A Laboratory-Based Science Course
for
Non-Science Majors

Report of the Committee

In partial response to the State of Maryland's mandate that all students at UMBC be required to take at least one laboratory-based science course, the Provost appointed a committee of faculty members whose task it was during the summer of 1996 to consider how best the University can respond to what appears to be the State's desire to see an enhanced level of scientific literacy in university graduates. The committee consisted of members from the departments of Biology, Chemistry, Geography, and Physics as follows:

Phillip Sokolove, Professor of Biology
Aristotle Kalivretenos, Assistant Professor of Chemistry
Andrew Miller, Associate Professor of Geography
Eugene Parker, Associate Professor of Geography
Robert Reno, Associate Professor of Physics

Carl Weber, Assistant Professor of Biology, participated in preliminary discussions only
The Committee also engaged in discussions with Susan Blunck and Wendy Saul of the Education Department

The committee began meeting in May and has met frequently during the summer to consider:

1. The general philosophy of a lab-based science course for non-science students.
2. Similar courses currently offered at other institutions, if any.
3. The structure and content that such a course should have.
4. The facilities needed to implement such a course.
5. A unifying theme that would make the course exciting and relevant to students.

The committee's full report follows.

A Laboratory-Based Science Course for Non-Science Majors
Executive Summary of Committee Report

This report was prepared by a faculty committee constituted at the request of the Provost in response to the state mandate that all students complete at least one laboratory science course prior to graduation.

Philosophy and Course Objectives. The proposed laboratory course offers non-science majors an interdisciplinary lab science experience that integrates biology, chemistry, earth sciences, and physics into a single, three-credit course with a unifying theme. The AAAS report *Science for All Americans*, as well as many additional studies, note that effective learning occurs most easily in situations that actively engage students in the learning process; this is particularly the case for many non-science students. The proposed course is designed such that students, working in groups, become co-investigators. The emphasis is upon an "inquiry-based" approach in which students generate questions to be explored, formulate investigative strategies, and collectively engage in the analysis of results.

The course is designed around an overall theme of water. Five modules are identified, each occupying 2-4 weeks: Water Quality, Unique Physical and Chemical Properties of Water, Water and Life, Water in the Earth's Environment, Water and Policy. Among course objectives are the following: the identification of scientific concepts that are transdisciplinary; the introduction of mathematics to enable students to quantify measurements and to identify patterns; understanding of the predictive value of scientific theory as well as the limitations of theory; increasing sophistication in analysis skills as the course progresses.

Administrative Considerations. The basic course unit is a 125-student lecture group divided into 25 lab teams. The course will need a lecture hall as well as a lab room with approximately 1200 ft^2 that could accommodate five teams of five students. This arrangement would allow a maximum of three units per semester to be offered (for a total of 375 students). The course will entail equipment expenses (discussed in the full report) but the committee believes they are quite reasonable given the alternatives.

The committee proposes the establishment of a Center for General Science Education the director of which would be a master teacher responsible for administering and teaching the lab science course(s). Each course would necessitate two teaching assistants. A course designation such as SCI 100 or GSE 100 would reflect the interdisciplinary nature of the course.

Evaluation and Assessment. Consistent with a "continuous improvement" model of course development and delivery, the committee recommends that evaluation and assessment of student learning and instructional practice be an integral part of the course design.

Implementation and Pilot Course. The course we propose is non-traditional and a phase-in period is recommended. In order to offer a single course unit (125 students) for the Fall 1997 semester, the committee believes it is imperative to organize a small (25 student, five team) pilot course to be offered in the Spring 1997 semester along with a teaching assistant training program in the summer of 1997. It is anticipated that 2-3 course units would be offered for the Spring 1998 semester.

I. General Philosophy to be Used in Developing a Lab-Based Science Course for Non-Science Majors

The Committee assumes that the intent of the State of Maryland in requiring that all students at UMBC take at least one lab-based science course was to ensure that graduates of a Maryland state university have an understanding of what science *is*, how it relates to the everyday life of the individual, and how science can be used (or misused) in risk assessment and policy planning. The Committee also assumes that the requirement of a *laboratory*-based science course was imposed in order to ensure that students acquire some hands-on experience in planning a research protocol, making measurements, and analyzing data.

Accordingly, the Committee, very early in its deliberations, came to the conclusion that these goals would best be served by an *interdisciplinary* approach that integrates biology, chemistry, physics and earth sciences into a single three-credit course with a unifying theme.

It has also become clear that the traditional lab/lecture format employed in most college science courses for over half a century is not the best method for motivating students who have had a poor pre-college science education or who, worse still, are convinced that they are not capable of understanding science and are afraid to take science courses in college. There is increasing evidence, discussed for example in the AAAS report *Science for All Americans* (See Appendix A for some excerpts), that effective learning occurs most easily in situations where students actively participate in the process by generating the questions and providing each other with support through team discussions and a dialog with the instructor. To achieve this in the course under discussion, the Committee envisions that the course be run with students in teams of five, meeting once a week for a 90-minute discussion with the course instructor acting as a facilitator, and also once a week for a 110-minute laboratory/discussion period. As many as 25 teams would participate simultaneously in the discussion period and a maximum of 5 teams would be present in a typical laboratory/discussion period. The format of the course militates against an enrollment in excess of 125 students per instructor or discussion leader.

The Committee sees the following as a set of ideals to be achieved with such a course:

- Students should come away from the course with an appreciation of what science is and how scientists examine nature

- Students should develop a positive feeling for their own ability to understand science and to evaluate scientific claims that affect their lives

- Students should understand the logical structure of scientific investigation and the role of quantitative analysis in formulating and answering questions

- Students should develop an independent approach toward problem-solving and assessing information

Thus the fundamental purpose of this course is to change the way students think.

II. Administrative Considerations

Because of the interdisciplinary nature of the proposed course, the integration of laboratory and discussion, and the number of students that will be served by the course, there are several unique administrative considerations that need be addressed. While the Committee is not in the position to make decisions that bear on resource allocation, it would like to point out some areas where the Administration needs to provide strong institutional guidance as well as resources in the form of space, personnel, and materials.

1. Jurisdiction

The Committee proposes that the Administration establish a Center for General Science Education on the UMBC campus. The center's director would be responsible for administering and teaching the science lab course, which could have a designation such as SCI 100 or GSE 100. The director also should have a part-time appointment in the Education Department. An interdisciplinary faculty steering committee will participate in the center's activities. Funds to support teaching assistants in the lab science course will be awarded through the center, and eligible candidates for assistantships will be selected on a competitive basis from among the pool of graduate students in various academic disciplines who have suitable background and experience. Following an initial startup period it would be reasonable to anticipate the possibility of attracting external funding through the center in support of this and related initiatives.

