that they are only a small part of the potential supply of thinkers, and (ii) that we must continue to sacrifice the teaching of subject matter by renouncing effective but "easier" methods. A more sensible program is to analyze the behavior called "thinking" and produce it according to specifications. A program specifically concerned with such behavior could be composed of material already available in logic, mathematics, scientific method, and psychology. Much would doubtless be added in completing an effective program. The machine has already yielded important

relevant by-products. Immediate feedback encourages a more careful reading of programmed material than is the case in studying a text, where the consequences of attention or inattention are so long deferred that they have little effect on reading skills. The behavior involved in observing or attending to detail—as in inspecting charts and models or listening closely to recorded speech—is efficiently shaped by the contingencies arranged by the machine. And when an immediate result is in the balance, a student will be more likely to learn how to marshal relevant material, to concentrate on specific features of a presentation, to reject irrelevant materials, to refuse the easy but wrong solution, and to tolerate indecision, all of which are involved in effective thinking.

Part of the objection to easy material is that the student will come to depend on the machine and will be less able than ever to cope with the inefficient presentations of lectures, textbooks, films, and "real life." This is indeed a problem. All good teachers must "wean" their students, and the machine is no exception. The better the teacher, the more explicit must the weaning process be. The final stages of a program must be so designed that the student no longer requires the helpful conditions arranged by the machine. This can be done in many ways—among others by using the machine to discuss material which has been studied in other forms. These are questions which can be adequately answered only by further research.

No large-scale "evaluation" of machine teaching has yet been attempted. We have so far been concerned mainly with practical problems in the design and use of machines, and with testing and revising sample programs. The machine shown in Fig. 2 was built and tested with a grant from the Fund for the Advancement of Education. Material has been prepared and tested with the collaboration of Lloyd E. Homme, Susan R. Meyer, and James G. Holland (8). The self-instruction room shown in Fig. 3 was set up under this grant. It contains ten machines and was recently used to teach part of a course in human behavior to Harvard and Radcliffe undergraduates. Nearly 200 students completed 48 disks (about 1400 frames) prepared with the collaboration of Holland. The factual core of the course was covered, corresponding to about 200 pages of the text (9). The median time required to finish 48 disks was 14½ hours. The students were not examined on the material but were responsible

for the text which overlapped it. Their reactions to the material and to self-instruction in general have been studied through interviews and questionnaires. Both the machines and the material are now being modified in the light of this experience, and a more explicit evaluation will then be made.

Meanwhile, it can be said that the expected advantages of machine instruction were generously confirmed. Unsuspected possibilities were revealed which are now undergoing further exploration. Although it is less convenient to report to a self-instruction room than to pick up a textbook in one's room or elsewhere, most students felt that they had much to gain in studying by machine. Most of them worked for an hour or more with little effort, although they often felt tired afterwards, and they reported that they learned much more in less time and with less effort than in conventional ways. No attempt was made to point out the relevance of the material to crucial issues, personal or otherwise, but the students remained interested. (Indeed, one change in the reinforcing contingencies suggested by the experiment is intended to *reduce* the motivational level.) An important advantage proved to be that the student always knew where he stood, without waiting for an hour test or final examination.

Some Questions

Several questions are commonly asked when teaching machines are discussed. Cannot the results of laboratory research on learning be used in education without machines? Of course they can. They should lead to improvements in textbooks, films, and other teaching materials. Moreover, the teacher who really understands the conditions under which learning takes place will be more effective, not only in teaching subject matter but in managing the class. Nevertheless, some sort of device is necessary to arrange the subtle contingencies of reinforcement required for optimal learning if each student is to have individual attention. In nonverbal skills this is usually obvious; texts and instructor can guide the learner but they cannot arrange the final contingencies which set up skilled behavior. It is true that the verbal skills at issue here are especially dependent upon social reinforcement, but it must not be forgotten that the machine simply mediates an *essentially verbal* relation. In shaping and maintaining verbal

knowledge we are not committed to the contingencies arranged through immediate personal contact.

