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ABSTRACT

The history of the use of laboratory work in teaching science is traced from the 18th century to the present laboratory-centered curricula. Major rationales and objectives for laboratory work are presented, and different types of laboratory activities are discussed from the standpoint of learning theories and research findings. Also discussed is the use of the laboratory in various science disciplines, and the use of vicarious experiences as a substitute for laboratory work. An extensive bibliography is included. (MH)

# Technical Report Series







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technical report 10

# THE ROLE OF THE LABORATORY IN SCIENCE TEACHING

by

Pinchas Tamir

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Robert E. Yager, Coordinator
Science Education Center
University of Iowa

Pinchas Tamir
School of Education and Israel Science Teaching Center
Hebrew University, Jerusalem
Visiting Professor, University of Iowa
Iowa City, Iowa 52242

The Role of the Laboratory in Science Teaching

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The learning laboratory is defined, for the purpose of the present paper, as a lesson or a place in which students actually perform observations, tests and experiments as part of their study of science. Since the end of the 19th century, when schools began to teach science systematically, the role of the laboratory has been under continuous debate. Specifically disagreements have related to the interrelationships between the laboratory on one hand and other instructional modes, such as lectures and demonstrations, on the other hand.

J. Priestley argued as early as 1790 that children should be trained to perform experiments and deal with the theory and practice of inquiry at an early age. In this way they would have acquired the skills and capability to proceed in their own original ways. By the end of the 19th century and in the beginning of the 20th century the individual work of students in the laboratory had been firmly established in Britain in biology (Kingsley, 1890), in chemistry (Armstrong, 1891), and in physics (Worthington, 1885). The views of the proponents of laboratory work were expressed in statements such as "There is only little value to the experiment if you do not perform it yourself, question it, or modify it in order to provide answers to your queries" (Kingsley, 1890), or "The use of eyes and hands -- namely the scientific method -- can be learned neither by the use of chalk and blackboard nor by lectures which describe experiments and demonstrations. Children should use their eyes and hands right from their first years in school" (Armstrong, 1891).

In the United States in 1880 hardly any school offered a course in physics or in chemistry with laboratory work. By the late 1880s the picture began to change. Provisional lists of experiments in elementary physics and in elementary chemistry to be performed by high school students who sought admission to Harvard initiated the change. In physics a course of experiments in the subjects of mechanics, sound, light, heat and electricity, not less than forty in number, actually performed at the school by the pupil, was required (Rosen, 1954). Similarly, a pamphlet describing the kind of high school course preferred and the type of experiments acceptable in chemistry was written by Professor Josiah Cooke for distribution to the secondary schools. Under four major headings and 27 subheadings were listed 83 experiments demonstrating both qualitative and quantitative aspects of laboratory chemistry. Cooke made it quite clear that the kind of high school chemistry course he considered adequate was one in which (1) the major concern was with fundamental principles; (2) demonstrations by the teacher supplemented the experiments of the students in a systematic way; (3) the study of chemistry began with observation and was particularly concerned with the leading of the student to general principles by the use of his own inferences; and, most important, (4) quantitative as well as qualitative experiments were performed by the students (Rosen, 1956).

Between 1887 and 1900, "the laboratory has won its place in school. Its introduction has proved successful. It is destined to revolutionize education. Pupils will go out from our laboratories able to see and to do" (Griffin, 1892, as cited by Rosen, 1954). Only few schools were constructed after 1890 without physics and chemistry laboratories: "Empiricism is the watchword of today. 'Read Nature in the language of the experiment,' cries the reformer. The cry has been heard and heeded; and the high school or academy which is not well equipped with laboratories and apparatus is not looked upon as 'progressive,' as 'up to the times'" (Conant, 1893, cited by Rosen, 1954). By 1910 the physics and the chemistry laboratories had become an accepted part of the high school curriculum in the U. S. This rise of the laboratory in the public schools during the period 1821-1910 was influenced by four general cultural conditions: (1) the growing feeling that the curriculum which included studies in science was more important than the older program emphasizing the classics; (2) the increasing emphasis on laboratory work and empirical research in the universities and colleges; (3) the influence of college admission requirements on the high school curriculum; and (4) the peculiar optimistic American habit of popularizing to emotional extremes certain progressive ideas (Rosen, 1954).