2. Staffing

<u>Full-time course instructor and center director</u>. At a minimum the course will require a primary instructor who is a "master teacher" with both advanced research training (Ph.D. in science area) and a broad spectrum of inter- and/or cross-disciplinary teaching experience. Ideally, he/she should also be familiar with current, "best practice" science teaching methods which have been recommended by AAAS and the National Research Council such as in-class use

of cooperative learning groups, concept mapping, and other student-centered, active learning approaches based on constructivist learning principles.

The course instructor will serve as Director for the Center for General Science Education and have a half-time academic appointment in the Department of Education. He/she will have direct responsibility for all aspects of the proposed non-majors course and will teach all of its large "lecture" sections. In addition he/she will be involved in developing alternative assessment tools and approaches, will engage in refining the course curriculum (e.g., developing new lab exercises and topic modules), will be responsible for the selection and training of teaching assistants (both graduate and undergraduate) and will have line responsibility for administering the course budget. The Committee recommends that faculty members from appropriate departments on campus be encouraged to participate as part-time instructors on a rotating basis.

During the pilot semester and first year, the course instructor's time will be balanced between development activities and classroom/laboratory instruction. Beginning with the second semester that the full course is offered, the Director's instructional time commitment will increase substantially along with supervisory duties and staff oversight responsibilities.

Full-time laboratory assistant. In order to develop and deliver the non-majors laboratory portion of the proposed course, the primary instructor/Center Director will require adequate staff support. During the initial pilot semester of the course phase-in (see below), a laboratory assistant will be needed to assist with ordering of supplies and equipment, installation of equipment, lab set-up and trouble-shooting. Thereafter, the course will require a full-time laboratory assistant to set-up and coordinate supplies and equipment for multiple laboratory sections. The Committee believes this laboratory assistant staff position to be essential for the successful delivery of the proposed course. Graduate (and undergraduate) teaching assistants will also be needed to help with lab preparation and set-up, but students cannot be expected to be responsible for laboratory supply and equipment management and inventory associated with such a large course, or for budgetary accountability associated with ordering expendable items and supplies. We emphasize that this is a support-staff position with few if any instructional responsibilities.

Graduate teaching assistants. Since the Committee is recommending development and implementation of a highly interactive, student-centered approach to non-majors science instruction, we feel strongly that laboratory portion of the course will require two graduate teaching assistants to be present in each of the five 25-student lab sections. Two teaching assistants will be needed because the course will be taught in a more open and less "cookbook-driven" manner than other science courses, and because non-majors can be expected to require more instructional attention -- both in-class and out-of-class -- than science majors in traditional laboratory courses. Graduate TAs will be selected by the primary instructor from those among the available pool of science graduate students who are recommended by the science department Chairs. The selected TAs will also receive at least one month of special orientation and training provided by the course instructor prior to assuming their instructional role. During the initial, pilot phase of course implementation, it should be possible to make do with one graduate TA, but the full, recommended staffing ratio will be required thereafter, e.g., two GTAs for each large (125-student) section of the course.

3. Resource Allocation

One lecture hall capable of holding approximately 200 students needs to be available once a week for a 90-minute period. Although the class size is limited to 125, the additional seats would be used to provide buffer zones between the 25 teams, thereby allowing intra-team discussion. The lecture hall must have facilities available for performing experiments and demonstrations which may require movement of portable equipment and involve the use of flame, water, and compressed air. Currently, LH II and LH V seem to be the only suitable facilities. The laboratory area required is a room of approximately 1200 square feet, arranged to accommodate five teams of five students each. Each team should have a local table-top work area of approximately 25 square feet and the five "work stations" should constitute the periphery of a larger communal work area which would be used for demonstrations during the laboratory discussion and for experiments not common to all five teams. A sketch of the required layout is shown in Appendix B. The laboratory will be needed for five 110-minute sessions each week.

Using this model, it is clear that several 125-person groups could be handled in the same semester, each with a different discussion leader. Since a single laboratory room could be used for at most four sections each day (for the four days *following* the common discussion session), a maximum of three 125-person groups could be handled. This imposes a cap of 375 students per semester, unless a second laboratory is outfitted.

Equipment and supplies needed for the laboratory are listed in Appendices C and D and their use will become clear in Section III of this report. It is worth mentioning here that the Committee estimates that, aside from the cost of constructing a suitable laboratory room, approximately \$ 40,000 will be needed for permanent scientific equipment to outfit a suitable lab. Approximately \$ 5,000 will be needed for expendable supplies for each 25-student lab section, although some of this may be reused in subsequent semesters.

III. Course Outline

Objectives

The Committee spent considerable time identifying specific objectives. A consensus is that, at a minimum, the course should:

• Identify scientific concepts that cut across individual disciplines. These include an appreciation of dimension and scale, rates of change, methods of measurement and analysis, as well as an understanding of error, precision and accuracy in measurement. Additional topics include: phase changes and structure of matter; storage and transformation of energy as sensible and latent heat; entropy. The general systems concept, including inputs, outputs, storage and transformation of matter and energy, provides a logical framework for examining the commonalities among physical, chemical, biological, and environmental systems. (See the AAAS report "Science for All Americans".)

• Introduce an appropriate level of mathematics to enable students to: 1) quantify measurements and identify patterns; 2) visualize trends and relationships or correlations among measured quantities; 3) use these relationships as tools for prediction; 4) formulate and test hypotheses

• Enable students to see the predictive value of scientific theories, as well as to understand the limitations of any theory.

• Build an increasing level of sophistication in analysis skills as the course progresses.

• Make students aware that science is an evolving endeavor and that scientists do not have all the answers.

The Committee feels that an emphasis on factual material is an ineffective way to teach science and may even be counterproductive in a course for non-science majors. Rather it favors an "inquiry-based" approach, in which students are confronted with a problem and some tools for making observations, following which they are encouraged to develop their own questions and design their own experiments in response to those questions. The primary challenge of the course is to provide a setting that will successfully foster such activity.

Recommended Course Theme

To achieve the above objectives, the Committee suggests that the course be structured around an overall theme of **WATER**, with five modules each occupying 2-4 weeks.

The pedagogical approach to each module includes the following components:

The facilitator launches a theme by posing one or more provocative questions and eliciting students' responses.

This is followed by a class demonstration of some phenomenon that is relevant to the questions and that allows students to make direct observations that will stimulate further questions.

The facilitator then challenges the students to investigate further on their own, providing material support and encouragement but without providing a script that will lead to a predetermined set of results.

