DOCUMENT RESUME

ED 065 024 HE 003 136

AUTHOR	Thornton, John W., Ed.
TITLE	The Laboratory: A Place to Investigate.
INSTITUTION	American Inst. of Biological Sciences, Washington, D.C.
SPONS AGENCY	National Science Foundation, Washington, D.C.
REPORT NO	P-33
PUB DATE	Apr 72
NOTE	158p.
AVAILABLE FROM	AIBS Education Division, 3900 Wisconsin Avenue, N. W., Washington, D. C. 20016
EDRS PRICE	MF-$0.65 HC-$6.58
DESCRIPTORS	Biological Sciences; Biology; *Higher Education; *Laboratory Training; *Research; *Science Laboratories; *Scientific Research

ABSTRACT

This document on the undergraduate laboratory biology course is organized into 4 parts. Part 1 deals with the role of investigation in the undergraduate curricula. Chapters in this section deal with the time for laboratory reform; some special considerations in designing laboratory programs for nonmajors; the appropriate laboratory experiences for the biology major; Teaching and learning through investigation; and the concept, origin and current status of the investigative laboratory. Part 2 is involved with the practice of investigative laboratories. Chapters deal specifically with laboratories in the introductory courses at 4-year colleges and universities; investigative laboratories in advanced courses; investigative laboratories at field stations; and investigative activities in 2-year community colleges. Part 3 describes the laboratory curricula in general, with specific chapters on the laboratory curriculum at Marquette University and undergraduate biology laboratories at Massachusetts Institute of Technology. The fourth and final part deals with helping students learn how to investigate. (For related document see ED 064 112 in RIEOCT72). (HS)

THE LABORATORY:

a place to investigate

PUBLICATION NUMBER 33

THE COMMISSION ON UNDERGRADUATE EDUCATION IN THE BIOLOGICAL SCIENCES

THE LABORATORY: A PLACE TO INVESTIGATE

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April 1972

Published by the
Commission on Undergraduate Education
in the Biological Sciences

Publication Number 33

Supported by a grant from the
National Science Foundation
to the
American Institute of Biological Sciences

Copies of this report are available
free of charge from

AIBS Education Division
3900 Wisconsin Avenue, N.W.
Washington, D.C. 20016

Library of Congress Catalogue Card Number 79-1888237

Foreword

"A Lab is where you do science." This is how a fourth-grade youngster responded to my question during a visit to his classroom. The teacher, an energetic and courageous person, had each of her equally energetic charges "doing science," as one of the other youngsters explained. And, indeed, they were doing science: there were beans being grown in full and partial light, tadpoles in warm and cool places, and mice getting normal and calcium-free diets. The kids eagerly told me what they were doing and what they were trying to find out. They had log books on the bulletin board with data quite precisely recorded; reference literature was available, and even some reports on things they had already completed. For a portion of their school day, their classroom was even called, by them, a "lab."

Fervor, excitement, enthusiasm, interest — all the hoped for concomitants and outcomes of our educational endeavors, and all typically precluded by our pedagogical approaches. Nothing of what we do appears to be more effective in thwarting our real hopes than the laboratory which has become a place not to "do science," as my young mentor so beautifully perceived and expressed it, but as a place to "undo science." A beclouding drudgery for the besaddled instructor and a beguiling drag for the beleagured student.

It is easy to take pot shots such as this and then run, but CUEBS has not employed that tactic as part of its overall strategy of trying to improve biological education. In fact, one of the first defined jobs of the Commission dealt with the laboratory. The task proved to be an exceedingly tough one because so very few truly innovative approaches were being tried in laboratory teaching in the early 1960s. Time, urging, probing, and ferreting finally demonstrated again the not uncommon happenstance of people in isolation independently generating similar ideas, in this case, an investigative approach to the laboratory.

As the Table of Contents shows, this publication is documentation *par excellence* of a view I expressed in the foreword to CUEBS Publication 24 (*Preservice Preparation of College Biology Teachers*): "In reality, it is the whole biological community that works with Commissioners and staff to bring improvement to biological education." This is a compendium of contributions by those we were able to identify as trying to convert the laboratory into a vital part of the undergraduate program. To those people, and on behalf of teachers, students, and the Commission, appreciation and thanks are heartily conveyed. Various members of the CUEBS staff made significant contributions along the way, but the major kudos go to John Thornton who doggedly hounded and pounded to give the study a much needed comprehensiveness and to bring the job to completion. It is John who is responsible not only for collating and editing the various contributed sections, but for writing all those parts of the publication for which no author is specifically identified. Of particular merit is his thoughtful and provocative analysis of the components of investigation relative to teaching the processes of science (Chapter 12).

Here then is a wealth of ideas and experience, successes and failures, costs and accountability. It is now up to the community at large to move, to put life blood into the laboratory, to make it a place "where you do science."

EDWARD J. KORMONDY
Director, CUEBS
December 1971

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PART I

INVESTIGATION: ITS ROLE IN UNDERGRADUATE CURRICULA

"Much of our educational system seems designed to discourage any attempt at finding things out for oneself, but makes learning things others have found out, or think they have, the major goal. It is certainly true that it is easier to teach a set of *facts* than it is to encourage an inquiring mind (which most children have to start with) to make its own discoveries. Once a student has learned that he can find things out for himself, though, bad pedagogy is probably only an irritant."

ANNE ROE
The Making of a Scientist
Dodd, Mead & Company, New York, 1953

1. The Time for Laboratory Reform

During summer thundershowers, we used to gather in the front yard and play a game with nature. The object of this pleasant pastime was to try to dam up all the small ditches and channels along which the rain flowed from the gutter outlets to the ditch along the road. Although we worked like beavers to rob the ditch of its water supply and at times thought we were making progress, in the end nature always won. Unlike competitive games, however, the purpose of this one was not so much to win as it was to try to win. As we sought to meet the challenge of one channel, others would develop and suddenly capture the water which we had temporarily brought under control. Rushing to the new torrents, we would gather whatever resources were available and construct new dams, only to discover that in the meantime the original structure had been permeated by water and was being washed away.

Although the stakes are higher and the time span longer, the curriculum-building activities that occupy biologists' time are similar to that pleasant childhood game. While eagerly creating ways of meeting one set of challenges, we temporarily forget to give the necessary attention to other needs. During the downpour of information after World War II, for example, it became apparent that the content of our curricula had not kept pace with new developments in the discipline. Our response — construction of Core Curricula. Although these curricula are not as complete and satisfactory as we would like and the continuing downpour threatens to undermine them, they sometimes give us the temporary feeling that we are making progress. Stepping back to view our handiwork, we suddenly discover that in our eagerness to identify and transmit the core knowledge we have neglected other important educational needs—conveying the process side of our discipline, fostering the ability of students to learn on their own, humanizing the delivery of educational services, and responding to the individual needs and talents of students.

The consequences of this neglect are particularly apparent in the laboratory. Recently, a knowledgeable dean, pointing to the oversimplified colored charts which cover our laboratory walls, the gaudily stained slides, pressed plants and pickled animals which fill their cabinets and the superficial, cookbook-type exercises which are required of students, suggested that perhaps the instructional laboratories should be taken away from biology altogether. In his opinion, "A poor lab is worse than no lab." This may be so, but biologists also have reason to believe that if properly used, the laboratory offers one of the best environments we have for meeting the educational needs which are now so apparent. CUEBS has felt that the instructional laboratory should be reformed rather than discarded. With this goal in mind they appointed, in 1967, a Panel on the Laboratory in Biology,[1] charged with clarifying the function of the laboratory in the changing biology curriculum.

In the first product of that panel's deliberations (Appendix A),[2] several roles or functions which can be assigned to the laboratory were enumerated. These roles are: (1) to illustrate objects, concepts, processes, and experiments that have been introduced elsewhere in the curriculum; (2) to provide training in laboratory techniques; (3) to intellectually stimulate the student and develop appreciation for biology and living things; (4) to stimulate discussion; and (5) to engage the student in the process of investigation.

While recognizing that all these functions are legitimate, the panel members were firmly convinced that the highest priority should be given to the investigative role. In their words, "all other considerations in laboratory instruction must be deemed inconsequential beside it."

Several lines of thought led to this conclusion. First, the investigative origin and rapid rate of change of biological knowledge make it essential that we stress the processes by which the content of our discipline is generated and changed. Only if we do can we expect our students to develop the kind of scientific literacy that will permit them to accommodate new knowledge and use it in solving new problems, thus resisting the threat of obsolescence.

Second, science curricula should be planned to provide for increasingly complex inquiry activities as students progress from elementary and middle school to high school to college. As a result of the recent introduction of new curricular materials, some students are introduced to the individual components of the investigative process during their precollege years. The next logical step in their education should be one which pulls the previously scattered experiences together and assists them in using the full range of inquiry skills to carry out an actual investigation. Involvement in guided investigation at this stage serves to reinforce their previous training and to prepare them to take advantage of later opportunities for independent study and investigation. Hopefully, such opportunities will become increasingly available as a result of greater flexibility of curricula and national support through the Student-Originated Studies Program of the National Science Foundation.

A third consideration centers around the possibilities that investigation provides for individualizing instruction. Although the need for and value of individualized study are generally accepted, few existing college programs are

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[1] Initial panel members with their current addresses were: Charles E. Holt III (Massachusetts Institute of Technology); Louis V. Wilcox, Jr. (Fahkahatchee-Environmental Studies Center, Goodland, Florida); and David Barry (The Evergreen State College), then CUEBS Staff Biologist. Serving subsequently were: Val Woodward (University of Minnesota); Peter Abramoff (Marquette University); David Walden (University of Western Ontario); CUEBS Staff Biologists Dana Abell (W. H. Miner Institute for Man and His Environment, Chazy, New York); Darrel Murray (University of Illinois, Chicago Circle Campus); and John W. Thornton (Oklahoma State University) and Derek Patton, Earlham Student. It is currently called the Committee on Laboratory in Undergraduate Biology.

[2] Holt, C. E., P. Abramoff, L. V. Wilcox, Jr., and D. L. Abell. 1969. Investigative laboratory programs in biology. *BioScience*, 19(12):1104-1107.

successful in providing it. Courses which claim to provide for individualized learning often permit only self-pacing of prescribed instruction. As often as not, this serves only to encourage procrastination on the part of the learner. Individualized learning is probably most valuable when it draws out the nascent curiosity of each student and fosters opportunity and encouragement for him to use that curiosity as an aid to learning. In an investigation, the student identifies a problem, designs an attack on that problem, and works toward its resolution. An Investigative Laboratory (see Chapter 5 for a more complete description and Part II for examples), which very carefully prepares a student for investigation and then permits him to select and pursue a problem of his own choosing, provides an opportunity for each student, with the help of the instructor, to tailor his activities to fit his needs, interests, and abilities. Such programs are truly individualized — self-directing, self-motivating and self-rewarding as well as self-pacing.

A related line of thought, which also leads to the conclusion that students should be involved in investigation, begins with a consideration of the types of cognitive skills which should be stressed in college-level programs. Shouldn't students be given the opportunity to develop their creative and critical abilities as well as their powers of comprehension and memory? Don't they need opportunities to make decisions, develop effective work habits, and to use such attributes of scientific thinking as objectivity, thoroughness, and precision? Certainly such abilities are valuable both professionally and in taking a pragmatic approach to daily life. Investigative activities have a great potential for providing students with opportunities to develop and use a very wide range of cognitive skills which are often neglected in other parts of the curriculum.

Although the purpose of an Investigative Laboratory is not primarily to facilitate memory of information, it is an almost universal observation that students who use information in the process of investigation display a remarkably high comprehension and retention of that information. This suggests that even in "content"-centered curricula, the Investigative Laboratory can be of critical importance. As Jerome Bruner points out, "Intuitively it seems quite clear that as learning progresses there is a point at which it is better to shift away from extrinsic rewards such as teacher's praise, towards the intrinsic rewards inherent in solving a complex problem for oneself."[3] When used for engaging students in investigation, laboratory programs can easily be managed to provide a schedule of reinforcement very similar to that recommended by Bruner. In the Investigative Laboratory, for example, students receive immediate reward for their performance during the early preparatory phase of the course. On the first day, they may collect some useful data, learn a new technique, or find an interesting and helpful reference in the library. The internal rewards which are associated with success in such activities, coupled with the external reward provided by the teacher's acknowledgment of the success, provide strong encouragement to attempt more difficult and challenging laboratory activities. These rewards in investigation are frequent and natural as contrasted with those provided by the hour exams found in so many courses. As students enter later phases of the

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[3] Bruner, Jerome S. 1967. *Toward a Theory of Instruction.* Belknap-Harvard, Cambridge, Massachusetts.

Investigative Laboratory, the rewards tend to become internal and deferred. As the work begins to yield data and the student has the experience of finding a solution to a problem, creating a bit of knowledge, and uncovering additional problems, the internal rewards are very great.

The reasons listed above for engaging undergraduates in investigation are probably at least as important for the student who does not intend to become a biologist as they are for the incipient professional. There are, of course, special considerations which apply when one concerns himself exclusively with programs for particular groups of students. Some of these considerations are discussed in Chapters 2 and 3.

2. Some Special Considerations in Designing Laboratory Programs for Nonmajors

Efforts to place people in categories are typically unsuccessful and the designation "nonmajor" is no exception. As usually applied by biology departments, it includes students who have selected, at least temporarily, majors other than biology as well as those who have not yet decided upon a field of specialization. Invariably, it includes a few students who will eventually become biologists.

To avoid the futile task of trying to stereotype the nonmajor or identify what we consider to be his needs, let us define "nonmajor biology courses" as courses designed for all students, regardless of their eventual field of specialization. Perhaps such courses could be appropriately called "Biology for Everyperson" rather than "Biology for Nonmajors."

What factors or principles might one profitably keep in mind when designing a biology course, or more specifically a laboratory program, for Everyperson? Perhaps we should begin with a consideration of the characteristics of the students who enroll in such courses.

1. Those taking the laboratory will be doing so for diverse reasons. At one extreme will be students who are there because it is required for graduation. There are usually some whose aim is to get a good grade and others who are there because they don't want to be somewhere else. Hopefully, some will have enrolled out of a desire to learn biology or at least learn about biology.
2. The previous experiences and educational backgrounds of those enrolled will be very diverse. For example, some may be college seniors majoring in chemistry who have had an extensive and strong background in the laboratory sciences, but just never got around to taking biology until their senior year. Others may have picked up their only conceptions of experimental science from television commercials.
3. Because of differences in background and natural aptitude, one can expect to find a wide range of intellectual and manipulative skills. At one extreme will be those who are "all thumbs" and at the other those who can perform some tasks with greater proficiency than the instructor.
4. Attitudes and feelings about the laboratory and laboratory work are often quite diverse. Some may be so insecure that they are afraid to try anything on their own, while others may have so few inhibitions that they will try to do things which endanger their own health and safety. Some may not wish to work with living (or preserved) specimens, while others take delight in such activities.

5. Expectations are typically quite varied. Some may expect to be told exactly what to do and feel quite frustrated when open-ended activities are included. Others may expect to be permitted to do real science and consequently be critical of prefabricated exercises which give them specific instructions to follow.
6. The extent to which those enrolled will have an opportunity in the future to use the biological information and intellectual skills which they learn is likely to be extremely varied. It is conceivable that some might become public officials responsible for drafting legislation which will determine the future course of scientific research, while others will find themselves in jobs and life styles which require relatively little understanding of biology.

In short, students in a "Biology for Everyperson" are extremely diverse in terms of goals, experiences, backgrounds, skills, attitudes, expectations, and future needs. Considering this diversity, is it any wonder that courses which require all students to study the same things in the same way at the same speed and achieve the same level of proficiency should be labeled as "irrelevant"?

It seems obvious that if the laboratory courses and programs which a biology department offers are to be interesting and useful, they must be capable of responding to the diversity which is inherently present in courses for nonmajors. Most existing courses are extremely unimaginative in this regard. Although it is not uncommon for several dozen sections of the laboratory to be offered, these are usually carbon copies of each other. Further, the laboratory activities themselves are often rigidly structured with all students being expected to perform the same operations at the same time. In a typical case, for example, all observe onion root-tip sections and draw cells in various stages of mitosis in the boxes provided in the laboratory manual. That some have done this before and that others see no purpose in repeating observations which have been made by hundreds of thousands of students before them is either ignored or rationalized by statements such as "they may have done it before, but they didn't learn it" or "they need to learn it whether they realize its significance or not."

Are there ways that laboratory programs can be made responsive to the diverse needs and talents of students? Of course. The audio-tutorial technique, for example, has shown that laboratories can be designed to accommodate students who learn at different rates, but we should remember that this is only a minor component in the total diversity which must be considered. Another approach, which seems to be particularly suitable for schools with a large and varied faculty, is to offer a variety of different programs and then let the students elect those which they feel are most appropriate. This has been developed quite successfully by Ian E. P. Taylor, who supervises the general biology course at the University of British Columbia. In this course,[1] which had an enrollment of almost 1500 during 1970-71, each student registers for one lecture section which meets three times per week and a laboratory section which meets one afternoon during the week. The initial portion of the course is rather traditional in format,

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[1] Taylor, I. E. P. 1971. The elective laboratory. *BioScience*, 21 (23): 1973-1176.

with all students carrying out a prescribed set of open-ended laboratory activities. Shortly after mid-year, however, each student is presented with a catalog (published by the biology department) which lists and describes over 75 laboratory electives which will be offered during the last 4 weeks of the course. Guided by his interests, each student signs up for one of these. The content and approaches taken in the electives are quite varied. For example, the 1971 offerings included: seashore ecology; lichens and air pollution; basic population biology and computer simulation techniques; animal communication; patterns and behavior of chromosomes in the study of plant evolution; taxidermy for fun, profit, and science; distribution of proteins and nucleic acids in cellular fractions; etc.

Every faculty member and graduate student in the department, whether he is otherwise associated with the course or not, is invited to offer an elective. He may limit the number of participants and prescribe the schedule. As indicated by the number and diversity of the electives offered, the response of the faculty and graduate students to the invitation to participate in the elective program has been very good. Although each elective is supposed to consume an amount of time equivalent to four laboratory periods, the actual meeting schedules reflect the nature of activities to be done. In some, the entire time is consumed by a weekend field trip, while in others it is scheduled to take advantage of low tides or a particular experimental protocol. Some electives require specific skills — the study of subtidal marine communities is open only to experienced scuba divers — but most do not.

We interviewed students and faculty involved in the program and found both groups to be very enthusiastic. As one of the teachers of an elective put it:

> Maybe the reason the electives are so much fun for everybody and work so well is that they recapture some of the vitality which must have originally given rise to educational institutions, that is, students and teacher working together on a topic of mutual interest and in which the teacher has some special expertise. So often the regular laboratory exercises seem artificial wi'' neither students nor teacher genuinely interested. In contrast, the electives seem genuine.

The coordinator attributes some of the success of the elective program to the fact that it permits the rich diversity of human and physical resources of the institution to be made available to the equally rich population of students who enroll.

Another way of responding to the diversity of the Everyperson population is by means of an investigative-type laboratory. In its classic form, the I-Lab carefully prepares students for individual investigation and then frees them from rigid schedules and outlines to pursue a problem of their own choosing and design. This type of program, like the electives at University of British Columbia, can serve to transform the laboratory from an artificial routine which is received with little enthusiasm by students or teacher to a more genuine experience which is rewarding for all involved. It can be implemented even in small institutions. It does, of course, place a good deal more responsibility upon individual students than does the elective approach. Instead of selecting from a list of activities designed by the faculty, the student must create, or at least identify, a problem for himself. Rather than following the schedule designed by the teacher and using the equipment and supplies assembled for him, he must plan his own schedule and ferret out the resources which he needs. He may find it necessary to secure assistance from appropriate members of the faculty and community. Giving students such responsibility, and the freedom which accompanies it, is of great potential value in preparing students for life in a free society, but it must also be recognized that many students seem unwilling, or perhaps they are unprepared, to accept such freedom and responsibility. It is for this reason that the success of an I-Lab depends so heavily upon a carefully planned sequence of activities during the initial phase of the course. These activities are designed by the instructor and serve to prepare each student both intellectually and psychologically to strike out on his own. In the absence of such carefully planned initial activities, the laboratory can become a sink-or-swim affair, with a high potential for permitting students to flounder and drown.

We have placed great emphasis on the importance of designing laboratory programs which respond to the diverse needs, interests, and talents of students. But some would argue that we cannot afford, nor should we attempt, to cater to the individual needs and desires of students. Rather, they might argue, our programs should be designed to help meet society's needs for a well-educated or well-trained populace, and the scientific community's need for a citizenry which understands and is willing to support our work. It is with these general needs in mind that Joseph Schwab in the 1961 Inglis lecture[2] said:

> What is required is that in the very near future a substantial segment of our public become cognizant of science as a product of *fluid enquiry*, understand that it is a mode of investigation which rests on conceptual innovation, proceeds through uncertainty and failure, and eventuates in knowledge which is contingent, dubitable, and hard to come by. It is necessary that our publics become aware of the needs and conditions of such enquiry and inured to the anxieties and the disappointments which attend it. . . . Otherwise, adequate support and assent will not be given to the enquiries our national problems require.

How can this need be met? We agree with Schwab when he says, "What will fulfill this need can be stated in equally simple terms. It is, ironically enough, that science be taught as science."

This line of thought, like the one based on a consideration of the diversity of students, leads to the conclusion that the laboratory should create an environment in which students can experience the processes and attitudes associated with true scientific investigation. The prefabricated exercises and audio-tutorial packets which are used in many existing laboratory programs for nonmajors seem poorly designed to create this environment. Rather, they are usually designed to serve a demonstrative role and to "prove" to the student that the concepts to which he has been introduced in other parts of the course are "true." That this is the case is demonstrated by the frustration which is experienced by both students and instructor when a laboratory "experiment" does not "work."

There is a third and more idealistic reason which may be given for planning the laboratory to be an environment in which Everyperson may become

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[2] Schwab, Joseph J. 1962. "The Teaching of Science as Enquiry," in *The Teaching of Science*. Harvard University Press, Cambridge, Massachusetts.

involved in an investigation. Many of us, having become involved in investigation sometime in our life, and having found it to be a truly enjoyable and useful experience, simply want to make it possible for our students to have the same kind of experience. To delay such opportunities until graduate school or to make them available only to majors may be depriving most of our students of the most valuable gift we have to offer.

Regardless of the approach used, the improvement of laboratory programs will probably ultimately depend upon our ability to get outstanding teachers back into the classroom, laboratory, and field where they can work with students. The flight of knowledgeable and mature scientists from beginning laboratories and their replacement with graduate assistants has been due, in part, to the existence in higher education of a reward system which places top priority on research and publication. But this is not the whole story. Many of our best scientists not only find current freshman laboratories counterproductive in terms of their salary advances and promotion but they also find them boring and unchallenging in themselves. They just don't want to spend their time "showing freshmen where the pipettes are and pointing out the spleen." Of course, graduate assistants don't enjoy teaching this type of laboratory either, but they often seem to have no other choice. Experience at the University of British Columbia (which offers the laboratory elective program described earlier), and at several institutions which offer Investigative Laboratories, suggests that laboratory programs which provide opportunities for the teacher to work with students in research areas close to their interest and competence may be viewed by mature faculty members in quite a different light. Not only do they see in them an opportunity to advance their own interests and identify prospective graduate students, but many seem quite eager to get back into teaching where they can experience the gratifying internal rewards which come only from helping students discover that science can be fun, exciting, and relevant.

In summary, there are several lines of thought which lead to the conclusion that investigative-type laboratories are particularly appropriate in courses designed for nonmajors. Obviously, many of the same reasons also make them valuable for the majors as well. Not only do they offer a means of responding to the student diversity which is typically present in such courses, but they can help facilitate the kind of learning upon which the improvement of society depends and at the same time provide a deeply rewarding experience for both the students and teachers involved.

3. What Kind of Laboratory Experiences Are Appropriate for the Biology Major?

The arguments in favor of using the laboratory as a place to engage students in investigation which were presented in preceding chapters apply to the major as well as to the nonmajor. In this chapter we wish to call attention to a few other considerations which make the investigative laboratory particularly appropriate for those who think they want to become biologists. It is now generally assumed that the curricula we design for majors should provide opportunities for each to develop an understanding of the core knowledge of the discipline. But the students for whom our curricula are planned are not empty containers into which the "core" can be poured, nor is the knowledge we have generated inherently so interesting that we can expect them to become infected with its vitality by merely hearing it presented in a logical and competent manner. As was noted in the Newman Report on Higher Education,[1] "Many students lack the experience and sense of adult roles that would help them see how courses can be relevant." Thus, if for no other reason than to insure the transmission of the essence of our discipline to the next generation, we must give attention to the importance of developing programs which can assist students in developing a sense of purpose, enjoying their studies and appreciating their relevance, and making wise career choices. And of course there *is* another, and probably more important, reason for giving consideration to these traditional functions of the major — our concern for students as persons.

When we fail in meeting these responsibilities, students often tend to float into critical points in their lives unprepared to make the decisions which are called for. Faced with such a situation, a typical response seems to be simply to continue to float with the current, unaware that this response, in itself, is an important decision which will shape the future.

Consider, for example, the student who chooses to major in biology because of his childhood interest in animals. As an undergraduate, he takes the core courses and, although he does not find them exciting, they seem more interesting than his other subjects and he passes them with a B average. Encouraged by an assistantship and the possibility of a draft deferment, he enters a master's program in which he completes some more courses and does thesis research on a problem which has been carefully planned by an advisor (whose research grant is paying his stipend). The research seems somewhat more interesting and challenging than the courses, but he is convinced by this

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[1] *Report on Higher Education*. 1971. Prepared for secretary of the Department of Health, Education, and Welfare by a committee chaired by Frank Newman.

time that he does not wish to spend the rest of his life as a research biologist. He considers switching to another field but rejects this notion, partly because it would require him to extend his education for several more years and partly because he hasn't had enough experience to know whether he would enjoy some other career more than that of a biologist. Consequently, he drifts into a Ph.D. program and eventually takes a position as a teacher in a small college.

Such drifting is unfortunate not only because it may trap persons into careers to which they are not committed but also because it robs them of the enjoyment and relevance which can come from working toward goals which have been consciously chosen and enthusiastically embraced.

Stated more positively, it seems clear that it is often very useful for students to discover, early in their undergraduate years, an area to which they can honestly and vigorously commit themselves. This is important whether they decide to become biologists or not.

But how can we formulate a program which will help students discover or design for themselves a meaningful niche in society? The Newman Report on Higher Education suggests that one thing which might help would be to adopt policies which discourage some of the isolation that has developed between the academic community and the rest of society, and which would make it easier for students to "stop-out" or delay entrance into college in order to gain other types of experiences during their formative years. Such policies would be desirable but they may be slow in coming and, in the meantime, the attitudes which place strong pressures on young people to enter college, quickly choose a major, and gain certification through degree programs will remain. These realities suggest that we must build curricula which provide for "guidance" as well as transmission of information and training in skills. My own experience suggests that if this guidance is to be useful, it must do more than simply inform students about what biologists do—it must permit them to experience it firsthand.

That an undergraduate investigative experience can do this is indicated by the research of Anne Roe. Using the techniques of clinical psychology, she tested and interviewed 64 eminent scientists (including 20 biologists) as a means of identifying factors which contribute to *The Making of a Scientist.*[2] She reports that "In the stories of the social scientists and of the biologists it becomes very clear that it is the discovery that a boy can himself do research that is more important than any other factor in his final decision to become a scientist." She also noted that "Once any of these men had actually carried through some research, even if of no great moment, there has never been any turning back. A few of them feel that they would be equally happy in some other field of science but only one has ever seriously wanted to do something else. This is a Nobel prize winner who has always wanted to be a farmer but could not make a living at it."

Of course it is not surprising to find that eminent scientists found their early research experiences to be valuable and meaningful, but does the same apply to those who are not in the "eminent" class? My own experience and that of a number of my colleagues suggest that it is. Of course, it seems

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[2] Roe, Anne. 1953. *The Making of a Scientist.* Dodd, Mead, & Co., New York.

unlikely that every biology major will find investigation to his liking, but it is also important for students who do not enjoy investigation to discover that fact early in their college careers, so that they will have time to explore other kinds of study and work.

This line of thought leads one to the conclusion that it would be desirable to provide opportunities for investigation which come early in the undergraduate years and which accurately reflect investigative activities as they are actually performed by practicing biologists. In the past, however, it has usually been assumed that to try to provide for investigative experiences which are both early *and* authentic is to want to "have your cake and eat it too." Undergraduates, it is argued, do not typically have sufficient grasp of the field of biology to do authentic research and thus one must choose between early "mickey-mouse" projects or delayed but high-quality research. Given this apparent choice, most departments have chosen to use the undergraduate laboratory as a place to illustrate concepts and techniques and have delayed the involvement of students in investigative activities until they are upperclassmen, or graduate students.

But the experience of those who offered investigative laboratories (see Part II) suggests that the notion that freshmen and sophomores cannot do worthwhile investigation is an educational myth whose perpetuation depends upon it being believed by the faculty and students. Perhaps the myth got started and is reinforced by the frequent observation that undergraduates rarely seem to profit from independent study electives. But such failures are not surprising when one remembers that two of the lessons which are almost universally, although unintentionally, communicated to students during high school are: "Science is hard and you can't learn it without a science teacher," and "Discovering new knowledge is done only by well-prepared scholars." Because students believe such half-truths and are therefore hesitant to identify and tackle problems on their own, this does not mean that they are incapable of learning to do investigation. It does mean, of course, that a teacher who wants freshmen or sophomores to do some investigation may have to find ways of helping them revise some of their false notions about research. But shouldn't we take time to do this early in their college career? By helping freshmen or sophomores discover that they can do investigation and assisting them in developing the skills and attitudes which are needed to select, plan, and conduct projects, we can teach many lessons about the nature of science and can help provide the kind of perspective which will give relevance to their other study, assist them in future independent learning, and aid them in making informed career choices. Helping the biology major in these ways is at least as important as transmitting the "core" to him.

4. Teaching and Learning Through Investigation: A Case for Participatory Evolution

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So many of the arguments about what's good and what's bad in education end in a stalemate. Usually the contestants represent defense of status quo or impatient demands for change. One gets the impression sometimes that the defenders are defending more than an educational format—maybe a school system, country, even God. Those who call for change give the impression of having just seen impending doom, and their warnings are at times as frantic as they are believable. The polemic has been going on long enough now to have dulled the response centers of many, a fact which itself may be signaling warnings of impending doom.

Maybe our adjustments to change would have been more natural if we hadn't "discovered" the "fact" that evolutionary change happened just to produce *us*, and now that change has accomplished its goal, enough of it. Our posture toward "truth," underpinned as it is by superstition, is stiff if not petrified. We teach truth as if it were immutable, and we shelter that down-deep feeling that to change it is to invite the wrath of a superior force. In a somewhat exaggerated way, truth is that which we repeat most often and enforce most rigidly; truth is not to be examined, investigated, questioned, or discovered, except in those rare niches in which have been forged respites from some of the superstitions, with permission to investigate and discover. Science is such a niche.

People who proceed toward maturity, learning of their universe as if truth had been discovered by an earlier generation, or revealed (which is the same thing if you haven't participated in discovery), possess a qualitatively different means for adaptation to change than persons who have participated in discovery. This is not to say that there are just two kinds of people. To the contrary, the attitude of discovery is one of the most characteristic traits of young children, but its half-life is too short! We may question the role of education in conditioning what appear to be two kinds of people, since it may be that the method of teaching either turns students on or off, i.e., the format of education may repress or derepress curiosity. An inference from this is that a less stereotyped educational format may repress less and derepress more. This is the first reason for introducing into the educational format the *attitude of discovery*.

Whether the attitude of discovery enhances one's trust of senses or whether trust of one's senses leads to the attitude of discovery is not clear, but it is clear that those who depend upon investigation for increased awareness do trust their senses. It is difficult to believe that one who lacks self-trust will ever enjoy the excitement of investigation, and it is equally difficult to believe that people are born lacking self-trust. Witness the unquenchable curiosity of young children and the variety of ways they employ to discover the world they live in. Then witness what happens to their curiosity after they have *been told* what the world is like. Is it coincidence that the period of life during which learning is most rapid (ages 1-6) terminates at the time formal education begins?

Highly creative people honor the attitude of discovery and they trust, in some measure, their senses. Yet it is important to consider that creativity is not merely present or absent, but, rather, that different people possess different degrees of creativity and different motives for and modes of expression; meaning, of course, that environmental circumstances act as determinants, or repressants, of expression. If, for example, there exists an environmental threshold below which curiosity is curbed and above which it is unleashed, the appearance would be that some people are creative and others are not. Environmental circumstances, i.e., the educational apparati, act to raise or lower the threshold, depending upon the values of society. Leaders may wish to raise the threshold simply because noncurious people are easier to lead. On the other hand, a society may conclude that species survival is directly proportional to species creativity, and choose to lower the threshold. In either case, education is the handle by which the threshold is manipulated.

Science is an example of concerted activity within which the relationship between the investigative attitude and increased awareness is apparent, but appreciation of the fullness of this relationship demands historical perspective. Recall the social pressures exerted upon scientists a few centuries back, when their discoveries were negated simply by reference to dogma. Some were executed, some exiled, and many of their discoveries annulled. Todd Gitlin is quoted as saying, "Society continues to make radicals more rapidly than the radical movement turns them off" (Lynd, 1971). It may have been during the awakening in Europe that society continued to make more scientists than were turned off. At any rate, they popped up in ever increasing numbers until the forces of discovery became an equal match with the forces of repression.

Today, no one disputes the effects of the forces of discovery (included are the new "truths" discovered as well as the methods and attitudes used for discovery) upon the society into which they were reluctantly integrated. Yet, and important to the present thesis, both new discoveries and the methods used to discover them are still resisted by the greater part of society.

A large part of this resistance can be traced to the way we teach young people. Certainly we have never applied the methods we use in discovery to the processes of teaching, and as a result these processes have changed little during the past two or three millennia. The scientist himself approaches science differently from the way he approaches teaching. He may walk from the laboratory, where respect for investigation and discovery is maximal, to the classroom, and talk of science as if it had just been revealed by God. He may talk for hours without asking or provoking questions, with no intention of exposing students to the attitude of investigation, until the students demonstrate their mettle through obedience, memorizing, or both. This presents an interesting paradox. It says, in effect, that the greater forces of society are able to negate the attitude of discovery even among discoverers, except while they are in their laboratories protected as they are by a short tradition and government grants. It means also that teaching method and the attitude of discovery reside in quite different compartments of the house of intellect.

These greater forces of society are in the province of education, not science. However, it would seem that scientists who wail so righteously for public support would "supersupport" wider dispersal of the attitude upon which science depends for its survival. With or without their support, the function of education is wholly different from the function of science.

I have used the phrase "attitude of investigation." I am not sure how to define it, but somehow it encompasses an evolutionary view of things. We know, for example, that the primordial ooze would have appeared static at any given moment of hypothetical observation, and so with the dinosaurs, *Australopithecus robustus*, and *Homo sapiens*. Before the view of relatedness between points in time became apparent, new thought dimensions were needed. Darwin is remembered because he was among the first to supply us with these new thought dimensions. After playing with the idea for many years, he came up with an astounding notion, that biology is related to itself in time and all living things are related to one another. This was a hard pill for some to swallow, even for those who later supported the idea, since it had previously been so obvious that each species had its origin in a separate creation. Yet after the concept of relatedness had found its way into the "comfortable feeling" part of the brain, it appeared just as obvious as the folklore which preceded it.

The attitude of discovery is much the same. Once it is realized that no matter how smart the ancients were they didn't know everything, it becomes easier to accept the view that if they didn't know everything, there still must be some things to discover. In fact, the ancients might have been wrong about some of the things they thought they knew, and likewise for modern scientists. Most of what scientists tell us is no more and no less than their best approximations of reality, and this does not mean that we should believe nothing or that we should become cynical of reality. Rather, our understanding forms a continuum. Today we perceive things this way, and tomorrow we may perceive them in a modified form. Education is the primary vehicle by which most of us acquire our perceptions. Education can give perception either a static or a dynamic appearance. My thesis is that education will maximize dynamism by encouraging participation in the processes by which perceptions change, i.e., in discovery. When one feels in his bones the nonstatic nature of the universe, he or she will feel decidedly more comfortable about participatory evolution, even to the point of aiding discovery, or rearranging of facts into more and more meaningful patterns.

There is more to the investigative attitude, however, than a feeling of the dynamism of nature. Investigation demands a trust of one's senses, a self-confidence. Education enters the equation because education can either provide or deny access to the environmental circumstances which lead to self-confidence, to a lowering of the threshold for expression of curiosity. This, in short, is the case for putting investigation into the educational format.

Self-confidence is directly proportional to success, and in our society success is not something available to everyone. Scholastic progress is evaluated in most schools and universities with linear scales. There can be only one best, one second best, third, etc.; yet in some cases there can be many persons in the medium-poor to medium-good category, and there always is room for many failures. The rules of evaluation are set to provide a clothes-line spread in order to rank the rankable. Those at the head of the line usually have more than average self-confidence, and those at the back of the line usually have less. There doesn't seem to be a way (or if there is, it isn't popular) to find out what it is that *each student is good at.* Consider the psychological effects of permitting each student to succeed at something! I predict we'd see more creativity expressed.

To get from the abstract to the real, I will indulge in anecdote. Several years ago when I taught introductory biology in a university with open admission, I introduced students to investigation by inviting them to design their own experiments. Their investigations were prefaced with informal discussions about questions which can and those which cannot be answered by experimentation, but this discrimination was seldom understood until after the experience of asking and trying to get nature to answer questions. By the time each student had gotten to the point of executing an experiment, each had spent time with me discussing the question and the experimental design.

One group of five students wanted to know whether "lower" animals exhibit what we call "race prejudice." In discussion, they demonstrated awareness that most species of animals exhibit a variety of body colors, from albino to, in many cases, black. During the discussion period, it came out that *Drosophila melanogaster* would be a good species to work with since so many mutant types are available. A two-part experiment was designed. Both parts included a "home-made" series of cages built in the design of a wheel. The hub of the wheel was a large-mouth, gallon bottle in which there was no food. The spokes of the wheel were built of ½-inch diameter tubing connecting the hub bottle to smaller milk jars, with food, each with 40 specimens of a particular mutant or strain. Six such jars were used in each apparatus, and each was seeded with ebony, vestigial wing, white eye, yellow, vermilion, or wild-type flies.

