THE TEACHING OF SCIENCE

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The possible answers to the question **"What is science?"** have very different implication for the teaching of science.

I. What is science?

Three views of the nature of science have been widely discussed in past years. Since the teaching of science, and especially the methods used, will depend on what the teacher considers to be the nature of science, I will first give a brief introduction to each of these views of science. They are:

(i) science as **knowledge**,
(ii) science as **language**, and
(iii) science as the **process** of finding out.

(i) The oldest, and still the most common, view of science holds that 'science' is synonymous with 'knowledge'. According to this opinion, science is neither more, nor less, than all of the accepted theories and facts which we have about the world. Science thus becomes what you can read in textbooks on science. Not only that, but if the textbooks were perfect there would be no need at all for science teachers: the only requirement for science teaching would be very good teachers of reading! Unfortunately for this easy view, science is much more than simply 'that which men have discovered'.

(ii) In a somewhat different view, science can be seen as a set of languages. Each language in everyday use by the people of the world grew up originally as a tool not merely to communicate, but to communicate **about something.** Men must work together to live in the world, and language began as a way of cooperating in understanding and using the world. A good language is therefore not just a tool for communicating, but a tool for communicating **about the world.** When languages began, the world was very poorly understood; there was no science, and no conscious experimentation. The languages which resulted could be no better than the understanding on which they were built, and hence are not very good for describing and studying the world around us. As human understanding of the world has improved, especially since the introduction of experimentation in the 17th century, the need for new and better languages has become greater and greater, and scientists have been very active in adapting existing languages (by better definition of terms and by refinements of meaning) and by inventing new ones — especially mathematical languages.

(iii) Neither of the foregoing descriptions of science has much to say about the life of a scientist, yet if we have scientists we should be able to describe what they do. Basically, the activity of a scientist can be described **as finding out.** It does not matter very much whether he is a theoretical physicist or mathematician who works only with pencil and paper, or an engineer supervising the construction of a bridge: his job is **discovery.** In the example cited, it can be seen that discovery does not need to be limited to a new theory; making the general idea of a bridge fit a special location also involves discoveries such as: are there materials nearby which can be used, or must I bring them from far away? is the river ever bigger than it is now? will the banks of the river hold the bridge I want to build? will the local people assist in its construction or do I need workers from another area? how strong does the bridge need to be to carry the traffic I expect? — and so on. Perhaps discovery is not the best description of the scientific process after all. A better term would be **problem-solving.**

Does the idea of science as a process of solving problems fit the activity of the theoretician? I think it is clear that it does: in discovering a new theory, or explanation of physical events, the theoretical scientist must solve a **problem of understanding.** His work begins with the recognition that he, as well as other men, cannot explain something. This 'something' may be a new observation, which does not fit any existing theory, or it may simply amount to noticing that two accepted theories do not fit together — that they make different predictions in similar situations.

II. The process of science.

I have described science as a process of solving problems, but have not yet attempted to outline what the process is and how it works. Prof. Karl Popper has summarized the process beautifully in three words: "conjectures and refutations." It may seem fantastic that a method as powerful and useful as science can be summed up as a guess-work and disproof, but a clear look at science does indeed show these to be the most important parts of the process. Let us see how it works.

First, of course, the problem-solver must know what his problem is. He must have become aware that something around him — a thing or an idea — was not ideal. Finding problems is never difficult, but finding problems which can actually be worked on is not quite so easy. That is to say, some problems are obviously too big, or too difficult, for us to try solving them. Another common difficulty is finding the **right** problem — in correctly defining the problem. An investigator is unlikely to make much progress if he is looking in the wrong place, or using the wrong tools.

Secondly, the scientist must form a hypothesis. Very often, this guess at the answer comes to him along with recognition of the problem. Also very often, such a first guess is easily proven wrong — the first 'refutation'. Now the problem-solver has a harder job, because he must find, or invent, another possible answer. Since many men have tried to solve all the more obvious problems for many thousands of years, finding a new possible answer, that has not been disproved before, can be a very hard job indeed.