A required component of each exercise will be a report that identifies

- the questions that were asked
- the observations that were made
- the methodology that was used
- a quantitative evaluation of trends observed (including any noise or error in the data)
- explanatory hypotheses for the trends observed (or for lack of observed trends)
- suggestions for followup investigations to test hypotheses

The five modules are listed below. Each module may include one or more sets of investigations, and the intent is that these investigations add successive layers of meaning and illustrate a series of connections that will demonstrate the interdisciplinary nature of scientific inquiry. The committee has done some work in developing conceptual maps that illustrate these connections (See Appendix E).

1. Water Quality
2. The Unique Physical and Chemical properties of Water
3. Water & Life
4. Water in the Earth's Environment
5. Water & Policy

{The last module is preferably interwoven throughout, e.g. starting with questions about how pure water is, how we decide what is an acceptable risk and how much we would pay to meet certain quality standards, etc.}

For Module 1, a suggested opening question would be "How pure is your water?" During discussion, additional questions should arise such as "What do we mean by purity?", "How do we measure purity?", "Which water are we talking about?", "Is all impure water bad for us?" and "How do we improve the purity of bad water?". To test the demonstration and experimental component of this module, the committee went into the laboratory and began with a conductivity meter, several water samples from different sources, and a container of salt. We first measured the conductivity of distilled water and water from the ocean, from a local storm detention pond, and from a laboratory sink. We next established a link with salinity by adding a pinch of salt to a sample of distilled water and measuring the conductivity. This created an observation requiring a response. One avenue of investigation would be to suggest to students that they develop a series of experiments that would make it possible to predict the salt content of an unknown sample with the help of a conductivity meter. Creative and entertaining approaches are available, including for example a separate team that attempts to calibrate a salinity scale by taste and that competes against other teams using conductivity meters.

This initial exercise is based on examination of only a single dimension of water quality. We also brought a pH meter into the laboratory and we envision a series of investigations based on comparing different dimensions of water quality for the same samples. The fact that pH is a fundamentally different kind of measurement with a different scale (i.e. logarithmic rather than linear) introduces some of the fundamental conceptual and quantitative issues that were identified earlier in this report, but our goal would be for students to perceive these issues for themselves. By emphasizing the multivariate nature of water quality, we can quickly lead students to a higher understanding of the broad range of possibilities that extend far beyond the simple notions of "good" or "poor" quality.

While the Committee has not developed a complete syllabus for the course, it has identified some questions and demonstration experiments that would be pertinent for each module.

1. Water Quality

   Questions: Sample questions listed above.

   Demonstrations & experiments: Conductivity and pH changes in solutions; solubility of chalk in water or other liquids (e.g. vinegar, Coke)

   Concepts: Correlation between two physical properties; reproducibility of measurements; concentration of solutions; solutions *vs* mixtures

2. The Unique Physical and Chemical properties of Water

   Questions: "How many forms of water are there?"; "How cold is ice?"; "Why do we put salt down on icy roads?"; "Is it easier to boil water or to freeze it?": "Why does ice float and what would happen if it didn't?"

   Demonstrations & experiments: Investigate phase changes between solid, liquid, and gas, with attention to the energy absorbed or given off as a result of phase changes.

Freeze pure and salty water and examine the effect of impurities on phase changes. Mix hot water with ice.

Investigate light penetration and turbidity in water

Investigate connection between energy, temperature, density, and fluid flow leading to convection. (lava lamps as demonstrations? flow in a closed chamber with hot and cold sources?)

Concepts: Phase changes; temperature; energy contained in matter, thermodynamic equilibrium, entropy; absorption of radiant energy and factors affecting absorption; viscosity and friction; density or specific gravity; buoyancy; surface tension; turbulence vs. laminar flow

3. Water & Life

Questions: "What's in your Urine?"; "What's in your blood?"; "What's in the blood of a diabetic?"; "Why is a membrane essential for cell life?"; "What IS Life?"

Demonstrations & experiments: Urinalyses, glucose tests, slugs and salt; water uptake by plants; microscopic examination of organisms in pond or stream water; comparison of abundance and diversity of life forms in water from different sources

Concepts: Osmosis; diffusion; relate chemical and physical properties to biological processes. Water as an environment for life (e.g. "life in water") and as a medium for internal biological processes ("water in life"); relation between water quality and species diversity

4. Water in the Earth's Environment

Questions: "How does runoff get generated when it rains?"; "How are sediments and pollutants picked up and transported by running water?"; "What are the spatial patterns of point and nonpoint sources on campus or in your neighborhood?"; "How does running water sculpture the land surface?"; "How does water affect climate and temperature patterns?"

Demonstrations & Experiments: Flow through porous media; The 1960's

Lava Lamp; Settling and sedimentation; Heat-lamp experiments with wet and dry surfaces. Field mapping of runoff-producing zones and related water-quality patterns on campus. Description and measurement of flow patterns in streams on campus. Sandbox experiments with soil erosion and sculpture of drainage patterns by running water.

Concepts: convection; fluid flow; changes in the earth's structure

5. Water & Policy

Questions: To be folded into discussion in conjunction with each of the other modules; policy questions may be used to motivate scientific inquiry

Concepts: Risk assessment and societal choice; what would you pay to reduce your risk by how much?

Since it is envisioned that student experiments will be predominantly self-selected with only minimal guidance from the TA, only a tentative list of equipment can be generated at this time. The Committee has performed several of demonstration experiments during the summer and has identified a set of equipment that *appears to be* essential. Appendix C contains this list.

IV. Evaluation and Assessment

Consistent with a "continuous improvement" model of course development and delivery we believe strongly that evaluation and assessment of student learning and instructional practice should be an integral part of the course design. In addition to traditional end-of-semester student course evaluations, we recommend that evaluation and assessment be ongoing throughout the semester. The Department of Education Chair, Dr. David Young has been contacted by the Committee and has agreed to provide department assistance in this effort. The first step must be to identify clearly and unambiguously the educational and instructional objectives of the course, and then to agree on the measures needed to assess how well these objectives are being met.

In this document the Committee has tried to be explicit about overall course objectives, and it has provided examples of concept learning goals for each module, although it recognizes that some may be common to more than one module. Input is needed from specialists in science education and program evaluation to help sharpen and define learning objectives within and across modules (and perhaps to suggest additional ones). The Committee recommends that expert advice be employed to help develop outcome measures specific for each objective, to interpret the results of ongoing assessment and to suggest strategies for improvement of instruction that can aid attainment of these objectives.

Prior work indicates that student learning can be assessed in six domains, and the Committee recommends that ongoing assessment instruments be developed for each:

- Conceptual understanding. (Do students perform well on low-level recall questions in multiple-choice exams, but fail to exhibit higher level understanding in response to integrative and application-oriented essay questions?)

- Process skills. (Can students ask questions? How well do they observe? Can they make measurements and accumulate and display data appropriately? Can they spot and describe trends? Are they able to evaluate the validity of information sources?)