In one apparatus, all the males were sterilized by X-irradiation. The idea was, simply, to observe migration, exclusion, etc. In the other apparatus, the males were fertile and the idea was to observe changes in population numbers of the various strains.

Without going into detail, the results showed that, in the apparatus with sterile males, the vestigial winged flies were the more gregarious. After one week, they were distributed about equally in all the containers. Wild-type flies were nearly as free-floating, but the ebony flies rarely left their original milk jar. White-eyed flies were only slightly less "unsociable." In the apparatus with the fertile males, it was only a few generations until most of the flies were phenotypically wild-type. Upon backcrossing samples of flies from each of the jars, it was observed that the mutant gene for white eyes had disappeared completely, while only a few flies were heterozygous for ebony.

I had fun watching the flies, but quite a bit more watching the students. They set up a round-the-clock observation schedule. The number of interested students rose from five to about 200 within a week (I've never seen so much enthusiastic, volunteer labor). Other experiments were in progress all the while, but this one literally captured the imaginations of hundreds of students, in and out of the class. Because of the *natural* questions, there was no problem organizing informal seminars, and because of this, *information transfer* was *natural.*

Another interesting outcome of the course was the ingenuity displayed by the students in sequestering equipment and supplies. Many experiments were executed in local hospitals, in doctors' offices and in other laboratories of the university. Upon informing a student I couldn't provide the desired apparatus, often he or she would build it, borrow it, or, as I found later, steal it. I may sympathize, but I'll never again be impressed with the teacher-argument, "we simply do not have the facilities to do that sort of thing." If permitted, students will help solve lots of problems.

At another university, a few years later, I had the opportunity to try the investigative approach with different kinds of students. The second university was small, private, well off financially, and its student body was highly select. The class was beginning genetics and the students were junior and senior biology majors. My experience extended over a period of 5 years, one class of 18 students per year and with space in my research laboratory available only to the students.

Each class was begun by offering a "crash" course in microbiological technique, accompanied by simple discussions of molecular genetics, but these were not mandatory for students with prior experience. After most of the students had proposed a project and "cleared" it with me, we held a mini-genetics meeting during which each student presented his research proposal (this included reference to similar work, the major question, the experimental approach, and discussion of the probable outcome).

During the 5-year experience, nine students published the results of their work in reputable scientific journals. At least as many did equally good work but came up with negative results. Many began but did not finish good experiments, and many took the option to work on experiments that I had suggested. At the end of each semester, we staged another mini-meeting, and sometimes these lasted all weekend. The excitement was high, the input was in excess of previous course efforts, and in some cases the results were good. In all cases, the learning rates were adequate or better. I know it is difficult to measure this kind of success, but by conventional measures the program was successful; a significantly higher proportion of these students went on to professional scientific careers, and many have become productive scientists.

It is the psychological imprint gained by such an experience that is difficult to evaluate. There was no question but that the students were excited about their work. They worked "overtime." They seemed to grasp the relationship between asking a question and setting up an experiment to answer it, between collecting data and deciding what the data mean, and especially between what they read in textbooks and the relativity of "truth." My conclusions were that the understanding of science is not restricted to those with IQ's above 130; self-discipline and desire are better motives than outside forces, including insults. Not all students in a class need work on the same project or meet at the same hour of the day; students can and do teach one another. The investigative laboratory makes more demands upon a teacher than the more standardized, "canned" laboratories; teaching in this way is fun.

My confidence in the investigative approach to learning goes beyond personal experience. Psychologists and educators have published reams of evidence supporting the general idea; I can recount only a sample of these studies here. Kagan (1970) has presented evidence that the environment can be manipulated not only to enhance the attention span of very young children but also to enhance their desire to explain discrepancies (formulate hypotheses). From the time of birth until a child reaches 4-6 months of age, strong contrasts of color and sound increase the time a child will focus upon an object. During this time children create for themselves what Kagan calls schema, i.e., somewhat loose images of how things are and reference points by which familiar objects are distinguished from novel ones.

At about 4 months of age, children begin to focus maximally upon discrepancies to their schema, but not upon differences so great as to be novel. By the time children reach the age of 12 months, they begin to rationalize discrepancies, i.e., to hypothesize. From these observations, it is reasonable to conclude that it is natural for children to become caught up by the unexpected and for them to try to explain variation, sometimes to the point of making generalizations. Children who are not exposed to high contrasts and discrepancies are less likely to explain the variation within their private worlds than children who are, and outside pressures seem to be ineffective as stimulants of hypothesis formulation.

In a different kind of study, Anderson (1970) looked for an explanation for the "observation" that black children are less mathematically inclined than white children. Since school children between 6 and 12 years old seem to fit into two groups with respect to mathematical ability (the cans and the can'ts), it has been tempting for some to hypothesize a math gene, the recessive allele of which determines math-smartness and the dominant allele math-dullness. However, the environmental threshold hypothesis explains the data equally well, and it was this hypothesis that Anderson tested. Anderson observed first that black children, as a rule, are not introduced to mathematical games; they hear more often than white children that math is difficult; they become aware through experience that math is a white man's game; and more often than not black children are introduced to mathematics by white teachers. Anderson has shown that black children who are introduced early to mathematical games and are taught by black teachers in the company of black children do in fact learn mathematics quickly and they enjoy it more than their counterparts in the white school system. I think Anderson's general argument may apply to the majority of young children who are put off by mathematics (and other subjects), no matter their color or nationality.

What these kinds of studies indicate is that most of us possess a greater potential for learning and for discovery than we exhibit in normal, educational environments, and that these environments can be changed for the better with relatively little effort. Both motive and reward for discovery can be self-provided, given the proper environmental circumstances. Since we are not sure what "proper" means in this instance, it is not entirely wild to propose that our search for proper environmental circumstances ought to become a cooperative effort between teacher and student. True, this is not neat, but for too long we have stunted individual development with neatness.

We have examples, within existing educational structures, of environments which do encourage individual expression of talent, desire, and self-reward. In addition, these environments come as close as any to achieving excellent performance by students, especially by undergraduate students. Consider the athletic departments of most universities. These departments demand excellence from the professionally oriented students and they provide opportunity of participation by the nonprofessionally oriented. First stringers are urged to peak performance by study, practice, theory, and real, live participation. Others may simulate first-string performance through the more relaxed intramural programs, classes, etc. Still others may participate in even more relaxed circumstances simply by going to the gym. Athletic programs differ from biology programs in several ways: first, undergraduates in biology never get to play the real game; second, there is only one degree of intensity for participation (i.e., there are no intramural programs in biology, and no "drop-in" participation); and third, biology programs provide little or no opportunity for students to discover their individual talents because everyone does the same thing at the same time and close to the same rate of speed. I know from experience that some 18-20-year-olds are good at karyotyping, some at organ transplanting in rodents, some at enzyme assay, but I can't see how these talents can be used or improved in most university biology programs.

For an additional analogy, consider also the game of baseball. People play baseball for fun and/or for money. Those who play well encourage others to play, and to a large extent professional baseball is supported by sandlot baseball, i.e., the game is enjoyed at many skill levels. The fun-rewards for playing are not restricted to any one skill level, and at all skill levels the self-rewards seem sufficient both for participation and for improvement of skills. As far as I can tell, there is nothing comparable in physics, chemistry, molecular biology, or biology, granting the existence of a modicum of amateur participation.

It is true that athletics is not for everyone. Athletics caters to males more than to females, to whites more than to blacks and Indians (this trend is changing in baseball, football, basketball, and track), and to the physically fit more than to the unfit. But science is still more restrictive. Many children are interested in science, but as they grow older, the restrictions imposed by professionalism work to subdue interest, often by restricting participation. There is no support for sandlot genetics; there is no chance under the present system of education to create spectator support for physical chemistry.

However, outstanding scientists get their due even though very few of their names become household words. Among their peers, the good scientists are recognized as much for the questions they pose as for the answers they provide (discover). The good scientist usually is skeptical (at least in the area of his expertise), and his challenge seems to be to discover a closer approximation of "reality." Often discovery is preceded by a creative question. Not everyone is able to ask creative questions, just as not everyone is able to hit as many home runs as Harmon Killebrew. Yet persons capable of asking questions of lesser global quality may, in certain environments, be in a position to appreciate the good questions as well as to improve upon the quality of their own questions. Anyone who has taken a swing at a fast ball is in a position to appreciate the talent of Killebrew, but more people have taken a swing at a fast ball than have tried to ask meaningful questions. The people who are good at asking questions *teach by providing answers!* Killebrew doesn't teach youngsters to swing a bat by having them memorize the batting averages of Willie Mays and Henry Aaron!

Why is it that scientists teach science by having the students memorize the box scores of science? Why not teach science by engaging students in discovery? A wheel taught is impotent compared to a wheel discovered, and the fact that the wheel had been discovered by others, earlier, fails to detract from the excitement of discovering it again. However, the value systems of research and teaching are not always the same; scientists depend for security upon making the discovery first, publishing first, getting the credit. Scientists deprecate rediscovering the wheel. Teachers could, but most often don't, depend for security upon discovery as an aid for teaching and imparting to students the idea that each is or can be a dignified human being. This takes time and scientists usually spend no more time than is absolutely necessary discharging their teaching duties. In fact, when they do teach, they take every opportunity to advance their research, most obviously by lecturing on subjects related to their research. Students almost never see scientists in the act of learning.

This is a pity because the things scientists do are fun. Investigation is fun. Building generalizations from smaller bits of information is fun. Discovery is fun. Knowing lots of things is fun. Tennis is fun too, but if, before playing, we had to memorize what has been written about it, most of us would quit before learning the meaning of "love-15." Learning can be fun, and one suggestion for the educational revolution is to put the fun back into education. Contrary to the work-ethicists' religion, fun isn't inimical to high quality, discipline, rigor, etc. In fact, some who have done good science have taken a much looser view of how science can be done (Platt, 1962; Watson, 1968) than is reflected in science courses. Fun isn't the serious sin it used to be.

For several years now, CUEBS has investigated the investigative approach to science teaching. Those involved in the study are not world-renowned scientists, but many of them have played a fair to middlin' game at one time in their lives. Most have treated the subject of science teaching seriously, to the point in some cases of trying to discover teaching-learning environments that combine fun with efficiency of learning. Our conclusions are tentative, but even so we regard them as being significant. Probably the foremost conclusion is that most of what we have to say applies only to those teachers who enjoy being with people who enjoy learning; we have not constructed an argument with sufficient punch to convince the indifferent or bitter teacher.

Scientists created a myth which states that students cannot engage in research before gathering mountains of background information. Scientists justify adherence to this myth by evaluating student research on the same terms with "good science." However, if student research is evaluated in terms of student growth and development, the cards fall in a different pattern.

Individual growth and development is a continuum (sound biological principle). Since no phase of any continuum can be skirted, the teacher *can* become committed to evaluating student activities in terms of progress of each next step, whereas the scientist seems concerned only about the end product. The trick to good teaching is to ascertain in which phase of the growth process each student resides, the events which led to that stage, and the most probable events which will lead to the next. In contrast, the scientist selects from the population of students those who show promise of contributing to science, he trains these, and somehow gets rid of the others. He mistakenly calls this teaching.

True, most college students do not ask relevant scientific questions, but almost all of them are capable of asking the kinds of questions which will lead to their next stages of development. Most students, in other words, are capable of investigation. This does not mean that most students are capable of doing good science, only that they are capable of designing experiments, executing experiments, and interpreting data. Part of the interpreting process includes the recognition that their work is not good science, but only a precursor to good science. It is possible to play tennis, *according to the rules*, and not beat Poncho Gonzales; it is possible, and legal, to play tennis and *not want* to beat Poncho; it is legal also to want to play well enough to beat everybody. Why not in science education too? Yes, this would mean more work, time, and a reordering of values, but so did getting to the moon.

A corollary of this general theme is that even though the conclusion that college students don't ask relevant scientific questions may be largely true, the conclusion could not have been reached by scientific investigation, simply because the methods used to assay the talents of students are not designed to determine the question-asking talents of students. The conclusion, correct or incorrect, is more a rationalization of a life-style than determined. The majority of students, exposed to science as they are in American universities, will not reveal more of themselves than is absolutely necessary; the consequences of being found stupid are difficult to live with, and a future job may lie in the balance. In simple biological terms, the educational environment mutes the full expression of the genetic capacity to query nature. Data show that less restrictive environments "augment the capabilities" of students.

Another tentative conclusion is that it is easier in most cases to modify student-teacher relationships in laboratory courses than in lectures. However, most laboratory courses have failed to take advantage of this, partly because graduate student-teaching assistants conduct many of the laboratory exercises, and partly because of the extension of the psychological barriers between students and teachers created in lecture courses. Many "canned" laboratory exercises serve as much to keep students busy and/or at bay as to acquaint them with biology. And no one accuses such laboratories of exposing students to science.

Without modifying teaching modules, class times, or the curriculum, student laboratories could provide opportunity for teachers to discover what students would do if given a choice. This does not mean choice between two or three teacher-determined exercises; this means discovering what students would do *if each one could design his/her own approach* to the study of biology. Once this is done, the teacher is in a position to discuss with the student the merits and drawbacks of the approach, whether the approach can be made by experiment, etc. In most cases, the quality of the student question can be improved by discussion. At this point, the relevance of the question to the advancement of science is unimportant; the important thing is involvement and plans for the next step. As the discussion leads to experimental activity, as mistakes are made, and as the importance of the original question is measured against the insights gained through activity, there will be plenty for student and teacher to discuss. Success will lead to the realization that students and teachers are on the same team, and self-confidence will become an important by-product of the interaction. My own "data" support this conclusion.

Investigative learning experiences are not either-or propositions. It's not sink or swim, A or F. Rather, investigation leads to an acquaintance with facts and theories; it aids learning by making meaningful the act of participating; it leads to self-confidence by revealing in a clear way the fact that "I too" can experiment, collect data, and question the data of others. Teaching is helping students become better acquainted with themselves, and investigation lubricates the process. No matter where a student resides on the long scale between total ignorance and complete understanding, the function of teaching is to aid him in moving toward better understanding; it is the task of the teacher to be creative in the discharge of this function.

Nearly every teacher who has communicated with us his experiences with investigative laboratories has made it abundantly clear that in such environments students teach one another. In my own experiences I have seen seminars arise *de novo*, a beautiful thing to see. A characteristic behavior in such classes is the sharing among peers of successes and failures. In environments where *it is possible for everyone to succeed*, the cross-reactive fears generated by strict competition are minimized, and cooperation seems more the rule. I acknowledge the impossibility of quantitating the observations of students absorbed in the search for answers to their own questions. I can't define a cat either, but most of the time I'm able to identify one when I see it.

In addition to the benefits, real and idealized, the investigative approach to teaching is complex and frought with difficulties. First, it requires an attitude quite different from the attitude of "lock-step." For example, the notion that to be fair with students all grades must be awarded according to the same scale of accomplishment must be jettisoned. In fact, after feeling comfortable with the investigative approach, it seems strange that the notion of linear, uniform measurements were ever invented in the first place, since people come in so many different sizes, colors, sexes, etc. It could only have been invented by institutions who desired to use people, and somehow those institutions conned education into performing the nasty chore of *sieving* and *training.*

Second, neatness and order will have to give way to a little confusion. Neatness and order often have a dehumanizing effect upon students. The desire for neatness and order is mainly to insure that each student is treated "fairly" (samely) and to contribute to the tranquility of the teacher. The investigative approach won't work for the teacher whose penchant is for a neat classroom, a neat record book, and teacher-made assignments.

Third, the investigative approach demands a great deal of teacher-time. This problem also can be traced back to the mores set by scientists who teach. The scientist meets with a scheduled class, then goes back to his laboratory. He makes it appear that teaching can be done in 50 minutes a day, 3 days a week, 10 weeks a year, or there-a-bouts. Teaching-only institutions took this to mean that teachers who do not have to rush back to the lab could do instead five or six of the 50-minute performances per day, and this schedule is as opposed to investigative teaching as the desire to get back into the lab. However, the trend is shifting; teachers who, for whatever reason, have initiated innovative-teaching formats have been granted time in which to innovate. This means that teachers and students are our only hope for educational change; change will never come from the "top."

Teaching formats mirror the values of a society. If technology is important above all else, students will be made into technicians, or at least enough of them will to insure technological progress. When technocrats become the social elite, nontechnocrats will become second-rate citizens. This approach to evolution soon catches up with a society because viable societies are more complex than technocracies. When the unattended multiply and become restless, or when they begin their own search for fulfillment, an otherwise stable (tranquil?) ecosystem will become agitated.

Our mode and manner of teaching signals whether, as a society, we are ready to live with sustained and open-ended uncertainty, or whether we will persist to encircle ourselves with limited dimensions which, in time, demand the kinds of upheavals that negate the advances we *have* made toward an understanding of our higher qualities. The surest deterrent to the kinds of self-destruction which are inevitable if human values continue to be sapped by institutional values (disenfranchisement) is the deinstitutionalization of educational process (Illich, 1971). I support this action because of an intuitive feeling that our species will be better off *without* alphas, betas, and gammas, but *with* societies of individuals transcending themselves.[1]

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[1] Contrast the articles by John Platt (p. 63) and Carl Oglesby (p. 66), *The Center Magazine*, March-April 1971.

5. Investigative Laboratory: The Concept, Its Origin and Current Status

In the preceding chapters, it was pointed out that there are many compelling reasons for using the laboratory environment as a place in which to engage students in investigation. But when CUEBS staff biologists and the Panel on the Laboratory studied existing undergraduate programs, they found that the investigative role is almost universally neglected. The prefabricated exercises and audio-tutorial modules which dominate the current laboratory scene are almost exclusively illustrative in nature. It is quite common for an undergraduate who is majoring in biology to complete all of his program without having been engaged at any time in a truly investigative experience. Even when opportunities for investigations are provided, they are frequently reserved for the gifted student or are delayed until the senior year. Programs to provide investigative experiences for nonmajors are even less frequently encountered.

Why is there such a paucity of investigative-type undergraduate programs? One of the reasons, of course, is that the practices and policies of institutions serve to discourage development of and participation in such programs. Students make the honor roll and gain admittance to professional schools by learning to construct clever answers to the questions asked by teachers rather than by developing skills in designing and carrying out investigations to answer questions of their choosing. Teachers are selected, promoted, and given tenure on the basis of the number of research papers they publish rather than on the basis of the number of students they have helped to become independent learners and investigators.

A second reason is that the undergraduate programs which have traditionally been used to engage undergraduates in investigation (independent study, undergraduate research participation, senior thesis) are based on an individual tutorial relationship between a student and researcher. Although this relationship is very desirable, it rarely seems possible or wise to try to extend it to the large number of lower division undergraduates which seek education in biology departments. Very often, development and continuation of these types of undergraduate programs depend upon extra-institutional money to pay stipends and buy supplies and upon the willingness of the professors to provide space for novice investigators in their research laboratories.

With this in mind, CUEBS set out to identify alternatives to traditional undergraduate programs, with an eye to attractive, practical, and effective means for teaching the art of investigation within an institutional environment whose practices are not at all supportive of this educational goal.

Examining several approaches, the staff biologists and the Panel on the Laboratory found that several of the most successful offerings had a number of features in common. Believing that these common features could provide useful guidelines for those attempting to teach investigation, the panel coined the term "Investigative Laboratory" to designate programs with the following characteristics:

1. Students are made aware from the beginning that the purpose of the course is to engage them in an investigation of their own choosing.
2. The laboratory begins with a series of activities which are carefully designed to prepare the student for investigative activity. During this stage, students are introduced to both cognitive and manipulative skills which can be used in the investigative process. This initial phase often has a traditional flavor and may benefit from the use of film loops, guided readings, audio-tutorial exercises, "dry"-laboratories, tours of research and library facilities, programmed instruction, open-ended exercises, and inquiry role techniques. This phase of the course ends when the student has developed sufficient competence and confidence to identify a problem and design an attack on it. The length of this phase varies with the ability of the students involved and the subject area and level in which the course is offered.
3. In consultation with the teacher, each student formulates a problem and investigative procedure for resolving it. Frequently, written or oral proposals are submitted for criticism by the instructor and other students. Problem selection is, of course, limited by the natural constraints of available time, space, equipment, and supplies.
4. Experimental and observational work is carried out over a period of time sufficiently long that experiments can be repeated and the direction of the work can be modified if necessary. It is not unusual for students to make use of physical and human resources outside both the course and the college during this phase of the program.
5. The laboratory terminates with the submission of written and/or oral reports by each student.

This extended, multiphasic program should not be confused with several other recent innovations in laboratory instruction. In the words of the Panel on the Laboratory:

> The Investigative Laboratory is not the same as the simple enquiry approach in which the student is asked to respond to questions which begin in the manner of, "What happens if . . . ?" or "What is the effect of . . . ?". Questions of this sort have become commonplace in laboratory manuals and direction sheets. When applied in the manner described by Schwab,[1] the enquiry approach can be a useful one, and it should probably be included in a major way throughout all parts of a course or curriculum. But it is similar in only a very general way to the investigative laboratory which we are proposing.
>
> The investigative laboratory should not be confused with what we shall call the "open-inductive approach." In the latter type of laboratory, the student enters a sequence of work almost entirely uninstructed and is asked to build his own generalizations from observations that he makes in the laboratory or field. Patterns of reasoning thus developed are assumed

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[1] Schwab, J. J. 1962. The Teaching of Science as Enquiry. The Inglis Lecture in *The Teaching of Science*. Harvard University Press, Cambridge, Massachusetts.

> to be of use to the student throughout his life. It is conceivable that both this kind of experience and the more carefully planned and executed investigative laboratory should be included in a total program of science instruction at the college level. We emphasize, however, that science does not ordinarily proceed from an open-inductive base but relates new facts to prior generalizations. Typically, progress in science derives either from questions that fill small niches in informational patterns or from challenges made to earlier conclusions in the light of new evidence. To make such contributions, the scientist must prepare himself carefully, and any student who would follow him must consequently be closely guided.
>
> The idea of open-ended laboratories has never been clearly defined and has come to mean different things to different people. In its commonest form the open-ended laboratory is roughly synonymous with problem-solving, but with the added qualifications that there must be no "correct" outcomes to the work and that the work can proceed to indefinite length, depending upon results. Typically, however, the problem is assigned, the means are rather clearly specified, and the student is still forced into the attitude of dealing with a series of exercises. This kind of laboratory is clearly a move toward the investigation of which we speak, but it ordinarily lacks the necessary involvement of the student with the whole process of deciding what is to be studied, how the work can be accomplished, and how the conclusions are to fit with information that is already in hand. We feel that it does not satisfactorily fulfill the investigative objective for these reasons.[2]

Subsequent to the publication of the above description of the "Investigative Laboratory," CUEBS sponsored a symposium in 1969, and a summer workshop and symposium in 1970, to stimulate further development and implementation of the Investigative Laboratory concept. The papers presented at the 1969 symposium were published as CUEBS Working Papers No. 1, and those from 1970, in Volume 7, Numbers 1 and 2 of *CUEBS News*.

In response to these urgings by CUEBS, several biologists established new Investigative Laboratories in a variety of different types of institutions. Several of these are described in Part II of this publication. Visiting and corresponding with the institutions, CUEBS staff biologists and laboratory committee members found the teachers and students of the new programs to be genuinely enthusiastic about the value and power of this mode of teaching. It should be stressed, however, that they did not find the Investigative Laboratory approach to be easy or without problems. Quite the opposite, they reported that it was time-consuming and that difficulties arose which taxed their ability and which occasionally led to some confusion and frustration. Some of the factors which most frequently lead to difficulties in offering Investigative Laboratories are:

a. Failure of the instructor to provide activities during the initial phase of the course which adequately prepare students for the independent work which they are to undertake later in the term. This may happen because of the lack of expertise by the teacher or his failure to recognize the difference between Investigative Laboratories and independent study.
b. Failure to provide adequate time and give appropriate credit for the work involved.

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[2] Quoted from C. E. Holt, P. Abramoff, L. V. Wilcox, Jr., and D. L. Abell. 1969. Investigative laboratory programs in biology. *BioScience*, 19 (12): 1104-1107.

c. Belief on the part of an instructor that his students are not capable of doing high-quality investigations. Even when not verbally expressed, such a belief may be perceived by students and seems to discourage them from making a vigorous and creative response to the opportunity to investigate.

d. Insistence, by the instructor, that projects be "original" and that final reports be of "publishable" quality. Such insistence, if stressed early in the course, seems to inhibit the willingness of some students to select the relevant problems which they are really interested in pursuing and to design innovative approaches for their resolution.

In spite of these difficulties, the teachers who had initiated Investigative Laboratories were unanimous in their commitment to continue them. It seemed obvious that this was due to the response and change which they had observed in their students. Several mentioned that students became so interested and were spending so much time with their work in the laboratory and library that they began to worry that it might be detracting from their other studies. A number of the teachers reported that they had never observed such hard work and critical attitudes among students. They continually found themselves thinking of the students as graduates or colleagues rather than as undergraduates. It seemed particularly significant that the teachers and students were vigorously encouraging development of more Investigative Laboratories in their institution even though they recognized that such laboratories would be difficult and time-consuming to offer. In one case (Catonsville Community College), a teacher-exchange program was devised for the purpose of establishing an Investigative Laboratory at a nearby college (Baltimore Community College).

Currently, we must view the Investigative Laboratory as a promising "hot house plant." To date, it has been cultivated primarily in environments which have been manipulated for its health by the green thumbs of those who are eager to see it prosper. Some of the factors which contribute to and detract from its successful transfer to new environments have been identified. Because of its potential value for dramatically improving the quality of undergraduate science instruction, it now seems appropriate to try to transplant the Investigative Laboratory into biology programs throughout the nation and see if it can continue to survive and produce useful fruit in a variety of typical undergraduate curricula. This publication is designed to aid teachers in that endeavor.

PART II
INVESTIGATIVE LABORATORIES THE PRACTICE

In its initial publication on the laboratory, CUEBS promised that "additional papers, describing specific investigative laboratory programs . . . will appear separately." The importance of delivering on that promise has become increasingly clear as we have talked with biology teachers and discovered that their reservations about offering investigative laboratories typically involve questions of feasibility as well as desirability. Repeatedly, teachers have asked:

> Do Freshmen and Sophomores know enough to do respectable investigation?
>
> Can an investigative laboratory be successfully offered for a class of several hundred students?
>
> Can an institution offer an investigative laboratory if its faculty's involvement is primarily in teaching rather than research?
>
> Can investigative laboratories be offered in two-year colleges and at economically impoverished liberal arts colleges?

Our examination of functional investigative laboratory programs leads us to believe that an affirmative answer can be given to all of these questions. But of course we have wanted to believe that investigative laboratories are feasible and our observations have undoubtedly been biased by that desire. Therefore, rather than attempting to give definitive answers to all the practical questions which can be raised about the investigative laboratory, we submit some data, in the form of descriptions of existing programs, and invite you to draw your own conclusions.

6. I-Labs in Introductory Courses at Four-Year Colleges and Universities

Considering the number of persons who are served, the introductory courses in biology are by far the most important ones in our curriculum. Considering their quality, we often do our poorest teaching in them and the laboratory portions of these courses are often particularly grim. One of the roadblocks to improving introductory courses seems to lie in the inability of faculty members to visualize how laboratory innovations can be implemented, particularly when large numbers of students are involved. To provide some guidance in this regard, we asked the faculty members at three baccalaureate-granting institutions to describe the investigative-type laboratories which they have successfully implemented in recent years. It is interesting to note that in all three cases the impetus to introduce an investigative laboratory was provided by a reorganization of the entire undergraduate program and by a desire to have the laboratory reflect more accurately what practicing biologists actually do. The programs themselves are quite different, however. At Marquette University, the program is specifically designed to accommodate 600-700 nonscience majors. It is completely uncoupled from the introductory lecture courses and provides students with an opportunity to investigate a wide range of biological organisms and phenomena. At Goucher College, on the other hand, the investigative laboratory accommodates both majors and nonmajors, is closely integrated with the lecture courses, and is somewhat more restrictive in the type of individual investigations which are encouraged. At Indiana University, the program is specifically planned for majors and makes use of audio-tutorial techniques to prepare students for individual investigations in three carefully selected areas of biology.

The accounts which follow, in addition to outlining what is actually done in these laboratories, describe why the investigative approach was chosen and give a subjective analysis of the success achieved.

THE INVESTIGATIVE LABORATORY IN AN INTRODUCTORY BIOLOGY COURSE FOR NONSCIENCE MAJORS AT MARQUETTE UNIVERSITY*

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Introductory science course offerings traditionally have a coupled lecture-laboratory organization. Frequently, the laboratory has been used to

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*Originally published in CUEBS NEWS, February 1971.

illustrate material previously introduced in the lecture, to teach a multiplicity of techniques which of themselves are of doubtful importance, or to illustrate the diversity of living organisms. Because of time limitations, attempts to provide breadth of coverage have so formalized lab work that it is reduced to an exercise in manual dexterity rather than intellectual skill. Students criticize undergraduate laboratories because of the repetition of simplistic exercises, the answers and conclusions of which either elude the student entirely or are understood before the exercise was begun. The laboratory experience has to assume a more meaningful role, especially to the student whose only college contact with science is the one course he takes to satisfy his liberal arts science requirement.

A recent change in Marquette's undergraduate biology curriculum (see Chapter 10), involving the divorce of laboratories from lectures, provided a unique opportunity to introduce a laboratory course in which the student, science-oriented or not, could become familiar with the analytic method of obtaining information. Thus the laboratory would be used to engage the student in the process of investigation.

At Marquette, liberal arts students may satisfy their science requirement by completing eight credits in biology. This is accomplished by taking three one-semester courses: Biology 1 and 2 (lecture courses), and Biology 3, a one-semester laboratory course carrying two credits. Biology 3, offered both fall and spring semesters, has Biology 2 as its prerequisite and may be taken concurrent with or subsequent to that course.

Biology 3 is divided into two parts. The first, consuming about one-third of the semester, is used to prepare students to carry out individual research problems. The remainder of the semester is devoted to independent study on some topic of interest to the individual student.

By and large, college students want and enjoy the challenge of the unknown that I-labs provide. It is the rare student, however, who can be thrust into such a lab and be expected immediately to "start investigating." An introduction to experimental design, laboratory procedures and equipment, and the effective use of library facilities has been found to be a necessary preliminary step to student investigation. Thus laboratory activities during the first part of the course are designed to develop these skills and to give the student confidence in his ability to carry out meaningful investigation.

The first meeting is devoted to a class discussion of an experiment on the effects of gibberellin on dormancy in woody plants.[1] This study is approached as a "dry lab" and includes: (a) background observations; (b) formulating hypotheses; (c) testing hypotheses and setting up controls; (d) collection, analysis and interpretation of data; and (e) suggestion for further studies.

Initially, the class is provided with background information on gibberellins and the phenomenon of dormancy in woody plants. Then, through directed

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[1] Individual topics may vary from semester to semester, although this particular one has proven quite effective.

questioning by the instructor, the students attempt to develop a hypothesis relating a possible role of gibberellins to dormancy.

Following establishment of a testable hypothesis, questions by the instructor (and not infrequently by students) bring out some of the basic questions that should be considered before proceeding with the experiment. For example:

> How many plants should be used? What size plants should be used . . . trees, seedlings, or seeds?
>
> Where should the experiment be carried out . . . outdoors, in the greenhouse, or in special growth chambers?
>
> Where does one obtain the gibberellin? How is the hormone applied . . . spray, injection, or into the soil? How much should be applied?
>
> How often should measurements be made? How should data be collected and recorded? (The value of accurate records and use of a data book are also brought out.)
>
> How can one be reasonably certain that any effects observed are due to treatment with gibberellin? (This leads into a discussion of the concept of "controls" and the value of statistical analysis in experimental studies.)

At the conclusion of this lab, each student is asked to design a hypothetical experiment centering on gibberellin and dormancy and bring it to the next laboratory meeting where individual "experiments" are discussed by the class.

How to use the library, particularly with regard to the use of various abstracts and journals, is provided through a formal audio-visual lecture given to Biology 3 students by the director of the reference section of the main library. A library assignment is then given so that each student has the opportunity to make use of the library facilities. For example, last semester students were asked to write a 200-word summary (with bibliography) on abscisic acid, including studies involved in its discovery and its biological role.

The second laboratory meeting consists of individual presentations and class discussions of the hypothetical gibberellin experiment discussed the previous week. During the last half of the period, students are given 20, week-old bean seedlings and an aqueous solution of an unknown growth substance. They are assigned the task of determining what effect the substance has on the plants. There are no restrictions as to their experimental approach or the parameters used to determine the effect of the chemical on the plants. Students are only informed that the solvent is water, and they are to submit their results in 2 weeks: their paper consisting of a brief introduction; a detailed description of the methods and materials used; and the results, presented in tabular or graph form, or clearly described if consisting of a series of observations.

Students come up with a variety of approaches to this study. Some dilute the solution, others use it at the concentration issued. Some spray it on the leaves or inject it into the stems, others remove the plants from the pots and place the roots into the solution. Students not only measure increases in height but determine changes in wet or dry weight. The approaches used and the parameters measured are as varied as the student population.

At the conclusion of the study, selected experiments are discussed and "constructively criticized" as to experimental design, method of collecting data, and so forth. This "wet lab" has proved to be an effective way to have the student use information from the dry lab and, according to a number of student comments, has added to the student's confidence in his ability to design and carry out a controlled experiment, albeit a relatively simple one.

The third and fourth weeks (the 2-week interval during which the students are working on their "wet" lab study) are devoted to laboratory procedures and basic instrumentation. This includes use of pipets and other volumetric glassware, balances, pH meters, colorimeters, and the preparation of per cent, normal, and molar solutions. These studies are supplemented by the use of film loops for those individuals who want to spend additional time on specific procedures.

Although we place few restrictions on areas of investigations, we have found that the majority of our students select studies involving bacteria, frogs, tadpoles, chick embryos, and various plant materials. Thus, during the fifth and sixth weeks of this preliminary phase, students are introduced to a few specific techniques in microbiology and developmental biology. We have used studies involving the preparation of nutrient media, sterile techniques and methods of incubation, studies on the early development of the frog that involve artificial stimulation of ovulation and fertilization, and studies in which the student incubates chick eggs and examines the developing embryo periodically during its development. Little is done with formal exercises on plant materials at this time since earlier laboratory studies dealt with aspects of plant growth and development.

During the last 2 weeks of this introductory phase, students identify and refine an area of investigation. They may arrive at this point from a number of directions. Some come into the course "knowing" just what they want to investigate. Some have ideas or questions generated as a result of the formal laboratory studies. Others become interested in an area after examining "bound" copies of student investigations carried out in previous semesters.

Some Investigative Studies Carried Out by Students in Biology 3, the Introductory Laboratory Course

1. The effect of crowding on planaria.
2. Toxicity studies of Malathion on *Drosophila* larvae.
3. The effects of calcium cyclamate on the developing chick embryo.
4. Resistance of *Escherichia coli* to streptomycin following U-V irradiation.
5. The effects of acetyl choline on classical conditioning in *Catostomus* sp.
6. The effect of proflavine on the development of chick lens.
7. Responses of planaria to shock.
8. The effect of light on learning rate in mice.
9. The effect of proflavine on regeneration in planaria.
10. Osmoregulation in *Catostomus commersonnii.*

Regardless of where or how individual students become interested in a topic to investigate, the questions they ask are frequently much too broadly defined and need to be narrowed considerably. This is done through individual conferences with the instructor either during the laboratory hours or during scheduled office hours. This is a time-consuming activity since each instructor is essentially tutoring 60-75 students; each teaching assistant handles 25-35 students. This aspect of the course is critical and no student is permitted to begin his study until he has submitted a proposal that includes the question he is asking, the rationale leading to his study, a tentative hypothesis, and a brief statement of materials needed and the approach to be taken. A bibliography, citing references to similar studies, must also be included. Once his proposal is approved, the student is no longer bound by formal laboratory attendance. He is, however, required to meet biweekly (or oftener if desired) with his instructor to report on his progress (or lack thereof). Records of these meetings are kept by each instructor. This apparent contradiction to open labs accomplishes the following:

1. It provides time for the instructor to become familiar with the student's project. The need for this becomes more apparent when the student has to be evaluated;
2. It presents an opportunity for questions, by the student as well as instructor, regarding any problems in techniques, interpretation of data, and so forth; and,
3. It is a device (unfortunately needed) to protect the instructor from the small number of students that "disappear" and then either claim they never had anyone available for help, or turn in a report suspect in its professionalism.

Some students do not need these conferences. Such students, however, are found to have no objection to this requirement and indeed use it to their advantage.

Approximately 10 weeks are devoted to individual study, with the last 2 weeks set aside for the reporting of results in a paper patterned after the standard format of most scientific publications. Titles of some of the studies undertaken by students in past semesters are listed on the preceding page. It should be noted that no student is penalized if he fails to get "results" through no fault of his own. Indeed, some become so involved in working out techniques that the course ends before they have generated any data. (The value of the biweekly conference becomes apparent in this situation.)

Final grades in the course are based upon three criteria, weighted as follows: 20% is given for the initial design and originality of approach; 30% is given for effort, interest, and persistence in solving difficulties during the course of the study; and 50% is assigned to the paper and is based upon attention to format, clarity of writing, a discussion that includes relationship of the study to published data or to the results of classmates carrying out similar studies, and so forth.

Because the course must accommodate 600-700 students annually, there are some problems involving space, assignment of equipment, and procurement of materials.

Space: We routinely schedule 12-16 laboratory sections per semester, with an enrollment of 20 students per section. Because of the open laboratory aspect of the course, two rooms have proven to be adequate space for the number of students involved. Indeed, because there is no absolute requirement that the investigation be carried out in the teaching laboratory, we have fairly large numbers of students working outside of the labs. Examples follow.

> Several students, interested in the detection of coliform bacteria, contacted the health department laboratories. The staff willingly worked with these students and appraised us of their performance.
>
> Two students who wanted to investigate the effects of ethylene on plant growth contacted the plant physiologist on our staff for advice. During their discussion, they became more interested in a growth factor he was involved with and ended up working under his direction.
>
> Others interested in immunology were provided space in a research laboratory and were guided by a graduate student majoring in this area. This student, also a teaching assistant in Biology 3, provided advice and assistance in studies involving selected immunological techniques.
>
> A fairly large number, 65-70 students, were provided bench space in the greenhouse for studies on plant growth and development.
>
> Approximately 35-40 students who elected to work with bacteria were located in an unused prep room and provided with a hood, incubator, and other basic materials needed for culturing bacteria.
>
> A small number of medical technology students carried out studies in cooperation with the staff of the medical school, and in some cases, hospital laboratories.
>
> One student, a psychology major, obtained the advice and guidance of a faculty member in that department.