In the years following 1910 the progressive education movement under the leadership of John Dewey had a major impact upon the nature of science teaching and the role of the laboratory. Dewey (1916) advocated an investigative approach to science education, and he was one of the first to argue that the attitudes students developed about science were at least as important as the scientific knowledge acquired. The philosophy underlying Dewey's (1938) position emphasized problem solving in the curriculum as well as the application of science to problems that were relevant to students. Dewey's ideas stimulated the growth of "practical" science courses that focused upon utilitarian applications of science. During this era, for example, secondary school physics texts were filled with trolley cars and steam engines, and high school chemistry courses offered laboratory "experiments" that included making everyday products such as soap and ink. While the progressive education movement was gaining power, a number of arguments against excessive use of the laboratory were advanced both in the U. S. and in Britain.

a) "In the laboratory the student is introduced at once to the difficult subject of measurement, required to make immediate use of unfamiliar instruments . . . to report . . . to discuss errors . . . to deduce laws from data that cannot be made to prove anything, and to apply these laws to a set of problems that have no apparent relation to his immediate scientific environment, or to the questions that he is so anxious to have answered" (Packard, 1903).

b) "Laboratories have not solved the problems of science teaching . . . we do not know how to use laboratories most effectively" (Mann, 1910).

c) There is a lack of teachers in secondary schools who are competent to instruct science. Teachers trained in laboratory methods are scarce (Mann, 1910).

d) Too much emphasis on laboratory exercises leads to a narrow conception of science. The humanistic, theoretical and technological aspects of science have been neglected (Woodhull, 1907, as cited by Rosen, 1954; British Association, 1917; Kerr, 1963).

e) Many schools waste too much time in trivial experiments done by students (Lowrey, 1921; Stephenson, 1930). In the time that can be saved by performing more demonstrations, students can be taught to understand the relationships between the experiments and the principles of science as well as the history of scientific methods (Committee on the Position of Natural Science, 1918, p. 55; Humbey & James, 1942, p. 90).

By performing demonstrations teachers will have time to do more experiments and more diversified experiments, thereby increasing their effectiveness for learning (Spens, 1938, p. 250).

f) Science will not be respected by students if they identify it with the kind of generalizations they are arriving at in their own experiments in class (Lowrey, 1921).

g) Laboratory work in schools is remote and unrelated to the capabilities and needs of children. It is too much a reflection of the university laboratory courses (Smith and Hall, 1902; Board of Education, 1932).

h) Demonstrations are clear and meaningful, and much more helpful than experiments, especially to slow learners (Newbury, 1934).

i) While boys prefer to do the experiments, girls usually tend to prefer demonstrations (Newbury, 1934).

j) It is not uncommon to find a student who shows no understanding of the process with which he himself worked yesterday in the laboratory (Philbrick, 1937). It is quite easy to do a practical work which does not involve any thinking. Most laboratory work in biology is geared toward confirmation of the facts provided by the teacher and the text (Green, 1954).

Interestingly, while some people were criticizing the work of students in the laboratory, others maintained that laboratory experiences were indispensable. In the U. S. Craig (1927) urged the development of programs emphasizing the scientific method. In Britain the Handbook of Suggestions for Teachers (1937) argued that the ideas acquired by the child through actual activities became part of his mental framework to a greater degree than those acquired vicariously, and that this was especially true with regard to the less able children. Some people went so far as to suggest that the whole of a science course should be based on the work of students in the laboratory, and any material which was not suitable for individual students' laboratory work should be discarded (Report of Science Masters' Association, 1953).

After World War One, the expansion of public education combined with the rapid increase in scientific knowledge resulted in a general mode of instruction centered around textbooks and lectures (see Figure 1). In the relatively rare occasions when laboratory work was practiced, it was considered as no more than a means for confirmation and illustration of information learned previously by reading textbooks and listening to lectures.