- Creativity. (How many questions do students ask? Are their questions unique and/or pertinent? Are they able to formulate testable hypotheses? Can they formulate investigative strategies? Are they flexible enough to alter their strategies?)

- Application. (Can knowledge "learned" be connected to out-of-class experience? Can students apply process skills and conceptual understanding in new contexts?)

- World view. (Do students understand the nature of science not only as a way of knowing but also as a social activity that values curiosity, creativity, imagination and beauty? How do they deal with misconceptions? Can they recognize and resolve conflicts between scientific concepts and their beliefs?)

- Attitude. (Do students feel positively or negatively about science? How confident are they in their ability to do or understand science? Are they interested in science and how it applies to them as individuals? Do they enroll in other science courses?)

We also recommend that teaching practice be evaluated and assessed on an ongoing basis. Aside from student course evaluations, we suggest that teaching be assessed in ways that focus on and encourage practices shown to enhance student learning:

- Encouraging and accepting student autonomy, initiation, and leadership.
- Allowing student thinking to drive lessons; shifting content and instructional strategy based on student responses.
- Asking students to elaborate on their responses.
- Encouraging students to interact with each other and with the teacher.
- Asking thoughtful, open-ended questions and allowing wait time after

questions are asked.
- Encouraging students to reflect on experiences and predict future outcomes.
- Asking students to articulate their own theories about concepts before presenting teacher understanding of the concepts.
- Designing lessons to identify and address student misconceptions.

V. Implementation

The introduction of such a unique course, coupled with the huge number of students that it will ultimately serve, leaves no doubt in the Committee's mind that there will be significant birth and growth pains for the first two years of implementation. Because of this, the committee urges a phase-in of the course as follows:

- Initiate a search for the Director of the Center for General Science Education as soon as possible who will have the teaching and planning responsibilities for the course upon full implementation beginning in Fall 1997. The Director should be in place at the latest by the end of May 1997 to insure that the course can be implemented during the Fall semester. Ideally, a suitable candidate will be identified and brought to UMBC during the Fall 1996 semester. This will provide the Director with the opportunity to be intimately involved in the operation of the Spring 1997 pilot laboratory course as the Instructor.

- In Spring 1997, the course should be offered on a limited basis to a maximum of 25 students, recruited from predominantly non-science programs. Included in that 25 should be perhaps five education majors who would serve as evaluators. If education majors could not be induced to take the course for credit, perhaps the Administration should consider paying them on a hourly basis to attend the classes and critique the course structure. The course would be run by the Director if available, if not, a suitable Instructor should be identified from the current UMBC faculty. It is also recommended that arrangements be made to employ a laboratory assistant and a graduate assistant (TA) during the Spring. The laboratory assistant would be responsible for ordering equipment and chemicals, stocking the laboratory as needed, as well as preparation of the laboratory for experiments on a day to day basis. The committee recommends that the laboratory assistant become a permanent position for the full implementation of the laboratory science course. The TA would have the role of facilitator for the laboratory portion of the course.

In addition to the laboratory assistant and TA, we plan to engage a group of upper-class undergraduates to try out a series of lab exercises for potential use in the regularly scheduled course. These students would not be enrolled in the pilot version of the course itself but would be engaged in testing, critiquing, and modifying or discarding lab exercises based on the degree of interest generated and on considerations of feasibility and level of difficulty.

The implementation of a pilot program has been positively received by the Departments involved in the development of this course. The Department of Chemistry and Biochemistry has offered to provide the required laboratory space and facilities to accommodate the pilot program in Spring 1997. The Department of Physics, while it has no laboratory space available for instructional purposes, can provide space for intermittent testing and development of laboratory experiments. The Department of Biology has identified an individual from their department suitable for the laboratory assistant position.

During the Spring pilot program, a clearer idea of additional required equipment will emerge and the Summer of 1997 will allow time for its purchase and installation.

- In Summer 1997, preparations will be made for the full implementation of the course for the Fall 1997. It is recommended that this time be used to train TA's who will be teaching the course in the Fall. It should be emphasized that the structure of this course is extremely non-traditional and the role of TA's as facilitators of a dialog (which will result in student-designed experiments) is extremely crucial for the success of this program. As has been found in similar programs at other institutions, e.g., NYU's three-semester Science-Core program, most graduate students have little or no teaching experience in non-traditional, inquiry-based, education and it will take significant learning on the part of TA's and some course instructors before they are able to perform as needed. Since the proper training of TA's is essential for successful implementation of the course, the committee recommends that resources be made available in the form of assistantships or stipends to support graduate students during the Summer training period.

- In Fall 1997, a full course open to 125 students should be offered for the first time, followed in Spring 1998 by perhaps two or three 125-student units, depending on need and the experiences of the previous semesters. The Director would be responsible for the lecture portion of the course and direct oversight of the laboratory portion of the course. The Director would also have the responsibility for further development, refining and future planning of the course to prepare for increasing enrollment in Spring 1998. Due to the innovative nature of this program for the education of non-science majors, the Director will also be in the unique position of seeking external funding for the future support and development of this course. It is expected that the Director will be actively seeking funding from government sources such as the National Science Foundation, as well as private sources. As can be seen from the committee's expectations of the role of the Director, a full time appointment for the Director is imperative.

Appendix A: An Excerpt from the AAAS Report "Science for All Americans"

SCIENCE

FOR ALL AMERICANS

PROJECT 2061

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

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CHAPTER 13

■ EFFECTIVE LEARNING AND TEACHING

Although Science for All Americans emphasizes what students should learn, it also recognizes that how science is taught is equally important. In planning instruction, effective teachers draw on a growing body of research knowledge about the nature of learning and on craft knowledge about teaching that has stood the test of time. Typically, they consider the special characteristics of the material to be learned, the background of their students, and the conditions under which the teaching and learning are to take place.

This chapter presents—nonsystematically and with no claim of completeness—some principles of learning and teaching that characterize the approach of such teachers. Many of those principles apply to learning and teaching in general, but clearly some are especially important in science, mathematics, and technology education. For convenience, learning and teaching are presented here in separate sections, even though they are closely interrelated.

Principles of Learning

Learning Is Not Necessarily an Outcome of Teaching

Cognitive research is revealing that even with what is taken to be good instruction, many students, including academically talented ones, understand less than we think they do. With determination, students taking an examination are commonly able to identify what they have been told or what they have read; careful probing, however, often shows that their understanding is limited or distorted, if not altogether wrong. This finding suggests that parsimony is essential in setting out educational goals: Schools should pick the most important concepts and skills to emphasize so that they can concentrate on the quality of understanding rather than on the quantity of information presented.