A number of other students, even though working in the teaching labs, contacted and received advice and encouragement from various faculty members in the department. Indeed, this type of course provides a unique opportunity for faculty to become "visible" at a time when students are seeking greater faculty-student contact.

Equipment: Specialized equipment, e.g., microscopes, water-baths, colorimeters, pH meters, etc., are signed out to individual students by the equipment supervisor. At the time equipment is issued, each student submits a card, signed by his instructor, indicating the equipment needed. This card has space for the student's name and signature, home and school address, university identification number, and the room where the equipment will be used. These cards are kept on file until the equipment is returned. Once issued, the equipment is kept in a locked cabinet in the teaching laboratory. The student may obtain the equipment by asking any instructor to open the cabinet. All equipment is signed out each time it is used, thus providing us with some control of equipment use and movement, and assuring the student that his equipment will be available when he needs it. Although we have not had to resort to it, grades are held back for equipment not returned at the end of the semester.

Chemicals: Standard laboratory reagents are kept in each laboratory. These include the more common carbohydrates, amino acids, nutrient media, plant growth substances, animal hormones, various vitamins, salts that comprise basic culture media, etc. The amount and kinds of chemicals routinely stocked are based upon the needs most often expressed by students in previous semesters. Specific needs by students are checked against chemicals on hand and are ordered if not in stock.

Live Materials: Each student is responsible for maintaining living materials used in his study. We have found, especially with respect to planaria, hydra, various algae, and other organisms requiring special handling, that it is advisable to have the student become familiar with culture conditions before ordering this material and that he demonstrate his readiness to receive and maintain the organisms when they arrive. Directions for handling such cultures are provided in the laboratory as part of a "Culturing Technique" book. Most living materials can be made available to the student within a week to 10 days after his needs are known. A list of the students, including materials ordered and tentative delivery date, is posted near the laboratories so that each student will know when his materials are expected to arrive.

Staff: The course is presently staffed by two faculty instructors (one M.S., one Ph.D.), two graduate teaching assistants, and a senior Biology student who has miscellaneous duties.

One might suspect that a course such as this is demanding of both instructor and student time. It is. Our instructors, however, feel that for the first time they are really getting to know the strengths and weaknesses of their students because of the personal contact this type of course promotes. And even though the contact hours spent exceeds those of the more traditional laboratory, they would not want to revert to the previous, more formal laboratory organization.

We find that students, even though spending about twice the amount of time in the laboratory, are generally enthusiastic.

Typical of the comments received on a course evaluation are those given below:

> "I like the fact that it is mostly an individual course. Perhaps this is what allows it never to become boring."
>
> "It makes the student take on more responsibility. It is a good exercise in working with people."
>
> "I don't know about anyone else, but I got all excited about my experiment and felt I learned something."
>
> "I complained a lot about this course but I can honestly say I got something out of it. A Liberal Arts student, no matter what field he is going into, will someday have to think for himself."
>
> "To Liberal Art's students who'll never pass this way again it should be a good remembrance of hard work."

In conclusion, students are asking colleges and universities to provide courses uniquely different from their high school courses. The I-lab approach provides the sciences with the opportunity to offer such courses.

THE INVESTIGATIVE LABORATORY IN THE INTRODUCTORY BIOLOGY COURSE AT GOUCHER COLLEGE*

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Our department first included an investigative laboratory in the introductory biology course 12 years ago, in 1958-59. We were so pleased with the

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*Originally published in CUEBS NEWS, December 1970.

results that we have continued to offer it ever since with various modifications.

The impetus for introducing an investigative laboratory came from the reorganization of two departments (biology, physiology and bacteriology) into a single Department of Biological Sciences. In the ensuing curricular reorganization, it was apparent that we needed a broadly based, up-to-date concepts course in biology to serve as a general education course and as an introduction to our major. The development of such a course was strongly urged and supported by the college administration. Initially, this concepts course was a two-term sequence, the first term primarily cell biology, and the second term dealing with higher organisms and populations. Helen Funk, a microbiologist, and the late Kornelius Lems, a young ecologist, were responsible for developing and teaching the course. In their opinion, the traditional laboratory did not produce in their students an understanding of the nature of science, and they decided to adopt the "project approach." The second term of this course subsequently evolved into other courses at the sophomore level. The first term has retained its original form and is, in the eyes of the students, an interesting and surprisingly sophisticated course that at least one-third of the Goucher students elect.

In this one term of cell biology (hereafter called Bio 100), the lectures cover cell structure, division, metabolism, genetics, and plant and animal development, with a few culminating lectures on ecology and human evolution or other topics of interest to that term's lecturer. The exact content of the course is, in part, colored by the fact that after 1959 and until a recent reorganization of our teaching loads, the lectures were always given by Helen Funk or Ann Lacy, a microbial geneticist.

So far, this introductory course has been taken as one of three concurrent 10-week courses, but beginning this fall, it will be one of four concurrent 14-week courses. It has 3 hours of lecture and 3 hours of laboratory per week. A year of high school chemistry with laboratory or a term of college chemistry is a prerequisite to this course. We find that students lacking such preparation usually have trouble with metabolic aspects of the course. More than 95% of those who enroll in Bio 100 are freshmen or sophomores, and 70% or more become nonscience majors. From this course, students can move directly into our second level courses, which include genetics, plant physiology, embryology, ecology, animal physiology, and microbiology.

In the 12 years since we initiated Bio 100, we have taught a total of 1659 students plus another 585 in the now defunct second term. During the same period, the total number of students graduating with a major in biological sciences was 150. Approximately 50% of these majors entered graduate school; several have already completed the M.S., M.D. or Ph.D. programs. Almost all of these 150 students are currently pursuing active careers in teaching, research, or medicine.

In any given year, approximately 30% of the freshmen-sophomore population enroll in Bio 100. The figures fluctuate somewhat, depending on college-wide course distribution requirements and which courses are available to meet these requirements. We have taught as many as 200 students in one year, with a maximum of 120 in one term. More recently, we have tended to enroll about 150 per year distributed in a pattern of 70-30-50 per term, a much more desirable distribution from the point of view of both staff and equipment.

Our intention in incorporating the investigative approach into the elementary course was to teach students what science really is, not a "body of organized facts," but a creative and critical effort whose ideas are not static but constantly subject to modification on the basis of further experimentation. Since the majority of our students do not become scientists, we feel that it is important for them to have an opportunity to understand the tentative nature of scientific information and the reasons why able scientists often disagree about their findings or the meanings of their findings.

As we state in our lab text . . . "We have found that a student who designs and conducts experiments, evaluates the results, compares them with the results of colleagues doing similar experiments, and then reports his findings and interpretations as a scientific paper, gains a good deal of insight into the joys, frustrations and seeming contradictions of scientific research."

We have found that the success of the investigative laboratory is strongly dependent on organization, both of time and nature of experimental work. It quickly became clear to us that limiting the possible experimental parameters is essential to the success of the student projects and to the efficiency and economy of operation. We limited the possible experimental organisms to four or five microorganisms: a yeast, a motile protozoan, a motile alga, and a photosynthetic bacterium. All of these organisms grow well in a single, all-purpose medium.

Most of our students' projects are designed so that the main variable is growth or inhibition of cell populations as determined by culture density. However, some students may also measure chlorophyll content or study cell morphology or motility. If a student has a burning desire to use some other organism or to carry out some project other than the general types we are equipped to handle, we allow it, if the project seems feasible and if the student is willing to do the extra work involved in collecting different equipment. Such cases are not frequent, but we do recognize that these mavericks are often ones who later choose to major in biology.

Initially, we chose microorganisms as the experimental organisms because the first term of the course emphasized cell structure and metabolism and because our microbiological backgrounds and training had shown us the advantages of using microorganisms for experimental work limited by time and equipment. In this respect, our opinions were reinforced by experience with investigations involving higher organisms in the second term of the course. The diversity of equipment and of techniques to be taught, the problems of maintaining higher forms, the difficulty of fitting projects into a limited time, the need for more space, and the problems of adequate numbers of experimental organisms all militated against meaningful results.

In recent years we have rotated responsibility for Bio 100 through the biology faculty (a plant physiologist, an embryologist, a comparative physiologist, a geneticist, an ecologist, and a microbiologist). Initially, we heard mutterings about the possibility of the projects being changed to include other forms, e.g., higher plants or pill bugs, etc. However, it has been interesting to see that each faculty member, regardless of discipline, decided that the use of microorganisms was the most satisfactory operating procedure. Now all members of our department teach the course with relative ease.

A very important factor in the confident participation of all of our faculty is the way in which the course is staffed. Normally, in any given term, one faculty member is in charge of the entire course. This professor gives most of the lectures (with occasional guest speakers) and teaches one laboratory section. Supporting the professor is a full-time teaching assistant who maintains the stock cultures of microorganisms, prepares materials for labs, helps with grading, and teaches one lab section. If there are more than two lab sections, other faculty members take responsibility for them. Our teaching assistant has an office close to the laboratory and is available during most of the day to answer student questions. The amount of responsibility the assistant can carry depends, of course, on the person. We are particularly fortunate in having a Goucher biology alumna who is an experienced research assistant in microbiology. We have in the past had to train high school graduates as assistants, and much more work thus devolved on the faculty member in charge. Such staffing problems made the teaching more difficult for the nonmicrobiologists on the faculty. However, it can be done provided the assistant is given on-the-job training.

For people from other small colleges, we should point out that we do not have graduate students available to do the work. Too often research-oriented laboratory programs are dependent on that source of labor for their success. In addition to the full-time teaching assistant, we also employ Goucher undergraduates, who have previously done well in the course, as assistants in teaching the labs (at least one student assistant per lab of 24 students). These student assistants answer many of the routine questions, find equipment, teach techniques, and otherwise free the professor to discuss experimental problems and results. Our biology majors consider it a privilege to be invited to assist in this course.

The general stock of equipment needed for setting up this kind of laboratory is relatively simple. Major items include the following:

pipettes
pipette discard jars
test tubes with plastic caps
transfer loops
prescription bottles with screw caps
chemicals
compound microscopes
spectrophotometers
incubators
refrigerator
autoclave (or pressure cooker)
one good balance

Pipettes and test tubes are washed and sterilized by the crew in the glass washing room. The chemicals for making culture medium are provided to the students as stock solutions. Such stock solutions can be delivered by pipette with the precision that good experimental work requires; they also eliminate waste of chemicals and the need for costly analytical balances. The teaching assistant provides pure cultures of microorganisms as needed by students and runs the autoclave twice daily to sterilize media made by students for their projects.

The timing of our laboratory program has varied somewhat depending on the faculty member in charge. The following allotment of time seems to be the best for our 3-hour per week lab in a 10-week quarter system:

3 weeks for introduction to the materials and methods for the project.
4 weeks for the investigation. During this period the lab is open from 8:00 a.m. to 5:30 p.m. Monday thru Friday and on Saturday morning.
3 weeks for formal lab sessions in genetics and shark anatomy to introduce other approaches to biology and other types of organisms.

The 4-week project allows two or three repetitions of experiments and provides sufficient time for further investigation of a problem if initial experiments are successful. We have found that a 3-week project period is too rushed, with consequent poor quality of reports and a sense of frustration among the students. Next year, with 3 hours per week for 12 or 13 weeks, depending on the semester, we are going to divide our time approximately 3/5/4, which we expect may be better than the 3/4/3 schedule.

Our laboratory schedule coincides more or less with our progression in the lectures, that is, from cell structure and metabolism through genetics to the whole organism. This general relationship we find advantageous, although other writers on the investigative laboratory suggest complete divorcement of the two.

Our 3-week introduction to the materials and methods occurs prior to the beginning of individual projects and involves teaching the student how to examine a variety of cells microscopically, prepare a culture medium, learn aseptic technique, and measure the growth of microbial cultures with a spectrophotometer. In this period, the student works more or less at his own pace with a check list of skills to be achieved in the given time. The only work handed in during this time is a few drawings which are required not so much to teach the details of biological drawings, but to push the student into really looking at the experimental organisms available for their projects.

During the latter part of this introductory period, students formulate their projects and submit an outline that states how they expect to proceed and what materials they will need. Suggestions for investigations are given in the lab text and in lecture. Students are also encouraged to scan suggested books and scientific journals listed in the lab text. The less adventuresome student usually does not move beyond the experiments described in the lab text. The more creative student will initiate some very interesting projects. In the first case, consultation usually results in the student's elaborating on our published suggestions. In the second case, a student may have to narrow down an overly ambitious project.

Student interests vary considerably with time. A few years ago the big thing was antibiotics. Now, of course, the cry is ecology, and many of the projects involve such questions as the effects of detergents on fresh-water microorganisms.

Once a project has been approved, the student begins the experimental work. Depending on the organism under study, an experiment may take from 2 or 3 days to a week. As data is obtained, the student consults the instructor and discusses the next step — whether the experiment should be repeated or whether the experimental conditions should be refined. One important student insight of this early period results from the sorrowful statement, "But the experiment didn't come out the way it's supposed to." Our motto for this stage of affairs is: "The organism is never wrong." With our new 5-week period for the project, we plan to hold discussions at this time among students conducting similar projects.

Thereafter, the student runs additional experiments, depending upon time and available glassware. During this latter period, further insight is apparent: students who have previously expressed ideas as flat statements now begin to hedge and qualify. One student pinpointed this stage very aptly when she said, "I'm beginning to sound like a professor."

Two weeks are allowed in which to write the report in the form of a scientific paper. We require that data be presented in graphs, tables, or drawings. Students are encouraged to discuss the relation of their results to published data and to the results of classmates doing similar studies. Accident-prone students who have managed to drop their test tubes and to contaminate their cultures through the entire project period (and there are always 1 or 2 of these) are told to use the data of another student's experiments to prepare his paper; giving due credit to the student whose work is represented. Such activity gives the benefit of experience in critical evaluation and presentation of material even if they are all thumbs in the laboratory.

Critical reading of the papers by the faculty is, of course, time-consuming. But, just as the lab is more interesting to teach when you are discussing real experiments rather than the traditional prefabricated ones, so these papers are more interesting to read than myriad, identical, and predictable lab reports. The evidence from our student evaluations is that this type of project and paper does indeed give a view of science very different from the "body-of-facts-stereotype." There are other advantages: it lures some erstwhile nonscience students into a biology major, and it provides solid academic training useful in other fields as well. A highly respected colleague in the History department once told us that the Bio 100 graduates write more critical and better organized term papers than the other students in her courses.

For the future, we will undoubtedly continue to modify the course. We do feel, after a number of years of satisfied customers, that the investigative laboratory is a far more successful approach to teaching biology than the traditional one.

COMBINED AUDIO-TUTORIAL AND INVESTIGATIVE APPROACHES IN AN INTRODUCTORY LABORATORY COURSE FOR BIOLOGY MAJORS AT INDIANA UNIVERSITY*

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A recent revision of the undergraduate curriculum at Indiana University caused us to re-evaluate our introductory courses for biology majors. The new curriculum insured that all students majoring in the biological sciences would take at least one course in each of the major subject areas of biology. This freed the introductory course from its traditional role as a survey of the field. However, it also posed a perplexing problem. What can we offer the beginning student that will be useful to a professional biologist, but will not be redundant to the rest of the curriculum?

My answer was that these students should be introduced, in the most realistic way possible, to the world of the professional biologist.

It was felt that by structuring the course in a way that would accurately approximate the problems and duties faced by a biologist in his professional life, the students would be provided with a realistic foundation upon which to assimilate the more specialized and detailed information of subsequent courses. It was hoped that such an approach would heighten the student's appreciation of much of the work done by his predecessors and contemporaries in science.

An attempt was made to define the actual problems faced by a research biologist. While many different lists could be generated on this subject, the following is one based on personal experience.

1. To choose worthwhile problems that can be profitably attacked using the facilities available.
2. To design experiments that will help solve the problem.
3. To perform the experiments accurately. Organize and interpret the data.
4. To communicate the results of the research accurately and intelligibly both orally and in writing.
5. To evaluate the work of his scientific peers based upon his own knowledge and experience in a particular area of biology.

Having come up with such a list, it is not surprising that I turned to an investigative-type of laboratory. Where else can a student actually define his own problem and design his own experiment? It was felt that the first two

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*EDITOR'S NOTE. In the program described by Professor Sojka, students are assigned problems. In this respect, it differs greatly from what CUEBS has referred to as an Investigative Laboratory. In a true I-Lab, students are responsible for identifying a problem as well as designing and carrying out a strategy for its solution. We include a description of Indiana's program here as an illustration of how audio-tutorial methods can be used to *prepare* students for investigation. As Professor Sojka mentions at the end of the article, he is currently planning to modify the program to provide for greater student involvement in problem formulation. We feel that this represents movement toward an Investigative Laboratory.

items on the list could not be dealt with effectively in a noninvestigative laboratory, no matter how carefully the experiments were chosen. Saying that a student can learn to pose problems and design experiments by repeating someone else's work is similar to saying that one could learn to write science fiction by copying in long hand stories by Isaac Asimov. It was felt that it was more important for beginning students to actually come to grips with the fundamental problems of performing original research than to repeat the most sophisticated and up-to-date experiments in biology, regardless of how well these experiments demonstrated "major concepts."

The decision to employ an investigative approach, however, created a whole new set of problems. How can you provide beginning students with enough background to function productively in an investigative situation? How do you help them get started? How do you approach the logistic problems created by each student doing a different set of experiments? How do you prevent some of the "slow starters" from being left at the post? There is, of course, no single answer to all of these problems, but many of them could be partially solved by periodically gathering the group for short orientation periods during which a catalytic amount of background information is provided by means of traditional laboratory experiments. These orientation periods are considered simply as adjuncts to the investigative portion of the laboratory and are designed primarily to make the investigative experience more meaningful.

These orientation periods, it was felt, could best be approached employing audio-tutorial (A-T) methods. The free scheduling of the A-T lab fits nicely into the unstructured investigative format. A-T also gives the student the opportunity to work at his own pace, repeating certain operations, if necessary, in order to gain mastery. This last consideration is a critical factor in determining the success of the entire course. In order for the student to gain the most from the unstructured, investigative work, he must reach a certain minimum level of proficiency and understanding. The flexibility of A-T exercises permits each student to work until he is confident that he has mastered the material well enough to apply the newly learned principles in a less structured situation.

The combination of A-T exercises and investigative experiences was accomplished by dividing the first 12 weeks of the semester into three 4-week periods, each focusing on a different investigational area. The first week of each period consisted of A-T exercises designed to prepare the students for the subsequent 3 weeks of investigative work. Small discussion sections (nine students or less) met each week of the semester. In the first week of each period, the discussions dealt with the A-T lab and then set the stage for the investigative problem by introducing the students to the organisms and facilities available during the next 3 weeks. At that time, the students were instructed on what types of problems they should investigate. The other three weekly discussions in each investigational area were designed to give the students an opportunity to discuss their progress (or lack of it) with their fellow students and the instructor. It was hoped that these discussions would help prevent any of the students from getting left behind.

At the end of the first 12 weeks, the students were asked to review their three investigative projects and choose the one they wished to report on. They were then asked to write an abstract of the work and submit it for inclusion at a scientific meeting. At the meeting, each student gave a 10-minute oral presentation of his work. The meetings were attended by all the students and invited faculty members. The final assignment in the course was for each student to hand in written critiques on the work of their colleagues. The purpose of this was to start the students thinking critically about the work of others, based upon their own knowledge and experience in a given area.

To explain better how the course operates, the investigational area on growth and nutrition will be described in more detail. This subject area was chosen because it was felt that students with very little background information could carry out meaningful investigations without first having to learn a large number of techniques. The behavioral objectives of the A-T laboratories were to acquaint the students with the fundamental concepts of growth, problems of measuring growth, several standard methods of growth measurement, and the mathematical and graphical expressions of biological growth. In the laboratory, students determined a bacterial growth curve by doing direct bacterial cell counts in a counting chamber, and by following increases in turbidity in a spectrophotometer. As a take-home exercise, each student received two tubes, each containing different media and innoculated with *Neurospora crassa.* They were asked to make periodic measurements of the growth of the fungus in the tube and to determine the best medium by plotting linear increase against time. The exercise also contained a number of questions that were to be answered before the first discussion section. These questions were chosen to make the students manipulate the arithmetic associated with these experiments. For example, they were asked to calculate the dry weight of a single bacterial cell from their data. They were also asked to explain why the bacterial growth data was expressed on a logarithmic scale and the *Neurospora* data on a linear scale.

In the discussion section, several other important points were developed. The students were asked to compare the accuracy and usefulness of the two methods employed to measure bacterial growth (direct counts and turbidity). The classes were unanimous in their selection of the indirect turbidimetric measurements because the points showed less scatter than those of the direct counts. When questioned about the indirect nature of the experiment, they were quick to respond that they were given calibration curves that related turbidity to dry weight. At this point, the original calibration curve from which their copies had been made was brought out. The only difference between their copies and the original was that the original still had the data points through which a statistically determined line had been drawn. It was then explained why the actual points were rather badly scattered. (Centrifugation, washings, cell drying, and weighing of the dried pellet all contributed to the experimental error in each determination.) This demonstration appeared to make the point that indirect methods, though often convenient, must be calibrated by some direct measurement, and are no more accurate than the measurements used to calibrate them.

The next question was to decide which of the *Neurospora* media supported the best growth. There was some disagreement on this point because the linear growth rates appeared quite similar. This experiment had purposely been set up to create such ambiguity. The strain of *Neurospora* used was, in fact, a special serine-requiring mutant which needs serine for production of aerial hyphae, conidia, and certain pigments, but not for linear growth. The media were identical except that one had been supplemented with serine. The linear growth rates had been nearly identical on both media; however, the serine-supplemented medium had supported luxuriant, fuzzy, pigmented mycelial development, whereas the minimal medium yielded a colorless, sick-looking culture. When asked to look carefully at each culture, the students were all able to determine that the supplemented medium had produced the most growth. This demonstrated, in a dramatic fashion, that one must be careful in choosing the growth parameter he wishes to measure. The students all gained a new awareness for the fact that an uncritical choice of the parameter measured can result in an erroneous evaluation of a growth experiment.

Having accomplished these behavioral objectives, the students were confronted with the problem they would work on for the next 3 weeks. The challenge was to: "Develop a method for measuring the biological growth of one of the organisms provided. After you have developed this method, use it to tell something about the basic nutritional requirements of the organism." A list of organisms available for investigation was provided. These were earthworms, planaria, hydra, *Euglena*, and *Coleus*. The students were then informed of the reasons for this choice of organisms. First, these are all organisms in which critical growth measurement is difficult, and consequently few reports exist in the literature. This demands that the student be original and creative in his approach. The second reason was that I was not particularly familiar with any of these organisms. This removed the problem of a student-teacher relationship in which the teacher knows the answer before the student even begins. While this may seem like a minor point, it is a very important factor in creating an atmosphere similar to the one in which a professional researcher works. There is no point in doing research on a subject if someone else already knows the answer.

A wide variety of approaches was employed by the students in an attempt to answer this challenge. About one-half of them were able to devise experiments that yielded satisfactory growth data and permitted examination of some nutritional requirements. For example, one student, using direct cell-counting procedures, was able to demonstrate that *Euglena* has a greater dependence on Mg^{++} ions for photosynthetic than for heterotrophic growth. Another interesting experiment showed that CO_2 could be a limiting factor for growth of a *Coleus* plant; measurements of stem elongation, total leaf number, and average leaf area being used as growth parameters.

A significant portion of the students designed experiments that measured the wrong thing. Many of these experiments, however, proved to be pedagogically as satisfying as some of the more successful projects. A good example of this was provided by three students, each of whom chose to work on planaria. All three experiments were quite different in design, but each depended upon being able to equate regeneration and growth. It was gratifying to observe all three of these students (working completely independently) discover that regeneration occurs before, and independent of, net organismal growth. Even though they had not answered the challenge given them, these students had worked on a worthwhile investigation and all had arrived at an unexpected but valid conclusion.

At the end of 12 weeks, each student had completed three investigational areas similar to the one just described. At this point, he chose the area in which he wished to be graded. This provided a touch of realism since a research scientist is judged by his productive days. This is quite different from the situation encountered by physicians, performing artists, and others. Therefore, it is not inappropriate to evaluate the students on only one-third of their total performance. This system also allows the students more freedom to pursue experiments that may seem interesting. A grading system which evaluated each experiment might cause the students to "play it safe," and consequently undermine the whole program.

After choosing the area, each student completed an official abstract form. (Since I am a microbiologist, I chose the official form of the American Society for Microbiology). The students were asked to write these abstracts in the laboratory. This gave us a chance to work closely with each student, helping him develop this valuable technique in quite the same way that we would try to teach him to pipette or use the microscope properly.

Laboratory time was also used to help the students develop their 10-minute oral presentations for the meeting. The format for the meeting was based upon that of a meeting of a professional society. Copies of our program were mailed to 30 selected faculty members in the Division of Biological Sciences, in hopes that their presence would make for a more realistic setting. The students were informed in advance that faculty members would be present and would ask questions.

The writing of critiques of fellow students' work was handled as a homework assignment. The critiques were to cover such subjects as choice of problem, design and performance of experiments, analysis of data, conclusions, and method and effectiveness of oral presentation.

It is probably presumptuous to judge a course's success after only one offering. However, there was no question about the enthusiasm of the student response. I was convinced that many of our primary objectives were at least partially attained. Next year, we plan to incorporat several changes which may eliminate some of our most obvious problems. Undoubtedly, three separate investigational areas are too many. Next year, we will be content with one investigational area of 9-weeks duration. If possible, we will also try to develop a mechanism by which the students can have more input into the format of the course. I felt that this first attempt was an exciting and rewarding experience and for this reason I have great expectations for the future of this course at Indiana University.

7. Investigative Laboratories in Advanced Courses

Because upper division and advanced courses typically have smaller enrollments, more mature teachers, and better prepared and more highly motivated students, the approaches taken in the laboratory portions of these offerings have often been more imaginative and of higher quality than those in introductory programs. But as enrollments have increased and broadly based core courses, planned and taught by teams of professors, have replaced more narrowly based specialty courses, the quality and continuation of these creative laboratory activities have been threatened. Although it may be unnecessary and impractical for a department to provide laboratory work in all the areas in which it offers advanced courses, it is probably wise and important to provide at least a few high-quality laboratory- and field-based programs for those students who may wish to pursue their study of biology beyond an introductory level. This need can be fulfilled, to some extent, by independent study options. But students also enjoy and profit by working in groups, and if they have not been prepared to work independently during their freshman and sophomore years, they may be unable to take advantage of the opportunities which independent study offers. Even if a department has an investigative laboratory as part of its introductory program, this is no assurance that all its upper division students will be ready for independent study because of the increasing tendency of students to transfer between institutions and from two-year colleges to four-year colleges and universities.

The type of investigative opportunities which an institution offers should, of course, reflect the interests and talents of its students and faculty and the physical resources which are available. Some institutions have found that summer sessions or the one-month term in a 4-1-4 schedule are particularly useful periods in which to offer investigative opportunities, while others have been able to make effective use of field stations, community research facilities, and adjacent "natural" areas for this purpose.

The following descriptions and thumb-nail sketches indicate some of the ways in which the Investigative Laboratory concept has been implemented in upper division courses. Additional Investigative Laboratory Courses are described in Chapter 8 (I-Labs at Field Stations) and Part III (Laboratory Curricula).

AN INVESTIGATIVE LABORATORY IN CELL BIOLOGY*

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Several years ago, it became apparent that at my institution it would become increasingly difficult to maintain a good laboratory experience as an integral part of the undergraduate cell biology course. One of the reasons was cost. We estimated that it was six times as expensive to teach one student credit hour in laboratory as in lecture. Because we had changed the course from an upper division elective to an undergraduate degree requirement for zoology majors, the enrollment was rapidly increasing. Although the increasing number of students could be accommodated in lecture with little additional expense to the institution, the same could not be said for the laboratory.

In addition to the economic difficulties of maintaining instructional laboratories, there were other reasons for taking a closer look at what we were doing. In all fields of biology, but particularly at the cell and molecular level, the increased sophistication of methods and equipment being used in actual research made it difficult to maintain currency in the instructional laboratories. Finally, the information explosion made it tempting to add additional lecture hours to the existing course. A convenient way to do this was to simply substitute lecture hours for laboratory hours.

In spite of these compelling reasons for eliminating the laboratory, I was reluctant to do so. The reason for my reluctance, I suppose, was because of my own experience, which indicated that people don't become scientists or even come to understand and appreciate science by reading or hearing about it. I believe that we learn science by doing it and, in cell biology, this means getting into the laboratory and getting the glassware dirty. One does not learn golf by watching a tournament, even if it is narrated by Arnold Palmer and equipped with slow motion and instant replay facilities. One also does not learn cell biology by attending lectures and reading, even if the lectures are presented by excellent biologists equipped with the latest teaching devices.

Therefore, I committed myself to maintaining a laboratory experience in cell biology. To handle the enrollment and cost problem, I uncoupled the laboratory portion of the course from the lecture and made the laboratory optional. Over half the students now take only the lecture, but those who wish to be participants as well as spectators of science have the opportunity to do so by enrolling in the laboratory course.

It was then possible to develop the laboratory in an independent manner. From the beginning, my conviction was that the laboratory should be investigative; that is, I felt that the course should *not* be designed to simply demonstrate principles or techniques described in lectures. Rather, I felt that this course should provide the environment in which the student could develop and carry out a small program of investigation, experiencing firsthand the processes by which scientific knowledge grows.

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*Originally published in CUEBS NEWS, October 1970.

My initial ideas about what would be required of me, as an instructor, in facilitating student investigations were rather naive and I now realize that my students must have been very good sports to tolerate my inexperience. These initial strugglings may be worth repeating, however, for I gained a better understanding of what is necessary in order for students to successfully carry out investigations. In that first try at offering an investigative laboratory, I explained to the students at their initial class meeting that their assignment for the semester was to design, carry out, and report on the investigation of some problem, of their own choosing, in cellular biology. I explained that the first step was to identify and limit the problem and design an attack upon it. I gave them some tips on the use of the library and asked them to come back in 2 weeks with a project proposal complete with the materials that they would need.

Student response was something rather akin to cultural shock. Individually, they filtered into my office and confessed that they had no idea what to do or how to do it. Although they knew quite a lot about cell structure, composition, and metabolism, they couldn't identify problems worthy of investigation except for broad general ones such as "the cure of cancer." Moreover, the library had not been very useful. They felt that investigations similar to those reported in research papers were far beyond their capabilities.

As I met with the students in an effort to assist them in preparing suitable proposals, I began to perceive that there was a single ingredient which would very often bring them out of shock and get them started on the process of investigation. That single ingredient which most students needed but were unable to provide on their own was a source of suitable cellular material on which to carry out controlled experiments.

As I thought about the process of biological investigation, I began to realize that breakthroughs in cellular research have often been made as a result of the discovery of biological materials which are particularly well suited to the investigation of particular types of phenomena. Examples are *Drosophila* and *Neurospora* for genetic analysis, *E. coli* for metabolic studies, and squid giant axon for investigation of the mechanism of nerve conduction.

It would certainly be possible and valuable for students to develop their own systems just as researchers often do. At the cellular level, however, this activity is so time-consuming for most students that it typically takes up all or most of a semester. Since I was more interested in helping my students have an experience in designing experiments, collecting and analyzing data, and drawing conclusions than in helping them develop techniques, I decided that it would be appropriate for me to take responsibility for developing the cellular system upon which they would conduct investigations. Perhaps a second investigative laboratory experience for students could put more emphasis on the identification and development of "their own" system.

At that point, therefore, I began to look for a system around which investigations could be built. The term "system" is used here to refer to a set of basic materials, supplies, methods, and techniques. It seemed to me that this "system" should have the following characteristics.

1. If possible, it should be based upon a reasonably homogeneous cellular population. This greatly facilitates the design of controlled experiments and reduces the number of variables to be considered. Although

metazoan organisms are cellular, the variety of cells present and the extensive nature of their interactions limit their use for simple cellular investigation.

2. The cells need to be alive and reasonably easy to grow and maintain so that students can investigate dynamic phenomena as well as morphology. This means that a collection of stained slides, even though it is very extensive, is probably inadequate.
3. The cost of using the system cannot be excessive. At our institution, an initial investment of $5000 to equip the laboratory and subsequent expenditures of $10 per student per semester seemed like a reasonable limit.
4. The required supplies and materials should be readily available from commercial sources.
5. The time required to learn to use the system should be no more than half a semester, and preferably less. This is essential if the emphasis in the course is to remain on the investigative process rather than learning of techniques.
6. Students should enjoy working with the system. Mammalian cells probably have advantages at this point over microorganisms or plant cells.
7. The system must provide raw material for a wide range of student-designed investigations.

It also seemed desirable to develop a system which would help students obtain laboratory skills which have wide applicability in the many diverse areas of current biological investigation.

In our search for suitable material, we were attracted to in vitro cell culture. Permanent cell lines, cultured as monolayers on glass surfaces, have been used successfully for many years in the investigation of cellular phenomena by research biologists. Until recently, however, the techniques required to maintain cultures have been expensive and technically beyond the competence of undergraduates. With the development of suitable antibiotics to control growth of contaminants and the availability of cell lines, premixed media, and inexpensive, sterile, disposable supplies from commercial sources, it appeared that a simplified cell culture system which could be used by undergraduates in investigative laboratories might be developed.

We have tested several permanent cell lines and have found that most of them are satisfactory. Don hamster cells, obtained from the American Type Culture Collection Cell Repository, seem to be the most satisfactory because their chromosomes are large and constant in number. These large, fibroblast-like cells proliferate well on L-15 (a commercially available medium developed by Leibovitz, 1963) supplemented with serum and antibiotics. This medium is superior to other commercially available ones because it maintains proper pH in equilibrium with the atmosphere, thus eliminating the need for a CO_2 incubator. When purchased in large quantities, it costs only $0.25/100 ml. Typically, each student will use only 100 ml/week during the semester.

We have also found that primary cultures from a variety of embryonic and adult tissue may also be established in this medium. Five-day chicken embryos are a very useful source of cells for this purpose. For many experiments, however, primary cultures are not as satisfactory as the permanent cell lines because of their heterogeneity and lack of proliferation after several transfers.

The cells are cultured in inexpensive, sterile prescription bottles and on cover glasses in petri plates. The bottle cultures are ideal for routine maintenance and analysis of growth, while cover glass cultures are more suitable for high resolution and phase contrast microscopic studies.

This permanent equipment required for the laboratory includes an analytical balance, incubator (egg incubators are satisfactory), water deionizer, Millipore filter, and autoclave. Also available in the laboratory are microscopes (phase, inverted, and bright field), dust shields constructed of plate glass supported by fruit jars, burners, and basic supplies such as petri plates, disposable syringes, and staining dishes. A laboratory could easily be equipped in this manner for $5000 and would accommodate 75 students per semester.

Currently, at the beginning of the course, I present illustrated lectures on the basic techniques required in preparing media and glassware; establishing, maintaining, and transferring cultures; determining growth rates; and preparing cells for microscopic examination. Specific procedures which can be used to examine cells with phase microscopy, to determine karyotype, and to show the location of organelles and macromolecules are outlined for students. Procedures for measuring metabolic activities would be desirable but have not yet been developed.

An illustrated handbook describing the basic procedures is provided for each student.

Students are asked to practice, at their own pace, these basic techniques until they are familiar with them and proficient in their use. Most students spend about half the semester in acquiring the necessary proficiency. It is not necessary for me or a laboratory instructor to be present in the laboratory at all times during this phase of the course, but students do need to know where they can get in touch with the instructor for assistance.

Although this phase of the course is not unlike traditional student laboratory courses in techniques, it seems to capture a good deal more enthusiasm than the earlier courses did. There may be several reasons for this. The techniques of cell culture are challenging and new for almost all students. The techniques are not viewed as ends in themselves but as a first step to investigation. Students know that they can proceed at their own rate and realize that as soon as they develop proficiency they will be able to investigate a problem of their own choosing. This phase of the course is sufficiently "cookbook" and the ends are so obvious that no cultural shock problem is encountered. By mid-term, most students have developed enough self-confidence and understanding of basic procedures to be able to proceed with the planning and execution of an investigation.

Selection of a problem to be investigated does, of course, present difficulty for some students. We make available to them copies of *Tissue Culture Abstracts*, which leads them to the most current literature. Some of the student investigations grow out of observations made or difficulties encountered during the "practice" section of the course. For example, one student last term investigated the "Effect of Exposure to Room Temperature on the Average Number of Nuclei per Cell." The student doing this investigation had, during the initial part of the course, accidentally left her cultures out of the incubator for several hours. Subsequently, she noticed that although the cultures had survived the exposure to cold, there seemed to be a high frequency of multinucleation present. She felt that perhaps the exposure to cold had uncoupled karyokinesis from cytokinesis. Therefore, she designed an investigation to determine if there was any correlation between time of exposure to cold and levels of multinucleation.

Sometimes, investigations grow out of interest generated outside the course. For example, a student interested in tropical fish culture decided to use cell culture techniques to determine the chromosome number in two species of live bearers which were superficially very similar. He hoped, as a result, to determine if their similarity was due to close evolutionary relationship or convergence. Currently, students show great concern about the effects of drugs and environmental pollutants. Many investigations grow out of this concern.

Throughout this phase of the course, individual help is required in statistical analysis of data, redesign of experiments, and use of the library. By the end of the semester, most of the students had progressed to a point where they were able to present an acceptable paper at our course symposium. If time permitted, I think an earlier presentation of results, at about the time when the first data are coming in, would be very beneficial to all.

In conclusion, the development of a suitable system for use in undergraduate laboratory investigation courses in cell biology has produced the following results:

1. Students develop competence in skills which are applicable to a wide variety of biological phenomena. These include the preparation of reagents and media, cleaning and sterilization of equipment, sterile technique, microscopy, preparation of permanent slides, determination of population growth, design of experiments, sampling techniques, recording of data, statistical analysis of data, use of technical literature, and preparation of scientific reports. Students do not seem to consider the learning of these skills as "busy work," however, because most of them are learned as a natural part of preparing and conducting an investigation in which they are interested.
2. Students get a "feel" for cells as living, metabolizing units which are sensitive to their environment rather than simply as stained structures on microscope slides.
3. Students get to participate in an activity which is at the fore of current biological investigation. Since there is such an active literature in cell culture, they can quickly see that their own investigation is related to that of practicing research biologists.
4. All students have an opportunity to learn about the limitations, problems, and excitement of scientific investigation, and some are able to identify and get started on scientific problems which are worthy of further investigation.