Suppose that this problem-solver is actually a very clever man, and he does manage to invent a new hypothesis. Suppose, in fact, that he is wise enough to invent a hypothesis that is not disproved by facts that are already known. His third job is then to try his best to **disprove his own hypothesis,** to refute his own hypothesis. In all scientific work, this attempted disproof takes three distinct steps to complete. They can be called: deduction, experiment, and comparison. Deduction is a logical process, in which the scientist assumes that his hypothesis is true, and mentally works out what the result would be in various situations. In the stage of experiment, the problem-solver must devise experiments which will test his hypothesis; he must find out by experiment whether the results which logically follow from his hypothesis actually do happen in nature, when the experiment is carried out. The third stage is rather obvious — comparison of his experimental results with his logical deduction will tell him if the hypothesis **might** be true, or if it is disproved.

The word **might** in the previous sentence is a very important one. A scientist can destroy a hypothesis with one good experiment, but he can never **prove** a hypothesis. The reason for this is quite clear if you think about it carefully. If a hypothesis tells you, by good logic, things which must be true if the hypothesis is true, and experiment shows that those logical deductions are NOT the case, then the hypothesis must be false. On the other hand, agreement of the result of one type of experiment with these deductions does not disprove the hypothesis, but it also does not say anything about the results of **other** types of experiment! These considerations illustrate the second half of Popper's recipe for science: we can learn by refutations that we have a wrong hypothesis, but we cannot **prove** we have a correct one. The nearest we can come to actual proof in science is to say: we have tried every means we can think of to disprove this hypothesis, and we have failed. On such a basis, a problem-solver is allowed to say: "I **think** this hypothesis is correct." But if he is honest, he will **never** say "I **know** this theory is correct", because he knows inside himself that a new kind of experiment, or a more accurate one, might at any time be found which would **disprove** the hypothesis.

This analysis of the activity of science clearly indicates why the textbook definition of science is not complete: the textbook approach assumes that knowledge once gained is proved and final, which it is not, because it can be falsified at any time by a new experiment, and because it continues to grow and change from year to year. The textbook conception of science also fails to account for the various activities which scientists engage in while acting as scientists. These activities may take place in various orders, and mixed and intertwined, but they can be described as:
(i) problem definition,
(ii) hypothesis formation,
(iii) deduction of consequences,
(iv) testing of consequences by experiment,
(v) Conclusion by comparison of result with deduction.

If the conclusion is "hypothesis is false", then a new hypothesis is required, and then its testing. When the conclusion is "hypothesis may NOT be false", then more experimental tests are called for until either the hypothesis is falsified, or the scientist is satisfied that the hypothesis is a good and useful idea about the world.

It is important both for students and teachers to recognize this tentative and uncertain quality in scientific knowledge. Science can NOT, by its very nature and by the way in which it is discovered, ever be considered as proven beyond any doubt. On the other hand, it is also important to recognize how complicated scientific knowledge has become. Our accepted hypotheses in all fields now overlap and **confirm each other** in a very strong way. That is to say, our scientific beliefs in physics are consistent with our beliefs in chemistry; they agree with each other and support each other. Further, they both support biological theories which in turn help our ideas in chemistry and physics. Thus all sciences help define all the others, and it is very unlikely, and difficult to imagine, that they will be all torn down by some new experiment. But it is nevertheless logically possible, so we must continue to be aware of at least the possibility that tomorrow's science will be completely different from today's. On the other hand, it will certainly continue to grow and change in detail as long as men are interested in improving their understanding of the world and each other.

III. The teaching of science.

What effect should this new conception of the nature of science have on our approach to teaching science? First of all, we must guard against throwing away all tradition and every part of the old way of teaching science. We can observe that although the time-honored methods of teaching science from textbooks and lecture-notes (as if it were something sacred and final) has been discredited by the more accurate view I have described, it still has some small merits. For one thing, there are very good textbooks available, for all sciences, at all levels, and they actually do describe the whole framework of ideas of the various sciences, and give clear, well-tested explanations of everything which students have found difficult to understand. Furthermore, in the many cases in which the teacher is poorly prepared or not an expert in the subject he must teach, a good textbook provides the only useful crutch and teaching-method available.