What Students Learn Is Influenced by Their Existing Ideas

People have to construct their own meaning regardless of how clearly teachers or books tell them things. Mostly, a person does this by connecting new information and concepts to what he or she already believes. Concepts—the essential units of human thought—that do not have multiple links with how a student thinks about the world are not likely to be remembered or useful. Or, if they do remain in memory, they will be tucked away in a drawer labeled, say, "biology course, 1995," and will not be available to affect thoughts about any other aspect of the world. Concepts are learned best when they are encountered in a variety of contexts and expressed in a variety of ways, for that ensures that there are more opportunities for them to become imbedded in a student's knowledge system.

But effective learning often requires more than just making multiple connections of new ideas to old ones; it sometimes requires that people restructure their thinking radically. That is, to incorporate some new idea, learners must change the connections among the things they already know, or even discard some long-held beliefs about the world. The alternatives to the necessary restructuring are to distort the new information to fit their old ideas or to reject the new information entirely. Students come to school with their own ideas, some correct and some not, about almost every topic they are likely to encounter. If their intuition and misconceptions are ignored or dismissed out of hand, their

original beliefs are likely to win out in the long run, even though they may give the test answers their teachers want. Mere contradiction is not sufficient; students must be encouraged to develop new views by seeing how such views help them make better sense of the world.

Progression in Learning Is Usually From the Concrete to the Abstract

Young people can learn most readily about things that are tangible and directly accessible to their senses—visual, auditory, tactile, and kinesthetic. With experience, they grow in their ability to understand abstract concepts, manipulate symbols, reason logically, and generalize. These skills develop slowly, however, and the dependence of most people on concrete examples of new ideas persists throughout life. Concrete experiences are most effective in learning when they occur in the context of some relevant conceptual structure. The difficulties many students have in grasping abstractions are often masked by their ability to remember and recite technical terms that they do not understand. As a result, teachers—from kindergarten through college—sometimes overestimate the ability of their students to handle abstractions, and they take the students' use of the right words as evidence of understanding.

People Learn to Do Well Only What They Practice Doing

If students are expected to apply ideas in novel situations, then they must practice applying them in novel situations. If they practice only calculating answers to predictable exercises or unrealistic "word problems," then that is all they are likely to learn. Similarly, students cannot learn to think critically, analyze information, communicate scientific ideas, make logical arguments, work as part of a team, and acquire other desirable skills unless they are permitted and encouraged to do those things over and over in many contexts.

Effective Learning by Students Requires Feedback

The mere repetition of tasks by students—whether manual or intellectual—is unlikely to lead to improved skills or keener insights. Learning often takes place best when students have opportunities to express ideas and get feedback from their peers. But for feedback to be most helpful to learners, it must consist of more than the provision of correct answers. Feedback ought to be analytical, to be suggestive, and to come at a time when students are interested in it. And then there must be time for students to reflect on the feedback they receive, to make adjustments and to try again—a requirement that is neglected, it is worth noting, by most examinations—especially finals.

Expectations Affect Performance

Students respond to their own expectations of what they can and cannot learn. If they believe they are able to learn something, whether solving equations or riding a bicycle, they usually make headway. But when they lack confidence, learning eludes them. Students grow in self-confidence as they experience success in learning, just as they lose confidence in the face of repeated failure. Thus, teachers need to provide students with challenging but attainable learning tasks and help them succeed.

What is more, students are quick to pick up the expectations of success or failure that others have for them. The positive and negative expectations shown by parents, counselors, principals, peers, and—more generally—by the news media affect students' expectations and hence their learning behavior. When, for instance, a teacher signals his or her lack of confidence in the ability of students to understand certain subjects, the students may lose confidence in their ability and may perform more poorly than they otherwise might. If this apparent failure reinforces the teacher's original judgment, a disheartening spiral of decreasing confidence and performance can result.

Teaching Science, Mathematics, and Technology

Teaching Should Be Consistent with the Nature of Scientific Inquiry

Science, mathematics, and technology are defined as much by what they do and how they do it as they are by the results they achieve. To understand them as ways of thinking and doing, as well as bodies of knowledge, requires that students have some experience with the kinds of thought and action that are typical of those fields. Teachers, therefore, should do the following:

Start with Questions About Nature. Sound teaching usually begins with questions and phenomena that are interesting and familiar to students, not with abstractions or phenomena outside their range of perception, understanding, or knowledge. Students need to get acquainted with the things around them—including devices, organisms, materials, shapes, and numbers—and to observe them, collect them, handle them, describe them, become puzzled by them, ask questions about them, argue about them, and then to try to find answers to their questions.

Engage Students Actively. Students need to have many and varied opportunities for collecting, sorting and cataloging; observing, note taking and sketching; interviewing, polling, and surveying; and using hand lenses, microscopes, thermometers, cameras, and other common instruments. They should dissect; measure, count, graph, and compute; explore the chemical properties of common substances; plant and cultivate; and systematically observe the social behavior of humans and other animals. Among these activities, none is more important than measurement, in that figuring out what to measure, what instruments to use, how to check the correctness of measurements, and how to configure and make sense out of the results are at the heart of much of science and engineering.

Concentrate on the Collection and Use of Evidence. Students should be given problems—at levels appropriate to their maturity—that require them to decide what evidence is relevant and to offer their own interpretations of what the evidence means. This puts a premium, just as science does, on careful observation and thoughtful analysis. Students need guidance, encouragement, and practice in collecting, sorting, and analyzing evidence, and in building arguments based on it. However, if such activities are not to be destructively boring, they must lead to some intellectually satisfying payoff that students care about.

Provide Historical Perspectives. During their school years, students should encounter many scientific ideas presented in historical context. It matters less which particular episodes teachers select (in addition to the few key episodes presented in Chapter 10) than that the selection represent the scope and diversity of the scientific enterprise. Students can develop a sense of how science really happens by learning something of the growth of scientific ideas, of the twists and turns on the way to our current understanding of such ideas, of the roles played by different investigators and commentators, and of the interplay between evidence and theory over time.

History is important for the effective teaching of science, mathematics, and technology also because it can lead to social perspectives—the influence of society on the development of science and technology, and the impact of science and technology on society. It is important, for example, for students to become aware that women and minorities have made significant contributions in spite of the barriers put in their way by society; that the roots of science, mathematics, and technology go back to the early Egyptian, Greek, Arabic, and Chinese cultures; and that scientists bring to their work the values and prejudices of the cultures in which they live.

Insist on Clear Expression. Effective oral and written communication is so important in every facet of life that teachers of every subject and at every level should place a high priority on it for all students. In addition, science teachers should emphasize clear expression, because the role of evidence and the unambiguous replication of evidence cannot be understood without some struggle to express one's own procedures, findings, and ideas rigorously, and to decode the accounts of others.