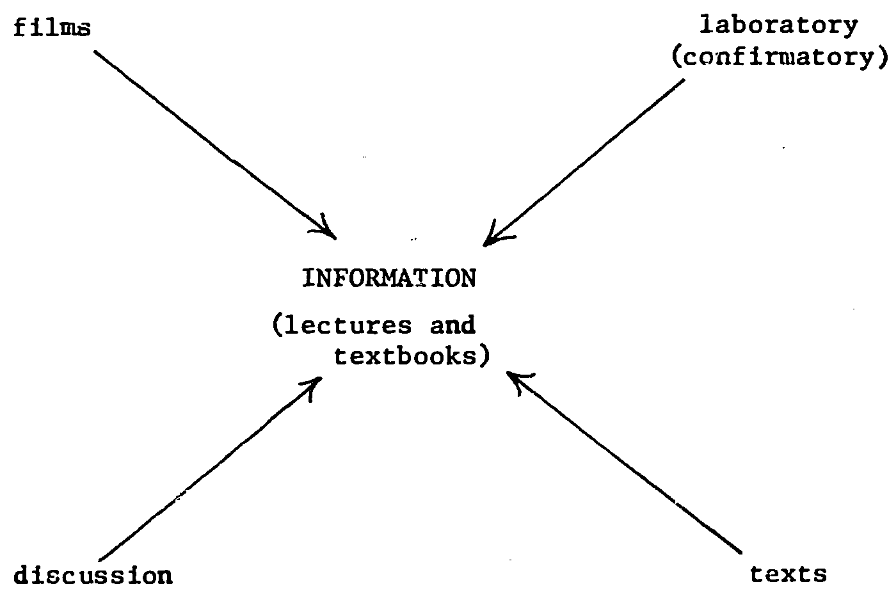


Figure 1: The role of the laboratory in science teaching in the years 1918-1960 (after Romey, 1969).

With the "new" science curricula of the late 1950s, the laboratory has become the center of science instruction (Figure 2).

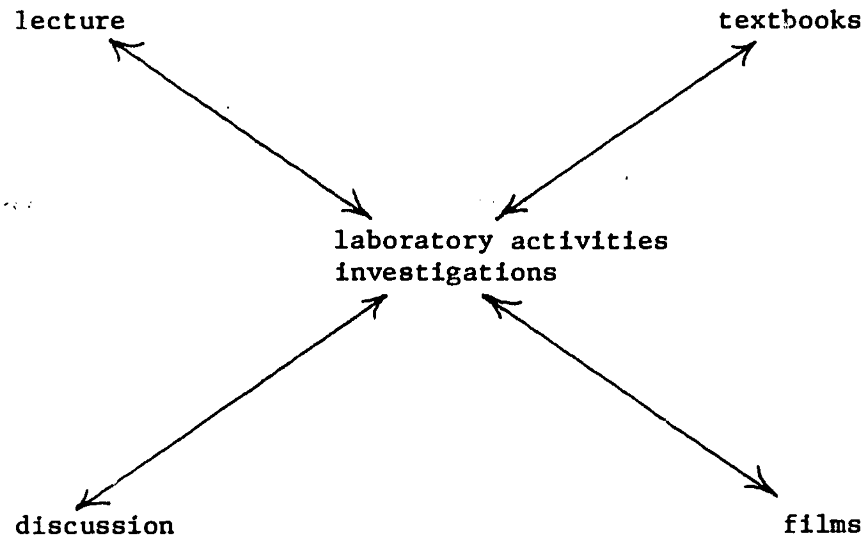


Figure 2: The role of the laboratory in the "new" curricula (after Romey, 1969).

Over the years many studies were made to assess the relative effectiveness of laboratory and demonstration methods. Most of these studies failed to establish any superiority of the laboratory as measured by paper and pencil achievement tests (Horton, 1928; Van Horne, 1929; Goldstein, 1937; Chester, 1938; Cunningham, 1946; Mallinson, 1947; McKibben, 1953; Lang, 1959; Coulter, 1966; Yager et al., 1969).