There is still another reason that textbooks should never be out-moded by new developments in methods of teaching science, and it is this: besides being a process of finding out, science is also a system of concepts. Science turns out to be **both** what we know today and how we progress to better understanding tomorrow. The student who knows the method but is ignorant of all that is known already must begin again with the work of Newton, Lavoisier, Galileo, and the rest.

That is fairly obvious, perhaps. The principal point of this essay is that the student, as we teach him what is now known, must also gradually learn how knowledge is built. He must somehow learn, or be taught, how to go himself and do science; in short, how to solve problems. As I indicated earlier, the process of discovery is a complex one. It has steps which require difficult techniques of careful thinking, as well as processes requiring very precise work with things — the experimental stage. These skills which taken together, make up the general art of problem-solving, are like skills in any fields: they cannot develop without practice. A good teacher can be extremely helpful to students in developing the art of science, as well as in learning the conceptual part of science, but skills are taught by entirely different methods from facts. Besides practice, the most important factor in learning a skill is imitation. The wise student is the one that chooses the most effective master; the lucky apprentice-scientist is the one who gets assigned to a capable investigator.

The teacher, or master, has a double function in the process of instructing the novice; he must be an able practitioner of the art, so that he can demonstrate the best technique for the learner to imitate. Secondly, the teacher must understand his art in great detail, so that he can serve as an accurate critic, and set the student right whenever he begins to go wrong. These two aspects of learning teaching skills often go hand in hand. After the first instruction and demonstration, the student will try the technique; often he will make a mistake, and the master will say, "No, No — not like that! Do it this way."

These observations apply to the process of learning of all the kinds of action which join together to make the overall process of science. That is, the teacher will need to assist and guide in detection and definition of problems, in the invention of hypotheses, in devising, carrying out and interpreting experiments, and in the drawing of conclusions.

IV. Some practical suggestions.

It might be thought at this stage that I have set an impossibly high standard for teachers of science — that they should be capable and experienced investigators, even to teach beginners in the schools. There are several ways around this situation. This is fortunate, because if there were not, good science instruction, would be a practical impossibility in any developing country. These means to get around the problem have been developed mainly in the most advanced countries, but they are applicable anywhere that one can find intelligent, willing teachers — regardless of their previous experience.

The first is usually called the case-study method. It has been found to be an excellent way of teaching the arts of litigation and legal practice, and in recent years has been adapted very well to teaching scientific thinking, all the way from problem-recognition to conclusion-drawing. It can be combined very well with standard procedures of science instruction using a basic text, at any level of science teaching. The method is simplicity in itself: rather than present the students with a conclusion to be memorized, the teacher leads them through all the steps (and maybe through some of the false guesses and bad experiments) of the discovery. In the hands of a teacher who has prepared the lessons well, such a step-by-step reconstruction of a scientific advance can bring the students to a stage of active appreciation of, if not actually participation in, the mental events of the process of invention. After a few such case studies, the students can profitably be encouraged to participate in the guesswork as the case develops. (Sometimes they cannot be prevented from participating!) In later stages, case histories are best taught as a dialogue of questions — and hints — from the teacher, and answers or guesses from the class. Practice, and hence skill, in thinking develops well under conditions of joint effort toward solving thought-experiments of this type.

This approach teaches more than problem-solving: examples are readily available in every science from the known development of important hypotheses — hypotheses which the student must learn anyway if he is not to remain scientifically illiterate. The advantages for the students are obvious; for the teacher the case-study method means more preparation, and perhaps more effort expended during class hours. On the other hand, teaching this way has an excitement, and hence a reward, of its own. "Will the class solve today's puzzle?" "Can I show them the way to the answer without giving it to them?"