Machines may still seem unnecessarily complex compared with other mediators such as workbooks or self-scoring test forms. Unfortunately, these alternatives are not acceptable. When material is adequately programmed, adjacent steps are often so similar that one frame reveals the response to another. Only some sort of mechanical presentation will make successive frames independent of each other. Moreover, in self-instruction an automatic record of the student's behavior is especially desirable, and for many purposes it should be foolproof. Simplified versions of the present machines have been found useful—for example, in the work of Ferster and Sapon, of Porter, and of Gilbert (8)—but the mechanical and economic problems are so easily solved that a machine with greater capabilities is fully warranted.

Will machines replace teachers? On the contrary, they are capital equipment to be used by teachers to save time and labor. In assigning certain mechanizable functions to machines, the teacher emerges in his proper role as an indispensable human being. He may teach more students than heretofore—this is probably inevitable if the world-wide demand for education is to be satisfied—but he will do so in fewer hours and with fewer burdensome chores. In return for his greater productivity he can ask society to improve his economic condition.

The role of the teacher may well be changed, for machine instruction will affect several traditional practices. Students may continue to be grouped in "grades" or "classes," but it will be possible for each to proceed at his own level, advancing as rapidly as he can. The other kind of "grade" will also change its meaning. In traditional practice a *C* means that a student has a smattering of a whole course. But if machine instruction assures mastery at every stage, a grade will be useful only in showing *how far* a student has gone. *C* might mean that he is halfway through a course. Given enough time he will be able to get an *A*; and since *A* is no longer a motivating device, this is fair enough. The quick student will meanwhile have picked up *A*'s in other subjects.

Differences in ability raise other questions. A program designed for the slowest student in the school system will probably not seriously delay the fast stu-

dent, who will be free to progress at his own speed. (He may profit from the full coverage by filling in unsuspected gaps in his repertoire.) If this does not prove to be the case, programs can be constructed at two or more levels, and students can be shifted from one to the other as performances dictate. If there are also differences in "types of thinking," the extra time available for machine instruction may be used to present a subject in ways appropriate to many types. Each student will presumably retain and use those ways which he finds most useful. The kind of individual difference which arises simply because a student has missed part of an essential sequence (compare the child who has no "mathematical ability" because he was out with the measles when fractions were first taken up) will simply be eliminated.

Other Uses

Self-instruction by machine has many special advantages apart from educational institutions. Home study is an obvious case. In industrial and military training it is often inconvenient to schedule students in groups, and individual instruction by machine should be a feasible alternative. Programs can also be constructed in subjects for which teachers are not available—for example, when new kinds of equipment must be explained to operators and repairmen, or where a sweeping change in method finds teachers unprepared (10). Education sometimes fails because students have handicaps which make a normal relationship with a teacher difficult or impossible. (Many blind children are treated today as feeble-minded because no one has had the time or patience to make contact with them. Deaf-mutes, spastics, and others suffer similar handicaps.) A teaching machine can be adapted to special kinds of communication—as, for example, Braille—and, above all, it has infinite patience.

Conclusion

An analysis of education within the framework of a science of behavior has broad implications. Our schools, in particular our "progressive' schools, are often held responsible for many current problems—including juvenile delinquency and the threat of a more powerful foreign technology. One remedy frequently suggested is a return to older

techniques, especially to a greater "discipline" in schools. Presumably this is to be obtained with some form of punishment, to be administered either with certain classical instruments of physical injury—the dried bullock's tail of the Greek teacher or the cane of the English schoolmaster—or as disapproval or failure, the frequency of which is to be increased by "raising standards." This is probably not a feasible solution. Not only education but Western culture as a whole is moving away from aversive practices. We cannot prepare young people for one kind of life in institutions organized on quite different principles. The discipline of the birch rod may facilitate learning, but we must remember that it also breeds followers of dictators and revolutionists.

In the light of our present knowledge a school system must be called a failure if it cannot induce students to learn except by threatening them for not learning. That this has always been the standard pattern simply emphasizes the importance of modern techniques. John

Dewey was speaking for his culture and his time when he attacked aversive educational practices and appealed to teachers to turn to positive and humane methods. What he threw out should have been thrown out. Unfortunately he had too little to put in its place. Progressive education has been a temporizing measure which can now be effectively supplemented. Aversive practices can not only be replaced, they can be replaced with far more powerful techniques. The possibilities should be thoroughly explored if we are to build an educational system which will meet the present demand without sacrificing democratic principles.