AN INVESTIGATIVE LABORATORY IN CELL PHYSIOLOGY*

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The objectives of the investigative laboratory in cell physiology at Earlham College are to involve students with and to improve their competence in all facets of the process of experimental investigation. These include attaining familiarity with relevant literature; identifying and defining problems for investigation; formulating testable hypotheses; designing experiments to test hypotheses; executing experiments; interpreting experimental results; and communicating procedures, results, and conclusions. It is not only important that students develop competence in these areas, but that they also *perceive* that they have developed such competence. Accordingly, implicit in the objectives is our desire for students to develop *confidence* in their abilities to function as competent investigators.

Operationally, competence and confidence are best obtained by doing; simply having the students become involved in the process of investigation is undoubtedly our most effective "method." However, contact with the instructor — a more experienced investigator — is also important; frequent interaction with and feedback and support from the instructor, at all stages of the investigation, can greatly facilitate the attainment of the objectives. Furthermore, confidence in his investigative abilities seems to come more readily when the student brings his investigation to a successful conclusion. The approach described in this article was designed with these considerations in mind.

The first 3 weeks of the 10-week term constitute an introduction to three areas (mitochondrial metabolism, enzyme activity, active transport) of experimental investigation. The students spend a week in each of the areas, working through an exercise (I refuse to call it an experiment) directed in admittedly "cookbook" fashion by a mimeographed handout and supervised by the instructor. The purpose of this introductory phase is to instruct the students in techniques and familiarize them with procedures so that they will be better able to design their investigation.

The fourth week and part of the fifth are spent in the library and in the instructor's office. After choosing one of the three areas for investigation, the students, working in self-selected groups of one to three, research their topic in the library, gradually narrowing it down (often aided by frequent brief consultations with the instructor) until they have a problem of a scope suitable for investigation in the time allotted. (By the time they take this course, the students have become rather adept at library research strategy and the use of *Biological Abstracts* and *Science Citation Index* — see the article by Kirk, Chapter 15.

By the middle of the fifth week, each group submits a "pre-lab" — in effect, the introduction and methods sections of its paper. This includes a

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*Originally published in CUEBS NEWS, June 1971.

brief review of relevant previous work; an hypothesis or a statement of a problem, with justification; and a detailed statement of experimental design. The latter is probably the point where involvement by the instructor is most crucial and most fruitful. Designing experiments capable of answering questions which test hypotheses is often a difficult undertaking. The methods portion of the pre-lab frequently needs some reworking, and the instructor must help the student see how to devise an adequate control, determine the number of replications necessary, decide on appropriate concentrations, etc.

Equipped with a solid experimental design, the groups begin laboratory work on their projects in the fifth or sixth week. At least 5 full weeks are thus available for laboratory work on the project. The amount of student-instructor interaction during this phase is, of course, quite variable, some students consulting the instructor every day or two, others very infrequently. However, one further occasion for feedback is programmed into the course. During the eighth week each group submits an informal progress report, consisting of its results to date and an interpretation of them in light of the hypothesis. This report also contains a pre-lab for subsequent experiments, since some groups find it necessary by this time to further refine, modify, or extend their hypotheses.

A formal report, in the usual style for a journal article, is submitted by each group at the end of the term. Most of the reports are exemplary, both in their form and in the thought that goes into their preparation. However, on infrequent occasions there is, even at this stage, a marked need for revision. In these instances, the student is given an "Incomplete" in the course pending the submission of an acceptable report.

In summary, the format is designed to involve students sequentially in the various phases of experimental investigation. In addition to numerous informal opportunities, formal occasions of student-instructor interaction are built into the program. Examples and additional commentary are provided below.

The three investigational areas, for which students are prepared by the initial exercises and in which they are encouraged to conduct their projects, have been standbys of cell physiology laboratories for a long time, yet they are readily adaptable to an investigative laboratory approach. They are listed below, along with brief outlines of basic procedures.

Mitochondrial metabolism. Mitochondria are isolated from rat liver by a standard procedure of homogenization in a sucrose-EDTA solution and differential centrifugation. The respiratory activity is then determined by measuring oxygen consumption in a Warburg manometric apparatus. The main compartment of the flask contains pyruvate as substrate, phosphate buffer, NAD, mitochondria, and a hexokinase ATP-glucose mixture as an ADP-regenerating system. A piece of filter paper soaked with potassium hydroxide solution is placed in the center well to absorb carbon dioxide. While not included as part of our introductory exercise, it is pointed out that analysis for inorganic phosphate could be done to follow the course of oxidative phosphorylation.

Enzyme activity. Good success has been obtained with wheat germ acid phosphatase and with yeast invertase, both of which can be readily assayed colorimetrically; phosphatase activity is assayed using the Fiske-Subba Row procedure, and invertase by the dinitrosalicylic acid method. In my experience, invertase has given results which are more reproducible, whereas the phosphatase allows a greater range of possibilities for studying substrates or inhibitors.

Active transport. A bag is made from the skin of a frog's leg, into which is pipetted a dilute Ringer solution. The bag is tied and immersed in a test tube containing the same solution. This assembly is placed uncovered on a wrist-action shaker and shaken for several hours, after which aliquots are removed from the bag and the surrounding medium. After appropriate dilution, sodium ion concentrations are determined by flame photometry.

Each of these procedures can lend itself to a wide range of modification, and is thus amenable to the design of experiments to test a variety of hypotheses. The procedures are given here and are presented to the students during the introductory phase of the laboratory, not to pose as experiments in themselves or to closely specify subsequent studies, but rather to suggest approaches which can be fruitfully employed in the investigation of interesting cellular phenomena.

Each of the three general procedures described in the preceding may be employed, with modification, to investigate a wide range of interesting problems. For example, studies in mitochondrial metabolism which may be done include the determination of P:O ratios in the presence of various substrates, inhibitors, or artificial electron donors or acceptors; comparisons of respiratory activity of mitochondria isolated from different tissues, or from different developmental stages of the same tissue; studies of respiratory control through the use of uncouplers of oxidative phosphorylation and enzymes with ATPase or kinase activity; or determining the relative effects on Krebs Cycle and electron transport activities of mitochondrial disruption.

Enzyme studies, using the enzymes referred to above or others, could entail determining K_m values with different substrates, studying the effect of limited proteolysis of the enzyme on its activity, ascertaining the extent to which the substrate protects the enzyme from denaturation, determining whether a particular enzyme is allosteric, or doing kinetic studies to determine the types of inhibition shown by certain inhibitors.

Students studying active transport might carry out investigations to determine the relationship between sodium ion concentration and its rate of transport; to identify the nature of the metabolic energy source for the transport process; to determine whether ions other than sodium are transported, and if so, whether it is possible to dissociate the sodium pump from the other pump(s) or investigate the action of pharmacological agents on active transport.

Obviously, there is quite a range of possibilities for interesting and feasible studies. Below are listed the titles of a few investigations which have actually been carried out — in many cases with results of considerable interest — during the past 2 years. (In a few cases, the titles have been modified to make them more descriptive of the study.)

The Effects of Detergent and Osmotic Disruption on Mitochondrial Respiration.
Respiratory Control in Rat Liver Mitochondria.
Glycolysis and Respiration in Yeast.
An Investigation of Ethanol Metabolism in Rat Liver Mitochondria.
Effects of Freezing and Thawing on the Relative Rates of Oxidation of Pyruvate and Succinate in Rat Liver Mitochondria.

On the Energy Source for Inorganic Phosphate Transport by Rat Liver Mitochondria.
Reactivation of Heat-inactivated Acid Phosphatase.
On the Number of Qualitatively Different Active Sites in a Crude Preparation of Wheat Germ Acid Phosphatase.
Effects of Manganese Ion on Beef Liver Glutamate Dehydrogenase.
Allosteric Nature of Brain Monoamine Oxidase.
Localization of the Sodium Pump in Isolated Frog Skin.
Active Transport of Glucose Across the Frog Skin.
On the Necessity of Oxidative Phosphorylation for Active Sodium Ion Transport.
A Comparison of the Rates of Oxygen Consumption by Sodium Ion-transporting and Non-transporting Frog Skin.
Effects of Phenobarbital on Active Sodium Ion Transport by Frog Skin.
Active Transport of Sodium Ion by Frog Skin From Which the Epidermal Layer Has Been Removed.

While recognizing that the evaluative comments an instructor gets about his course are generally skewed toward favorability, I nevertheless feel that the investigative laboratory component of the course has been well received by the students. This judgment is based on oral comments from students in the course reflecting both their reactions and what they believed were the feelings of their classmates, on comments from other students and faculty members concerning remarks they had heard about the laboratory, and on anonymous written course evaluations submitted by students at the end of the course.

Nearly all of the students felt that it was a good idea to be introduced to the three investigational areas from which to choose their projects. They appreciated having a starting point, feeling that the guidance provided in this way saved them a lot of time that otherwise would have been largely wasted in attempting to choose an area in which to do a project which was both feasible and interesting. All were glad to have had complete freedom in choosing a problem within the area in which they decided to work. Nevertheless, many approved of my decision to let students having a strong desire to do so work on projects in other areas.

Without exception, students felt that there were ample opportunities to do interesting investigations within their project areas. They rated their project in particular, and the investigative laboratory experience in general, much more interesting and enjoyable than their laboratory experiences in most other courses.

The pre-lab was considered a very effective device for insuring that students focus early on what they are going to do, get into the literature, and plan carefully. Also receiving favorable comment was the interim progress report, both because of the incentive it gave to complete the work as early as possible, and because it was an opportunity to receive helpful criticism and suggestions from the instructor.

In terms of the objectives stated in the introductory section, most of the students felt that their experience had been reasonably successful in helping them in improving their abilities to identify problems, formulate hypotheses, and design experiments. However, they felt they had made less progress in the subsequent phases of the investigative process. Whereas a majority reported that their ability to function independently had improved, only a few claimed to have achieved confidence in the use of investigative skills.

Perhaps one of the most cogent comments on the investigative experience, the essence of which was expressed by several students, was this:

> It revealed to me what scientific research can really be like — a lot of hard work before appreciable results are obtained. I also came to see it as a challenge in which you become very self-motivated to dig into a problem to see how far you can go and how much you can learn. It's sort of like reaching out to find where your limits are and then pushing to expand them. I found out that one must be flexible in his thinking, not hesitating to use imagination, and above all that persistence is a prerequisite for results.

As I see it, the most fundamental difference between the approach used here and that used in most other investigative laboratory programs is the absence, in my approach, of complete freedom for the student in choosing his area of investigation. However, I feel that this restriction is more than compensated for by some distinct advantages:

1. Since the student is working in an area where we are familiar with the experimental system and have eliminated some of the major bugs, chances are good that the investigation will be successful (as most of them have been). I feel this to be an important point, too frequently neglected in other treatments of the investigative laboratory. A good opportunity for success and the positive reinforcement that comes with it are very desirable features of an investigative laboratory, especially for the development of confidence. This is particularly important for students who are involved in their first investigative situation. (I realize that there is educational value in failure, too, and that it would be a misrepresentation to portray all scientific endeavors as successful. Nevertheless, I feel that these goals are less important than the favorable attitudes toward investigation which will more likely come with success, so I am willing to defer them until later in the student's career.)
2. The experimental areas used here afford opportunities for many interesting and conceptually rather sophisticated hypotheses which are well based in the literature and are relatively amenable to experimental investigation.
3. A preliminary directed exercise does a much better job than simple reading would in allowing students to gain a working familiarity with a procedure and its possible applications, thus facilitating the design of feasible and meaningful experiments.
4. Many students are paralyzed for a time when given complete freedom; the availability of a starting point and guidelines for an investigation provides some helpful focus.

Students having a strong desire to carry out a project in a different area are allowed to do so if they can make a good case for its feasibility in terms of both available equipment and likelihood of success. One example is a project done last year by two students who, while interested in metabolism yet opposed to killing rats, investigated the effects of inhibitors on fermentation in yeast. Furthermore, they tried to develop some of their procedures for use as another investigative area. While only partially successful, their project is being continued by another student this year; hopefully it will be available next year as a fourth investigative option.

Some brief comments on two other features of our approach:

1. The expectation of a detailed experimental design in the pre-lab forces students to think through their experiments in advance and plan carefully, so that their decisions are made before going into the laboratory, rather than on a more-or-less *ad hoc* basis in the laboratory.
2. The interim progress report affords an important opportunity for feedback and correction; it helps avoid that uncomfortable situation in which the final report is the instructor's first as well as last look at the student's work.

Finally, repeating an opinion stated earlier, *involvement* is probably the most important ingredient for the attainment of the goals of the investigative laboratory. To the extent that this is true, probably any investigative experience, regardless of format, will go a long way toward achieving the objectives.

The enrollment in cell physiology is generally 30-35. Most of the students are juniors, but there are usually a couple of sophomores and six or eight seniors. Backgrounds vary widely; except for general biology, introductory chemistry, and one term of organic chemistry (which are prerequisites waived only infrequently), students may have had from zero to as many as eight or ten other biology courses, and from no other chemistry up to advanced organic, kinetics, or thermodynamics.

The course, which is given once a year in a 10-week term, consists of the laboratory component described here and a discussion-reading-writing-lecture component. Students take three courses a term, so cell physiology constitutes about a third of an average course load. The time spent per week in connection with the investigative project — in laboratory and library — averages about 10-12 hours.

The entire cell physiology course, of which the laboratory is one part, constitutes about half the teaching load for one faculty member during the term in which it is given. The faculty member is assisted by an upperclassman who sets up equipment, makes solutions, and sometimes helps instruct in the use of equipment. Since the time the faculty member spends in connection with the lab is largely fragmented into frequent and brief periods of consultation with students, reading pre-labs and progress reports, and so on, his expenditures are difficult to estimate — my guess is that about 8-10 hours per week are required for the laboratory.

The investigative laboratory represents a major step along the route from science appreciation to science in the biology curriculum. I am pleased to have traveled this far, I can't imagine returning to my point of departure, and I look forward to the journey ahead.

AN INVESTIGATIVE LABORATORY IN THE MORPHOLOGY OF VASCULAR PLANTS

In the summer of 1970, Dr. Marian J. Fuller attended a short course in the Investigative Laboratory which was sponsored by CUEBS in cooperation with Marquette University. Partly as a result of that experience, she developed and offered an Investigative Laboratory on the Morphology of Vascular Plants. While that course was being offered, Robert G. Thomson, Director of the short course, visited her at Murray State University, Murray, Kentucky, where she teaches in the biology department. The following description of the course is based on Dr. Thomson's observations.

Biology 510, Morphology of Vascular Plants, is offered for four credit hours and consists of two 1-hour lectures and two 2-hour laboratory periods per week. Enrollment is usually 10-12 students, all of whom are juniors, seniors, or graduates. The stated purpose of the lectures is to help students gain some insight into various evolutionary trends in the morphology of vascular plants. The following topics are considered.

- Possible ancestors to vascular plants
  - Problems faced by the earliest land plants
  - Significance of alternation of generations
  - Evolution of the sporophyte
    - Evolution of the root
    - Evolution of the stem
    - Evolution of the leaf
    - Evolution of the stele
    - Evolution of the xylem
  - Evolution of the reproductive systems
  - Significance of homospory and heterospory
  - Evolution of the male gametophyte
  - Evolution of the female gametophyte
  - Evolution of the strobilus
  - Evolution of the flower
  - Evolution of pollination mechanisms
- Environmental influences on plant structures
- Significance of dispersal mechanisms
- Evolution of specific plant groups

The purpose of the laboratory portion of the course, however, is to have the student become personally involved in the processes by which new knowledge concerning the morphology of vascular plants is generated. During the first 4 weeks of the laboratory, the structure of ferns, cycads, ginkgo, conifers, and flowering plants is reviewed. One purpose of this introductory phase is to illustrate the concepts and structures which are concurrently being described in the lecture. The other, and perhaps more important, function of this review is to provide a context in which to discuss and practice the location and use of library resources, keeping of research records, application of microtechniques, identification of relevant questions for investigation, the delimiting of research problems, and generation of hypotheses. After the fourth week, students are expected to identify and work independently on projects related to plant morphology. Most elected studies in which they became interested as a result of their readings, although some picked up leads from the teacher and some projects evolved from the laboratory work during the first 4 weeks. The individual work continues for a 9-week period. Guidance to students during this phase is provided by individual conferences.

Some of the investigations carried out included:

- Effects of a nematode on root development of tomato
- Development of sporangia in *Psilotum*
- Effects of phosphates on the development of duckweed
- Effects of gibberellic acid on shoot apices of *Psilotum*
- Seed germination and morphological and anatomical development of *Nelumbo* seedlings

Effects of pH on the rate of mitosis in shoot and root apices in the common garden pea
Development of male and female gametangia of a fern
Floral development in *Coleus* and one other species
Development of secondary roots in several species of flowering plants.

The last 3 or 4 weeks of the laboratory are spent in preparing reports of the work. Oral presentations of 15-20 minutes duration were presented to students and faculty at a mini-symposium.

All the students taking the course were interviewed and all except one were enthusiastic about the I-Lab approach. The one dissenter felt it focused his attention on too narrow an area — he wanted to learn, in detail, the anatomy and morphology of all vascular plants.

Although generally enthusiastic about the course, the instructor felt the need for additional library facilities, more adequate greenhouse space and staff, and more personal experience with the various methods of experimental biology.

A STUDENT INITIATED, INTERDISCIPLINARY INVESTIGATIVE LABORATORY IN ECOLOGY

In 1970, Dr. Allen W. Knight wrote CUEBS describing a problem-centered, interdisciplinary course which had been initiated at the University of California, Davis, in response to a request from students who wanted to get involved in finding a way to improve the water quality in a recently constructed lake. The following description of the course which developed is based on that correspondence.

A man-made lake had been constructed as part of a recreation project on the Davis Campus. After construction was completed and water was allowed to fill the lake, numerous environmental problems resulting from man's activities became apparent. Specifically, runoff from cattle pens, highways, lawns, cropland, etc., introduced sufficient quantities of nutrients, bacterial contamination, and silt into the lake to create a series of undesirable events.

A student contacted Dr. Knight and inquired as to what could be done to improve the water quality in the lake. It was quickly discovered that historical information on past conditions was not available nor were there data that would permit interpretation of the existing conditions, prediction of future problems, or the possible success of potential management techniques. The student indicated interest and concern among several fellow students and inquired about the possibility of establishing a group research program aimed at the intelligent management of a water resource.

The number of participating students quickly grew to more than 20. The students were allowed to enroll for variable credit up to 5 hours. A student coordinator was selected to manage the overall operation. The students were subdivided into areas of specialization and a chairman selected for each group. The subdivisions read something like the campus general catalog: Aquatic Pest Control (Entomology), Water Chemistry, Bacteriology, Hydrology, Zooplankton Studies, Phytoplankton Studies, Microclimatology, Environmental Toxicology, Environmental Planning, Parasitology, Fish Management, and Engineering Problems.

The students, in addition to data collection, progressed well into a search for constructive remedial methods to overcome the problems they had isolated in the lake. Pilot studies were initiated dealing with the removal of nutrients from water, the physical separation of algae from water, and overcoming the deleterious impact of man's activities on the lake.

The program created considerable interest among undergraduate students disenchanted with book learning and education in general. The class offered an opportunity to put its education to a practical test on a current problem and learn firsthand the problems associated with management of a natural resource. The class also succeeded in introducing engineering students to the environmental aspects associated with managing impoundments after they go into operation. These students learned biology, while students from other disciplines learned to appreciate problems associated with the engineering aspects of correcting existing deficiencies.

Based on the continuing interest, the class has been offered each quarter, with returning students training the new students entering the class. The class meets for one hour per week to discuss research design, problems encountered in initiating research programs, lake ecology, and ultimately the results obtained in the various field studies. For the field work, the class is subdivided into groups of two to eight members to form research units, with each evaluating a discrete segment of the lake ecosystem. The overall research objective of the laboratory is (1) to document the daily and seasonal changes in the biological, chemical, and physical parameters of the lake; (2) determine the procedures necessary for the intelligent management of the water resource; and (3) suggest the best possible solutions and alternatives in order to maintain the lake in the best possible condition consistent with multiple use.

Each study group (e.g., bacteriology, water chemistry, engineering problems, phytoplankton, or zooplankton) selects a chairman from within the group who is responsible for the needs and organization of his group. Collectively, the charimen relate their needs and accomplishments to the student coordinator, who in turn is responsible to the staff member in charge of the course.

During the initial week of each quarter, the students reorganize their groups and train the new recruits. Each group undertakes a research program designed to either provide information related to a specific problem or to devise or test a specific management technique. Many of the projects grow out of apparent conditions that pose either health or environmental hazards. For example, projects dealing with bacteria, algae, water chemistry, and hydrology were initiated as conditions of excess algal growth and bacterial contaminations were noted as potential hazards.

Other projects result from interest generated in environmental problems related to lake management and future planning. For example, a group of students conducted a survey program designed to determine present and future needs of the lake recreation complex. Their findings resulted in isolating several needs that had been previously overlooked in the lake operation.

The students not only learn by conducting actual field and laboratory studies, but come to appreciate the value of the multidisciplinary approach to the management of an ecosystem. The class has attracted students from such diverse departments as Engineering, Home Economics, Psychology, Zoology, Soils, and Environmental Planning.

At the termination of each quarter, the various groups jointly prepare a report on their findings. Experience in the writing of a scientific paper is coupled with acquainting the student with the literature in the area of his project.

According to Dr. Knight, the brief experience with this mode of teaching shows benefits to both students and staff in the following ways

1. Involvement — The classic educational situation of "playing house" — working on "pretend" problems — is replaced by working on a real problem to produce real results that will be put to real use. Additionally, this problem is in the field of environmental quality, in the spotlight of today's urgent needs. Understandably, the individual becomes involved, sometimes passionately so, in the work. The student further becomes a catalyst in bringing about staff enthusiasm and orientation to interdisciplinary efforts. Although this learning experience is for upper division students, arrangements have been made for a few lower division students.
2. A broadening — Working with other people in a wide range of disciplines familiarizes the student with the philosophy and problems of the team approach. It gives him experience in the cooperation and interdisciplinary attack demanded by the complexities of the world's affairs today.
3. Understanding — The student begins to emerge from the normal bewilderment of the young. A notion of himself and his possible place in the world begins to take form as he actually participates in the problems of the society in which he lives. He matures more rapidly from a new sense of partnership with staff members.
4. A head start — The transition from green student to experienced employee is accelerated by working in an atmosphere of real accomplishments in the face of the uncertainties and practical compromises inescapable in the real world.
5. Analysis and synthesis — Instead of considering a narrow problem in a single small field, the student is faced with a real situation — a problem that must be analyzed into many subproblems, and solutions that must synthesize a practical attack on the whole.
6. Initiative — Student initiative is challenged by embarking on a project with no procedure specified, working with inadequate funds and materials and equipment, on problems to be discovered and stated by the students themselves. This is usually a revelation to even the most experienced and competent students.

AN APPLICATION OF THE INVESTIGATIVE LABORATORY TO PLANT PHYSIOLOGY

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I first offered an undergraduate plant physiology course in 1964-65. At that time, the major emphasis was upon transmission of basic information, with discussions and examinations focusing on solution of problems related to the content of the lectures, reading assignments, and a series of laboratory exercises. The changes which have occurred in the course during its 7-year lifespan have transformed it into a laboratory-based course focusing on student involvement in investigation. The following description indicates the nature and structure of the course as it was offered at Earlham College during the last 2 years.

The general objective of the course is to involve students in investigating problems in plant physiology and thereby to assist them in the following ways:

1. To understand what a plant physiologist does.
2. To participate in an interdisciplinary approach to the solution of problems in plant physiology.
3. To increase their self-reliance.
4. To learn the routine and frustration of investigation and to experience the thrill of creating knowledge.

These objectives are intended for both the potential biologist as well as the student without professional ambitions in the life sciences.

Students who enroll usually have taken three 10-week terms of chemistry and three or four upper division courses in biology in addition to the introductory biology survey. The plant physiology course is an elective although it can be used to fulfill the biology department's degree requirement for one plant science course. Enrollment is usually between 10 and 20. The postgraduation fate of the students who have taken the course over the past 4 years is indicated in Table 1.

Table 1. Activities after graduation of students enrolled in plant physiology, 1967-70, inclusive. Data are per cent of total enrollment for the 4 years.

Activity	Per Cent
Graduate School	39.0
Medical or Dental School	12.2
Secondary Teaching	2.4
Armed Services	4.8
Not graduated yet	14.6
Unknown	26.9

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In 1970-71, each student attended two 1-hour discussion periods and one 3-hour laboratory period per week. In prior years, one or more lecture periods were scheduled in lieu of discussion.

The umbrella which serves as a focus for the initial phase of the course is "growth and development of *Zea mays.*" Students are introduced to some of the principles and investigative procedures of this area by the following series of readings, exercises, and discussions:

I. Sigmoid growth curve: Students germinate corn seeds. Dry weight data are taken to construct a growth curve in a form acceptable for publication.
II. Growth regulation: Prior to the course, corn is grown and treated with varying concentrations of gibberellic acid. Students decide how to take data and analyze a portion statistically.
III. Varieties of corn: Three varieties of corn are planted prior to the course. The students collect data on various aspects of the phenotypes and analyze the data statistically to determine if there are significant differences between the varieties of corn.
IV. Bioassay: Corn coleoptile straight growth test is used to prepare a standard curve.
V. Lecture and discussion of chromatography and resin columns.
VI. Lecture and discussion of tissue culture techniques.
VII. Discussion of collecting and organizing data.
VIII. Discussion of collecting and organizing information from the literature.
IX. Discussion of problem selection.
X. Lecture and discussion on the literature of plant physiology and library usage (done by Thomas Kirk, librarian — see Chapter 15 for methods used).

As part of II and III, students are introduced to analysis of variance, "t" test, and coefficient of correlation and regression. Included as part of most of these activities is a resumé of the particular literature pertinent to the growth and development of *Zea mays.* Other techniques needed for particular investigations are taught when needed and because of the background of students when they enroll, it can be assumed that they know how to prepare solutions, make dilutions, use balances and spectrophotometric equipment, and use the library. A textbook is used to provide additional information and a bibliography.

In addition to transmitting the concepts and techniques which they will use in their independent investigations, this series of activities indirectly serves to suggest to students some areas of study which they may wish to pursue. It should be emphasized, however, that *each student* decides and defines the area of his investigation — his natural curiosity is turned loose. Some of the topics selected as individual projects in the past 2 years have been: the effects of indoleacetic acid on adventitious rooting in *Phaseolus vulgaris*; the effect of varying concentrations of phosphate on *Lemna minor*; photoperiodic stimulation of indoleacetic acid production in radishes (*Raphanus sativus*); the role of the constitutents of coconut milk in vascularization in callus tissue; the effect of chromate on the growth of *Phaseolus vulgaris*; the effect of 2, 4-D on chlorophyll content of *Phaseolus vulgaris*; influence of amino acids of the glutamic acid family on the growth of *Phaseolus vulgaris*; the effect of root temperature on dry matter

Table 2. Sample of the number of references consulted in student investigations

Student	Year Course Taken	Topic	Number References Read	Number References Cited
1	1967	The effect of gibberellic acid on the growth of cucumber seedlings in vitro.	60	28
2	1967	The effect of coconut milk on carrot callus growth.	59	29
3	1967	The effect of light and gibberellic acid on stem elongation.	53	31
4	1970	The effects of indoleacetic acid on adventitious rooting in *Phaseolus vulgaris.*	31	8
5	1970	Photoperiodic stimulation of indoleacetic acid production in radishes (*Raphanus sativus*).	missing	12
6	1970	The role of the constituents of coconut milk in vascularization of callus tissue.	73	50

accumulation in *Phaseolus vulgaris*; and the role of exogenous carbohydrates in the growth of *Phaseolus vulgaris*.

Although it is not the stated purpose of this course to provide a broad "coverage" of plant physiology, I have found that when students present their reports at the end of the term that this is usually achieved, indirectly, through the reading they do as part of their investigation. To illustrate this point, the following outline indicates the areas covered by three students in the background reading they did in preparing for their individual projects.

1. *The role of exogenous carbohydrates in the growth of Phaseolus vulgaris:* seed germination; photosynthesis; intermediary metabolism; plant anatomy, growth, and development;
2. *The role of the constitutents of coconut milk in vascularization of callus tissue:* cell physiology: intermediary metabolism; hormones; organic nutrition, mineral nutrition;
3. *The effects of indoleacetic acid on bean leaf abscission:* hormones; plant anatomy; organic nutrition; photosynthesis; mineral nutrition.

In addition to this general background reading, each student consults numerous specific references related to his individual project. Table 2 indicates the number of such references used by some typical students in their investigations. Although none of these students covered what could be called the normal informational content of a plant physiology course, they did have a real reason for reading this material and a framework to hang the information on – their investigation.

In general, I have found that the investigative laboratory approach is a very satisfactory and exciting way to teach plant physiology. Success of this approach appears to be founded upon: (1) thorough preparation in the use of the library; (2) adequate technique preparation; (3) freeing the student so that his curiosity will take the lead; and (4) helping the student realize that he is capable of conducting an investigation. As a warning, however, I should point out that from the overall perspective of an undergraduate biology curriculum, this manner of incorporating the investigative laboratory in the curriculum may pose some difficulties. At Earlham, for example, the idea of this type of laboratory has become popular. As a result, two other biology courses and two chemistry courses now attempt to involve students in independent investigative projects. The students say that this is too much investigation – that they do not need that many investigative experiences as undergraduates. Perhaps this indicates that overall curriculum planning must give consideration to the types of activities in which students will be engaged as well as the content to which they will be exposed.

8. Investigative Laboratories at Field Stations

The flexibility of schedule, availability of living materials, favorable faculty-to-student ratio and *esprit de corps* which usually prevail at field stations create an environment which is particularly suitable for involving students in investigation. But the total length of time which students can afford to spend at these stations is often limited to a few weeks. As a result, it is extremely important that the undergraduate programs at the station be designed to prepare students to become quickly and significantly involved in investigative activities which take advantage of the rich opportunities which are available. The investigative laboratory approach appears to be particularly useful in this regard. The following two examples describe how the I-Lab model has been applied at two marine stations.

HOPKINS MARINE LABORATORY

Donald P. Abbott and his colleagues at Hopkins Marine Laboratory have offered an investigatory-type laboratory course in marine biology at the station in Pacific Grove, California, since 1963. The manner in which guided field work, lectures, discussions, team exercises, and individual study have been woven together is particularly interesting. The influence of the course on students and community activity is remarkable. Some of the research papers produced by those enrolled were published in supplements to volumes 6 and 11 of *The Veliger* and others have appeared individually in a variety of national and international journals. A description of the course as it was offered in 1963 appears as an introduction to the volume 6 supplement. That description is reprinted below with the permission of the authors and publishers.

AN EXPERIMENT IN UNDERGRADUATE TEACHING AND RESEARCH IN THE BIOLOGICAL SCIENCES*

Donald P. Abbott, Lawrence R. Blinks, and John H. Phillips
Hopkins Marine Station of Stanford University
Pacific Grove, California

The papers which form the bulk of this supplement to the *Veliger* are the outcome of an experiment in undergraduate teaching, conducted at the

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Hopkins Marine Station during the spring of 1963. The class, a group of 25 Stanford University biology majors, spent the entire 10-week quarter at the Marine Station, enrolled in a new 15-unit course called "Problems in Marine Biology," which met all day, 5 days a week.

The course was planned and conducted by a three-man faculty which included an invertebrate zoologist (Abbott), a general and plant physiologist (Blinks), and an immunologist-biochemist (Phillips), aided by a teaching assistant with experience in invertebrate development (M. Hadfield). Our general objective was to give a limited group of undergraduates an opportunity to make concentrated studies and to engage in research on individual problems in the area of marine biology.

Early in the planning stages it became clear that the faculty members were in essential agreement on certain features of the approach to be used:

1. We would plan to start with a broad but brief survey of the marine intertidal zone. Thereafter we would concentrate our attention on a single species, which would be studied in detail in both cooperative and individual research projects. By investigating many different aspects of a single species, we hoped to get broad views and insights as well as understanding in depth.
2. We would make our initial approach as naturalists, looking first at nature in the field. As questions and problems arose, we would try to combine the approach of the field observer with that of the experimentalist and laboratory biologist, making an effort to avoid any dichotomy between observation and experiment, or laboratory and field.
3. We would try to be holistic in our approach, ignoring the fact that biology has been sliced up, for practical convenience, into a number of fields and levels of organization, and considering only that the biologist sees in nature a nearly endless supply of questions and problems, and that he has at his disposal a wide variety of concepts, methods, and tools which he may use in trying to answer or solve them.
4. Finally, we hoped to plan and conduct the work in such a way that over the 10-week period the students would experience, on a miniature scale, not only the activities but also the inner feelings of a scientist engaged in research: the stimulus that comes from realizing how little man really knows and understands; the struggle to formulate a clear problem and a line of attack; the excitement and joy of inquiry and discovery; the intense intellectual and emotional commitment of the scientist to his research; the difficulties and frustrations that may accompany the work; the pleasure of sharing results with colleagues working along similar lines; the struggle to express the results clearly and concisely on paper; and the profound satisfactions that come from even a modest creative achievement in science.

Our attempts to apply this approach and achieve these ends are chronicled below.

Out of 30 applicants for the course we chose 25, 15 men and 10 women. All had had the minimum prerequisite courses (a year of chemistry, and either introductory botany and zoology or a year of biology), and in addition the majority had studied organic chemistry, comparative anatomy, vertebrate embryology, and one or more advanced courses in the biological sciences. As finally selected, the class consisted of 2 sophomores, 14 juniors, 7 seniors, and 2 beginning graduate students. Their previous grade point averages ran from B plus to C.

Before the first day of work, the faculty tabulated the students' past records, then split the class up into six teams, each with four or five students. An attempt was made to divide up the sexes, the talents, and the course-work backgrounds represented in the class into six evenly matched working groups. Following this, the faculty went out to the Marine Station's shoreline and selected six different field stations or study areas, one for each of the student teams.

We started work during a week of good tides, with low water occurring in the late morning and early afternoon. On the first class day, after registration and orientation, the class was given an introductory lecture on marine plants. Each team was then provided with graph paper and some elementary surveying equipment (stout cord, a line level, a yardstick, and marking materials) and sent to one of the selected field stations with this assignment: survey a profile strip perpendicular to the shoreline in your study area, extending from the highest splash zone out as far as you can get with safety; along this profile, plot the distribution of the common species of intertidal plants present. The teams were told not to attempt to key out species in the field, but instead to collect all of the different kinds of plants present (insofar as these could be recognized by students in the field), to label each type with a number or letter, and to record their occurrence on the profile charts. The teams went to work without further specific instructions, but faculty members observed the field work, made suggestions where these seemed needed, and called attention to things which might be overlooked. In the afternoon, after the rising tide enforced retreat, the teams returned to the laboratory, identified their collections with faculty help, tabulated and compared results, and in class discussion tried to relate differences in the occurrence and abundance of species with differences in habitat.

The second day, after a lecture on common macroscopic intertidal invertebrates, each team worked its profile a second time, this time recording the occurrence and distribution of common benthic animals. The third day, the profile exercise was repeated, the concern this time being the commoner microorganisms, both those in the water and those forming films on the surfaces of rock and weed.

This 3-day survey, though brief and superficial, allowed each student to become intimately familiar with the topography of one small area and allowed him to sample the more abundant species in each of the kingdoms of organisms present. During the survey everyone became familiar with the most conspicuous of the larger intertidal gastropods, the black turban snail *Tegula funebralis* (A. Adams, 1854), though the students were still unaware that we had selected this creature to be the hero of the course.

On the fourth day, the students were given a lecture on the concepts of organism and environment and were sent out on the ebbing tide with a different type of assignment. Each team was told to "describe the population of *Tegula funebralis* in your profile area." No instructions as to what this involved or how one might go about doing it were given. We stated only that there was no single "correct" approach or method of procedure; that each team should discuss the assignment, decide for itself what was essential to a "description of a population," formulate its own methods, and get busy for the rest of the day. The students were also told that after lunch on the following day, each team would be assigned a panel of the blackboard on which to plot what they considered to be the essence of their findings, and that each team should elect one member to report to the class on (1) *what* their team had done, (2) *why* they had done what they did, and (3) what they thought they had found out. The teams went to work. The instructors observed, but tried to avoid making suggestions on what to do and how to do it.

Morning on the fifth day passed with a lecture on the sea as an environment, and in student preparation for afternoon reports. These reports, each delivered for the whole class, were most interesting. No two teams had handled the assignment in quite the same way. For example, one team laid out a line of quadrats, counted and measured all *Tegula* present, then plotted numbers and mean sizes against intertidal elevation and distance from shore. Another team with a different orientation recorded *Tegula* distribution in a semi-quantitative manner along a broad strip, noted that the species population was grouped in discontinuous clusters, set up hypotheses which might account for this curious pattern of distribution, and spent the remaining time in designing and carrying out observations and simple experiments to test these hypotheses.

The student reports brought out numerous provocative observations and raised many questions which the faculty either could not answer, could answer only in general terms, or could answer only in terms of predictions based on knowledge of other snail species. It became clear that, to most of us, *Tegula funebralis* was little more than a black shell; that we knew almost nothing in detail of its food, habits, responses, tolerance limits, enemies, growth rate, life span, reproduction, and a host of other matters. We began to tabulate categories of things we did not know about *Tegula*, and out of this came the program for the work of the next 6 class days.

During this period the tides were poor for field work, and the days were devoted primarily to intensive indoor studies of *Tegula*. Lectures were used to lay a foundation of concept and background information for the practical methods and exercises carried out in the laboratory on the same day. Faculty members alternated in charge of the work, but each attended his colleagues' lectures and observed their laboratory exercises, and each made a real effort to relate his topic of the day to material covered earlier. A brief outline of the program of this part of the course follows (Table 1).