Use a Team Approach. The collaborative nature of scientific and technological work should be strongly reinforced by frequent group activity in the classroom. Scientists and engineers work mostly in groups and less often as isolated investigators. Similarly, students should gain experience sharing responsibility for learning with each other. In the process of coming to common understandings, students in a group must frequently inform each other about procedures and meanings, argue over findings, and assess how the task is progressing. In the context of team responsibility, feedback and communication become more realistic and of a character very different from the usual individualistic textbook-homework-recitation approach.

Do Not Separate Knowing From Finding Out. In science, conclusions and the methods that lead to them are tightly coupled. The nature of inquiry depends on what is being investigated, and what is

learned depends on the methods used. Science teaching that attempts solely to impart to students the accumulated knowledge of a field leads to very little understanding and certainly not to the development of intellectual independence and facility. But then, to teach scientific reasoning as a set of procedures separate from any particular substance—"the scientific method," for instance—is equally futile. Science teachers should help students to acquire both scientific knowledge of the world and scientific habits of mind at the same time.

Deemphasize the Memorization of Technical Vocabulary. Understanding rather than vocabulary should be the main purpose of science teaching. However, unambiguous terminology is also important in scientific communication and—ultimately—for understanding. Some technical terms are therefore helpful for everyone, but the number of essential ones is relatively small. If teachers introduce technical terms only as needed to clarify thinking and promote effective communication, then students will gradually build a functional vocabulary that will survive beyond the next test. For teachers to concentrate on vocabulary, however, is to detract from science as a process, to put learning for understanding in jeopardy, and to risk being misled about what students have learned.

Science Teaching Should Reflect Scientific Values

Science is more than a body of knowledge and a way of accumulating and validating that knowledge. It is also a social activity that incorporates certain human values. Holding curiosity, creativity, imagination, and beauty in high esteem is certainly not confined to science, mathematics, and engineering—any more than skepticism and a distaste for dogmatism are. However, they are all highly characteristic of the scientific endeavor. In learning science, students should encounter such values as part of their experience, not as empty claims. This suggests that teachers should strive to do the following:

Welcome Curiosity. Science, mathematics, and technology do not create curiosity. They accept it, foster it, incorporate it, reward it, and discipline it—and so does good science teaching. Thus, science teachers should encourage students to raise questions about the material being studied, help them learn to frame their questions clearly enough to begin to search for answers, suggest to them productive ways for finding answers, and reward those who raise and then pursue unusual but relevant questions. In the science classroom, wondering should be as highly valued as knowing.

Reward Creativity. Scientists, mathematicians, and engineers prize the creative use of imagination. The science classroom ought to be a place where creativity and invention—as qualities distinct from academic excellence—are recognized and encouraged. Indeed, teachers can express their own creativity by inventing activities in which students' creativity and imagination will pay off.

Encourage a Spirit of Healthy Questioning. Science, mathematics, and engineering prosper because of the institutionalized skepticism of their practitioners. Their central tenet is that one's evidence, logic, and claims will be questioned, and one's experiments will be subjected to replication. In science classrooms, it should be the normal practice for teachers to raise such questions as: How do we know? What is the evidence? What is the argument that interprets the evidence? Are there alternative explanations or other ways of solving the problem that could be better? The aim should be to get students into the habit of posing such questions and framing answers.

Avoid Dogmatism. Students should experience science as a process for extending understanding, not as unalterable truth. This means that teachers must take care not to convey the impression that they themselves or the textbooks are absolute authorities whose conclusions are always correct. By dealing with the credibility of scientific claims, the overturn of accepted scientific beliefs, and what to make out of disagreements among scientists, science teachers can help students to balance the necessity for accepting a great deal of science on faith against the importance of keeping an open mind.

Promote Aesthetic Responses. Many people regard science as cold and uninteresting. However, a scientific understanding of, say, the formation of stars, the blue of the sky, or the construction of the human heart need not displace the romantic and spiritual meanings of such phenomena. Moreover, scientific knowledge makes additional aesthetic responses possible—such as to the diffracted pattern of street lights seen through a curtain, the pulse of life in a microscopic organism, the cantilevered sweep of a bridge, the efficiency of combustion in living

cells, the history in a rock or a tree, an elegant mathematical proof. Teachers of science, mathematics, and technology should establish a learning environment in which students are able to broaden and deepen their response to the beauty of ideas, methods, tools, structures, objects, and living organisms.

Science Teaching Should Aim to Counteract Learning Anxieties

Teachers should recognize that for many students, the learning of mathematics and science involves feelings of severe anxiety and fear of failure. No doubt this results partly from what is taught and the way it is taught, and partly from attitudes picked up incidentally very early in schooling from parents and teachers who are themselves ill at ease with science and mathematics. Far from dismissing math and science anxiety as groundless, though, teachers should assure students that they understand the problem and will work with them to overcome it. Teachers can take such measures as the following:

Build on Success. Teachers should make sure that students have some sense of success in learning science and mathematics, and they should deemphasize getting all the right answers as being the main criterion of success. After all, science itself, as Alfred North Whitehead said, is never quite right. Understanding anything is never absolute, and it takes many forms. Accordingly, teachers should strive to make all students—particularly the less-confident ones—aware of their progress and should encourage them to continue studying.

Provide Abundant Experience in Using Tools. Many students are fearful of using laboratory instruments and other tools. This fear may result primarily from the lack of opportunity many of them have to become familiar with tools in safe circumstances. Girls in particular suffer from the mistaken notion that boys are naturally more adept at using tools. Starting in the earliest grades, all students should gradually gain familiarity with tools and the proper use of tools. By the time they finish school, all students should have had supervised experience with common hand tools, soldering irons, electrical meters, drafting tools, optical and sound equipment, calculators, and computers.

Support the Roles of Women and Minorities in Science. Because the scientific and engineering professions have been predominantly male and white, female and minority students could easily get the impression that these fields are beyond them or are otherwise unsuited to them. This debilitating perception—all too often reinforced by the environment outside the school—will persist unless teachers actively work to turn it around. Teachers should select learning materials that illustrate the contributions of women and minorities, bring in role models, and make it clear to female and minority students that they are expected to study the same subjects at the same level as everyone else and to perform as well.

Emphasize Group Learning. A group approach has motivational value apart from the need to use team learning (as noted earlier) to promote an understanding of how science and engineering work. Overemphasis on competition among students for high grades distorts what ought to be the prime motive for studying science: to find things out. Competition among students in the science classroom may also result in many of them developing a dislike of science and losing their confidence in their ability to learn science. Group approaches, the norm in science, have many advantages in education; for instance, they help youngsters see that everyone can contribute to the attainment of common goals and that progress does not depend on everyone's having the same abilities.