References and Notes

1. The Navy's "Self-Rater" is a larger version of Pressey's machine. The items are printed on code-punched plastic cards fed by the machine. The time required to answer is taken into account in scoring.
2. S. L. Pressey, *School and Society* 23, 586 (1926).
3. ———, *ibid.* 36, 934 (1932).
4. B. F. Skinner, "The experimental analysis of behavior," *Am. Scientist* 45, 4 (1957).
5. ———, *Verbal Behavior* (Appleton-Century-Crofts, New York, 1957).
6. ———, "The science of learning and the art

of teaching," *Harvard Educational Rev.* 24, 2 (1954).
7. This material was prepared with the assistance of Susan R. Meyer.
8. Dr. Homme prepared sets of frames for teaching part of college physics (kinematics), and Mrs. Meyer has prepared and informally tested material in remedial reading and vocabulary building at the junior high school level. Others who have contributed to the development of teaching machines should be mentioned. Nathan H. Azrin cooperated with me in testing a version of a machine to teach arithmetic. C. B. Ferster and Stanley M. Sapon used a simple "machine" to teach German [see "An application of recent developments in psychology to the teaching of German," *Harvard Educational Rev.* 28, 1 (1958)]. Douglas Porter, of the Graduate School of Education at Harvard, has made an independent schoolroom test of machine instruction in spelling [see "Teaching machines," *Harvard Graduate School of Educ. Assoc. Bull.* 3, 1 (1958)]. Devra Cooper has experimented with the teaching of English composition for freshmen at the University of Kentucky. Thomas F. Gilbert, of the University of Georgia, has compared standard and machine instruction in an introductory course in psychology, and with the collaboration of J. E. Jewett has prepared material in a'gebra. The U.S. Naval Training Devices Center has recently contracted with the University of Pennsylvania for a study of programs relating to the machine instruction of servicemen, under the direction of Eugene H. Galanter.
9. B. F. Skinner, *Science and Human Behavior* (Macmillan, New York, 1953).
10. K. Menger, "New approach to teaching intermediate mathematics," *Science* 127, 1320 (1958).

The Microfluoroscope

An x-ray microscope for direct visual or photometric measurements in biological specimens is described.

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The x-ray microscope in several forms has become increasingly valuable as a complementary instrument to light and electron microscopes. It is especially suited to quantitative *in situ* measurements of the mass or thickness of microscopic structures, and to specific types of elementary microchemical analysis. Present methods of x-ray microscopy may be grouped into four classes: (i) contact methods in which the x-ray image is initially recorded or detected at unity magnification, (ii) true focusing systems in which mirrors produce images by convergent x-rays, (iii) point-projection

systems in which the image is formed as a geometrical shadow cast by divergent x-rays, and (iv) scanning systems in which a likeness is recreated by a time-sequential light pattern representing the x-ray absorption in the object. These methods and their applications are described in detail elsewhere (*1*).

In all x-ray microscopes the problem of obtaining adequate intensity is serious, especially at the long wavelengths (2 to 20 angstroms) which are necessary for observing most biological material at high magnifications. This is a consequence of the inefficiency of x-ray production at the low excitation voltages and atomic numbers of targets which are practical for producing these long wave-

lengths. The point-projection x-ray microscope can form a reasonably bright fluorescent image at about 1 micron resolution with 5 or 10 kilovolt x-rays, but as the source diameter and excitation voltage are reduced below this, the image becomes too dim for direct viewing. The scanning system may offer some advantages in the display intensity, but it is limited ultimately by the photon noise, in the same way that the point-projection method is. Order of magnitude estimates of this ultimate speed of point-projection and scanning systems do not give much hope for direct viewing at high magnification and useful field width, especially at soft wavelengths (*2*). In reflection x-ray microscopes, some gain in intensity at long wavelengths may result from an increase in useful mirror aperture, but this increase is not enough to overcome the inherently low intensity of reflection systems in comparison with other methods of x-ray-image formation. In most cases, as we shall show, the proper contact image geometry can still provide the highest x-ray intensity at the detector for a given resolution and width of field. It has the further practical advantage, that the specimen may be mounted in air, even for viewing with ultrasoft x-rays, since the total x-ray path may be made short enough to prevent appreciable atmospheric absorption.

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