The shift towards laboratory-oriented courses has not been based on "hard" data which show unequivocally the superiority of such courses. Rather, it has developed following the opinions and biases of leading personalities, often scientists, who took part in the design of the new curricula. Today, more than fifteen years since the introduction of PSSC, we envisage enormous increases in the number of laboratory-centered courses at all levels (see Lockard, 1975). Slowly we begin to obtain data which show that the laboratory does play unique roles in the development of concepts, skills and attitudes (e.g., Yager et al., 1969; Pella and Sherman, 1969; Tamir and Glassman, 1971; Henry, 1975). Yet the controversy concerning the role and relative emphasis of the laboratory has not been resolved. While some educators feel that the la- tory merits eighty per cent of class time (FAST, 1976), others ugge that "at least half of the class time should be spent on activities and laboratory exercises" (Romey, 1969); some would be satisfied with a third of class time given to the laboratory (Organization for Economic Cooperation and Development, 1962), and still others have "a minimum objective" of "one laboratory period or field trip each week" (Novak, 1970). Ausubel (1968) believes that since the laboratory is very time-consuming and inefficient it should typically carry the burden of conveying the methods and spirit of science whereas the teacher and the textbook should assume the burden of transmitting subject matter content. Clearly, debates over the distribution of hours depend on the objectives and roles assigned to the laboratory within the framework of specific courses, with certain kinds of students, teachers and school environments.

## Rationale and Objectives

Four major rationales are generally advanced for the extensive use of the laboratory in teaching:

1. Science involves highly complex and abstract subject matter. Many elementary and even high school students may fail to grasp such concepts without the concrete props and opportunities for manipulation af-

forded in the laboratory.

2. Student participation in enquiry in actual collection of data and analysis of real phenomena is an essential component of the enquiry curriculum (Schwab, 1960). It gives students appreciation of the spirit and methods of science, it promotes problem-solving, analytic and generalizing ability (Ausubel, 1968), it develops important attitudes and provides confidence in acquired scientific knowledge (Henry, [illegible]).

3. Practical experience, the Practical Mode [illegible], are particularly adequate for the development of skills with a wide range of generalizable effects (Olson, 1973; Tamir, 1975).

4. Students enjoy activities and practical work and conseqently become motivated and interested in science (Selmes, Ashton, Meredith, Newal, 1969; Henry, 1975; Ben Zvi et al., 1976b).

A variety of laboratory objectives have been suggested (Bingman, 1969; Glass, 1960; Henry, 1975; Klinckman, 1970; A. Novak, 1973; J. D. Novak, 1970; Nuffield, 1965; Pella, 1961; Rorey, 1969; Sund and Trowbridge, 1967; Wilson, 1962) and they are remarkably coextensive with the objectives generally adduced for science learning per se (Bingman, 1969; Pella, 1961). The stated objectives fall into one or more of the following areas:

Skills: e.g., manipulative, inquiry, investigative, organizational, communicative;

Concepts: e.g., data, hypothesis, theoretical model, taxonomic category;

Cognitive abilities: e.g., critical thinking, problem solving, application, analysis, synthesis, evaluation, decision making, crativity;

Understanding the nature of science: e. g., the scientific enterprise, the scientists and how they work, the existence of a multiplicity of scientific methods, the interrelationships between science and technology and among various disciplines of science;

Attitudes: e.g., curiosity, interest, risk taking, objectivity, precision, perseverance, satisfaction, responsibility, consensus and collaboration, confidence in scientific knowledge, self reliance, liking science.

## Types of Laboratory Activities

Pella (1961) identifies five degrees of freedom available to the teacher in the utilization of the laboratory in the relative amounts of responsibility assumed by the pupils and the teacher (see Table 1).

| Degree of Freedom | I | II | III | IV | V |
|---|---|---|---|---|---|
| Steps in procedure: | Performed by: | | | | |
| 1. Statement of problem | T | T | T | T | P |
| 2. Hypothesis | T | T | T | P | P |
| 3. Working plan | T | T | P | P | P |
| 4. Performance | P | P | P | P | P |
| 5. Data gathering | P | P | P | P | P |
| 6. Conclusion | T | P | P | P | P |

Table 1: Degrees of freedom available to the teacher using the laboratory (T=teacher; P=pupil).