It seems worthwhile here to underline a particularly significant difference in emphasis, separating the present course from the more conventional college biology courses oriented around "principles" of a selected "field," or around particular biological taxa. The organization and stress in these courses generally reflect the viewpoint of the scientist in his capacity as a *teacher*; his stress tends to be on imparting organized knowledge. In principles courses, a firm grasp of the principles is regarded as the important thing; specific examples are regarded as illustrative rather than of great importance for themselves. In courses dealing with a specific taxon, imparting a knowledge of the group is the main desideratum. In both types the scientist, as a teacher, is trying to pass on that material within the scope of the course which is of *general* rather than merely specific significance; he is dealing in statements

TABLE 1

Lecture	Laboratory
Basic molluscan morphology, torsion and its consequences, the early evolution of the gastropods, and the anatomy of the Trochacea.	Dissection of *Tegula,* to work out the gross anatomy.
Physical and chemical factors in the marine environment, tolerance limits of organisms, and the concept of limiting factors.	Observations of responses of *Tegula* to various physical stimuli; determination of tolerance limits for several physical factors.
Energy sources and nutritional types of organisms; biogeochemical cycles; enzyme action in proteases and carbohydrases; methods of determining enzyme action; digestion in *Tegula.*	Determination of food of *Tegula* from gut contents; assays to determine the categories of enzymes present in different segments of the gut in *Tegula.*
Obtaining energy; transport of O_2 and CO_2; the excretion of nitrogenous wastes.	Determination of myoglobin and lactic acid in muscles; determination of hemocyanin; determination of nitrogenous waste products in excretory organs.
Receptors, nervous system, and effectors of *Tegula;* responses of *Tegula* and other snails to predators; responses of commensal species to the *Tegula* host.	Observing and measuring responses of *Tegula* to starfishes and predatory gastropods; measuring responses of *Crepidula adunca* and *Acmaea asmi* to *Tegula funebralis.*
Photosynthesis in marine algae; concepts of standing crop and productivity; intertidal and oceanic productivity; methods of measuring productivity.	Survey of food plant supply for *Tegula* in the field; field determinations of photosynthetic rate using Winkler methods.

describing that part of the behavior of the cosmos or of its parts which seems orderly and consistent. In the principles course, organization is around the principles, concepts, or laws. In the taxon-oriented course, while generalizations are sought, principles may or may not receive emphasis; nevertheless they are always assumed to form a constant part of the background. In courses of both types, the orientation and emphasis is usually that of the scientist-*teacher*, striving to impart organized knowledge and clearer understanding.

Our own treatment of principles and other subject matter in the present course differs from the above. And the difference in treatment reflects the difference in attitude between the scientist in his role as a teacher and the scientist in his role as a *researcher.* The dedicated researcher is not so concerned with the broad and balanced view, and with orderly generalization in matters peripheral to his research; for him the most important thing is the problem under investigation. In the researcher's mind and in his hands, principles, concepts, instruments, techniques, and all the rest of accumulated human knowledge and knowhow became mere tools to be brought to bear on the task of answering his question. All human experience and capability become means, to be applied to achieving his specific ends. The tools, in such a view, have no real value in themselves; those which are immediately useful are used, the others are laid aside.

And so it was in the present course. Our aim was *not* to pass on to the students a better grasp of biological principles as such, or a greater knowledge of marine snails as a group, or an increased facility in the use of scientific apparatus, or even a better understanding of *Tegula funebralis.* Our aim was to involve all of the students, intellectually and emotionally, in an intensive and comprehensive investigation of a common local species. We chose *T. funebralis* to work with, but it could well have been another species of animal or plant. We looked at the animal and we asked questions. Then we selected those principles, concepts, methods, and instruments which were needed now in pursuing the answers to those questions; we introduced them, not as things of intrinsic interest or value, but as tools for effective inquiry. At this stage of the work, familiarity with the tool was all we expected; mastery could come later where, in particular cases, a given tool proved crucially important. But our attitude was this: the proper understanding and expert use of tools is not the prime objective of the researcher but only a necessary incidental to his work.

Discoveries new to both students and faculty were made each day. Moreover, the class was beginning to use its time and its tools more effectively in investigation. By the time the tides had again become favorable for field work, it is safe to say that the least informed student in the class knew more about *Tegula funebralis* than had the best informed malacologist in the world only a few days before. Starting with a poorly studied species, this result could hardly have been otherwise; nevertheless, the knowledge that they were breaking new ground provided a continuing source of stimulation to the class.

With the return of good tides, the students were given their next big field assignment. We posed these general questions: How does a typical *Tegula funebralis* spend its time? What is the general activity pattern of the *T. funebralis* population (1) during a 24-hour cycle of day and night, and (2) over a nearly 25-hour cycle of tides?

To facilitate round-the-clock observations, the six original teams were combined to form three teams, each with eight or nine members, and only three of the original profile areas were selected for the proposed study. Each team was instructed to set up its own work shifts, and to plan its approach, methods, and program without faculty aid. Three days were allowed for the exercise.

The first day saw a flurry of activity which ranged from the testing of fluorescent paints and other materials calculated to facilitate night observation, to the laying up of food supplies for the night shifts. Excitement in the exercise ran high and continued high, despite rains, rough water, long hours, and the frustrating difficulties of trying to follow and record the activities of a partially submerged population of purplish black animals at night. This was at least partly because information new to both students and faculty was continually coming in. Up to this time practically all of our field work had been carried out during daytime periods of low tide, when the *Tegula* population is usually highly clustered and quite inactive. In the present exercise, it quickly became apparent that the population was far more mobile and dynamic than suspected; animals dispersed, became clustered again, moved up and down, and otherwise shifted about in pronounced fashion along with changes in light, tidal level, and local current.

Much overtime went into completing this exercise, and when it was over, we found the team oral reports absorbing, as much for the student attitude reflected as for the findings on *Tegula*. As one faculty member remarked to a colleague after the reports, "Excellent! Who would have thought you could get a group of 25 Stanford undergraduates so stirred up over the doings of a little black snail?" Reports were followed by a reassessment of the things we had found out about *Tegula*, and further, a listing of some of the questions, problems, and good leads that remained. The list was a long one.

Students were given the weekend and the first part of the following week to survey the list, do a bit of reading and perhaps a bit of pilot investigating, and to select for themselves individual problems which would occupy them for most of the remainder of the quarter. They were lectured on biological literature sources and the use of a research library, and instructed how to use the abstracting and indexing serials, such as *Biological Abstracts*, *Chemical Abstracts*, and the *Zoological Record*. Toward the end of the fourth week, each member of the class handed in a written prospectus for a research problem. This was gone over very carefully with a faculty member, revised, resubmitted, and often rewritten again. A real effort was made to get students to frame their problems in fairly concrete terms, to formulate them in terms of specific and answerable questions, and to limit them to such a degree that there was a reasonable hope that some answers could be obtained before the end of the quarter.

The fifth week of the class began with a talk from each student, covering what his problem was, and how he was planning to tackle it, or at least start on it. Some idea of the scope of the projects attempted may be gained from the following list of abbreviated project titles.

Distribution and movements of the *Tegula funebralis* population.
Factors governing the upper and lower limits of distribution of the *Tegula funebralis* population.
The activity pattern in *Tegula funebralis*.
Orientation and dispersion of *Tegula funebralis* with respect to current.
Responses of *Tegula funebralis* to starfish and gastropod predators.
Interactions between populations of *Tegula funebralis* and hermit crabs.
Photoreception and responses to light in *Tegula funebralis*.
Chemoreception in *Tegula funebralis*.
The anatomy of *Tegula funebralis*.

Structure, growth, breakdown, and repair of the shell in *Tegula funebralis*.
Algae on the shell of *Tegula funebralis*, in relation to the distribution, food, and feeding of the commensal limpet *Acmaea asmi*.
Attraction of the larvae of *Acmaea asmi* to *Tegula funebralis*.
Dispersal of the young of the commensal gastropod *Crepidula adunca* to new *Tegula funebralis* hosts.
Reproduction and larval development in *Tegula funebralis*.
Food preferences and feeding in *Tegula funebralis*.
The carbohydrases in the gut of *Tegula funebralis*.
The proteinases and lipases in the gut of *Tegula funebralis*.
Yeasts living in the gut of *Tegula funebralis*.
Diurnal fluctuations in the O_2 consumption of *Tegula funebralis*.
Production and fate of lactic acid in the muscles of *Tegula funebralis*.
Hemocyanin of *Tegula funebralis*.
Excretory products of *Tegula funebralis*.

In a few cases the projects above were handled by two students working in close collaboration, but the majority were carried out by individuals. Each student was assigned a faculty advisor who aided in finding references and equipment and in getting the project started. For a time there were real problems of space and equipment. Also, it very quickly became clear that no real class work schedule was possible, and that the laboratory would have to be open and available 24 hours a day, 7 days a week. No formal lectures or labs were therefore held. Students were expected to report to their advisors periodically, but student independence and initiative were encouraged as much as possible. There was surprisingly little "goofing off."

By the middle of the seventh week, work had progressed to a point where the findings of one student were beginning to throw light on projects tackled by others. We therefore scheduled a series of small conferences, each attended by a few students working on interrelated problems and by one or two faculty advisors. Topics around which discussions were organized included the following:

Distribution of *Tegula funebralis* and ecologically related species, and factors affecting that distribution.
Sensory reception.
Commensals and predators of *Tegula funebralis*.
Food habits and feeding.
Digestion.
General physiology.
Structure, development and growth.

In most cases, an individual student was assigned to two different groups, so his findings could be considered from at least two different points of view. Students were asked to bring in their data in organized form, and to be prepared to present and discuss them with others.

We hoped the interchange in these discussion groups would in some ways compare with that experienced at small scientific meetings limited to investigators working on closely related problems. The results in most cases did not live up to our expectations, and in retrospect it is clear that those expectations were too high. A number of students were still struggling with methods, and discussions in some areas centered on these. Some students brought in quantities of undigested data. Only a minority presented findings effectively in the form of tables or graphs. Among the lessons learned was this: that unless problems and findings were presented in clear, concise, organized form, and illustrated graphically in some manner, the investigator failed to get much across to his audience, and discussions lagged or never got started, or were restricted to comments by the faculty advisors. Nevertheless, it appeared at this stage of the work that the findings of a majority of students included some small but original contributions to science, of particular interest to malacologists.

With this in mind, the faculty contacted Dr. Rudolf Stohler, editor of *The Veliger*, presented a brief outline of what the student group was doing, and inquired whether or not papers resulting from the course might be considered for publication in that journal. Dr. Stohler's response was immediate; the course sounded interesting, and any papers resulting from it would be considered for publication providing they passed editorial board inspection. There was no guarantee that all or any papers would be accepted, but if a sufficient number proved suitable, it might be possible to issue a sort of "Symposium on *Tegula*" as a supplement to *The Veliger.* Word of this response was passed to the students, and this provided an additional stimulus.

The eighth and ninth weeks of the course passed in research and in conferences between students and their advisors, and the lights in the laboratory burned very late. A deadline for turning in final drafts of papers to faculty advisors was set at the end of the ninth week, a full 7 days before the end of the course, in order to allow time for rewriting. In a lecture on the subject of writing and illustrating scientific papers, it was stressed that not only must a scientific paper have something to say, but it must say it in an organized fashion, concisely, and with unequivocal clarity; students were referred to current biological periodicals for specific examples.

Oral reports on research projects occupied three successive mornings of the final week of class. These talks were attended not only by all members of the class and faculty but also by other graduate students and investigators in residence at the Marine Station at the time. An effort was made to hold the talks under circumstances approximating those of a regular small scientific meeting. Individual reports were limited to one-half hour each, and were accompanied by illustrations and graphs from student papers, projected by means of an opaque projector. The reports went very well. For the most part they were organized and had been rehearsed, and were delivered in a manner comparing favorably with that of professional scientists at meetings. We were exceedingly proud of student performance here.

All of the remaining time during the last week went into criticism and revision of the written research reports. Despite instructions, most of the written reports resembled first drafts of undergraduate term papers rather than scientific manuscripts. The best were none too good, while the worst were longwinded, chatty, poorly organized, and frequently incoherent. The papers were gone over in student-advisor conferences, criticized in real detail, sentence by sentence, torn apart and reorganized, and sent back for rewriting. The rewritten version was also criticized, and often sent back for further revision.

RECENT CHANGES AND SOME RESULTS

According to Professor Abbott, the general philosophy and organization of the course has undergone no fundamental change since 1963. The particular species chosen for intensive study has varied.[1] During the last 2 years, it was decided to take advantage of students' concern about environmental degradation by tackling problems of immediate environmental significance. In 1969, the general problem of DDT in the marine ecosystem was considered, with emphasis on Monterey Bay. According to Abbott:

> Part way through the work the results we were getting were so disturbing that we got involved at the political level. With the collaboration of legislators from our own and other districts in California, and the help of a good many other interested people, we were instrumental in getting the legislature to take action, and the California Department of Agriculture to greatly curtail use of DDT and other persistent chlorinated hydrocarbons in the state. Response of the students was magnificent. It is clear that many students want to do something constructive about the problems facing man in the modern world. Denied a chance to do this, a few may become destructive. But given a chance to do something positive, nearly all respond superbly.

In 1970, the matter of sewage pollution in Monterey Bay and Carmel Bay was tackled, not as a practical engineering problem but as an ecological study. The results of the work were transmitted to local, state, and regional agencies. Local newspapers sent reporters to cover the final oral reports presented by students. According to Dr. Welton Lee, who directed the program that year:

> Although ours was not the only work on bay pollution, I think it fair to say that the input provided by the undergraduate research team was critical in important community decisions. Partly as a result of these efforts, all those peninsula communities which had not already done so, held and passed bond elections for secondary sewage treatment. The peninsula is now developing a regional plan aimed ultimately at reclamation and re-use of waste water. The students were delighted with the results. They have learned that the right kinds of decisions can be made if decision-makers are adequately informed, and that student groups can have a real impact if they will collect important needed information and present it to the right people in an objective and serious way.

There can be little doubt about the excellence of this program. It encourages us all to seek ways of offering similar opportunities for students at other institutions. In addition to providing a marvelous experience for students, it provides professional enrichment and opportunities for the teachers involved. Many may feel, however, that their institution simply cannot afford to release three faculty members to teach a single course of 25 students. It should be pointed out, however, that this course generates just as many student credit hours (375) as do many other, more "acceptable" distributions of faculty work load.

For example, if each of the three professors had taught a separate three-credit course for 25 undergraduates and a one-credit seminar for 15 graduate students, the total number of student credit hours generated would

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[1] Abbott, Donald P., David Epel, John H. Phillips, and Isabella A. Abbott, 1968. Undergraduate research and the biology of *Acmaea*. The *Veliger*, 11 (Suppl.): 1-4.

have been only 370. It may not be possible for all institutions to provide this type of enriched experience for all students, but most institutions, if they can find the will, should be able to provide similar programs for those students who are interested in becoming involved in real investigation.

At first the course was operated on a shoestring, without any outside financing. Success of the venture has attracted support from the NSF Undergraduate Research Participation Program during the last few years. This has helped immensely (1) by providing stipends for students who could not otherwise afford to give up part-time jobs to attend, and (2) by providing some funds for supplies and equipment which have broadened the investigative capabilities of the group.

Another interesting Investigative Laboratory program is the one described below, which has been operated by Earlham College at its station in the Bahamas.

UNDERGRADUATE INVESTIGATION IN TROPICAL ISLAND ECOLOGY*

Louis V. Wilcox, Jr.**
Hummingbird Cay Biological Laboratory of
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Three years ago, Earlham College undertook the development of programs focusing on tropical biology. Two programs were established, including a spring term in marine biology at the University of South Florida, and a summer investigation program in tropical island ecology in the Bahamas. The latter program is discussed in this paper.

The general objectives of this program were not unlike those of Abbott, Blinks, and Phillips (1964) [see preceding article in which there is a reprint of their paper], but the operation of the program was decidedly different. The objectives of our program were as follows:

1. To involve undergraduate students in a variety of aspects of the ecology of mangroves, or closely related areas.
2. To focus upon problems, rather than selected disciplinary approaches. The students were encouraged to: (a) examine the problems in an area rather than attempt to function as either a field biologist or laboratory experimentalist; (b) utilize a holistic approach in searching for answers. Disciplines and subdisciplines were looked upon as sources of information to solve problems, not as the basis of an approach. The students had access to the literature from these many areas and were trained thoroughly in the use of the library (Kirk, 1969). In addition, the students had available to them several noted authorities during their investigation and were encouraged to contact other authorities upon their return to the United States, particularly in the areas of systematic identification.

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*Originally published in CUEBS NEWS, April 1971.

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3. To allow the student to experience the life of a scientist. This included many realizations, not the least of which was the status of man's understanding of his world, the emotional side of the scientist, the large amount of "routine" involved in scientific investigations, the thrill of discovery and learning, and the dedication required to learn. In addition it was hoped that the student would learn the satisfaction that comes from a creative accomplishment and that he was, in fact, capable of this creative accomplishment.

How did this approach work in reality? In brief, the first year (1968) was spent in doing some background investigation and planning the approach we would use, and the following two summers (1969, 1970) were devoted to actual operation of the program.

Five undergraduates spent the better part of June and July 1968, with me, on the island. We initiated studies on the structure and distribution of mangroves in the Jewfish Chain and completed an inventory of populations extant in the area. Potential problems that might be investigated profitably by undergraduates were enumerated. On the basis of this initial survey and in consultation with the participating students, the program was operated in the following manner in 1969 and 1970.

Students selected for participation spent spring vacation (19 days) on the cay surveying various problems that would lend themselves to investigation and participating in on-going investigations in the mangroves. The purpose of this preparatory survey was to give students an idea of the type of problems which they could investigate in the unique environment of the station. Following this trip, each student spent the 10-week spring term: (1) selecting a problem for investigation; (2) completing a literature search on his selected problem; (3) planning out his study in detail; (4) purchasing all necessary equipment and supplies; (5) participating in eight evening seminars to discuss the various proposed investigations; and (6) making an oral presentation on his proposed investigation. During this time, the students also received instruction in the use of techniques pertinent to their investigation. Thus, when a student arrived at the cay in the summer, he had already identified a problem and prepared himself to pursue its solution vigorously and professionally. At the end of the summer, each student was expected to report the results of his investigation in a form that would be suitable for publication.

The group of students that applied for the program in the spring of 1969 was not much larger than the number of spaces available. With time, the number of applicants has increased to the point where there are about twice as many applicants as positions. Ten students from Earlham College participated in the 1969 spring trip, and these same ten students carried through and participated in the summer of 1969. They did their preparatory work for the summer investigation at Earlham during the spring term. Five students from Tufts University participated during the summer also. The Tufts students had no spring preparatory period prior to the trip, though most of them had visited the cay the previous January. They needed far more help than the Earlham students since they had done little or no planning. There was a total of 15 students conducting investigations during the summer of 1969. The prime responsibility for directing the research was on the shoulders of the *students*, though I and four visiting scientists provided assistance.

During 1969, all living and research activities were conducted in a small cottage which consisted of a living room (19 ft. x 18 ft.), two bedrooms, three screened porches, and an extremely small kitchen. We lived and worked coeducationally in very cramped quarters. At first, we thought this would be a detriment to the operation of the program, but it turned out to be one of the stronger features. We lived and worked together 24 hours a day and learned a great deal about the feelings and emotions of one who is intensely involved in an investigation. This mode of living and working has been continued, albeit the intensity is not as great with the completion of our new 4900 sq. ft. laboratory building in 1970. This building was made possible by a grant from the Arnold Bernhard Foundation.

With the extensive work done during the spring, there was no need for introductory lectures, discussions, or other types of preparatory activity upon arrival on the cay in the summer, except for the students from Tufts. The morning following arrival, the students simply got out of bed, ate breakfast, and went off to work on their investigations. Living as we did precluded the necessity of planned meetings, though we did have an informal evening seminar each week to discuss problems encountered in various investigations.

Investigations conducted during that summer were as follows: habitat preference in intertidal crabs; factors influencing distribution of molluscs in mangroves; mangrove fish populations; factors influencing the distribution of algae in mangroves; the role of *Avicennia nitida* and *Laguncularia racemosa* in mangroves; primary productivity in mangroves; factors influencing the distribution of invertebrates on sand flats; the nesting behavior of the white-crowned pigeon in mangroves; pubescence in *Conocarpus erecto*; a survey of mangrove insects; and bush medicine in the Exuma area. Five of the students who conducted the investigations had just completed their freshman year, four their sophomore year, and six their junior year. Three of the papers from this work have been published (Wilcox, Patton, and Coriell, 1969; Semple, 1970; Yocom, 1971). Four other papers are in preparation for publication and the work of four other students has contributed to other papers presently in preparation for publication.

The students who participated in the summer of 1969 had a varied background. All were biology majors save for one who was majoring in geology. All had taken our introductory course (two, 10-week terms) and the more advanced students had taken two or three upperclass biology courses and three 10-week terms of chemistry. No emphasis was placed upon particular prerequisites, however. Rather, the emphasis was placed upon the willingness and interest of the individual to become involved in a demanding investigation. Three criteria were used for selection: (1) willingness to work and get one's hands dirty; (2) psychological make-up for living in a small, tight-knit group on an uninhabited island; and (3) academic record. In terms of batting averages, two students flunked; of those now graduated, five out of six are in graduate school (one each in ichthyology, zoology, botany, medical school, and marine biology); of those still remaining in undergraduate school, four are making plans for graduate school. Those already in graduate school are for the most part pursuing the same general topical area investigated during the summer of 1969.

In 1970, 16 students participated in the spring trip. Of these, ten were selected for the summer program, nine from Earlham and one from Carleton College. Two of the ten had been involved in the program the previous summer. There were three students in this group who had graduated; six who had completed their junior year; and one, the freshman year. Of the three graduating seniors, two are now enrolled in graduate school and one is fulfilling his military service obligation. The background of these students was very similar to that of the students in the summer of 1969, except that this group had taken more biology courses. The problems that were investigated were as follows: the role of sunlight and dessication on the distribution of algae in mangroves; the reproductive behavior of *Strombus costata*; distribution and behavior of *Littorina angulifera*; feeding behavior of *Cyclura figginsi*; factors controlling pubescence in *Borrichia arborescens*; factors controlling the distribution of algae on sand flats; primary productivity in mangroves; and nesting behavior in mangrove birds. As you note, students have branched away from investigations only on the intertidal area. Five of the papers produced in 1970 are presently in preparation for publication.

Each student enrolled in this program received one academic credit (3-1/3 semester hours) for the work conducted during the summer months, though not all participants registered for the credit. There is no academic credit for the spring trip. (Starting with the summer of 1971, students will receive two academic credits for their summer work — 6-2/3 semester hours.) In addition, there were funds available at the beginning of this program to defray the costs of students participating in the program. These monies have decreased to the point that, during the summer of 1970, only about half the students received a portion of their expenses. Starting with 1971, students will be financing the trip entirely on their own in the same manner that they pay for enrollment in other portions of the college program. It is difficult to evaluate the role that this financing played, though the students felt that it played a rather significant role. A number of them stated that they would have been unable to participate in the program had it not been for the funding. We look forward to the impact of no stipends and two academic credits during the summer of 1971.

But, how well did we do in achieving our goals?

From the student's point of view, the most significant component of the program was not spelled out in the original set of goals and objectives. They feel that the greatest advantage to this program has been what they learned by living and working in a very confined space over a period of 8 weeks. Specifically, they point to lessons they learned about themselves in terms of their interactions with other people and their effectiveness in learning; their understanding of what it means to accept responsibility within a group; and the understanding they gained about how people function (including themselves). They are quick to point out that these accomplishments are really within the prescribed goals and objectives as this is helpful in maturing as an effective scientist.

It would appear that there were several reasons for the success of this program. One was the extensive preparation prior to the summer program (the necessity of the preparation stage is discussed elsewhere [Holt et al., 1969]). Each of the students did an extensive literature search on his topic and also wrote up his research proposal. Another reason for success was the fact that students and instructor lived and worked together 24 hours a day. In the early part of the program, we had no choice. Later, it was decided upon mutual agreement that we would all live and work together. Living together, when we were all struggling toward the same goal — solution of closely related problems — led to an *esprit* that contributed very significantly to the realization of the objectives. The stated expectation of publication added considerable stimulus. All students recognized the potential benefits should they publish as an undergraduate.

From my perspective, a great deal of the success of the program can be attributed to the time spent during the spring trip and during the spring term in preparation. It was frustrating and difficult for all concerned because we did it on an overload basis. But the rewards in terms of creative accomplishment made it more than worthwhile.

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9. Investigative Activities in Two-Year Community Colleges

The development of investigative type activities at three two-year community colleges has come to the attention of the CUEBS staff during the past 2 years. The three programs are quite different and illustrate the range of possibilities which exist for integrating the investigative activities with a more traditional, "series of exercises" approach.

CATONSVILLE COMMUNITY COLLEGE

At Catonsville Community College, Catonsville, Maryland, Carol Paulis and Agnes Wilhelm have achieved a complete substitution of an Investigative Laboratory for the traditional program which was formally offered. The laboratory is offered as a separate course (Biology 104, Laboratory Studies in Biology). Many students enroll concurrently in a course on the Principles of Biology (Biology 103). Most who enroll are not pursuing a biology major but the course is approved as an elective for other curricula. Enrollment is limited to 24 students per section, with the number of sections varied to accommodate the demand.

The laboratory activities are divided into two phases: the first being carefully planned by the instructor to prepare students for independent investigation; and the second left unstructured to permit each student to carry out an investigation of his own choosing. In phase one, students attend a regularly scheduled, 3-hour laboratory period each week during which they discuss the investigative process, learn to locate library resources, see demonstrations of selected techniques, and carry out exercises calling for the collection and analysis of data. They are made aware from the beginning that this is to prepare them for independent investigation.

Although it is anticipated that the exercises used in phase one of the course will be varied from semester to semester, those currently being used include a "dry" (talk through) laboratory on gibberellins and "wet" laboratories in which students observe living chicken embryos at different stages of development, isolate and culture soil microorganisms, identify some of the living components of a natural ecosystem, study the effect of an introduced chemical or physical factor on the structure of an artificial micro-ecosystem, assay for the presence of enzymatic activity in egg albumin, and analyze the effects of physical and chemical variables on the rate of enzymatically catalyzed reactions.

Many of these are similar to the open-ended exercises currently described in laboratory manuals prepared for introductory courses in biological principles. In the Investigative Laboratory, however, their primary function is not to illustrate biological principles. Rather, they are used to provide students with insight into investigative processes and to build confidence in their ability to carry out meaningful investigation. To achieve these objectives, the instructors use inquiry and problem-solving approaches. A list of questions designed to evoke student analysis of the investigative processes is distributed each week. Discussions built around these questions and the concrete laboratory experiences of the students are also part of each week's activities. Judging from the comments of students and their performance during the second phase of the course, this carefully planned mix of questioning, laboratory work, and discussions seems to do an excellent job of preparing them to play the role of an investigator.

By the third or fourth week of the semester most students have identified a general area in which they wish to carry out an investigation. The following table of contents of the student-produced journal indicates the topics chosen during one-semester.

The Catonsville Community College Journal of Biological Research

Established 1970

SEPTEMBER

Volume I **Contents** **Number 1**

Behavioral Studies

Environmental Studies

A Study of Mutagenic Effects of ^{60}Co Radiation on Chick Embryos Irradiated at the Fertilized Egg Stage, by Karen Lightner

A Bacteriological Analysis to Determine Raw Sewage in the Patapsco River, by Karen Noe

A Quantitative Analysis of pH Difference Above and Below Simpkins Industries, Inc., on the Patapsco River, by Ronald R. Robinson

The Biodegradability of Gain Detergent by *Chlamydomonas*, by Ann Rodman

The Effects of Continuous Sound on Mice, by Theodore Shipley

The Effect of the Pesticide Raid on Goldfish, by Michele Stimson

A Quantitative Comparison of Organisms Found Above and Below Simpkins Industries, Inc., on the Patapsco River, by Robert Tavenner

Genetic Studies

Growth Stimulation and Mutations in Relation to Dosages of X-Ray Radiation Using String Bean Plants, by Mary Chalker

Sexual Identification of Normal Human Female and Normal Human Male Can be Made Using the Interphase Nucleus of a Living Cell, by Anne Gentner

An Experiment to Find How Cinnabar and Brown Eye-Color are Inherited in *Drosophila melanogaster*, by Thomas Riddle

Growth and Development Studies

A Study of the Growth and Development of Chick Embryos Injected with Vitamin B_{12}, by Janet Coblenzer

The Effect of Changing the Effective Direction of the Pull of Gravity on the Direction of Growth in Grass, by Judy Drake

Regeneration in *Planaria*, by Dave Magez

The Effects of Thyroxin and Thiouracil on the Forelimb Development of *Rana pipiens* Tadpoles That Have Reached the Hindlimb Stage, by Thomas Dan Misotti

The Effect of Thyroxin on the Eyes of Embryonic Chickens, by Donna L. Neserke

An Experiment to Find Out at Which pH Level *Phameobus limensis* Grows Best, by Mark Nonnemaker

The Effect of Nicotine on the Growth of a Lima Bean Plant, by Mary Slade

The Physical Effects of Birth Control Pills on the User's Offspring Using Mice, by Paul Trimble

The Effect of the Presence of *Rana pipiens* Larvae Tail Tissue on the Developing Tail Tissue of *Rana pipiens* Embryos, by Carl Turner

Does Cigarette Smoking Have any Effect on the Body Growth of Weaning Mice?, by Sally Wyatt

Microbiological Studies

Do Bacteria Live in the Mouth?, by Susan Noe

Does Listerine Kill Mouth Germs Any More Effectively Than Coca Cola and If So, For How Long?, by Charles Winkelman

Nutritional Studies

The Effects of Proteins and Starches on Male Rats, by Thomas E. Cooper
The Effects of Alcohol on the Eating Habits of Mice, by Mary Katsafanas
The Effect of a High Protein Supplement on Weight-Gain in Mice, by Leonard Nichols
Effects of Red and Blue Environments on the Appetite of Mice, by Cecilia Shipley
The Effect of Deprivation of Specific Minerals on Tomato Plants, by Ted A. Zlatin

Physiological Studies

The Effect on the Blood of White Mice of Acetyl Salicylic Acid, by Karen Hess
The Effects of a Chlorpromazine-Based Tranquilizer on the Cardiac Cycle of the Rat Heart, by John Clay Marshall
Caution: Cigarette Smoking May Be Hazardous to Your Health, by Brian Yingling

In many instances, the area of investigation is chosen on the basis of experiences which the students have had outside the course, while in others the open-ended laboratory exercises have captured their interest.

By mid-term, students must submit a proposal of the investigation they wish to pursue. This proposal states the questions for which answers will be sought, states hypotheses, and describes techniques. Materials, equipment, and supplies which will be needed are specified and references to previous studies on the topic are cited. The proposal is presented by each student to the class for criticism.

According to the instructors, it has not been necessary to artificially limit the areas which may be investigated, but the natural constraints of time, money, space, and ability tend to provide natural limiting factors which keep the proposals within the "reasonable" range.

After the proposals have been approved, the class does not meet, formally, until the end of the semester. The laboratory is left open for student use and the instructor is available for consultation. If students are working outside the laboratory (home, field, etc.), weekly progress reports are required. In spite of the absence of formal class meetings during this period, instructors report significant exchange of ideas and information among students and between students and themselves. This exchange seems to be catalyzed by the genuine interest which the participants in the class have in their own and others' projects. Interest and enthusiasm by the instructors are, of course, an important factor in stimulating this exchange.

During the phase of the course when students are working on individual projects, the instructor schedules an extended, individual tutorial session with each student. In this session, all the work submitted by the student during the first phase of the course is reviewed and a detailed discussion of his project ensues. The instructors report that this session is particularly helpful for those who are shy or hesitant to seek help.

The course terminates with a symposium in which each student presents a brief résumé of his project. A written report, using the format for a scientific paper, is submitted. These are ultimately published in the *Journal of Biological Research*, an in-house publication created specifically for this course.

The teachers feel that the objective of the course is to teach students to understand and appreciate the processes which give rise to biological knowledge. Since this objective is stated in nonbehavioral terms, it is difficult to quantitatively measure the success of the program. Based upon my interviews with the students involved in the program, however, I would certainly give it high marks for effectiveness. In addition to achieving its stated objectives, the course seems to have accomplished the following worthwhile ends:

1. *New knowledge*. Although few, if any, of the student papers would meet the standards for publication in national professional journals, they do represent a much greater contribution than the repetitious laboratory reports typically produced by undergraduates in introductory biology courses.
2. *Personal development*. The instructors teaching the course feel that the investigative approach contributes much more to the students' intellectual growth than did the previously used exercise approach. Both instructors and students report that the emphasis upon individual projects decreases cut-throat competition for grades, increases cooperation between students, and improves student-faculty rapport. As with almost any course taken by freshmen, this one seems to aid some in making a career choice. Students seem to think the course was particularly helpful in this regard because it gave them insight into what biologists actually do in their professional work. For example, one student commented: "I think the course was an excellent one, for it forced me to think about the process of science and taught me how to use the scientific approach in trying to answer questions. This may cause me to change my major."

Some students also believe that the course may have been influential in changing their general life style from one in which they blindly accepted what authorities told them to one in which they feel a need to look for evidence and to investigate problems on their own. If the course can be credited with such a change, it has indeed been effective.

There are, of course, some difficulties created by the course and areas in which the students and instructors recognize the need for improvement. The 1- or 2-hour credit which is assigned to the course does not adequately reflect the amount of effort expended by students and faculty. During the second phase of the course, it is not at all uncommon for a student to spend several hours each day on his investigation. In some cases, this may detract from other studies. For example, one student had to be locked out of the laboratory so that he would not spend all his time on his investigation and, as a result, fail in his other courses. Students do not object to spending considerable time in the laboratory, but feel that the course credit should reflect their effort more accurately. Three or four hours of credit could probably be justified for most students.

The time spent by the instructor is also extensive. Teaching three sections of the course consumes all of the instructor's time. Calculation of the teaching load on the basis of student credit hours or official contact hours does not give adequate recognition to the amount of faculty time actually spent teaching the course.

Finally, if unexpected problems are encountered during the investigation, there may not be sufficient time to redesign or repeat the experiments or observations. Faced with the inflexible deadline imposed by the school calendar, these problems can be extremely frustrating for students. Students encountering such problems are, of course, advised that this is to be expected in any worthwhile investigation. They are encouraged to report their partial results and are assured that they will receive a good grade if their report indicates that the investigation was well-planned. Even so, such students are robbed of the self-fulfillment which comes from carrying an investigation to the point at which conclusions, based on data, can be drawn. An arrangement which would permit students to enroll for additional credit and continue their investigations in a subsequent semester might provide a partial solution to this problem.

HAGERSTOWN JUNIOR COLLEGE

The program which has been developed under the direction of professors Montgomery, Hess, Loganathan, and Elliott at Hagerstown Junior College is much less extensive than the one at Catonsville. It occupies a 5-week block of time in the general biology course and it is designed for nonmajors. Approximately 160 students are enrolled. Like the program at Catonsville, it is divided into two phases. During the first phase (2 weeks in duration) which is designed to prepare students to undertake individual projects, those enrolled learn some basic techniques for culturing and measuring the growth of three types of microorganisms; they are introduced to simple experimental design; and they are given instructions for writing scientific reports. During the second phase, students work in pairs and are expected to design and conduct a simple experiment of 2-weeks duration, using the organisms and techniques to which they were introduced during phase one. Students are allowed free access to the laboratory during this period.

The following is a list of some of the projects which were undertaken by the students at Hagerstown:

The growth rate of *Euglena gracilis* when exposed to different detergents.
The effect of old and new dimes on the growth of *E. coli.*
The growth rate of yeasts in fruit juices.
The effect of varying quantities of vitamin B_{12} on the growth of *Euglena gracilis.*
The effect of pH on the growth of *E. coli.*
The effect of different sugars on the growth of *E. coli.*
The effect of mercury salts on the growth of *E. coli.*
The effect of reduced light intensity on the growth of *Euglena gracilis.*
The growth of *E. coli* on sterilized sludge from a sewage treatment plant.

The best papers were bound and placed in the library for student use.

In an effort to determine the students' opinion of the program, each was asked to rate it using the following categories and scale.

Sample Evaluation Form with Rating Scale
Investigative Laboratory

Content								
Interesting	7	6	5	4	3	2	1	Uninteresting
Creative	7	6	5	4	3	2	1	Not Creative
Not Worthwhile	1	2	3	4	5	6	7	Worthwhile
Purposeful	7	6	5	4	3	2	1	Not Purposeful
Not Intellectual	1	2	3	4	5	6	7	Intellectual
Unstimulating	1	2	3	4	5	6	7	Stimulating
Procedures								
Clear	7	6	5	4	3	2	1	Not Clear
Inadequate	1	2	3	4	5	6	7	Adequate
Guidance	7	6	5	4	3	2	1	No Guidance
Student Work Load								
Excessive	1	2	3	4	5	6	7	Not Excessive
Open Laboratory								
Functional	7	6	5	4	3	2	1	Not Functional
Not preferable	1	2	3	4	5	6	7	Preferable

The following averages were obtained for the four major categories:

Content — 5.63
Procedure — 5.70
Student Work Load — 4.06
Open Laboratory — 6.06

NORTHERN VIRGINIA COMMUNITY COLLEGE

Representing still another approach for involving two-year community college students in investigation is the program which has been developed by the faculty at Northern Virginia Community College, Bailey's Crossroads, Virginia. The general biology course, with companion laboratory, runs for three quarters. During the first quarter, all students come to laboratory once a week at a scheduled time and complete some prefabricated exercises. In addition to illustrating some of the concepts which are being introduced in lecture, these exercises also provide training in techniques; the use of the microscope; qualitative chemical tests of foods; assay of enzyme activity; and measurement of photosynthesis and respiration. The faculty feels that this rather traditional and structured laboratory experience helps prepare students for the second and third quarter laboratory activities which require greater independence.

Most of the second quarter is built around the theme of "Techniques and Materials in the Investigation of Hormone Effects." As an early part of the work of this quarter, the "scientific method" is discussed with students and they are introduced to some literature-search techniques and the format of standard bibliographic references. This phase of the work is guided by the following behavioral objectives which are presented to students in the laboratory guide:

Part I: Scientific Method

1. Distinguish between direct and indirect observation.
2. Describe three problems that can interfere with the accuracy and repeatability of observations.
3. Given an observation, pose a relevant, scientifically testable question about the observation.
4. Given an observation and a relevant testable question, state an hypothesis.
5. Devise an experiment to test the hypothesis.
6. Carry out the experiment and collect evidence.
7. Using only the evidence you have collected, state your conclusion.
8. Compare your data with what other scientists have observed in similar experiments and state a theory about the general phenomenon you have been studying.