Materials for teaching by case studies are no longer as hard to find as they once were. Besides the many books on the history of science, which are liberally sprinkled with good examples, there are now a number of books devoted entirely to complete case-studies which are applicable to teaching at various levels in several sciences. In addition to these sources, some of the best new textbooks from America and England are planned to teach entire courses by the case-method, and include all the necessary material for such teaching.

The case-study method has one major defect: it gives no practice in the actual conduct of experiments. But this, too, can be remedied, even by a teacher with very little previous practical experience in research. All that is required is a spirit of adventure and a clear head. It helps, of course, to know some basic scientific facts, so that the students can be guided away from fruitless questions toward those for which answers may be possible.

The necessary courage can be obtained by considering that what? how? and why? are questions natural to every human being. As soon as a student, or a class, has arrived at a suitable question, science teaching begins with the challenge, "All right — let's try to find out! How shall we begin?" With a prior knowledge of the general steps through which a scientific or problem-solving process must go, the teacher is not likely to have much trouble leading his students through the adventure of finding out for themselves.

Problems in biology are the most obvious ones to young children, and they can often be studied (in a simple way, of course — remember that at first it is the process, not the equipment which is important) with materials available in any village in the world: effects of varied environment on growth (for example) can be studied with a few containers, earth, water, seeds, light and dark, dung and compost, etc., and a measuring rod. Taking dead things apart is another way to learn about the living world. In chemistry and physics, more equipment is often needed, but it is still surprising how much can be done with very simple materials. In any case, the teacher should always keep in mind some of the important qualities of good investigation: accuracy of measurement and reporting, co-operation with other investigators, completeness in exhausting possibilities, caution in drawing conclusions from too little or doubtful data, and so on.

Although the situation in each developing country — in each individual school, in fact — is different, and thus requires different approaches to this kind of teaching, there are still some general ideas which are valuable. As in the case-study method, the development of experiments with easily available materials — for beginners in sciences — has come a long way in the past few years, and several excellent books are available to guide the interested teacher. New materials are constantly being developed, often with special reference to particular geographical areas, so the teacher's job will get easier as the years go by. I suspect, though, that many teachers will always prefer to work out their own experiments, with their own students, because that is where the fun and the adventure lie.

V. Conclusion.

In these paragraphs, I have touched here and there upon the word **adventure**, and in closing, I want to emphasize to teachers and students alike the possibilities in science for excitement. Science need not, must not, be dulled into a routine memorization of facts. Science is, on the contrary, a **search** for solutions of problems — it is an activity directed to an end, either of understanding, or of doing. Any search can be exciting if the finding is desired but held in doubt. In the necessary teaching of facts, letus never forget to show how facts are found, how things are done, and how much pleasure can be gained from these activities which make up science in its truest meaning. Furthermore, since the facts will change while the skills remain, experience in **how to do** science is the most durable and valuable thing we can possibly give our students.

At least one member of every Department in the Faculty of Science, H.S.I.U., is very much interested in the problems of science teaching. Personal and written inquiries are invited, on any aspect of the teaching of science. The faculty is not only obliged, but eager, to assist in every way available to it, in making science education in Ethiopia the best attainable.

Some suggestions for further reading:

BECK, W.S., **Modern Science and the Nature of Life** Penguin Books (Pelican No. A473).

B.S.C.S. (Biological Science Curriculum Study) **Biology.** There are 3 versions of this secondary-school text.

BRONOWSKI, J., **The Common Sense of Science**, Penguin Books (Pelican No. A507).

BRONOWSKI, J., **Science and Human Values**, Penguin Books (Pelican No. 543).

C.B.A. — **Chemistry — an Experimental Science;** another new chemistry text.

CHEMS — **Chemical Sytems**, a new secondary school chemistry text.

CABOR, D., **Inventing the Future**, Penguin (Pelican No. A663).

HAWKINS, D., **The Language of Nature**, Freeman, San Francisco (1964).

P.S.S.C. (Physical Science Study Committee) **PHYSICS.** A new American secondary-school text.

SCHNEER, C.J., **The Search for Order**, English Universities Press, London (1960).