Degree I represents the confirmatory laboratory, the purpose of which is to verify the information presented by the textbook or the teacher. This laboratory will follow the teacher or the textbook presentation. In the other degrees the student has to reach his own conclusions; in laboratories with these degrees of freedom, the laboratory work generally precedes the teacher description or textbook reading phase. Degrees IV and V represent the inquiring laboratory, in which students have the opportunity to be engaged in research and practice inquiry skills.

A similar framework for viewing the degree of guidance in the learning laboratory has been provided by Schwab (1960) and elaborated by Herron (1971); they distinguish three components of the learning situation: problems, ways and means for discovering relations, and answers. As can be seen in Table 2, there are a number of possible ways to permute thse components to arrive at different levels of guidance, or, in Schwab's terms, "openness and permissiveness."

| Level of Discovery | Problems | Ways and Means | Answers |
|---|---|---|---|
| Level 0 | Given | Given | Given |
| Level 1 | Given | Given | Open |
| Level 2 | Given | Open | Open |
| Level 3 | Open | Open | Open |

Table 2: Levels of openness and discovery in the learning laboratory.

Herron (1971) analyzed the proposed laboratory exercises in the lab manuals of PSSC and BSCS Blue Version, using the framework outlined in Table 2. He reported that of the 52 PSSC laboratory activities 39 were at the zero level, 11 were at level 1, two in level 2 and none in level 3. The data for BSCS are hardly more impressive: 45 out of 62 laboratory exercises were at level 0, 13 at level 1, four at level 2 and, once again, none at level 3.

We may observe the importance of analyses such as the one performed by Herron. It is so often taken for granted that a curriculum accomplishes what it purports. Herron demonstrated the need for teachers to analyze the teaching materials even before they are used in the classroom to see to what extent the product falls short of the claims of its developers. With regard to laboratory exercises the use of the laboratory inventory presented in Table 3 (page 13) is recommended. Such an analysis will help program developers, teachers and students in monitoring the skills exercised in their laboratory experiences. The categories listed in Table 3 can be used also to guide observers in classroom interaction analysis.

| In this laboratory exercise the students: | yes | no |
|---|---|---|
| 1. Recognize and define problems. | | |
| 2. Formulate hypotheses. | | |
| 3. Predict. | | |
| 4. Design observation and measurement procedures. | | |
| 5. Design experiments. | | |
| 6. Carry out observations, measurements, and experiments. | | |
| 7. Record results. | | |
| 8. Transform results to standard format. | | |
| 9. Explain. | | |
| 10. Make inferences and draw conclusions. | | |
| 11. Formulate generalizations and models. | | |
| 12. Define limitations. | | |

Table 3: Content analysis of laboratory activities -- task dimension analysis.

Examples of two types of laboratories dealing with the same topic are presented in Table 4 on the following page.

| | Confirmatory Laboratory | Discovery Laboratory |
|---|---|---|
| Topic: | The effect of PH on the reproduction rate of yeast. | Does the PH affect the reproduction rate of yeast? |
| Purpose: | [illegible] hat yeast reproduce [illegible] in aci[illegible] PH. | To test the effect of various PH levels on the reproduction rate of yeast. |
| Procedure: | Detailed instructions including a table for the data and specific directions for three replications and computation of mean results. | General description of what to do, no table, no reference to replications and means -- the student is expected to do all these by himself. |
| Questions: | 1. In which test tube did you find the largest number of yeast? | 1. What were your findings? |
| | 2. Why did we use glucose agar? | 2. What are your conclusions? |
| | 3. What is the optimal PH for yeast? | 3. Are your data similar to those obtained by your friends? |
| | 4. How would you explain the presence of acidic PH in the regular environment of yeast? | 4. Design an experiment to test the effect of another variable on the reproduction rate of yeast. |
| | 5. Enter your data in the graph provided by the manual. | 5. Draw a graph to show the relationship between the reproduction rate of yeast and the PH level. |
| | 6. Why did you mark test tube number 9 as control? | 6. What was the role of each of your test tubes? |

Table 4: A comparison of confirmatory and discovery laboratories.