Part II: Locating, Reading, and Evaluating Scientific Papers

1. Using some of the reference aids listed below, locate an article on a topic of interest to you.
2. Given the standard format, write a reference for your article as it would appear in a bibliography.
3. Identify the problem being investigated in your article.
4. State the hypothesis being tested.
5. Describe how the scientist set up the experiment to test his hypothesis.
6. Summarize the results of his observations.
7. Restate his conclusions — how he interpreted the results of his observations.
8. Evaluate the paper as a contribution to science.

After meeting these objectives, each student is given an opportunity to design an experiment and do some background reading to accomplish the following objectives:

1. Select a problem that you are interested in investigating.
2. Locate and read two or three references concerning your problem in the literature.
3. Prepare bibliographic references in the standard format and make some notes on what you read for later use in writing your report.
4. State the hypothesis you plan to test.
5. Describe in detail how you plan to test your hypothesis.

Group discussions and individual conferences with instructors are an essential part of these first phases of the investigative experience. According to Dr. Joan Creager, instructor at the college and part-time CUEBS Staff Biologist (1969-71), "Many students find it rather difficult to get started on an investigation, possibly because they are preconditioned to expect to be told which exercise to do or which set of directions to follow. As they get into the actual doing of their investigations and interact with other students in the laboratory, enthusiasm picks up."

Each student is required to submit a written description of his planned investigation which must be approved by his instructor before he can carry out the experiment. According to Dr. Creager,

> There are three reasons for requiring a written proposal: (1) to assure that the student has carefully thought out the investigation he plans to do; (2) to provide the instructor with an opportunity to suggest modifications if he feels they are necessary; and (3) to alert the laboratory technician either to arrange to provide the materials the student will need or indicate to the student that some materials will not be available. Information about available materials and facilities are, of course, provided before the students begin to design their experiments. Even so, many students come up with requirements beyond the available facilities and we make every effort to provide what is needed.
>
> Because so much of the second quarter is spent in preparing students for an individual project, they have only about 2 weeks to actually carry out their experiments. This short period of time imposes serious constraints on the kinds of experiments that are possible. It has the advantage of forcing the student to narrow down his topic to a very simple investigation but has the disadvantage of frustrating some students who really get interested in their investigation and want to carry it further. To minimize this frustration the students have the option of extending their investigation of the same topic during the third quarter.

During the time when students are getting their investigation underway, various methods of presenting scientific data — graphs, tables, etc. — are discussed. These discussions are guided by the following objectives:

1. Given a list of observations, construct a table with row and column headings which 90% of your classmates agree are clearly labeled.
2. Given a list of observations, construct a graph so that the process or trend is quickly grasped by 90% of your classmates.
3. Given your own project, construct a table shell or the axis of a graph which would be useful in presenting your data.

After completing their investigations, students prepare a written report and also give a brief oral presentation. Some evaluative criteria — hypothesis clearly stated, data presented clearly, conclusions justified from the results, conclusions related to the findings of other scientists, adequate bibliographic references given — are provided as a guide for the preparation of reports. Students are encouraged to have other students read their reports and evaluate them much as reviewers evaluate articles submitted for publication in scientific journals.

The investigative portions of the third-quarter laboratory extend over 6 weeks, and are built around the theme, "Techniques and Materials in the Investigation of Growth and Development." Students are encouraged to review (on their own) the material in the study guide on scientific method and the use of scientific literature. Three or four weeks are allotted to carrying out the experiment and 1 or 2 weeks to reports.

The 1970-71 academic year was the first full year in which investigative-type laboratory activities were incorporated as a part of the general biology course, although some such experiences were tried in the winter and spring quarters of 1970. Currently, Dr. Creager feels that it would facilitate the investigative portions of the laboratory if a variety of short, modularized self-instructional materials on techniques were available for any students who might need them. Already they have developed materials for such techniques as serial dilutions, aseptic technique, cell counts, injection of materials into chick eggs, and preparation of observation windows on chick eggs. They plan to expand the number of modularized instructional materials, to increase the variety of materials available, and to improve the laboratory facilities as time and money permit. They also have decided to expand the investigation portion of the third quarter from 6 weeks to the full term.

Dr. Creager summarizes the current status of their program and the importance of an Investigative Laboratory to a two-year college in the following terms:

> We recognize that imposing limitations on the kinds of investigations students may do is not entirely consistent with the pedagogical goals of the investigative laboratory, yet we believe that even with the occasional limitations we have to impose, the students generally profit from their experiences. In fact, we have frequently observed unusual ingenuity and creativity on the part of students who are forced to improvise because of limitations. That extensive research facilities are not usually available in the two-year college is no reason to reject the possibility of providing an investigative experience for two-year college biology students. We have been able to offer our program for four hundred students even though we only have one lab with twenty-eight stations.
>
> Investigation is the backbone of science; an introductory science course may be the only opportunity a student will have to discover how scientists investigate problems. Especially for students who will have no further exposure to science, the investigative laboratory can provide experience which will be useful to the student in his future role in society. To the average citizen, an understanding of how scientists work and a feeling for some of the rewards and frustrations of scientific investigation are long-term values of a science course which persist long after the details of the content of the course are forgotten.

PART III

LABORATORY CURRICULA

At most institutions, laboratory offerings have received little or no special attention in undergraduate curriculum planning because of the almost universal practice of linking laboratory activities to lecture offerings and using them to illustrate concepts and principles which are introduced and explained elsewhere. When considerations of laboratory instruction have been raised at all, it has usually been in the context of whether a course should have laboratory activities associated with it and, if so, how they should be scheduled.

The recent introduction of investigative laboratories, the uncoupling of lecture from laboratory activities, and the development of self-instruction laboratory modules have forced departments to ask themselves what they have been doing and what they should be doing with that forgotten segment of the curriculum — the laboratory. The following are some of the questions which usually force themselves to the surface as departments begin to give attention to the role of laboratory instruction in undergraduate curricula.

> Are there several different types of investigative activity in biology? If so, do they differ with respect to their locus (field vs. laboratory), their approach (experimental vs. descriptive), the level of organization where they are applied (cellular vs. population), the type of organisms which is being studied (bacteria vs. animal), or in some other basic way?
>
> Should a department design a laboratory curriculum based upon different types of investigation or should it be designed to reflect the components which are present in any investigation (observation, questioning, collecting data, drawing conclusions, etc.)?
>
> Should the laboratory portion of the curriculum be sequential — perhaps one course on observation followed by one on data collection and analysis followed by one on experimentation — or would it be better to plan for a more or less complete consideration of investigation in a single course?
>
> If investigative laboratories are introduced, should they replace existing illustrative laboratory activities or should they be added to traditional programs?
>
> How many investigative experiences does an undergraduate need, how extensive should each one be, and when should it come in his program?
>
> How can an institution best use its human, physical, and economic resources to provide the optimal investigative opportunities for its undergraduates?

Marquette University and Massachusetts Institute of Technology are among the institutions which have given serious consideration to these questions over the past few years and the laboratory curricula which they have devised point to some of the answers which they have found. At both institutions, the faculty is continuing its deliberation on the role of the laboratory, and as a result the programs are in a continuing state of revision. Even so, we believe that the following descriptions of the development and current status of their programs can provide guidance to other institutions which are attempting to evaluate their laboratory offerings.

10. The Laboratory Curriculum at Marquette University

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THE OLD PROGRAM AND ASSOCIATED DIFFICULTIES

Until recently, Marquette's undergraduate curriculum consisted of a two-semester, general biology course offered at the freshman level and upper division core courses in cell biology, environmental biology, genetics, and developmental biology. Each of these courses had an associated laboratory. The introductory course was taken by majors as well as nonmajors, and each major took all the core courses as well as several biology electives.

We experienced several difficulties and inadequacies with this rather standard curriculum. The enrollment in the General Biology course ranged from 750-800 students and the core course enrollments were 100-125. Although meaningful instructional experiences could be provided for such large numbers of students in a lecture situation, the difficulties associated with simply ensuring adequate logistic support for the laboratories had become formidable, and we could see that they would grow worse with time. Of more importance than logistic support, however, was the problem of ensuring that each student was provided with maximum learning opportunities.

Careful examination of our program revealed that laboratory time was often used primarily for the illustration of selected principles previously introduced in the lecture. Even if this form of laboratory usage could be entirely justified, time limitations were such that, despite considerable skill in design, a given student could not be expected to gain more than a superficial insight into the half-dozen or so phenomena which he could personally investigate. It was our opinion that this facet of undergraduate laboratory use could be effectively replaced, with considerable saving in time, by more imaginative classroom techniques.

The laboratory was also being used to teach experimental methodology. However, time limitations often resulted in programs centering around the utilization of a few readily mastered and relatively unsophisticated procedures which actually did not indicate either the capabilities or the limitations of contemporary research methods. Furthermore, approaches of this and the foregoing kind have in some instances led to repetition of subject matter in different courses; a situation difficult to justify and expensive to sustain.

THE NEW PROGRAM AND ASSOCIATED BENEFITS

After considerable deliberation and soul searching, we finally came to the conclusion that the laboratory could best be exploited for the purposes of developing the critical capacity of the undergraduate; to provide scope for his creative development in the handling of real questions; and to increase his appreciation for the operation of the research mechanisms which provide the basis for present-day biological thought. The close student-professor interaction which was potentially possible in the laboratory suggested that it was uniquely suited for this purpose. We realized, of course, that the employment of the laboratory in this role is compatible with neither large sections nor the highly structured exercises typical of many of the present undergraduate laboratory programs. It was quite obvious that our major task was to devise a program which would make maximum use of our faculty, financial, and physical resources.

Uncoupling Lecture and Laboratory

As an initial step, we decided that we would uncouple lectures and laboratories. Under this system, the units of the suggested core lecture program would continue to perform what had been their original function — that of presenting to the undergraduate, in sequence, the fundamental themes of modern biology. We felt that the imaginative use of more illustrative classroom techniques could partially compensate for the omission of the traditional companion laboratory. The potential of the laboratory could then be directed toward the exploration of the rationale and method of the investigative process, and to the development of the creative and critical abilities of the student.

Reduction in the Laboratory Requirement

Concomitant with the design to uncouple laboratories from lectures and to offer these as separate courses was the decision to reduce the number of such laboratory courses. We felt that our biology majors could best be served by a few investigative-type laboratory experiences rather than requiring an uncoupled laboratory course for every lecture course taken. The decision as to which laboratory courses were to be offered was one of the most difficult decisions to be made. After careful analysis of the strengths of the faculty and needs of our particular group of biology majors, we decided to offer only four uncoupled laboratory courses at the upper division level. Accordingly, we recommended laboratory courses oriented toward Molecular, Cellular, Regulatory, and Developmental Biology, these being the major areas of research competence of our faculty. Each course was designed to have two 3-hour meetings per week, and to carry three semester hours of credit. The first two courses cover subcellular and cellular phenomena, whereas regulatory and developmental biology are directed toward organismic activities. Each undergraduate is required to complete one course from each group as a formal requirement for his biology major. However, a student may take any of the others for elective credit toward his major.

The implementation of such a core laboratory curriculum had several immediate benefits with respect to the use of the department's physical, financial, and faculty resources. First of all, this meant an immediate reduction in the number of laboratory courses being offered by the department. Furthermore, we found that we could schedule laboratory courses so that they no longer had to compete for utilization of space with other courses taught in the same semester. This meant that students could set up their experiments and not have them disturbed by students from other classes scheduled to use the same laboratory facilities at some other time during the day or week. Furthermore, students could now have free access to the laboratory to conduct their experiments. The latter factor is an important and essential component of any investigative laboratory program. Needless to say, the task of scheduling courses became a considerably simplified task for the department. We also found that we could readily accommodate all of our undergraduate laboratory courses without resorting to evening or Saturday classes, without any further consideration of renovations, or without additions to our building to provide more instructional space. As a matter of fact, we were able to convert two of our small teaching laboratories into graduate student offices.

Separation of Teaching Responsibilities

Another important aspect of our decision to uncouple and reduce the number of laboratory courses was that we were now able to separate the teaching responsibilities of our faculty. In accordance with their personal preferences and competencies, specific faculty members were assigned to teach the core lecture and laboratory courses. No longer are faculty forced to split their efforts between the lecture and the laboratory, with the supervision of the laboratory often being delegated to a teaching assistant. In establishing faculty loads, the teaching of laboratory courses carries the same weight as that of lecture courses. Thus we now have direct faculty involvement in our laboratory program. Regardless of all other benefits that have accrued from this type of approach, we consider this to be one of the most salient features of our program.

Another important benefit of the decision to require our students to take only two of the four laboratory courses is the immediate reduction in the number of students taking a given core laboratory course. Where our coupled lecture-laboratory courses carried enrollments of 120-125, we now have manageable class sizes of 30-35. Furthermore, we rarely have to schedule more than two sections of a given core laboratory course whereas we normally had six to eight sections to accommodate the equivalent core lecture-laboratory course. The educational advantages of enrollments of this size need hardly be described to any faculty member who has had to handle large enrollments in a laboratory program. Furthermore, the financial savings which accrued to the department from such a program were applied to purchasing more sophisticated instructional equipment and for the wider variety of materials demanded of an investigative laboratory approach. The latter was accomplished without any additional funds being added to our operating budget and yet we have a far more sophisticated and higher quality program than before.

The uncoupling of the laboratory and lecture and the development of a laboratory core was based upon a consideration of what the majors needed. It was our opinion that the primary purpose of the laboratory for the nonscience major should be that of illustrating the experimental method of science through an investigative approach rather than a superficial demonstration of known facts presented in the lecture. Having made this decision, we could see no obvious benefit accruing to the student from the extension of such a laboratory over two semesters. Accordingly, we reorganized our General Biology course into three one-semester courses: Biology 1, 2, and 3; the latter being the laboratory component of the introductory program. The laboratory course (Biology 3) has as its prerequisite Biology 2 which can be taken concurrently with, or subsequent to, that course. Finally, we also reasoned that the student majoring in biology would derive no great benefit from this introductory laboratory since he would be getting an intensive experience in the investigative laboratory approach in his upper division years. Consequently, we do not require that our biology majors take the General Biology (Biology 3) laboratory course although they are required to take the freshman lecture sequence (Biology 1 and 2).

It should be immediately obvious that a considerable saving of faculty and financial resources has derived from the implementation of this general biology program, resources which have been redeployed to the support of other undergraduate and graduate programs. First of all, there is the substantial saving in instructional laboratory space which was effected by such a program. With reduction of the freshman laboratory requirement from two semesters to one and the absolving of biology majors from this requirement, we immediately reduced the number of laboratory sections from 30-35 to 12-16 per semester. Furthermore, we were able to limit the enrollment per section to 20 students as opposed to an average of 24-28 under the previous arrangement. Instead of using four laboratories exclusively for our general biology course we were now able to accommodate these in only two laboratories, thereby freeing two classrooms for upper division and graduate laboratory usage. This move also enabled us to schedule our freshman laboratories at more reasonable hours during the day and has effectively removed any need to go to Saturday laboratory sessions. What had previously been an onerous logistic task of scheduling and handling large numbers of students has been reduced to an easily manageable job for the department. Furthermore, the substantial savings of departmental resources have enabled the department to strengthen its total curriculum while significantly improving the quality of its commitment to the nonscience major taking our freshman biology course.

Reduction in the number of freshman laboratory sections offered per semester also significantly reduced the number of teaching assistants assigned to this course. This enabled us to implement a series of discussion-review sessions to accompany our General Biology lecture program. Since we lecture to all 750-800 of our biology students at one time, we were desperately in need of providing some mechanism for these students to have open discussion on the material presented in lecture. We have used the teaching assistants freed by the reduction in laboratory sections to staff these discussion-review sessions. In those institutions with smaller numbers of students taking General Biology, these teaching assistants can be used to upgrade undergraduate and graduate laboratory instruction.

For the biology major, we have substituted a new lab course entitled "Principles of Biological Investigation," which is normally taken in the first semester of the sophomore year and is a prerequisite for each of the uncoupled core laboratory courses. This course has been designed to give the background we have found to be essential for meaningful experience, and a satisfactory level of achievement in investigative laboratory courses. It consists of lectures and laboratory studies designed to provide basic instrumentation, technology, and principles of experimental design.

Centralized Equipment Facility

The cost of providing the equipment necessary to implement an investigative laboratory program is a major concern of many departments. This problem is compounded by the fact that equipment is usually assigned to specific laboratories and is consequently unavailable to other courses even though the equipment is not being used when needed in another laboratory. Furthermore, this practice frequently leads to an excessive duplication of equipment and an investment which is out of proportion to the variety of equipment available. For example, departments may have four or five laboratories, each equipped with a complete set of microscopes, and yet lack the funds to purchase a refrigerated centrifuge or UV spectrophotometer. Such an investment in microscopes may indeed be justified if they are all being used in each of the laboratories at the same time. This rarely proves to be the case. Careful examination of our own equipment utilization, even during peak laboratory periods, showed that we rarely found the same types of equipment, whether it be microscopes or colorimeters, being used at the same time.

Based on the facts described above, we decided to establish a central equipment facility where all readily moveable instructional equipment is stored when not needed for a particular laboratory experiment. Concomitantly, we set up a comprehensive card index on every piece of equipment owned by the department. This procedure gave us a complete inventory of all equipment owned by the department which not only proved to be an invaluable asset for insurance purposes but also permitted us to control the movement of all equipment in the building.

An immediate asset provided by this system was the discovery that our need to duplicate certain items of equipment such as microscopes, water baths, and colorimeters was eliminated. Savings proved to be substantial enough for us to justify the hiring of a full-time equipment supervisor in place of the part-time help which had been used to maintain and operate this facility. We quickly realized additional financial savings because such an individual soon became able to service and maintain most of our equipment. Constant equipment maintenance not only resulted in substantial savings to the department but also reduced the rate and extent of damage, thereby extending the life of the equipment. Finally, we achieved the satisfaction of having maximally functional equipment available to our students. The value of the latter cannot be measured in dollars and cents. There is nothing more demoralizing to a student in the laboratory than to find his equipment inoperable. In some cases the student cannot proceed with an experiment because he must wait for the equipment to be sent off campus for repair or for a qualified serviceman to come to the department. This is not to say that we do not have to do this but the number of times that we must has been significantly reduced.

In addition to the hiring of an equipment supervisor from the savings realized from centralizing of equipment storage was the fact that we were able to purchase a wider variety of equipment and to coordinate our purchases more effectively. Rather than duplicating existing equipment, we are now able to purchase such major items as DU spectrophotometers, refrigerated centrifuges, fraction collectors, incubators, and freezers.

When we began to revise the instructional laboratory program at Marquette, we were not at all sure that it would be possible to replace our traditional program with an investigative one without either diluting the quality of our other offerings or pouring significantly greater human and financial resources into its operation. But in the process of working toward our stated goal — to develop an undergraduate program built around a core curriculum in which the laboratory offerings are of an investigative type — we have discovered that we have been able to provide greater flexibility for students, increase student-faculty contact, provide separate rooms for each laboratory, decrease the number of students in each laboratory, buy additional laboratory equipment, hire an equipment manager, and reduce the number of courses which each faculty member must teach. These benefits, in addition to those which students receive as a result of the investigative experience itself, have been possible even though we have a large number of students to accommodate and limited resources.

11. Undergraduate Biology Laboratories at Massachusetts Institute of Technology*

Prior to 1963, MIT's biology faculty taught a sequence of two introductory laboratory courses (7.011 and 7.021) and a variety of advanced offerings. Although each of the introductory courses had its own number and was listed separately in the catalog, they were integrated and taken concurrently with specified lecture courses. Each of the introductory laboratory courses was assigned six credits (equivalent to two semester credit hours) and consisted of a series of short exercises. In the advanced laboratories, considerable emphasis was placed upon teaching the techniques used by professional biologists in conducting research. At about that time, there developed throughout the Institute a general feeling that this traditional approach to laboratory instruction was not working very well — students found the exercises boring and the faculty felt that they did not adequately reflect the true nature of a scientist's work in the laboratory. Responding to this general feeling of dissatisfaction, the Institute's Committee on Curriculum Content Planning, chaired by the eminent physicist and science educator Jerrold Zacharias, studied various means of improving laboratory instruction and recommended, in 1964, that a new type of laboratory elective be developed. The committee visualized these new offerings in the following way:

> These laboratory electives would not be designed to teach specific subject matter or to provide broad coverage of a particular field; rather they would be intended to give the students some real idea as to what laboratories are and what is meant by solving experimental problems in science and engineering. The laboratories should be essentially professional in flavor. The students should get the feeling that they are working on a problem as a professional would work on it, even though they may be repeating an experiment which has already been carried out and published.[1]

The committee suggested that these new laboratories be offered at the lower division level and be given for 12 credits (equivalent to four semester credit hours).

Even prior to the submission of the committee's report to the general faculty of the Institute, Dr. Charles E. Holt, III, of the biology department, developed a course which rather closely fit their recommendation. Designated

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*By John W. Thornton based on interviews with MIT faculty members and students.

[1] From Report of the Committee on Curriculum Content Planning to the Faculty of the Massachusetts Institute of Technology, May 1964.

Biology 7.02, it had 1 hour of lecture, 3 hours of discussion, and 8 hours of laboratory work per week. Students received 12 units credit. Although the course changed somewhat from year to year, it followed the same general format from 1964 to 1967. In 1966, Dr. Holt described the course as follows:

> The first laboratory in biology (course number 7.02) introduces students to experimental biology through a series of projects. The primary aim of the course is neither to teach a series of techniques nor to provide contact with any prescribed list of materials or phenomena. Rather, the course aims to convey the nature of real experiments, where a real experiment is one conducted on a professional level to answer questions of genuine interest.
>
> The course is divided into thirds. The first and second parts include experiments in molecular biology and neurophysiology, respectively. Two different professors teach these aspects of the course. In the final third, each professor takes half of the students for project work. Students work in pairs throughout.
>
> The experiments change from year to year but a description of the studies done in 1966 will serve as a guide. The experiments of the first third of the course concerned the mechanism of enzyme induction. In the initial sessions of the course, students learned to assay histidase and measure the incorporation of radioisotopes. This served as preparation for the next five periods, during which each pair of students designed and carried out a set of experiments either taken from the papers or closely related to them. Lectures covering the work and its background were given at the same time.
>
> The second third of the course followed a similar pattern in the study of the electro-physiology of vision. The experiments here concerned the responses in the brain to specific light stimuli on the retina. In one set of these experiments, signals are found in the frog's brain which depend in a predictable fashion both on the location of the stimulus in the visual field and on its nature. (*J. Gen. Physiol.*, 43: 129, 1960).
>
> In the last third of the course, emphasis is on student initiative. Lists of suggested projects are made available and are usually, but not always, followed in one form or another. There are opportunities to discuss the work frequently and the laboratory is open 6 days a week.
>
> The course has always run over its listed hours in the catalog. Serious laboratory work is intrinsically time-consuming and keeping within the hours is not an easy matter. To a fair extent, the extra hours spent have been a matter of choice by students.[2]

With the development of this new course (7.02), the introductory laboratories which had formerly been offered (7.011 and 7.021) were discontinued. All students planning to major in biology were expected to take 7.02, but others could take the introductory lecture courses without enrolling in a laboratory course. During this period (1963-67), the upper division laboratory offerings retained the form which they had had prior to 1963.

In 1967, additional changes in the laboratory curriculum were initiated which led to the program as it now exists. Several factors were important in producing this second round of revisions. One was the success of 7.02. Students had found it to be very exciting and, as a result, enrollment was large and the hours which students spent in the laboratory were long. This placed extremely heavy demands on the professors' time and the course was

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[2] From a memorandum to the Biology Faculty at Massachusetts Institute of Technology, June 28, 1966.

running over its scheduled hours rather badly. In addition, the exhilarating experience which students were having in 7.02 was causing them to become dissatisfied with the exercise approach which they encountered in the upper division laboratory courses.

An obvious solution seemed to be to replace the existing upper division laboratories with four new ones using the investigative approach, which had proven so successful in 7.02. To avoid the problem of time overrun which had been encountered in 7.02 and to make them more appropriate for the upper division, each of the new laboratories was to be offered for 24 units (equivalent to eight semester credit hours) and be restricted to a single research area (microbiology, cell biology, biochemistry, or neurophysiology). These laboratories were to be offered on a 2-year cycle; each course was given only once every fourth term. In this way, all four courses could share the same physical space (a single large laboratory with adjoining preparatory rooms) and basic equipment.

Since it was anticipated that each undergraduate major in biology would have time in his program to take only one of these upper division project laboratories, there was concern that he might not be adequately introduced to investigate procedures and techniques in other areas of biology. There was also some feeling that it might not be wise to delay all laboratory work in biology until the junior and senior years. To solve these problems, the faculty decided to reintroduce a lower division laboratory (7.011) in which some of the major investigative methods in various fields of experimental biology would be introduced. It was also anticipated that this course might teach students some of the basic laboratory techniques which they would use in the upper division project laboratories.

It took 3 years to complete the planning and development of these five courses. Currently, the only laboratory course regularly offered in the lower division is *Introduction to Experimental Biology* (Biol. 7.011). It has one lecture-discussion and two 4-hour laboratory periods per week. The students carry out a series of prescribed and rather sophisticated exercises in cell biology (morphological study of living cells, isolation and analysis of nuclei, fractionation of radioactive amino acid-labeled cells), microbiology (replication of phage, isolation of mutants, genetics of β galactosidase, mapping of gene loci) and biochemistry (isolation and purification of enzymes, kinetics of enzyme-catalyzed reactions, isolation of DNA and RNA). Enrollment is limited to one hundred students, divided into two sections each term. All majors are required to take this course and it serves as a prerequisite to the upper division labs. Dr. B. S. Gould, who developed the course, refers to it as a semi-project laboratory.

Each course of the four in the upper division series is of the investigative or project type and is offered once every 2 years for 24 credits (equivalent to eight semester credit hours). Each major elects one of these courses during his junior or senior year. Enrollment in each is about 30 students. The four courses are:

Experimental Genetics and Microbiology (Biol. 7.031). This offering consists of two lecture-discussions and 16 hours of laboratory work per week. It is taught by Dr. D. Botstein. Early in the course students learn to produce, isolate, and maintain temperature-sensitive mutant strains of *E. coli.* Later, each produces and isolates "his own" mutant strain and spends the remainder of the term designing and carrying out experiments aimed at characterizing the mutant form.

Experimental Cell Biology (Biol. 7.041). This course has two lecture-discussions and 16 hours of laboratory per week. It is taught cooperatively by Dr. D. Baltimore and Dr. B. W. Burge. At the beginning of the course, students do four prescribed experiments in order to learn methods for culturing animal cells, synchronizing them, determining the length of the phases of the cell cycle, karyotyping, virus plaquing, and fractionation. Equipped with this technical background, each student then selects a problem in cell biology and works on it for the remainder of the term.

Experimental Physiology (Biol. 7.061). Students meet for two lecture-discussions and 16 hours of laboratory per week. It is taught by Dr. J. E. Brown. Initially, students are taught basic methods for exposing excitable cells and recording their electric potentials both extra- and intracellularly. The visual systems of *Limulus* and grass frogs are used as experimental materials and the equipment is of research quality. Each student selects a physiological problem and pursues its solution using electrophysiological techniques.

Experimental Biochemistry. This course was developed by Dr. P. W. Robbins and was to be offered for the first time during the spring term, 1971. In preparation for the course, Dr. Robbins isolated, by enrichment culture techniques, about a dozen microorganisms from the local estuary where oil is unloaded and transferred. Each of these microorganisms can grow on some component of oil as its only source of carbon. Each student in the course will be given one of these microorganisms and be expected to design and carry out experiments to determine the biochemical pathway which it uses to degrade the petroleum component on which it lives. To help prepare students to undertake such work, Dr. Robbins has prepared three bibliographies (petroleum biochemistry, marine pollution, and biochemical techniques) and will use discussions to guide them in developing the conceptual and technical background needed.

Judging from the program which has evolved in MIT's biology department, its position on undergraduate laboratory instruction seems to include the following principles:

1. The most important considerations in planning laboratory programs for undergraduates is that they conduct "real experiments" with a "professional flavor," that they be encouraged to develop their own ideas and resourcefulness and that they find out what it means to solve an experimental problem.
2. To accomplish these objectives requires a substantial commitment of time both on the part of the students and professors. To prevent overloading, each laboratory should be assigned substantial credit (up to 24 units or eight semester credit hours). This means that the number of different laboratory courses taken by an undergraduate will be very limited.
3. By offering several different laboratory courses on a rotating basis, the professional quality of the programs can be maintained and the work load distributed among the faculty. This also contributes to maximum utilization of space and equipment and provides students with a choice of which area they will pursue in depth.

4. **At the lower division level, a laboratory course which uses the exercise approach to introduce a student to a variety of experimental approaches can serve to broaden his experience and prepare him for more authentic work in the upper division.**

PART IV

HELPING STUDENTS LEARN TO INVESTIGATE – ADVICE FROM THOSE WHO HAVE EXPERIENCE

In the past few years, the staff at CUEBS has talked with many teachers who agree with the idea that undergraduate laboratories should be used as places in which students learn to investigate. Almost without exception, those teachers have asked: How do you begin? What seems to help facilitate the learning of investigation? How do you finance and grade such an undertaking? What are the pitfalls?

In search of answers, we asked a number of those who have been involved in developing investigative laboratories or have observed several in operation to give their advice. That advice is reported in the following essays.

12. AN ANALYSIS OF THE COMPONENTS OF INVESTIGATION AS THEY RELATE TO TEACHING THE PROCESSES OF SCIENCE

In his thoughtful book, *The Purposes of Higher Education,*[1] Houston Smith notes that:

> At the root of every discipline there are a few apparently simple questions which regularly deflate its experts because they cannot answer them in unison. In education these all swirl around one which is absolutely basic: *What are we trying to do when we teach?*

He goes on to point out that:

> The answers abroad today are far from clear.... Until this confusion regarding the basic purpose is replaced by greater clarity and agreement, education will continue to compromise its possibilities, with occasional instances of real effectiveness only highlighting the general mediocrity.

I doubt if it will ever be possible for all of us to agree on what it is we should be trying to do when we teach. But certainly each teacher needs to be clear about what it is he is attempting to help students learn. If he isn't, how can he plan what he will do to facilitate their learning and how will he be able to evaluate his efforts? In this regard, I rather agree with the notion expressed in a limerick written by Robert Mager.[2]

There once was a teacher
Whose principle feature
was hidden in quite an odd way.
  Students by millions
  Or possibly zillions
  Surrounded him all of the day.

When finally seen
By his scholarly dean
And asked how he managed the deed,
  He lifted three fingers
  And said, "All you swingers
  Need only to follow my lead.

To rise from a zero
To Big Campus Hero
To answer these questions you'll strive:
  Where am I going
  How shall I get there and
  How will I know I've arrived?

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[1] Smith, Houston. 1955. *The Purposes of Higher Education*, Harper & Brathey, New York.

[2] Robert F. Mager. 1968. *Developing Attitude Toward Learning*, Fearon Publishers, Belmont, California, $2.00.

When we try to help students learn the processes of science or the art of investigation, what is it we are trying to teach? Where is it we are going?

In attempting to clarify my own thoughts in this regard, I found it useful to create a diagram (Figure 1) which shows the relationship of some of the components of the investigative process.

In the diagram, use is made of symbols similar to the ones created by biochemists to illustrate metabolic processes. Arrows designate the energy-requiring activities of investigators (making observations, posing problems, generating proposals, collecting data, reducing data, making interpretation, and recording and communicating the results) while words in boxes symbolize the products (observations, problems, proposals, data, interpretations) which are produced and used as the investigative activities are carried out. These products (collectively called knowledge) are recorded — if not on paper, certainly in mind — and are constantly fed back into and modified by the investigative activities.

Although this simple diagram illustrates that investigation is a rather complex network of integrated activities in which several kinds of information are produced and used, it does not capture the uniqueness and creativity which characterizes true investigation. The generation of scientific knowledge is not a simple mechanical activity. At every stage, significant choices which influence the future direction and outcome must be made. Investigations are personal creations, as is illustrated by our frequent use of possessive pronouns when referring to the process and its products — "his" study. A related consideration concerns the fact that each of the investigative activities is facilitated by personal attitudes (curiosity, openness, confidence) and skills (ability to use symbols, logic, instruments, the library, statistics, and to discriminate and measure). Just as biochemists know that metabolic reactions will not proceed at any appreciable rate unless appropriate enzymes, co-enzymes, and co-factors are present, so also the teacher knows that investigation cannot proceed in the absence of the appropriate facilitating attitudes and skills.

That investigation involves personal choices and is facilitated by human attitudes may seem to run counter to the general notion that science is objective rather than subjective. This apparent contradiction stems from the belief that objectivity and subjectivity are opposites and thus mutually exclusive. But science is both objective and subjective. Its objectivity is related to the focus of its study — natural objects and phenomena which presumably exist whether or not we choose to study them. The subjectivity is due to the fact that the products of investigation are human creations — words, formulae, diagrams, ideas, concepts, etc. Thus when we speak of science as being objective we do not mean to imply that its processes are not subjective or that scientists are somehow able to free themselves of biases when they investigate. Rather, we mean that the knowledge which is created by investigation is judged on the basis of its ability to reflect natural objects and predict phenomena.

To summarize, when we teach investigation, I think we are trying to communicate that it is

> an integrated web of human activities — observing, questioning, generating proposals, collecting data, reducing data and making interpretations, recordings and communicating results,

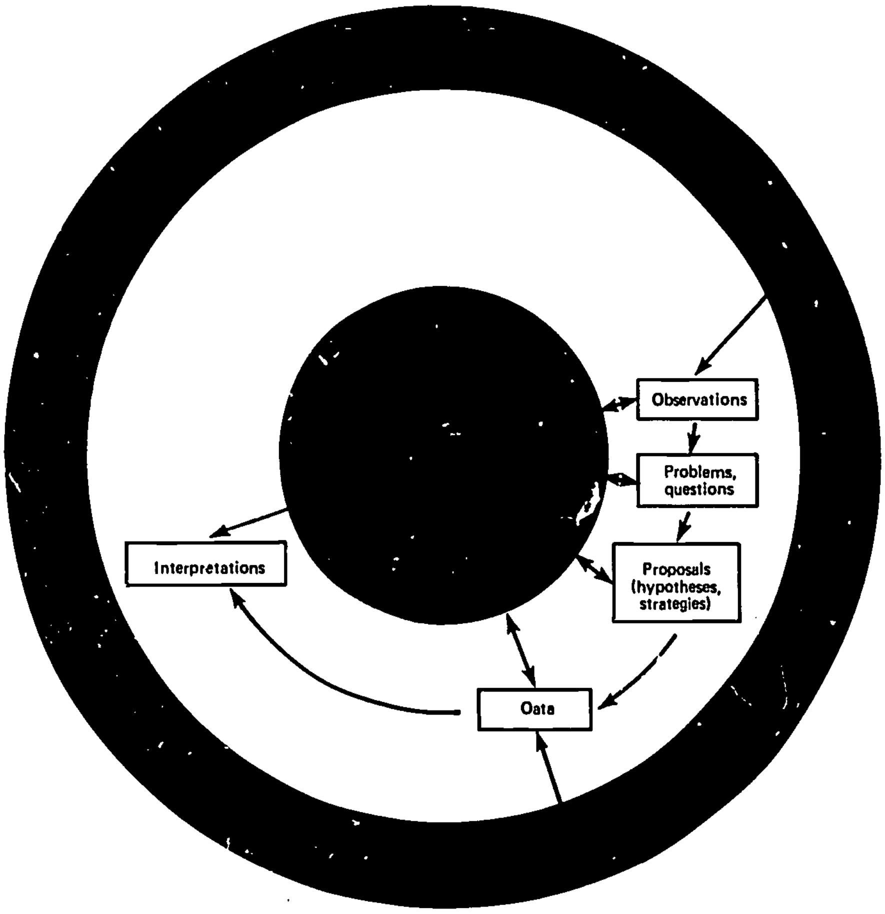

Figure 1 – The Activities and Products of Investigation

which is

facilitated by a characteristic set of attitudes — curiosity, openness, confidence — and skills — the ability to use symbols, logic, instruments, the library, statistics, to discriminate and measure,

that it

produces knowledge — observations, questions, proposals, data, interpretations —

which is

evaluated on the basis of its ability to reflect natural objects and predict phenomena.

Having outlined what it is we might be trying to help students learn when we teach investigation, we can now turn to the question of what a teacher can and should supply to facilitate that learning. In search of answers to that question, I interviewed students and teachers who were involved in the Investigative Laboratories described in the preceding sections of the publication. I became convinced that there is no "one-best-way" to teach an investigative laboratory. What works well at the upper division level may be ineffective with freshmen, and programs developed by the teachers at a research-oriented university may not work at all in the hands of a two-year college professor. What did emerge from the interviews was a clearer picture of the kinds of learning environments and strategies which seem to encourage the learning of investigation by students. Thus, I feel that I am in a position analogous to that of a guide at a fishing camp. He cannot give you rules which will insure that you will catch fish, but his experience with the natural environment and behavior of fish permits him to point out some of the factors which you might profitably keep in mind as you begin to fish in new water. In my opinion, the developer of a program designed to facilitate the learning of investigation should keep the following factors in mind.

1. The nature of investigation seems to be extraordinarily difficult for scientists to communicate to students via verbal symbols. In this regard it is rather like love; it is learned by experience rather than from description. This may be due, in part, to its complexity and variability, or it may result from the fact that as scientists we wish to convey it as a somewhat more orderly and rational process than it actually is. But for whatever reason, attempts to help students learn investigation by telling them about it in a series of lectures or having them read someone's description in a textbook almost always fail unless those lessons are linked with actual experience in investigation.
2. When for the purposes of instruction the investigative process is fragmented into its several activities, each of the activities tends to lose some of its challenge or relevance. Investigation seems to be one of those activities in which the whole is more than the sum of its parts. Perhaps an example can help clarify this point. I formerly had students who were enrolled in a general zoology course perform an exercise in which they measured the activity of an enzyme at various temperatures. Although they were obedient and generated the data called for in the laboratory manual, they had little enthusiasm for the work and found it irrelevant. My attempts to increase motivation were of little help in stimulating enthusiasm. Recently, some students in an investigative

laboratory ended up doing very much the same kind of work in an effort to determine whether or not differences in temperature optima of enzymes in different organisms might be responsible for the changes in flora and fauna which occur after the introduction of thermal pollution into a stream. They approached the laboratory work enthusiastically and found relevance in it. In the first case, the collecting and analyzing of data had been taken out of its normal investigative context. The result was that it lost its challenge and relevance for the students.