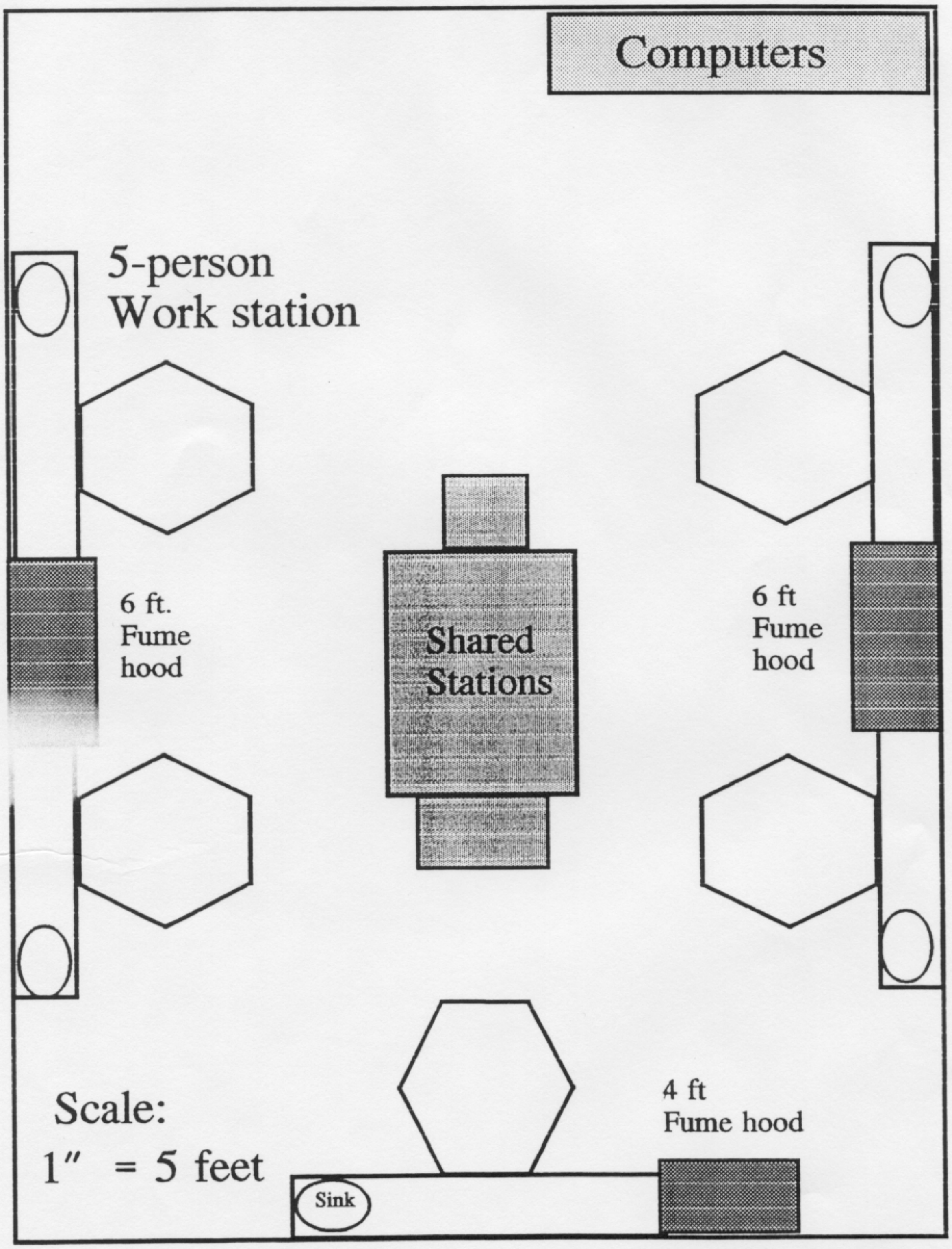
Science Teaching Should Extend Beyond the School

Children learn from their parents, siblings, other relatives, peers, and adult authority figures, as well as from teachers. They learn from movies, television, radio, records, trade books and magazines, and home computers, and from going to museums and zoos, parties, club meetings, rock concerts, and sports events, as well as from schoolbooks and the school environment in general. Science teachers should exploit the rich resources of the larger community and involve parents and other concerned adults in useful ways. It is also important for teachers to recognize that some of what their students learn informally is wrong, incomplete, poorly understood, or misunderstood, but that formal education can help students to restructure that knowledge and acquire new knowledge.

Teaching Should Take Its Time

In learning science, students need time for exploring, making observations, taking wrong turns, testing ideas, doing things over again; time for building things, calibrating instruments, collecting things, and constructing physical and mathematical models for testing ideas; time for learning whatever mathematics, technology, and science they may need to deal with the questions at hand; time for asking around, reading, and arguing; time for wrestling with unfamiliar and counterintuitive ideas and for coming to see the advantage in thinking in a different way. Moreover, any topic in science, mathematics, or technology that is taught only in a single lesson or unit is unlikely to leave a trace by the end of schooling. To take hold and mature, concepts must not just be presented to students from time to time but must be offered to them periodically in different contexts and at increasing levels of sophistication. ■

Appendix B: Suggested layout for Lab



Appendix C: Laboratory Equipment
Tentative List for Pilot Course

Quantity Required	Item	Cost per Item	Total Cost
	Permanent Equipment		
6	Portable conductivity meters	$230	$1,380
1	High precision conductivity meter	$895	$895
6	Portable pH meters	$79	$474
1	High precision pH meter	$450	$450
12	Digital thermometers	$22	$264
2	Optical microscopes	$1,000	$2,000
6	Toploading digital balances	$249	$1,494
1	Analytical balance	$1,500	$1,500
1	Centrifuge	$495	$495
1	Refrigerator/freezer	$700	$700
6	Support stand sets with clamps	$50	$300
6	Magnifiers, assorted	$30	$180
6	Carboys	$30	$180
2	PC-compatible microcomputers	$1,500	$3,000
1	Microcomputer printer	$600	$600
2	Sets of Software for data analysis	$500	$1,000
1	Dissecting microscope	$700	$700
6	Filtration Modules	$75	$450
6	Insulated baths	$25	$150
6	Infrared heaters	$295	$1,770
6	Cooling fans	$50	$300
6	Low temperature alcohol thermomet	$33	$198
12	Electronic timers/stopwatches	$65	$780
6	Bunsen Burners	$25	$150
2	Spectrophotometers	$1,500	$3,000
2	Large drying ovens	$1,350	$2,700
6	Pressure sensors	$250	$1,500
6	Liquid flow meters	$795	$4,770
1	Video camera, VCR & Monitor	$1,200	$1,200
6	Test tube racks	$15	$90
6	Aspirators	$50	$300
6	Hotplates with stirrers	$365	$2,190
6	Ice Buckets, insulated	$55	$330
	Equipment Total:		**$35,490**