It is important to realize that laboratory work is not one kind of activity but a range of activities, with a variety of potential purposes, procedural options, and outcomes.

## Organization and Dynamics of Laboratory Work

In "theory" lessons or lecture-demonstration lessons student activitiy is often restricted; few students play an active role while others exhibit various levels of passivity. In contrast, the laboratory offers an excellent opportunity for active participation by all the students. This active involvement, as well as the environment itself (which is less formal and more flexible and allows for a diversity of concurrent activities), can make an important contribution toward individualization of instruction on the one hand and toward communication, cooperation and the development of interpersonal relations on the other. A number of different ways to organize laboratory work can be employed in laboratory teaching. Some of them will be described under two headings.

### 1. Individual work

The student follows the instructions of either a laboratory manual or a tape recorder and carries out observations, measurements and experiments on his own. Typically he will write a report and submit it for examination by the instructor. Occasionally, while working on an individual project he may be engaged in reviewing the literature, formulating the problem, hypothesizing, planning experiments, collecting and processing data, drawing inferences and conclusions and finally writing a report. The merits of such individualized work are that the student is totally responsible for his work, he is free to follow his personal inclinations, and the product as well as the rewards belong entirely to him. The disadvantage, on the other hand, is the lack of interaction with peers (see below). Yet even as an individual worker he can still consult with the instructor and may get the opportunity to report on his work to the entire class, thereby getting criticism and an opportunity to defend his work.

2. Pairs or teams

In most laboratory classes work has been done in pairs or in teams of three or four students. When functioning properly, each member of the team actively participates in the work, so that to a large extent students enjoy the advantages of individual involvement. At the same time the framework of a group allows for a variety of interactions, such as:

- opportunity to discuss, to consult with one another, and to criticize and be criticized;
- increased efficiency by division of labor;
- opportunity to compare results and to interpret data within the group and among groups;
- consideration of the work of each team as a replication of the same investigation, thereby allowing for a more representative and reliable pool of findings which will permit statistical analysis.

These attributes pertain to situations where the whole class performs the same investigation. Another good organizational strategy is for each team to perform a different task, matching the interests and abilities of the team. The BSCS Second Course (Interaction of Ideas and Experiments), for example, offers a framework in which the whole class first performs the same investigation, thereby allowing for experiencing certain techniques and getting involved in a specific research area. In a later stage, each team identifies a specific problem related to the original investigation and works independently for three to four weeks. At the end of this time each team reports to the whole class. Under this framework the whole class acts as a research force with the teacher playing the role of coordinator and counselor. A similar strategy may also be employed in laboratory investigations which require a much shorter time for completion.

The role of the teacher in guiding group investigations is far from easy. The teacher needs to provide direction without offering excessive guidance. He needs to be familiar with research and prepared to help his students in finding solutions for problems for which he himself may not know the answers. At the same time he needs to be able to handle the dynamics of social relations, which are rather complex in the laboratory. Educational research has not been able to offer much guidance in this area. Hurd and Row (1966) studied the group dynamic within the laboratory setting and identified important differences between college-bound and non-college-bound students. Undoubtedly we need much more research to guide teachers toward creating a social environment which will be conducive to learning in the laboratory.

## Different Types of Students and Laboratory Work

Many studies have shown that, on the average, students like laboratory work and many prefer it to lectures and demonstrations (e.g., Horton, 1928; Tamir, 1968; Ben Zvi, et al., 1976b). Yet there are students who

[illegible]

that girls [illegible]

[illegible]

biology at the university [illegible]

[illegible]

characteristics of the laboratory [illegible]

as well as on the personalities of the students and the teachers. [illegible]

oratory work requires concentration, perseverance, patience, critical thinking, divergent thinking, improvisation, uncertainty, team work and manipulation of instruments [illegible] the work [illegible] that are not easy to interpret and may even result in failure. Many students are challenged and motivated by the unique attributes of the laboratory [illegible] others may be deterred [illegible] frustrated [illegible] follow routine procedures, by experiencing repeated failures and the like. Once we can identify the attitudes of students toward various aspects of laboratory work, it may be possible to match certain experiences to certain types of students. Meanwhile it will be wise to strike an appropriate balance between laboratory and non-laboratory experiences.