3. The most difficult phase of the investigative process, particularly for the novice, is related to the identification of problems for study and the design of strategies for their resolution. This may be due, in part, to the failure of precollege science courses to prepare students for these activities. But I am inclined to believe that the difficulty of these activities may be related to the fact that identifying problems and preparing proposals call on the investigator to make many real choices. Making choices always involves uncertainty and risk-taking. Few people are eager to take risks and students are most unaccustomed to being called on to do so. When asked to make choices, it is quite natural for us to want to avoid or delay taking the risks by claiming that we don't know enough to identify significant scientific problems or design appropriate strategies for resolving them. This situation is not unlike that of a prospective swimmer who finds it difficult to swim because he is afraid of the real or imagined risks involved in getting in the water.
4. Having students do investigation usually consumes more time and is both more frustrating and more rewarding than the instructor initially imagines. I have no notion of why this is so but do remember that in my own first attempts at investigation (the doctoral thesis) these quantities were also badly misjudged.

What are the implications of these rules of thumb to the teaching of investigation? First, if we want to teach investigation, we should make provision for involving each student, individually, in the total process. Second, though it is tempting for reasons of planning and convenience to fragment the investigative process into a series of exercises (one on observing, another on problem generation, etc.), this approach seems likely to fail because of the tendency of the activities to lose their challenge and relevance when taken out of the context of a total investigation. Allowing each student to do a complete investigation helps keep each activity in context. Third, our first guess about the appropriate amount of time to set aside for the investigative laboratory will probably be too small. Finally, and most important, the teacher of an investigative laboratory usually finds it necessary to do much more than simply take his students into the laboratory and tell them to investigate. Although this sink-or-swim approach sometimes works and may be very appropriate for the occasional undergraduate who is a "natural investigator," the majority of students will flounder hopelessly in such an environment. Like the swimming coach, instructors of investigative laboratories find it useful, in the initial stages of the course, to plan activities which teach a few basic skills, capture interest, evoke enthusiasm, and most important, build students' confidence in their own ability to complete an investigation. But planned activities and pedagogic devices to prepare students for investigation are not enough. The teacher's attitudes must convey the message to students that they can do an investigation and that the risks are worth the rewards. Throughout the first investigative experience the instructor must make himself available to the student so that he can provide this personal encouragement and assistance.

13. IN PREPARATION FOR INVESTIGATION

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If one is going to initiate a laboratory in which students will actively engage in investigation, how does he begin? How does one prepare for helping students experience the generation of knowledge? This article is for those who want to adopt the investigative laboratory concept for their undergraduate students. The following thoughts are put forth as a starting point in preparing for investigation. Since no two investigative laboratories will be identical, the suggestions are not all inclusive and those made may not apply to every individual.

1. A mental inventory of the facilities, equipment, and supplies will prove helpful in defining the scope of investigations that can be pursued by students. However, don't assume that student choice of problems must be restricted only to those that can be solved using the immediate teaching laboratory; highly self-motivated students will often take their investigation beyond the confines of the lab. Some students find that the modification of existing equipment and materials is a rewarding part of investigation.

2. Since the library can be a valuable asset in the selection and pursuit of an investigation, close familiarity with the library facilities are of utmost importance for both students and faculty. In the initial stages of investigation, an introduction to some key general writings within the scope of potential investigations and some standard reference sources will probably suffice. As each student more clearly defines the scope of his investigation, literature of a more technical nature will probably be requested. Formal instruction in the use of the library, listings of potentially helpful references, and repeated emphasis on effective library use are important elements in opening the library doors to students. One of the most telling results of effective library use in conjunction with laboratory investigation is the increased awareness of library resources on the part of the teacher.

3. A universal characteristic of the investigative laboratory is a quest by students for assistance from others than the instructor. A mental inventory of colleagues with special competence in potential problem areas selected for investigation will prove helpful; this is particularly true as one gets closer to student identification of a problem area for investigation. Such an inventory will in all likelihood extend beyond the bounds of others in the department;

staff members of medical facilities, government agencies, industrial concerns, and other academic institutions are likely candidates for helping students interested in their areas of expertise.

4. Since the investigative approach is not ingrained in the teaching tradition, it is most desirable to find a colleague who shares a sympathetic interest in the art of teaching others to investigate. Such a confidant will be a most welcome companion in discussing the pitfalls and joys encountered as young people experience the activity of investigating biological problems. If such a colleague is not available, do not hesitate to cross departmental lines. The art of investigation is the handmaiden of many academic pursuits.

5. Although the investigative approach is the backbone in our science, few scientists have taken the time to write about this cultural process. Here are a few such writings that have proved to be personally interesting and helpful. These selections are also quite helpful for the interested undergraduate student.

Baker, J. J. W., and G. Allen. 1968. *Hypothesis, Prediction, and Implication in Biology.* Addison-Wesley Publishing Co., Reading, Mass.

Beveridge, W. I. B. 1960. *The Art of Scientific Investigation.* Vintage Books, Random House, Inc. New York.

Bronowski, J. 1953. *The Common Sense of Science.* Vintage Books, Random House, Inc., New York.

Dethier, V. 1962. *To Know a Fly.* Holden-Day, Inc., San Francisco, Cal.

Kaplan, E. H. 1968. *Problem Solving in Biology.* The Macmillan Company, New York.

McCain, G., and E. M. Segal. 1969. *The Game of Science.* Brooks/Cole Publishing Co., Belmont, Cal.

Selye, H. 1956. *The Stress of Life.* McGraw-Hill Book Co., New York.

Tinbergen, N. 1958. *Curious Naturalists.* Anchor Books, Doubleday & Co., Inc., Garden City, N.Y.

Twitty, V. C. 1966. *Of Scientists and Salamanders.* W. H. Freeman & Co., San Francisco, Cal.

6. Emulation plays a significant role in teaching the art of investigation. Adequate opportunity must be provided for students to observe you and others (mainly students) at work in the laboratory. This is particularly necessary for students whose attitudes toward investigation are not favorable. From the very beginning of the investigative laboratory, all students should have numerous opportunities to observe several persons engaged in laboratory activities. Ideally, the time lag between actual observance of laboratory work and performance should be short. Select those laboratory activities, methods, or techniques which are most likely to have immediate use by the student in pursuing potential questions in an area of investigation; introduce them not for their intrinsic interest or value, but as potential tools for effective inquiry. Early in the investigative process, familiarity with the tool is all that can be expected; mastery can come later if that particular tool is to be applied in an individual investigation.

7. Models or examples of those products which the student will create during the course of the investigation should be made available for study. If students are asked to pose a question, formulate a hypothesis, and design an

experiment to test the hypothesis, provide some examples to clarify your expectations. If a paper is to be submitted at the conclusion of an investigation, provide examples of such papers. I found it quite valuable to supply my students with sample student papers from *The Journal of Biological Research*, published by Catonsville Junior College. My students could more readily identify with and criticize other student works than those of the professional scientist, an obvious but, nevertheless, important point. The most outstanding student papers were suggested as models for emulation.

8. During the first few weeks of the investigative experience, it is necessary to prepare some "exercises" designed to: (a) develop a familiarity with laboratory facilities and equipment; (b) provide examples of the types of investigations that are within the scope of the course; (c) introduce techniques that may prove valuable to students for their own investigations; and (d) provide practice with forming a hypothesis that focuses on a clearly posed question and designing an experiment to test the hypothesis. It is important that the "exercises" be clearly presented as a means of introducing techniques, procedures, and suggestions that will help students in designing their own investigations.

9. Whereas investigative laboratories will follow no fixed schedule, it is most helpful to prepare an outline of investigative activities that will unfold as the course progresses. This outline should not be viewed as a schedule, but rather a forecast of major activities in relation to the lapse of time in the course. Any forecast is likely to include such components as: (a) goals and objectives of the investigative laboratory; (b) use of the library; (c) introduction to some useful laboratory techniques; (d) guides to selecting a problem, formulating a hypothesis, designing an experiment, and reporting the results of an investigation; (e) conferences and brainstorming sessions with individual students and groups of students; (f) experimentation in the laboratory; (g) paper writing; and (h) oral presentation and discussion of individual investigations.

10. Before undertaking an adventure with students in the activity of investigation, take a hard look into a mirror to assess your preconceived ideas about the abilities, background, competence, desires, and expectations of undergraduate students. Remember, most of our impressions of students concerning these matters are based on observations made while students are tackling tasks selected by us for them to do. The behaviors of students in this situation are quite different from those exhibited when they are undertaking activities of their own design. It is this latter situation which you will be observing if your students are investigating a problem of their own choosing, in consultation with you.

14. THE LABORATORY: LEARNING SCIENCE BY BEING A SCIENTIST*

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Whenever independent study and research for undergraduates are discussed, the talk seems to run to opportunities for student investigations undertaken *outside* the framework of organized classes. Virtually all colleges have such arrangements, but I have a suspicion that, in practice, many college students of science end their college careers with little exercise in independent investigation. A separate research activity entirely independent of a formal course serves a real purpose but it is not the *only* way to have students engage in research at their level, and in some cases it may even not be the best way.

Independent investigation can be achieved *within* the framework of an organized course. Since most of the science we present is organized into courses, it seems like opportunity lost if inquiry and scientific investigation are not very much a part of these courses which make up the bulk of the student's education.

I can best illustrate what I mean by describing how I attempted to do this in a bacteriology class at Baldwin-Wallace College. We began the course with structured bacteriology exercises, but as the quarter progressed, the students spent more and more time on an independent investigation of their own choice, until independent work took over most of the laboratory course.

The most difficult aspect of this way of teaching is the choice of a suitable problem for each student or pair of students. Obviously, since the students have not had bacteriology, they do not know what the problems of bacteriology are. Students unaware of the subject tend to choose enormous problems — those far beyond the resources available to them. Most no longer try to cure cancer in 3 months, but their proposals are usually far too grandiose. Actually, it is hard to find a problem too simple to be worthy if it is explored to its limits.

After the scheme had been in use for a few years, it became much easier to help students choose a problem, for students came to the course expecting to do a project. They had learned of the undertakings of other students and came with ideas of what they might do.

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*Originally published in CUEBS News, Vol. VI, No. 2, December, 1969.

A good problem must have these characteristics:

1. It must be a real investigation for the student, note that the emphasis is on the words "for the student."
2. A good problem involves worthwhile laboratory activities.
3. It must be something the student can really do and-do in the time available. He may well find at the end of the quarter that there are many ramifications he still wants to explore, but he should at least reach a satisfying point within the time allowed.
4. Above all, the problem must be interesting to the student himself.

Ideas for projects often come from the personal interest of the student in some related field. One student had a consuming interest in the chemical and medical aspects of cadmium and did very interesting work on the use of chelating agents in protecting bacteria from cadmium. One student worked on a lathe during the summer and became interested in the organisms living in cutting oil. Sometimes other faculty members come with problems they truly want solved or with problems which are suggested by their own work. One wanted to know, for example, how to control bacterial competitors in his slime mold cultures. Another suggested a source of many fruitful studies: the nitrification of organic material in marine aquaria.

Some of the problems are discovered through the students' reading. One girl was greatly troubled in reconciling her rather narrow religious background with what she had learned about evolution. In the course of the wide reading she did to resolve the issue, she found Lederberg's replica plating experiment the vital evidence she was seeking in support of the role of natural selection. She devised her own version of his experiment. Her performance was too important to drop at this point, so I had her demonstrate her experiment to my beginning classes until graduation cut short this opportunity to teach the mechanics of evolution in a meaningful way.

Some students turn in pedestrian performances, but most really get caught up in the spirit. In many cases, the work begun in this class has been continued as honors work or has been continued in graduate school.

Students must be prepared to accept failure. The instructor must resist the temptation to grade on whether the hypothesis was proved or not. Instead, the student should be rewarded for the way he pursued his inquiry.

This method of teaching provides a chance to break away from grades as the sole motivating device; a better motivation is the esteem of the student's classmates. If a student found a significant breakthrough or encountered a particularly baffling problem, we discussed this with the class at the time. At the end, each student, whether he proved his hypothesis or not, stood on his own feet and discussed his work with the class. This exchange was a significant part of the learning.

One must be careful that the projects are not merely exercises in the use of specific equipment or techniques. Equipment and techniques should be used to solve intellectual problems; experiments should not be designed to use equipment.

Even beginning courses can be designed so that virtually every activity involves problem-solving and a scientific investigation, even though the activities are simpler, less independent, and shorter in duration. In this way there can be a continuum so that independence increases from course to course, culminating in work which is completely independent of course structure. By the time the student reaches this point, he should have a good idea of what is worth investigating and a well-developed taste for research.

Students should not be thrust unprepared into research, and investigative activities should not be restricted to the elite. Investigative procedures should be an integral part of all laboratory activity.

I do not have the slightest idea of how this kind of teaching can be made available to the thousands of undergraduates in the larger universities; it may, in fact, not be possible for it makes such heavy demands on the instructor. The fact remains that the method *can be* used in the hundreds of liberal arts colleges of the country and such opportunity may be a good justification for the existence of the smaller college.

15. THE ROLE OF THE LIBRARY IN AN INVESTIGATIVE LABORATORY*

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Two main objectives for the investigative laboratory have been suggested (Holt, 1969). First, the investigative laboratory should provide an opportunity for the student to develop attitudes toward the utility, strengths, and limitations of the scientific approach. The second objective is to provide students with an opportunity to see the nature of scientific activities. Implicit in these objectives is the idea that the investigative laboratory will allow the student to develop his own ideas through a student-directed investigative project.

If the overall objectives of the investigative laboratory are to be achieved, the student's experiments in an investigative laboratory should not be isolated from the use of the library. There are three basic functions which the library can perform in supporting these objectives.

First, an exploration of scientific literature will reveal certain aspects of the nature of science. By using the literature in relation to a problem-solving operation, the student is required to do library research and, more important, to evaluate the literature in order to develop his experimental program. This activity will show him both the careless, confused experiment and the tenuous results it produces, as well as the simple experiment and the reliable results it produces.

If the student does a significant amount of literature review, he will have an opportunity to see how a specific topic has developed. For example, in plant physiology a student working on environmental factors affecting growth would find through his search that early plant physiology consisted mainly of observations on the gross morphological differences that could be demonstrated through changing the intensity or amount of the factor being studied. The further development of this field, as revealed to the student through the literature, includes more precise measurements of the factors involved, and more recently, the investigations of the biochemical mechanisms of the mode of effect of the environmental factor. However, this point should not be overemphasized. The student is not likely to come to any

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*Originally published in CUEBS News, June 1971.

significant understanding of the overall history of a field, although over the shorter period of the recent past he can see the development of his topic. Therefore he can appreciate the idea that science is not static.

The second and most practical reason for the students' use of the library in an investigative laboratory is the students' need to be informed. The beginning student obviously does not have the background that the experienced student has. This inexperience must be compensated for if the student is to have an adequate understanding of the field in which he is working and is to be able to ask the right questions in formulating his investigation. This does not mean that the library is a substitution for advanced training. Instead, it should serve as a reservoir of information which can be tapped whenever a student's subject background is not satisfactory for the problem he is trying to solve.

Third, and most important, through the use of the library the student learns the relationship between the prior art and an investigation. By doing the search of the prior work, the student can choose for his topic the appropriate methods and techniques, which the instructor has already shown him, what experimental data are now accepted in the field, and what work needs further experimentation. The literature will also reveal the current conceptual framework with which the laboratory data will either agree or disagree.

The role of the library and literature in the development of science can be demonstrated by having the student actually experience it during an investigation. He is to learn by doing — not by reading or talking about it.

The importance that library usage plays in reaching the objectives of the investigative laboratory means that effective use of the library is crucial. It is therefore essential that whenever an investigative laboratory is used a substantial component of library instruction be included. For this instruction to result in an effective program, it should have the following characteristics:

1. The faculty must be committed to having students learn the skills required to make effective use of the library. Snyder (1965) puts it properly when she writes:

> If he [the student] can successfully complete the academic program by reading the text, attending lectures, and passing an examination based on text and lectures, there will be little stimulus for him to build a competence in research or using research tools.
>
> Here the responsibility rests with the faculty members.
>
> Clearly the investigative laboratory idea would not permit a student to "complete the academic program by reading the text, attending lectures, and passing an examination. . . ." However, the crucial question is whether the faculty really expects serious library search *before* a laboratory investigation is formulated.

2. Library instruction should be an integral part of the students' class work. Therefore course work should be developed with the idea that it will provide opportunities to practice using the library (Snyder, 1965 and Knapp, 1966). This may seem like an obvious point. Yet the normal situation is the inclusion of library instruction as an afterthought. Instead, faculty members and librarians must work to develop meaningful assignments that include instruction and practice in the use of the library.

3. Library instruction should provide an opportunity for the student to carry out the actual steps of a library search. Phony exercises which ask students obscure questions about where to find a variety of facts are inappropriate busy work and should be avoided.

The general biology course at Earlham College, while not containing an investigative laboratory per se, does suggest a model for the library's role in an investigative laboratory. The Earlham course consists of two 10-week terms dealing with six general areas: (1) populations and ecology; (2) organisms; (3) behavior; (4) cells, genes and energy; (5) development-growth, differentiation and regulation; and (6) biology and society. In addition to the subject content objectives of the course, there are a number of collateral or behavioral objectives which are considered by the staff to be important. These objectives can be broadly summarized as communication and information processing. Improvement in communication is accomplished through the development and practice of oral skills and writing skills. Information processing involves the ability to gather, analyze, and synthesize biological information from various sources (e.g., field, laboratory, library, other students, faculty) in order to solve problems.

Each portion of the general biology course is designed specifically as a *modus operandi* for achieving these goals. A sequence of two lectures per week provides subject matter coverage as do the reading assignments. Quizzes, given weekly, provide a check of the student's progress in grasping subject matter. A brief set of readings is used in the weekly discussion groups to provide a focus for practicing the skills of communication and information processing in small group situations. The library component, about which more will be said later, and the laboratory work provide opportunities for attempting the laboratory aspects of information processing and the skills needed for effective written communication.

The library instruction program used in the general biology class is a program that meets the three criteria enumerated above. The faculty impressed upon the students the importance of the ability to use the library. They have done this by stating it in their objectives for the course, by allowing time for library instruction in the course schedule, and by evaluating students' written work partially on the basis of their information sources. In the final analysis, the staff made it virtually impossible to successfully complete the course without using the library effectively.

The structure of the library instruction program will best show how the student is given an opportunity to practice the actual steps of a library search. The instruction was provided in three stages. The first two occurred as part of a laboratory period early in the term. During the laboratory period, the science librarian talked to the class about certain routine matters (e.g., how to use microfilm readers) and then students were introduced to the "guided exercise," which was the second stage. Briefly, this exercise consisted of a simulated library search in one of three subject areas: ecology, genetics, or animal behavior. The simulation covered not only the search strategy (e.g., when to use a particular reference book), but also showed how to use the various tools. The simulation of search strategy covered such areas as: (1) the use of secondary and tertiary reference sources; (2) the author approach to the card catalog; (3) the subject approach to the card catalog; (4) the use and importance of annual-review-type literature; and (5) the use of serial indexes.

The major reference tools explained include the *McGraw-Hill Encyclopedia of Science and Technology*, the card catalog including the serials file, *Science Citation Index*, and *Biological Abstracts*.

The exercise was written in the form of programmed instruction. However, it depended on more than just going through printed frames at one's place of study. It required the student to go to the library and actually carry out a series of steps which encompass an appropriate search strategy. For a more complete description and an evaluation of the guided exercise, see Kirk (in press).

The exercise was exclusively a library assignment and was not related to other activities in the course at that time. However, because it leads naturally to later work in the course and was designed to prepare students for the later work, the overall effect was as a series of assignments which gave the student increasing independence to investigate his own problems. At about the time the students were doing the library guided exercise, they were finishing up an ecology laboratory in which the central task was to describe and compare "species composition, diversity, and productivity of trees on two slopes in Sedgwick's Rock Preserve" (a college-owned woodland plot). While students were not expected to use the library to complete the laboratory, many made a somewhat confused attempt to do so. This and several other assignments that might have involved the use of the library, but did not require it, created some motivation to use the library.

The first library exam was the third stage of the library instruction. The students were to answer a question through the use of information found in the library. The faculty's objective was to give a question which required evaluation and synthesis of information rather than a cut-and-paste job. In Appendix I are the instructions for the exam question along with five sample questions. The faculty evaluated the answers to these questions on the basis of: (1) coherence and logical presentation; (2) writing skills; and (3) literature sources and their evaluation as well as accuracy. This does not mean that the staff had developed a precise list of "must" references. Instead, a more general evaluation was undertaken, where we asked such questions as: Were appropriate sources for a paper in biology used? Were primary sources used? Were an adequate number of sources used?

Two weeks after these exams the first experimental laboratory was started. For the last several years this lab has dealt with bean root growth and the factors which affect it. Students were free to choose their specific areas of study within the limits of available equipment and the techniques required. The students were expected to do their library research, then present to the faculty members of their respective lab sections experimental designs based on their library work. The students had 2 weeks to develop their methods and about 4 weeks to complete the experiments and write-ups. Unlike students in an investigative laboratory, these students were dividing their attention between their bean experiment and other course activities. From that point on, and throughout the second term of the course sequence, it was expected that the library would serve as an important source of information whenever students had need for information for an assignment. In fact, what was being emphasized was a pattern of self-education which was the overriding goal of Earlham's general biology course.

In all upperclass biology courses it is assumed that students have had this program of library instruction in general biology. Therefore, investigative-type assignments can be made without taking time to make sure students know how to use the library. Some time is provided to deal with specific new reference sources (e.g., *Chemical Abstracts*) but the general skills required for effective library usage are assumed to be part of a student's repertoire of skills.

The role of the library in the general biology course, as well as the success of the specific program of library instruction, has been evaluated and reported elsewhere (Kirk, in press). Here these results can only be summarized. (1) The guided exercise taught the use of the library as well as a conventional lecture-demonstration. (2) Students' opinion of their library instruction was positive. (3) According to the students, the library was appropriately emphasized in the general biology course. (4) There was a strong feeling (92%) among students that the library exams were a valuable educational device. (5) Students felt they learned more through the library exams than through regular objective-type examinations.

These evaluations are based on the students who took the general biology course in 1968-69. Since then, additional evaluations have been made. The results of these evaluations are summarized in Table 1. The items on the questionnaires have been very similar from year to year so it has been possible to compare responses and look for any significant trends. The pertinent sections of the questionnaire for 1969-70 and 1970-71 are included in Table 1. The results are in agreement with the conclusions outlined above.

Table 1
Results of Student Questionnaire on Attitudes
Toward the Library and its Role in General Biology

	1969-70	1970-71
What type of examinations do you prefer?		
objective hour exams	6%	not used in
short essay hour exams	27%	'70-'71
long open-book essay exams	10%	questionnaire
library exams	46%	
other	11%	
Were library exams		
overemphasized?	30%	32%
appropriately emphasized?	67%	64%
not emphasized enough?	2%	4%
no response	2%	—
Students rated their competence in using the library to obtain information in biology.		
Excellent	31%	21%
Good	47%	54%
Average	17%	25%
Fair	3%	0%
Poor	1%	0%
No response	1%	1%

To convey more clearly the exact way in which the library could ideally relate to the investigative laboratory, the remainder of this paper will be devoted to a detailed look at a student's use of the library in relation to a bean growth laboratory in Earlham's general biology course.

Certainly this program is not an investigative laboratory. However, the type of library use in the Earlham program can and should be adopted as part of the investigative laboratory. It is hoped that this presentation will provide a picture of the nature of the involvement. The search described is that of an actual student. She was a junior, not majoring in any of the sciences, and was taking general biology as part of her science distribution requirement.

She was given seven pages of background and supporting information on "Factors influencing root development in *Phaseolus vulgaris* var. red kidney." This mimeographed handout provided directions on how to become familiar with basic plant structure and function through readings and observational laboratory work. Also included were general comments on types of culturing techniques and other techniques and experimental design problems. The handout concluded with two sample articles on plant growth which were intended to provide samples of how to write up an experiment (Israelstam, 1968 and Pimentel, 1962). She was to read the handout before coming to her laboratory session the following week. At this point in the term she had completed the library guided exercise and had taken one exam on "The Cause of Leaf Coloration in the Fall."

Sometime during the 3-hour laboratory period her instructor expected a generalized experimental design and a list of materials needed. She decided to work on the effect of radiation on bean root growth. During her conversation with the professor, she developed a very general hypothesis that "radiation will have damaging effects on root growth." She decided the dependent variables would be the viability of the seed, age of the seeds, and the effect of radiation on the seeds. The experiment's independent variable would be radiation levels.

The discussion with the professor also raised many questions of which only a few are listed here: Are there other dependent variables? How do you calculate radiation levels? What dosage should be used? How should the experiment be set up? What are the "effects" likely to be? How are the "effects" to be measured? During this conversation she was also told that her radiation would consist of gamma rays from a Cobalt 60 source with a strength of 3 millicuries.

She came to the library after the laboratory period to begin her search in an attempt to answer the questions that had been raised. By using the library skills she had learned in conjunction with other work in the course, she was able to make intelligent use of the literature. She began her search with a basic encyclopedic source (in this case, the *McGraw-Hill Encyclopedia of Science and Technology*, 1966). The index entry "radiation injury" directed her to two sections of the encyclopedia, volume 3:667-668 and 11:241-250. These two articles provided basic background materials (e.g., conceptual framework for the subject, definition of terms, and range of dosages). The bibliography on page 252 of volume 11 was useful in leading her to more detailed sources.

After exhausting this line of attack, she turned to the card catalog. First, however, she checked the subject heading list which is the basis for the subject entries in the card catalog (U.S. Library of Congress, 1966). She checked the term that was most obvious: Radiation. In the subject heading list she was able to establish the several headings that appeared useful: Radiation — Physiological effects, Radiobiology, and Gamma rays. Her check of the card catalog revealed several titles that potentially would be useful to her project. Careful examination of the titles revealed that *Radiation Biology* (Casarett, 1968) would be the most useful. This title was an excellent source which covered all aspects of radiation biology. There were extensive sections on the basic physics and biology of radiation and then sections on special aspects, of which "Effects of radiation on higher plants and plant communities" was the most useful. The study of this material proved most beneficial for her project. It not only provided more background information but gave her detailed material on specific problems: dosages and how to calculate them, experimental design and techniques. Most importantly, it opened up a new variable — water content of the seed. This eventually became her experiment's independent variable.

By this time she was sufficiently well versed in the problem of gamma radiation effects. It remained for her to determine more precisely how "effects" were to be measured and whether other research might suggest the approach her experiment should take. In addition, a more precise hypothesis or prediction of the results would be useful.

The first and most obvious approach she tried involved the use of the references in Casarett. Three of these references looked especially useful (Gunckel, 1954; Bieble, 1965; and Gordon, 1957). Gordon was the only reference available in the library. This turned out to be quite sufficient for continuing her research since it was one of a series of four articles under the title "Symposium in the Effects of Ionizing Radiation in Plants." The most useful of the four was Gunckel's "The effects of ionizing radiation on plants: morphological effects" (Gunckel, 1957). From the article a number of important pieces of information were drawn which included: (1) Results from one species or variety should not be applied to others. (2) The reference, Quastler, 1952, should be checked. (3) Many responses from gamma radiation are frequently observed in nature but are speeded up or accentuated by the radiation. (4) Chromosomal damage and/or mitotic inhibition in meristem cells may contribute to reduced growth. The article does not help on the question of effects of radiation on seeds.

The pursuit of the references in Gunckel (1957) produced no useful leads.

In many areas of science there are review-type publications which are easily identified by the heading *Annual Review in* or *Advances in*. Students were told in the guided exercise to find the appropriate title early in their search. She did check the subject index in each of the volumes of the *Annual Review of Plant Physiology* from 1964 to 1969. The indexes for volumes 16(1965) and 19(1968) both contain entries under gamma radiation or radiation effects.

In "Physiological effects of gibberellins" (Paleg, 1965) a recent work on gamma-irradiated wheat seedlings was mentioned (Haber, 1960). While this reference itself was not useful for methodology, etc., it did provide two references that would have been very useful (Schwartz, 1956; and Sicard, 1959). Unfortunately neither of these references was available in the library.[1] *Biological Abstracts* was consulted for summaries of the articles. Both summaries made the articles look more important. These references were noted and saved for later use in the *Science Citation Index*.

The other article referred to in the index of the *Annual Review* was "Ionizing radiations as research tools," (Haber, 1968). This article makes reference to an article also referred to in Paleg's article (Haber, 1960), and, in addition, to another article by the same author. This latter article did not turn out to be useful. Haber's article also talked about the importance of moisture in intensity of radiation effects.[2] Three references on this aspect were noted. They were not available, but abstracts were sought in *Biological Abstracts*. When located, it was found that they were on X-ray irradiation and were rejected.

The check of the *Annual Review* had led to two useful references, neither of which was available in the library. These two references were checked in the *Science Citation Index* and led to the following new articles:

Schwartz, 1956:		
Haber, A. H.	1964 Am. J. Botany	51: 151
Congdon, C. C.	1966 Cancer Res.	26: 1211
Vanhuyst, R.	1967 Radiat. Bot.	7: 217
Haber, A. H.	1968 Ann. R. Plant	19: 463
Haber, A. H.	1968 Radiat. Bot.	8: 39
Banerjee, S. K.	1967 I. J. Genet.	27: 417
Haber, A. H.	1969 Radiat. Bot.	9: 473
Reuther, G.	1969 Radiat. Bot.	9: 313
Wangenhe, K. H.	1970 Radiat. Bot.	10: 469
Sicard, 1959:		
Stein, O. L.	1964 Radiat. Research	21: 212
Campbel, W. F.	1966 Radiat. Bot.	6: 535
Haber, A. H.	1968 Radiat. Bot.	19: 463

These articles were not related to the question of gamma radiation effect on *Phaseolus vulgaris* seeds and she therefore did not investigate any of them.[3]

The final step was to search *Biological Abstracts*. Beginning with 1970 she checked the terms gamma rays (radiation) and *Phaseolus vulgaris* for useful articles. After finishing the 1970 issue, which located one useful article

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[1] Again the problem of inadequate library resources has ruined a good bibliographic lead. Admittedly this is a difficult problem with which the library must deal. The solution that seems most reasonable is to choose a subject area in which the investigative laboratory is to be involved and then commit funds to a gradual development of the library in that area. This can be done less expensively through the purchase of microfilm copies of journals and photocopies of individual articles. The limited resources of the Earlham Science Library have not prevented the students from doing an acceptable literature search, even when time limits restrained them from ordering photocopies of articles through interlibrary loan. The investigative laboratory, on the other hand, permits students to proceed at an individual pace, and therefore students do have time to order items on interlibrary loan.

[2] An important additional step of searching would have been to check important authors (e.g., Haber) in *Biological Abstracts* or *Science Citation Index*.

[3] This sample search was not selected to show a perfect search. Instead, a typical search, if such exists, is demonstrated. Therefore, some steps, such as the use of the *Science Citation Index*, do not produce the results that one would usually expect.

(Goranov, 1965), she reduced her search to *Phaseolus sp.* and particularly *P. vulgaris.* She continued her search backward through 1966 and found two references on the effects of water soaking (Heydecker, 1967 and Orphanos, 1968) and one on X-ray and neutron irradiation effects on *P. mungo* (Jana, 1964).

She had done a rather complete search and was ready to finalize her experimental design and sharpen up her hypothesis. If this had been part of an investigative laboratory, she might have completed the initial experiments and then conducted additional searches related to new questions raised by her experimental results.

This search took between 5 and 6 hours, including time spent actually reading the material located. This amount of time might be questioned by students if they felt it was unnecessary, tedious busy work. However, our strong impression is that this is not the case. The library exams mentioned earlier, which should involve about 5 hours of library search, actually take about 6-8 hours of search time. Yet students prefer the library exams over an hour factual recall examination. It is clear to the Earlham general biology staff and the Earlham library staff that the experimental laboratory experience and the associated library work were stimulating, educational assignments.

APPENDIX I

Exam instructions:

This examination is to be written outside the classroom. You should provide an essay-type answer limited to 5 double-spaced, typewritten pages (250 words per page) or 1250 words. Papers in excess of this will not be corrected.

Should you want to include figures, tables, graphs, etc., in your paper, they should be attached to the back of the paper and should not be counted in the total of 5 pages.

You should budget your time working on this examination approximately as follows: time in library — 5 hours; time in organizing — 1 hour; time in writing — 2 hours.

Please provide at the end of your paper a list of all references used in preparing your answer for this examination, and cite them in standard fashion (see *AIBS Style Manual*) in the context of your essays.

We would emphasize that you are free to talk with anyone while you are preparing to write your answer, but the expectation is that your answer will be yours and yours alone.

PLEASE HAVE RESPECT FOR THE LIBRARY! You are not the only one using the library. We would urge you to be considerate of others. Do not, during the examination, remove any book or materials from the library (whether or not you are the only one using it). Be sure to use your talents in the use of the library.

Sample questions:

1. Discuss the factors that control the distribution of barnacles. Select a single species. Support your discussion with evidence — *not your opinion.*

2. Downtown businessmen are continually concerned with the excrement covering the outside of their buildings. They, of course, have tried many things to remove the producer of the excrement — the Starling — from urban United States. Discuss the ecology of these increasing Starling populations and the problems involved in controlling them.

3. To maintain his agriculture, man has devised many methods. One of the most efficient methods of maintaining agricultural productivity has been to control the diseases and insects that attack his agricultural crops. In many instances, these so-called pesticides have been used without due consideration for the effect of these pesticides on other populations. Discuss the effect of Dieldrin on invertebrate populations using your ecological knowledge as a basis for your discussion.

4. Discuss five examples of possible exceptions to the rule that there is no such thing as sympatric speciation. Define your terms and take a position on whether or not you support the rule.

5. Document three examples of homology and three examples of anology in the evolution of plants or animals. Is phylogenic classification the best way to do it, or would a more ecologically oriented taxonomy be better? What are the advantages of each?

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16. SOME DISTINCTIVE FEATURES OF I-LABS

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Given the great variation that one finds in student ability, motivation, and self-expectations, in the personalities of college teachers, and in institutional character, it is remarkable that just a single concept of undergraduate investigative experience should enjoy any currency today. As it is normally invoked, this concept insists that the I-lab should be an undergraduate version of dissertation research, conducted within a laboratory, following the plan of the controlled experiment, and aimed at adding entirely new facts to the sum of knowledge. This is a fine ideal and it is a matter of great significance to college science teachers that a number of students are able, even as freshmen, to accomplish just what the concept describes. By expecting too little of our students, we often force them to play an excessively immature role — to swallow creativity and inquisitiveness and native ability that could make undergraduate education a delight for all concerned.

In actual practice, enough students do escape the confines of the laboratory and do break free of the restrictions that the experimental method places upon one's imagination to loosen up two sides of the box that the I-lab is ordinarily squeezed into. The third side — that the facts determined should be entirely new — can be broken open simply by putting students into the literature (see Kirk, Chapter 15) to discover for themselves that much research is directed at affirming and perhaps quantifying the obvious, and that great amounts of research effort go to testing the limits of earlier, very tentative "facts." Some of the introductory sessions should, in fact, be aimed at opening up student thinking in these (and other?) regards.

The final assumption about the I-lab, that it is an undergraduate equivalent to thesis research, was listed first in our initial overview because it is by far the most treacherous. It can, in fact, devastate the experience and can send students and teachers both back to traditional forms of laboratory instruction with an unshakable sense of relief. One case, which exaggerates both the conditions and the results somewhat but is nevertheless quite typical, is the instance a few years ago when two instructors at a private two-year college asked the entire introductory biology class of 65 to undertake individual projects in place of the traditional morphological laboratory. The instructors did what most people would take to be the logical things in starting off the laboratories, offering first a description of scientific methodology similar to the standard one in textbooks. Reading was then required in a small sample of published research reports, and students were asked to select projects in any subject area that interested them and then to proceed on their own. Project proposals ranged from grandiose to trivial, with only a very few being appropriate to the restricted facilities and schedule of the college and to the very limited interpretive capabilities of the students. A near majority of the students claimed to be unable to think of any project at all and had to be assigned topics, greatly overtaxing the creative abilities of the two masters-degree teachers, whose own research backgrounds were understandably limited. Needless to say, all of the other resources were similarly overburdened. Nor is there much need to describe the results, for the course was a disaster. The chaos that the students saw in the laboratory and the ridiculousness of many of the reports tainted the entire experience that these students had in biology. The one trial was enough to convince these two courageous instructors that the investigative laboratory just doesn't work.

The errors in this case were many. In the most immediate sense, the failure was due to lack of planning and the general naiveté of the instructors, but at a deeper level the important error was the assumption that there is a fundamental and inescapable equivalence between the laboratory project and the graduate thesis. The similarity is by no means coincidental, for both are investigations and both are intended to give students experience in the ways by which knowledge is acquired and put to test. Real as this similarity may be, it is nevertheless the *difference* between the course project and graduate research that must be emphasized in planning and executing investigative laboratories.

First, one must recognize that the real aims of the I-lab and thesis research are quite different, for in the latter case the student is consciously preparing to pass an evaluative hurdle. He has been challenged to demonstrate his ability to carry on scholarly work — all aspects of it — and he has willingly accepted the terms under which he will perform and by which he will be judged. Typically, he draws upon and intends to demonstrate innate ability, but he leans heavily upon mimicking behavior, which under the circumstances of most thesis work must be well developed. A few who mimic less well than others but who do have innate ability have to be tutored. However, practice in this regard is far short of the ideal of graduate education as a tutorial experience, and student failure is probably not well correlated with a real lack of ability.

The investigative laboratory must, out of necessity, retain some of the characteristics of group learning. More importantly, it must be organized not as a sequence of steps along the path to ultimate judgment, but rather as a deliberately educational experience which takes advantage of the affective milieu of "real investigation" largely as a substitute for the motivation that awareness of an impending judgment yields. The reward is in the *doing*, not in moving along, in duly certified manner, to a level of professional qualification. The I-lab is deliberately educational, too, in the sense that the student is expected to learn certain carefully selected behaviors that can be important to investigation, whether or not that represents formal research.

There are many other aspects of difference. Most conspicuous, perhaps, is the fact that the entry is different, but the list of important differences between thesis research and the I-Lab continues at considerable length. The teacher-student relationship is one of coaching rather than of trying the student's mettle. There is no conscious sense that this should be an ordeal and that pursuit of research should, in this phase, bear some resemblance to a monastic life. The community within which the student works in the I-Lab is different, too, for the commitment of most students is patently ephemeral and a residuum of competitiveness inhibits some of the sense of belongingness that is such an important aspect of graduate student life, although admittedly a light-hearted comaraderie does pervade most I-labs. The undergraduate community is less of a resource for both information and encouragement, though, than is the graduate student community.