## The Learning Laboratory in Different Disciplines

How are the laboratories in the various science disciplines different from each other? Do these differences justify the use of extensive laboratory work in each of these disciplines or will one integrated laboratory course be sufficient? Even an integrated course may not be necessary. Perhaps laboratory experiences in one science subject are sufficient in terms of the acquisition of skills and scientific methods, [illegible] Lawson and Blake, [illegible]

[illegible] hinder the development [illegible] thinking ability [illegible]

[illegible] research [illegible] nature [illegible] different [illegible] in different disciplines [illegible] differences [illegible]. In mathematics, for instance, the major purpose of concrete [illegible] appears [illegible] demonstration [illegible] relationships as well as [illegible] in problem solving and intuitive rule concept learning. [illegible] ical [illegible] and [illegible] nts. [illegible] a chemistry laboratory the students observe changes [illegible] appearance, hear explosions, notice different smells, and [illegible] changes in temperature. [illegible] perception [illegible]

Vicarious Experiences as a Substitute for Laboratory Work

While in the past the major controversy has been concerned with the differential effectiveness of individual laboratory work compared with the lecture-demonstration method, the unprecedented development of educational technology warrants further consideration. Television, slides, models, inquiry single-topic films and the computer are examples of the means now available for simulations of concrete situations. These simulations provide the learner with vicarious experiences which enable him to grasp the foundation of phenomena, much like actual laboratory experience (Bruner, 1960). Often a simulation has distinct advantages: it is designed very carefully to meet specific objectives; it is more convenient, easier to employ, less expensive, and less time-consuming.

Several questions may be raised at this point:

What are students going to lose if simulations take the place of laboratory experiences? What are they going to gain? Are there specific aspects of laboratory learning which cannot be satisfied by simulations? What are the aspects that can be satisfied by simulations, and to what extent is it possible and/or desirable for them to be thus satisfied?

As yet we do not have definite answers to these questions. Schwab (1960) has suggested that many aspects of science as enquiry can be learned outside the laboratory. Inquiry-oriented learning materials such as invitations to enquiry (Klinckman, 1970), enquiry into enquiry (Connelly et al., 1974), simulated experiments (Ben Zvi et al., 1976a; Lunetta, 1974) and others have been successfully used. Lunetta (1974) developed laboratory simulations that were supplemented by computer-based dialog designed to help students interpret data, understand relevant concepts, and develop certain inquiry skills. The interactive programs simulated physics experiments and graphed the data collected by individual students; they also provided feedback to each student regarding his generalizations about the data. Lunetta and Blick (1973) showed that concept learning was significantly greater for students using two simulation modes than for control students who used real laboratory materials and activities. Furthermore, control group students spent 8.3 times as long in instructional unit activities. Neither the experimental nor the control students showed significant losses in conceptual understanding as measured on a retention test six or more months later. Student attitudes toward the simulations were favorable. Still, the degree to which these experiences can substitute for the actual laboratory experiences is doubtful. If we agree with Olson's (1973) arguments about the limitations of the various media as far as the learning of skills is concerned, then it is doubtful whether much of what is considered to be the Practical Mode (Tamir, 1972) can have a substitute. Some evidence already exists which shows that as far as outcomes are concerned performance on practical tests is qualitatively different from paper and pencil tests (Tamir, 1975) and that even when simulation appears to yield similar results regarding certain outcomes, significant differences occur in other outcomes (Yager et al., 1969; Granger and Yager, 1971; Ben Zvi et al., 1976a, 1976b). It may be concluded that the unique role of the practical work in the laboratory should not be overlooked either in instruction or in evaluation.

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