We have alluded in several ways to a different pattern of motivation in the I-lab, with individual accomplishment tending to be more important than "please-the-teacher." This results largely from the very different reward system that exists in the undergraduate investigative laboratory. For one thing, the rewards that students expect at an early stage to gain from the experience are different from those which are actually realized, and very different from the rewards extended to the graduate student. An exploration of the elements and the timing and the contingencies of reward system in the I-lab should help greatly in providing an understanding of what an I-lab is and what it isn't — in increasing and sharpening the tools whereby the teacher makes the I-lab a valuable experience. At present, we can probably say merely that the promise of a final reward, contingent upon some ultimate judgment (a threat), is of little value and that something associated with the continuing personal interest and awareness of the instructor is most important. It is apparent, too, that this must be established quite early and that it must have a subtle informative function as well, indicating unequivocally what the teacher's real expectations for the project are. To say more about the all-important matter of rewards requires larger scale experimentation with different expressions of the I-lab idea, along with a very substantial commitment to the whole idea of undergraduate research, such that someone's time can be spared to ride through the I-lab as an observer-confidant who has no other purpose than to collect data on the sources of motivation and satisfaction in students.

Standing close by in this question of a different reward system for the undergraduate research experience (as exemplified by the I-lab and distinct from the independent or honors project) is the whole matter of the relationship to the affective domain, viz., the drives and feelings associated with the receptiveness and awareness, with responding and valuing, with commiting one's self and ordering his preferences and beliefs, and with developing an outlook or philosophy. Obviously, the I-lab situation is a unique one, and the instructor who works with an I-lab and is not deeply puzzled by the ways that these affective concerns influence his role as both a coach and an evaluator is probably not involving himself deeply enough in the students' collective experience.

How, then, do these matters affect implementation of the I-lab idea? It is not easy to say, for it is still quite early yet for the I-lab to be claiming much of a history and for that history to have yielded many lessons. But there are a few.

First, we can say that the I-lab is probably numerous things, not just a student-conceived, controlled, laboratory experiment aimed at adding new facts to the sum of knowledge. But we don't know yet what all can be regarded as in-bounds. Most importantly, different expressions of the idea will vary greatly with the individual instructor and institutional situation. What works for one instructor in one type of institution may be out of the question for another, but there should still be some version of the I-lab idea that will yield beneficial results for that instructor, provided that he can combine a little resourcefulness with the momentum gained from a general attitude of innovativeness. It is not an idea, though, that everyone should undertake. Some instructors will be best in a structured, even illustrative, lab and the total undergraduate experience should probably include some of these, though this is an assumption that should remain open to question.

Second, each instructor must be both open-minded and resourceful in deciding what specific educational objectives are to be served by his I-lab, and he must be cautious that these are kept within a limited range. Certainly, they must be few in number and chosen with the idea that an excess of ambition is probably the most common failing of all educational innovations. But, again, we are unable in this stage to say just what specific objectives fit best or are most seriously ignored on the process side of science education. Perhaps they will relate closely to the things that a scientist actually does as he explores the unknown, or, alternatively, the preferred objective may be more akin to the way the scientist's mind must work as he asks questions of nature and looks about for ways to obtain answers.

And third, it is quite safe to say that the oft-repeated generality, "playing the role of a true investigator is good for you — it adds things to your education that can be gotten in no other way," gets us nowhere. Efforts to explore just what is lacking on the process side of undergraduate education, and the affective side as well, must continue apace, with the thoughts clearly in mind that the I-lab may serve only a few of the existing needs, and that it may represent a distinct phase in the sequential development of the scientific consciousness of some or perhaps all college students.

The other questions about how best to make this a unique and universally productive experience remain open. For the imaginative, innovative, and resourceful instructor, the I-lab surely represents the most exciting of unexplored educational frontiers.

17. HOW STUDENTS VIEW THE ACTIVITY OF INVESTIGATION*

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As biologists with a tradition of research, we clearly perceive the importance of the laboratory in uncovering new knowledge, testing ideas, and formulating new understandings. However, it is a rare undergraduate who shares this perception of the laboratory. For the undergraduate teaching laboratory to survive the 70's, in the face of mounting financial difficulties and increasing student pressures, the laboratory must become to our students that which it is to us — a place for investigation.

An important step in this direction includes observations on how students view the activity of investigation. As a staff biologist with CUEBS during the academic year of 1970-71, I set out to record the views of students and their teachers on investigation. My study took me to five campuses, where I conducted interviews with nearly 50 undergraduates; many of these interviews were recorded on audio-tape. I have added to this large store of comments the recollections of 25 teachers interested in sharing the art of investigation with their students.

In the initial stages of investigation, there is a good deal of uncertainty as to what lies in store. As one teacher put it,

> By and large, college students want and enjoy the challenge of the unknown that I-labs provide. It is a rare student, however, who can be thrust into such a lab and be expected immediately to "start investigating."

Students perceive this fact quite clearly. This is reflected in their comments to questions about first impressions of the investigative laboratory. Some examples are:

> I really did not know what was going on at first.
> It was a shock.
> It was really different.
> I hadn't expected this type of laboratory.

Without exception, the successful teacher of investigation is aware of this initial sense of uncertainty and proceeds to build a foundation for investigation. The roots of uncertainty are quite individualistic. However, the

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*Originally published in CUEBS NEWS, June 1971.

more common sources of concern can be traced to difficulties of selecting a problem that is approachable through experimentation. Comments by teachers pinpoint this common difficulty.

> Students unaware of the subject tend to choose enormous problems — those far beyond the resources available to them. Most no longer try to cure cancer in three months, but their proposals are usually far too grandiose. Actually, it is hard to find a problem too simple to be worthy if it is explored to its limits.
>
> . . . the questions they ask are frequently much too broadly defined and need to be narrowed considerably.

In relating his own experience with this difficulty, one student said, "Choosing my problem was a snap; but stating it in the form of an experimental design, that was a different story."

The origins of problems for investigation are easily revealed through inquiry. Teachers and students cite the following sources:

> Some (students) come into the course "knowing" just what they want to investigate. Some have ideas or questions generated as a result of the formal laboratory studies. Others become interested in an area after examining "bound" copies of students' investigations carried out in previous semesters.
>
> Comments made in lecture got me started on a problem.
>
> My problem came out of a discussion in my fraternity about drinking alcohol.
>
> I happened to choose my project on the basis of outside reading.
>
> Recent surgery performed on my father stimulated my interest on the effects of cholesterol.

Since the selection and formulation of a problem is critical, most teachers allow several weeks for this process to take place. It is during this 3-4-week period that the student is developing his role as an investigator. At this time the teacher must provide a carefully planned mix of activities for the student including use of the library, laboratory experience with potentially useful techniques, group discussions, and individual conferences.

Closer examination of each planned activity reveals that while most students find initial planned activities helpful, few students are in agreement as to which activity is most helpful. Some students find that a search of the literature provides them with clues to the eventual formulation of a problem. Other students become interested in investigations that stem from difficulties with laboratory techniques. Still others cite group discussion and individual conferences with the teacher as the source of ideas for investigation.

Once individual investigations are underway, new problems begin to emerge. As might be expected, difficulties are encountered in obtaining materials and supplies for the investigation. On the whole, however, such difficulties are viewed as minor and alterations in experimental design are accepted as the outcome of "dealing with the real world."

As the results of investigation begin to take shape, a climate of excitement starts to build. This occurs in spite of the routine difficulties often experienced during the course of any investigative activity. In reporting the outcome of an investigation in marine biology, three teachers made the following observation:

> Excitement in the exercise ran high and continued high, despite rains, rough water, long hours, and the frustrating difficulties of trying to follow and record the activities of a partially submerged population of purplish

> black animals at night. This was at least partly because information new to both students and faculty was continually coming in.

Apparently, the knowledge that students are breaking new ground during an investigation provides a continuing source of stimulation to these neophyte investigators.

Throughout the investigation students encounter questions that require assistance from their teachers. As the investigation progresses, it is apparent that the traditional role of student-teacher is transformed to a relationship between colleagues. As one student put it:

> The advice given us was not just the answers to our questions; but advice that pointed us in the direction of finding answers to our own questions. For instance, I was having problems in getting my algae to grow. Instead of being told to try this or that, my teacher suggested several papers that I might find helpful. Sure enough, I found answers to my own questions. This approach to learning I feel was most valuable — because I found out on my own.

A natural outgrowth of some investigations is the quest for assistance from those outside the context of the course. Several examples of this were cited by one teacher:

> Several students, interested in the detection of coliform bacteria, contacted the health department laboratories. The staff willingly worked with these students and appraised us of their performance. One student sought out the plant physiologist on our staff for assistance. Another student called on a graduate student doing work in his area of investigation. A small number of medical technology students carried out studies in cooperation with the staff of the medical school, and in some cases, hospital laboratories. A psychology major obtained advice and guidance from a faculty member in that department.

Most investigative laboratories conclude with either a written or oral report of the investigation conducted by each student or team of students. It is the overwhelming consensus of students that such an opportunity should be provided. In fact, in one case where this opportunity was not provided a student commented:

> I was quite disappointed that I did not get an opportunity to share my investigation with my colleagues or to hear about their work. I had worked hard on my investigation, and I am sure that others did, and I would have liked to have told others what I had learned.

The following comments are typical of a summary of the benefits gained from the investigative experience:

> The investigative approach decreases cutthroat competition for grades, increases cooperation between students, and improves student-faculty rapport.
>
> As almost any course taken by freshmen, this one seems to aid some in making a career choice. Students seem to think the course was particularly helpful in this regard because it gave them insight into what biologists actually do in their professional work. For example, one student commented: "I think the course was an excellent one, for it forced me to think about the process of science and taught me how to use the scientific approach in trying to answer questions. This may cause me to change my major."
>
> Some students also believe that the course may have been influential in changing their general life style from one in which they blindly accepted what authorities told them to one in which they feel a need to look for evidence and investigate problems on their own.

> I found the principal value of the investigative laboratory to lie in the experience of feeling responsible for a project in which *I* was personally involved.
>
> The things we learned were not just about biology, but about ourselves.
>
> When asked by some of my friends — "Should I take this course?" I tell them that it was a very good experience for me and I recommend it very highly.

In summary, if you wish to share the vision of a laboratory as a place where others become "eager to learn," then the investigative laboratory is a good bet.

18. IF WE ENGAGE STUDENTS IN INVESTIGATION, WHEN WILL THEY LEARN THE CONTENT?

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As a graduate student, I was introduced to the fun, joy, and frustration of investigating aspects of the physiology of plants. This introduction was in a course which consisted of laboratory only. We were expected to investigate two to four problems in each of two semesters. At the end of the course, I realized that I had more fun there than in any previous course, had learned more plant physiology than I expected, and had a real sense of creative accomplishment. In terms of my teaching ambitions, this experience was tantalizing.

In my first academic appointment, I was expected to teach plant physiology — with two lectures a week, two 2-hour laboratories, and one discussion period. Enrollment hit about 30 per semester, so there were actually four laboratories to be met (two sections) and four discussion periods.

Those two experiences crystallized for me one of the most critical problems which any teacher of an investigative laboratory faces — finding time to provide both a broad coverage of the accumulated knowledge of a subject and a laboratory experience in which students can do some real investigation. The time required for accomplishing both of these objectives would appear to be at least twice that normally provided for a course. In trying to work out a satisfactory compromise, I have repeatedly pondered the following set of questions.

How much knowledge of plant physiology should a student be exposed to in a one-semester (or one-term) undergraduate course? Quick examination of any introductory plant physiology text suggested that the amount might be considerable. If one uses an investigative laboratory, how much knowledge of plant physiology is accumulated as a result of that activity? Investigating one problem over the course of a semester might be expected to develop a depth of knowledge in one small area, but little or no breadth of experience. How important is it for an undergraduate student to be exposed to a wide range of knowledge of plant physiology? Is it better that he know a small area well versus knowing many areas somewhat superficially? Certainly the world is changing so rapidly that knowledge has a large built-in obsolescence factor and it seems likely that students will be called on to cope with new, as yet unrecognized problems, soon after graduation. The relative importance which

I have assigned to these apparently competing demands of breadth of coverage and involvement in rigorous investigation has changed over the years.

In 1964-65, the topical outline of the course in plant physiology which I taught was as follows:

- I. Metabolism
  - Photosynthesis
  - Respiration
  - Nitrogen Metabolism
- II. Water Relations
- III. Nutrition
  - Mineral Nutrition
  - Organic Nutrition
- IV. Plant Growth and Development
  - Auxins
  - Gibberellins
  - Tropisms

At that time, the major emphasis of the course was upon knowledge accumulation. The discussions and examinations focused upon the solution of problems based upon knowledge accumulated in lecture, reading, and laboratory. In the laboratory, the students performed selected experiments.

At the end of the course, I realized several things: (1) the students were bogged down in the accumulation of "bits and pieces" with no framework to hang it on. Bruner (1960) has suggested that this is the outcome to be expected from the traditional approach to science education. (2) The routine laboratory exercises had not communicated the manner in which a plant physiologist works; and (3) the students were not very excited. Thus, the obvious question: What can I do to get the student involved in biology and excited about being a biologist?

At this juncture, my thoughts returned to the excitement generated in the course in graduate school which I referred to previously. Could I translate this to undergraduate education? Could I structure a course so that students would learn as biologists?

The students themselves suggested an approach which might accomplish this: pick one or two topics and pursue these in more depth. I assured them I would try. As a first step, I decided to try out the idea with a small number of students during the summers of 1966 and 1967; four students volunteered. They were given a small stipend. The only rule of the game: pick a problem and investigate it in depth. The problems investigated: (1) carbohydrate nutrition of selected fungi from the rhizosphere of *Fagus americana;* (2) factors influencing the velocity of root growth in *Phaseolus vulgaris* var. Red Kidney; and (3) amino acid secretion in selected fungi from the rhizosphere of *Fagus americana.*

Of the four students who worked in the summer, one has completed graduate study in plant pathology, one is finishing graduate study in plant physiology, one is in medical school, and the other is teaching science to deaf children. Their excitement and accomplishment finally pushed me over the threshold, but not without some problems.

The first attempt to have all students in the course involved in investigation was in 1966-67. This was received well and one student really went overboard. He followed the course by spending the summer at Michigan State University and his work was subsequently published (Hertel and Flory, 1968). He did this at the end of his freshman year.

Some of the topics selected for investigation in 1967 were: the effect of gibberellic acid on the growth of cucumber seedlings in vitro; the effect of coconut milk on carrot callus growth; the effect of light and gibberellic acid on stem elongation; the effects of indoleacetic acid on bean leaf abscission; the effects of maleic hydrazide-indoleacetic acid interaction of the growth of cucumber embryos; and the effect of maleic hydrazide on phototropism in *Avena* coleoptiles.

At this juncture, it was obvious that the investigative laboratory was very successful in stimulating student involvement and interest but there emerged a couple of new problems: (1) to get the most out of an investigative experience it was apparent that students needed to be able to use the library and literature; and (2) unexpectedly, the inclusion of investigative-type laboratories in other courses in the department.

A solution to the first problem was provided by Thomas G. Kirk, Science Librarian at Earlham College. The program he developed is described in Chapter 15. The second problem raised the question of content vs. investigation in a new context — the entire curriculum. Rightly, the students took the position that they could not take on two investigative laboratory courses in one term — particularly ones that have retained the traditional informational component — and expect to survive. But the curricula were not changed to allow for an investigative laboratory course other than within the structure of the present courses. As time went on, this was further complicated by inclusion of various types of investigations in chemistry courses. Thus, the final stage of the evolution: the plant physiology course lost its traditional emphasis on content over the next 3 years.

In 1967-68, lectures were given, but the amount communicated therein and the associated reading assignments were much reduced. This change was not altogether appreciated by the students at first. They wanted more structure to hang their "knowledge gathering" on as Bruner (1960) has suggested. Thus, it was clear that the investigation was not functioning as the focal point and framework of the course *at this point.* Some more compromising was indicated!

The lectures were changed to discussions oriented around topics related to the investigation in plant physiology. Examinations were reduced in number and de-emphasized. The course as it is currently offered is described in Chapter 7 of this volume. Basically, it focuses almost exclusively on involving students in investigation.

When considering the use of the investigative laboratory, to the exclusion of the normal lecture-text reading component of the course, what was the impact of this on the student's broad knowledge of the field of plant physiology? In the initial phases of my experience with this course, there was no question that the decrease in lecture-text reading had an obvious effect. But at that juncture, the course was really neither fish nor fowl as it was attempting to meet two time-consuming goals within the time alloted for only one of them. More recently, it has become clear that the students probably come away with a better understanding of plant physiology than they did prior to the introduction of the focus on investigation. Evidence for this comes from the reading that students do and the reports they present. Data on this are presented in my article in Chapter 7.

I have concluded that the idea that one must choose between content coverage or investigative experience is not altogether valid. It is true only if one assumes that learning "content" and "investigation" cannot occur simultaneously. They don't seem to occur simultaneously if the focus of a course is on content coverage but my experience indicates that if the focus is on investigation, the learning of content is coincidental.

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19. FINANCING AND GRADING

Because of the frequency with which they are asked, it is obvious that questions relating to financing and grading seem important to those who have not yet taught an investigative laboratory. But those who have actually offered such courses claim that these are, at best, minor problems. In the case of grading, this is not difficult to accept. A grading system which is both just and humane is probably never achieved, but we always seem to find compromises which we can live with. This is as true with an investigative laboratory as with traditional programs.

Most instructors and students grant that the grading in an investigative laboratory has to be somewhat more subjective than in a content-based course. My own experience indicates, however, that if time is spent in the laboratory with students and if the products of their investigation (reports, notebooks, talks) are discussed openly, it is not overly difficult to make an evaluation of their performance which they can accept as being fair. Needless to say, this is simplified if the grading is pass-fail rather than A, B, C, etc. Perhaps the most difficult decisions of grading are those relating to students who make an honest try but fail to bring the investigation to a satisfactory conclusion because of circumstances beyond their control — the animals die, the equipment breaks down, the supplies do not arrive on time, etc. Perhaps the easiest way to handle such situations is to give a grade of incomplete, and have them continue the investigation during the next term. But such a solution is not always possible if the student is graduating, has requirements which must be fulfilled, or if the space and equipment are to be used by other courses. In such cases, I usually resort to basing the grade on the work which was completed — quality of initial observations, clarity of questions and hypotheses, cleverness of experimental design, etc. Sometimes it is possible to judge their performance in the interpretive phases of the investigation by noting their criticism and evaluation of the work of their peers. Finally, I have sometimes found it useful to encourage students to withdraw from the course without prejudice of a grade. This seems to be particularly helpful when a student perceives rather early in the course that he doesn't really have the time for, or enjoy doing, investigation. In such cases I have found it futile to try to "force" them to remain in the course.

It is more difficult to accept the notion that financing is not a major problem. Certainly it costs money to offer an investigative laboratory and money is always in short supply in most schools. Several factors seem to make financing less of a problem than might be imagined. First, investigative laboratories are usually taught in lieu of some other laboratory offering. The decision to offer an investigative laboratory involves a choice of how to best use whatever resources are available, not a choice of what should be added to the curriculum. The experience of Marquette University (see Chap. 10) indicates that money may actually be saved by shifting from exercise to investigative-type laboratories. Such savings are related to the fact that the exercise approach, in which all students do the same thing at the same time, often requires that expensive items of equipment (i.e., microscopes) be present in multiple copies.

A second reason that investigative laboratories may not be as expensive as one might guess is that students show a rather remarkable ability to find or make what they need when given the chance. Not only can this lead to a real savings on the part of the institution, but it may prove to be an extremely valuable learning activity in itself. An example might help illustrate this point. If we were designing an experiment on learning which all students were to do on a particular day in the laboratory, we might find it necessary to provide each group of students with a maze, some rats, stopwatch, etc. But if a student decided to study learning phenomena in an investigative laboratory, he would probably want to design and build his own maze to fit the particular problem he was studying. He might also wish to choose and acquire the animals to be studied. It might not even be necessary to provide bench space, for he might prefer to do the work in his own room at home.

In a related matter, many nonschool facilities are frequently available to students doing investigation if they request them personally. As an example, a medical laboratory would probably be unwilling to make its blood-typing facilities available to all the students in a course, but it might be most happy to have a student who was working there, part time, use them in his off hours for an investigation of his own. The rigidity and standardization of laboratories often seem to make it impossible for us to take advantage of the personal resources of students and the community. The investigative laboratory, on the other hand, frequently opens doors to resources which the teacher did not know existed.

Finally, it should be pointed out that there are many areas in which good science can and has been done on a shoestring. The field, for example, is a marvelous laboratory in which much investigation can be done with a pair of eyes and a notebook. Field-based courses offered in a traditional way can be very expensive because they generate a need to transport large numbers of students to the same spot at the same time. In an investigative laboratory, however, each student can select and get to his own field at no cost to the institution.

To summarize: it is naive to assume that problems associated with financing and grading an investigative laboratory do not exist. But for those who believe that investigation is important for students, solutions can be found.

APPENDIX

INVESTIGATIVE LABORATORY PROGRAM IN BIOLOGY

A POSITION PAPER OF THE COMMISSION ON UNDERGRADUATE EDUCATION IN THE BIOLOGICAL SCIENCES*

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The Panel on the Laboratory in Biology was formed by the Commission on Undergraduate Education in the Biological Sciences (CUEBS) with the charge of clarifying the function of the laboratory in the changing biology curriculum. This paper, the first product of our deliberations, seeks to make a single point which we feel is of such great importance to the future of undergraduate biology that all other considerations in laboratory instruction must be deemed inconsequential beside it. Stated simply, the point is that the best use of the laboratory in undergraduate instruction is to engage the student in the process of active investigation. This paper will be devoted, therefore, to the development and support of the concept of such a laboratory program, which we will refer to as an "investigative laboratory." Additional papers, describing specific investigative laboratory programs in which three of the authors of this paper have participated, will appear separately.

The Objectives of Laboratory Instruction

Let us begin by identifying several roles which have traditionally been assigned to the laboratory so that we may separate those long-standing functions from, and thereby more clearly define, the investigative function.

The commonest use of the laboratory is to illustrate objects and experiments that have been introduced elsewhere. Illustration is obviously

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*Reprinted from *BioScience*, Vol. 19, No. 12, 1969, pp. 1104-1107.

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This paper is Publication Number 28 of the Commission on Undergraduate Education in the Biological Sciences.

important. It enhances learning by repetition, by increasing the number of sense modalities being employed, and by helping the student relate verbal abstractions to real objects and events. But time limitations are such that, despite considerable skill in the design of exercises, a given student cannot be expected to gain more than a superficial insight into the few phenomena which he can personally explore. The illustrative facet of the undergraduate laboratory can be largely replaced, with considerable saving in time, by displays and by more imaginative classroom techniques.

A second function of the laboratory has been to provide training in laboratory techniques. While any laboratory must involve the exposition of techniques, such activity fails as a central one on three grounds. First, a technique without a question has a limited meaning, for one can carry out a procedure to any arbitrary level of precision and in many different ways. What determines how one carries out an experiment is ultimately the scientific question that is being asked — not an arbitrary set of rules. Second, the study of most or all techniques is an uncertain investment. Technological advances come rapidly, and what is a standard method today will often be obsolete when the student comes to use it. Third, many of the students will enter fields in which the particular techniques they learn have no application.

A third function, which is not easily described but is nevertheless widely subscribed to, is that of intellectually stimulating the student and developing appreciation for biology and for living things. This is commonly a "last resort" position for traditionalists when the situation makes it appear that the two roles mentioned above do not actually provide justification for the time and expense necessary for laboratory instruction. Support for the position comes from the personal experiences of biologists, who must be granted some credence when they say, "I wouldn't have gone into biology if it hadn't been for the labs, where I could see and feel and actually work with living things." Although we recognize the validity of this function of the laboratory, we do not feel that it specifically supports the traditional form of laboratories. The investigative laboratory seems as well, if not better, suited to achieve this end.

A fourth position that one occasionally hears is that the laboratory serves primarily to stimulate discussion. Individual laboratory experience can serve as an effective base for dialogue involving many more facts and ideas than can be explored in the laboratory itself. Any instructional program ought surely to capitalize on such opportunities. However, this role does not guide laboratory teaching to any particular activity, and it is doubtful that the role alone could ever justify the effort that we put into laboratory instruction.

These four roles are in contrast to the investigative function of the laboratory through which the student becomes a part of the total process of converting simple observable facts to meaningful and often useful knowledge. Illustration, development of technical abilities, stimulation of an appreciation for living things, and creation of an environment for discussion can all contribute to, and be drawn from, the laboratory experience. But it is our firm conviction that laboratory programs should be designed to serve first the function of engaging the student in scientific investigation.

Rationale for Emphasizing Investigation

In teaching undergraduate biology, we emphasize concepts, generalizations, and theories. Facts are presented, but are selected to lead efficiently to the more abstract levels. That science can be taught and understood in this way is essential to its strength. But much is omitted. The theoretical structure of biology involves some arbitrary choices, its operational meaning is based on detailed research, and it does not contain a sense of the certainty and precision of the conclusions. These omissions are obviously essential. Only the professional can afford to study every detail, and then only in a narrow area.

But why do we teach biology? Partly, we teach biology to train new scientists. To a greater extent in the undergraduate years, we teach biology out of the conviction that it will be relevant to the student throughout his life. But considering these objectives, it seems inadequate to teach only the theories of science. Certainly the student should gain an appreciation of the major concepts of biology. But the professionally oriented student needs to think about what he will be doing as a graduate student and as a scientist. All students, whether headed toward research or not, need to develop attitudes toward the certainty and utility of science, the real meaning of scientific hypotheses, the strengths and limitations of scientific approach, and the value of public support for research. We must then ask whether these needs can be fulfilled, and if so, how?

The needs to which we have referred are associated more with the processes of science — with its modes of generation — than they are with its theoretical structure. What is required, then, is a way of describing how biology progresses. Elementary textbooks typically include a chapter in which an attempt is made to describe the processes of biology. Cast in the traditional mold of a single "scientific method," these descriptions consistently fall far short of communicating the nature of the whole scientific process. Many elements of the process are not mentioned and what little is mentioned cannot possibly be appreciated in the limited context of such a chapter.

There does exist a straightforward, effective means of communicating how science is generated. By carefully preparing the student to select and handle a problem of his own and then freeing him from subject syllabi and schedules to develop his own conclusions and to integrate them into a wider area of knowledge, he will come in contact with many facets of the processes of biology.

We have emphasized the role of the investigative laboratory in communicating the nature of biology as a branch of knowledge. A related line of thought, which leads equally to the investigative laboratory, begins with a consideration of the activities in which we want to engage our students. We submit that regular and serious demands need to be made not only upon the student's powers of comprehension and memory but also upon his creative and critical abilities. He needs the opportunities to make real decisions and to develop effective work habits. If he is to use such attributes of scientific thinking as objectivity, thoroughness, and precision, whether professionally or in taking a pragmatic approach to his own daily life, he needs experience in scientific thinking. These needs are fulfilled in a laboratory that emphasizes a broad range of the processes of science.

Investigative Laboratory Programs

While there are many forms that investigative laboratory programs can take, we find that our separately developed programs share some general features. The student's experience begins as a relatively structured one which leads to both technical and conceptual understanding of a problem area. This initial phase has a traditional flavor and may benefit from use of film loops, guided readings, audio-tutorial techniques (Postlethwait et al., 1969), and programmed instruction (National Society for the Study of Education, 1967). Carefully planned exercises are used to introduce the student to selected techniques and instrumentation, e.g., radioisotopic usage, spectrophotometry, microscopy, pure culture techniques, etc. An effort is made during this first phase to anticipate the greater independence that will be expected of the student later in the program. This can be accomplished by gradually increasing the number of options open to the student, and by involving him in the design of simple experiments.

Students then select and formulate a problem. Suggestions from the instructors are appropriate, but the student must have real choices open to him. The greater the involvement of the student in the selection and formulation of his problem, the more he will learn. While this process will not begin at some rigidly defined time and end at another, it is desirable to have a period of time when the main focus is on problem selection and formulation.

Experimental work follows and extends over a period of time sufficiently long that experiments can be repeated, controls carried out, and the direction of the work modified if necessary. The project is completed with a written report in introduction-methods-results-discussion format. It is often during the writing of a report that the student really understands what he has done. While the sequence of activities is obvious, the key elements are the provision of structured preparatory work, the selection and formulation of the problem by the student, and the preparation of a written report.

This extended, multiphasic program should not be confused with several recent innovations in laboratory instruction. The investigative laboratory is not the same as the simple enquiry approach in which the student is asked to respond to questions which begin in the manner of, "What happens if . . . ?" or "What is the effect of . . . ?" Questions of this sort have become commonplace in laboratory manuals and direction sheets. When applied in the manner described by Schwab (1962), the enquiry approach can be a useful one, and it should probably be included in a major way throughout all parts of a course or curriculum. But it is similar in only a very general way to the investigative laboratory which we are proposing.

The investigative laboratory should not be confused with what we shall call the "open-inductive approach." In the latter type of laboratory the student enters a sequence of work almost entirely uninstructed and is asked to build his own generalizations from observations that he makes in the laboratory or field. Patterns of reasoning thus developed are assumed to be of use to the student throughout his life. It is conceivable that both this kind of experience and the more carefully planned and executed investigative laboratory should be included in a total program of science instruction at the college level. We emphasize, however, that science does not ordinarily proceed from an open-inductive base but relates new facts to prior generalizations. Typically, progress in the science derives either from questions that fill small niches in informational patterns or from challenges made to earlier conclusions in the light of new evidence. To make such contributions, the scientist must prepare himself carefully, and the student who would follow him must consequently be closely guided.

The idea of open-ended laboratories has never been clearly defined and has come to mean different things to different people. In its commonest form, the open-ended laboratory is roughly synonymous with problem solving but with the added qualifications that there must be no "correct" outcomes to the work and that the work can proceed to indefinite length, depending upon results. Typically, however, the problem is assigned, the means are rather clearly specified, and the student is still forced into the attitude of dealing with a series of exercises. This kind of laboratory is clearly a move toward the investigation of which we speak, but it ordinarily lacks the necessary involvement of the student with the whole process of deciding what is to be studied, how the work can be accomplished, and how the conclusions are to fit with information that is already in hand. We feel that it does not satisfactorily fulfill the investigative objective for these reasons.

Developing Investigative Laboratory Programs

Our experience in the introduction of investigative laboratory programs has led us to the conclusion that these programs cannot be mounted as minor adjuncts to exercise-oriented laboratories. In order to provide a useful instructional experience in investigation, a substantial block of the student's time is necessary. Developing a familiarity with a problem area requires time far beyond the few minutes of preparation that precede typical laboratories. Framing questions that can be answered by any means at all takes time and experience. The latter can be provided in the give-and-take of tutorial and discussion sessions in the early weeks of the investigation period. Restating of questions and redesigning of experiments as data come in are nearly always essential parts of any investigation and ones which require time and individual help. Obviously, the change which we recommend cannot be accomplished by assigning only a small portion of the available laboratory time to it.

Inextricably involved with the time commitment that the investigative laboratory demands is the important matter of loosening the coupling between laboratories and specific courses. It is a simple fact that the laboratory experience cannot be integrated with a lecture course on a week-to-week basis if the educational aims of the investigative laboratory are to be achieved. Coverage of a pre-established block of material or even of selected subject areas or techniques in the laboratory places these subjects and techniques in a position of primary attention and relegates investigation to a subsidiary role. A certain amount of freedom in choosing the subject area is absolutely essential, and instruction in techniques must be handled to serve only the anticipated needs of the investigative program. Subject coverage must come largely or entirely from other parts of the course or curriculum.

An additional reason for reducing the usual coupling between the lecture and the laboratory derives from the fact that, in the coupled arrangement, faculty attention is likely to focus on the lecture part of the course. The laboratory becomes the province of less-skilled personnel and becomes relegated to a supplementary role. When the laboratory has an independent status, faculty members assigned to the course are more clearly responsible for the laboratory work and may be able to give the course more time.

A matter that needs careful consideration in the design of an investigative laboratory is the selection of a subject area. The subject area should be related to the interests and competence of the faculty members involved. When emphasis is on investigation, the necessity to cover unfamiliar material is removed and a faculty member can better advise the students in areas familiar to him. There is also an advantage to selecting a subject area which builds on ideas to which the student has been exposed in previous courses. However, the exposure can come entirely within the confines of a laboratory course, if that is necessary. Finally, it is important to choose an area which is likely to result in a wide scope of activities for the student. To be avoided are areas where the student is likely to become bogged down in methodological problems or to be unable to interpret his data. Field studies are appropriate, but the purely descriptive aspects should be avoided.

Much attention needs to be given to the role that scientific literature plays in the development of the student's investigative program. Contact with several primary sources is essential. Free exploration of the literature must be encouraged, and critical analysis of the content must become a habit. In many institutions adequate library resources may be difficult to provide, and plans to supplement library holdings and to aid students in their use must become a part of the planning process when investigative laboratories are initiated.

Most experience with investigative laboratories to date has been gained in situations where laboratory rooms are open continuously. It remains to be seen whether this is an essential factor

Meeting Costs by Consolidating Resources

A common initial response to the notion of the investigative laboratory is that it is a fine idea, but impractical because of the large number of faculty and assistants required and the high cost of supplies and equipment. Indeed, when a student is engaged in a genuine, if simple, investigation, the demands on his time and energy, on the faculty and assistants, and on the available facilities exceed those in traditional laboratory programs. Nevertheless, by consolidating resources, the investigative laboratory program can be less expensive than a traditional program involving a companion laboratory coupled to each course given by the department. The resources released by the elimination of a number of companion laboratories can, in many instances, more than compensate for the increased demands of a smaller number of improved investigative laboratories.

However, the matter of costs requires further study, particularly with regard to the provision of satisfactory laboratory experience for very large numbers of nonmajors. Since the approach rather than the subject matter is of prime importance, some thought should be given to pooling the resources of more than one department in an effort to ensure that each individual who wishes to study a laboratory science be given the opportunity to do so, and with the best laboratory available. Another device might be to involve only a fraction of the students at any given time. Each student would then have a more intensive, but shorter, experience in the laboratory. Thus, we do not feel that the idea of investigative laboratories can be dismissed as impractical.

Some Advantageous Effects

The achievement of the goals described under "Rationale" would, by itself, justify the existence of an investigative laboratory program. There are advantageous by-products to such a program, however, and these make its introduction even more attractive. A notable effect, in our experience, has been a rekindling of faculty interest in teaching. As a result, much longer and more stimulating contact with students has been noted. It is especially notable that assignment to investigative laboratory activities is frequently regarded as a prestigious activity, and one finds that instructors who avoid assignment to typically scheduled laboratories enjoy handling investigative laboratories. Thus, the investigative laboratory can provide the vehicle for more informal student-faculty interactions of the type increasingly sought by our undergraduates.

In addition, we point out that for the greatest part of his undergraduate career, the student has little option but to accept the statements of his professors. The passive attitude which it tends to induce discourages anything but peripheral participation. The investigative laboratory program should provide the basis from which a more critical approach to the material of the lecture curricula can be developed and would encourage more active participation by students in their course work.

Historical Perspective

The facts are obvious that one can learn many things simply by doing them, and the process of learning is more rapid by having another person show him how. In transmitting simple technical abilities, this is as appropriate a teaching method as there is. We can probably assume that in the early stages of human cultural development there was hardly any other instructional technique. If we accept Bruner's (1966) reasoning, a major change in human culture came with the shift of instruction to group situations, for it meant that verbal descriptions of objects and actions had to be developed. From this it is but a short step to the abstraction on which much of our modern culture is built. Science has been a notable beneficiary of such abstraction to the extent that verbal abstraction almost completely dominates education in the sciences. But many of us appear to have forgotten, in fact, that active use is still an essential step in learning.

Learning about science by engaging oneself in it may actually have persisted in healthy form up until only a few decades ago. Henslow's informal tutoring of Darwin through the simple expedient of an insect collection is a case in point. More pertinent, perhaps, is Louis Agassiz's practice of handing a student a fish and telling him to come back when he felt ready to explain everything important about it. The approach is akin to the open-inductive one, but as a result of his aggressive questioning, Agassiz converted it into a combined descriptive and analytical version of the laboratory approach that we are discussing here. Similar approaches deriving from the prevailing tutorial technique of the day persisted as a fairly regular practice up through about 1920, when the pressure of numbers and a notable rigidification of subject matter brought a shift to the intensively descriptive group laboratory through which most present-day biologists were trained.

One can probably argue either way on the appropriateness of the rigidly structured, illustrative, companion laboratory for evolutionarily oriented material. This type of laboratory is consistent, in fact, with most approaches to teaching which accept the transmission of factual material as a dominant aim. There can be little doubt, however, that the changes in biology after the Second World War demanded consideration of a larger role for active involvement in the processes of science. These changes coincided, however, with great increases in the numbers of students and a renewed emphasis on doctoral training for advanced work in biology. What seemed to be a natural separation between subject preparation (handled largely in the abstract for groups of students at the undergraduate level) and development of methodological abilities (more on an individual basis at the graduate level) was reinforced by these new conditions rather than subjected to the restudy that change in content was demanding.

From a position where education itself can be viewed in abstract terms, it seems strange that it should be difficult to convince biologists that the most appropriate way to teach students about science is to involve them actively in it. The average instructor, influenced as he is by his own educational experience and facing practical problems of heavy teaching schedules, large numbers of students, poor facilities, and weak preparation for investigative activities, sees the matter entirely differently. It is a rare individual, in fact, who can see beyond the complex of tradition and problems to sense that a vital link in biological education lies broken, that very significant advantages can be gained by providing real investigative experience, and that ways to overcome the problems inherent in the change are known.

More than anything, the problem of class size was probably to blame for the disappearance of personal investigation from undergraduate education in biology. It remains the most difficult one. The solution appears to lie in keeping the student-faculty ratio in mind and trimming out descriptive and cookbook laboratory time that is of relatively low value. The proposed consolidation of resources applies even more urgently to human resources than it does to instructional space and equipment. Much trial of such consolidation needs to be made. The incidental problems are many. However, the need to involve the undergraduate student in the processes of thought which he is supposed to learn is so compelling, we feel, that biologists have no choice at this time but to organize large-scale exploratory ventures in investigation for their students.

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