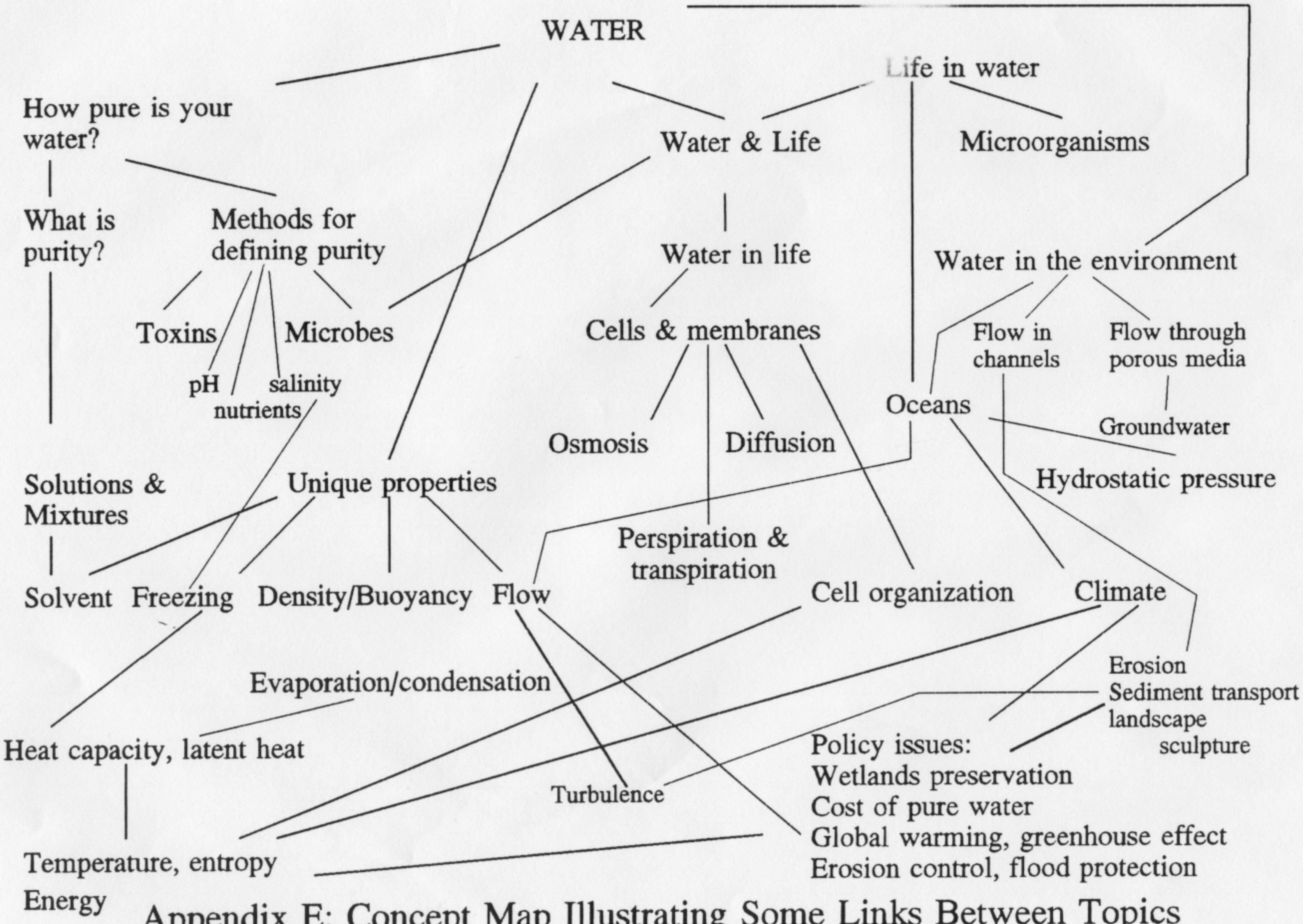
It is expected that this list will be expanded considerably as experience is gained from the pilot program.

Appendix D: Laboratory Supplies
Tentative List for Pilot Course

Expendables and supplies per 25 Student Lab Section

48	Graduated cylinders, asstd sizes	$10	$480
48	Beakers, assorted sizes	$8	$384
48	Flasks, asstd sizes	$15	$720
12	Stainless steel beakers	$33	$396
6	Tape measures	$8	$48
6	Meter sticks	$5	$30
18	Secchi disks	$15	$270
25	Safety goggles	$4	$88
2	Lab safety kits	$50	$100
3	Test tubes, asstd sizes, pkg 1000	$50	$150
24	Set of spatulas, spoons, stirrers	$10	$240
10	Sets of Analytic papers (litmus)	$10	$100
100	Bottles, assorted	$1	$100
24	Tongs, tweezers, asstd	$12	$288
1	Set of general lab supplies	$400	$400
1	Set of assorted chemicals	$1,500	$1,500
	Total cost of expendables:		**$5,294**

It is expected that this list will be expanded considerably
as experience is gained from the pilot program.



Appendix E: Concept Map Illustrating Some Links Between Topics

Ever Wonder What's in the Library Pond??

Attention Non-Science Majors!

NEED A SCIENCE COURSE??

Register for SCI 100

WATER: An Interdisciplinary Study

SCI 100 is an interdisciplinary lab science course intended for non-science majors. This 3-credit course integrates biology, chemistry, physics, and environmental science through the unifying theme of water. It consists of one 90-minute lecture/discussion and one 110-minute lab each week. General topics include Chemical and Physical Properties of Water, Water Quality ,Water and Life, and Water in the Earth's Environment. Water policy issues will be interwoven throughout the course. Emphasis is placed on group collaboration and investigation using the scientific method. Labs include hands-on activities and campus field trips.

Design Your Own Experiments!!
Pick Topics of Interest to YOU!
Learn About the Herbert Run Watershed !

Investigate Pig Pen Pond!!

Spring 2000 Schedule:

[4394]	SCI 100	0101	Lecture	Monday 2-3:30, Lecture Hall 6,	Lab Wednesday 11:50 - 1:20, Physics 111
[4395]	SCI 100	0201	Lecture	Monday 2-3:30, Lecture Hall 6,	Lab Wednesday 2:00 - 3:50, Physics 111
[4396]	SCI 100	0301	Lecture	Monday 2-3:30, Lecture Hall 6,	Lab Thursday 11:50 - 1:20, Physics 111
[4397]	SCI 100	0401	Lecture	Monday 2-3:30, Lecture Hall 6,	Lab Thursday 2:00 - 3:50, Physics 111
[4398]	SCI 100	0501	Lecture	Monday 2-3:30, Lecture Hall 6,	Lab Friday 2:00 - 3:50, Physics 111

SCI 100 Will Satisfy the GER/GFR Requirement For an MS Designated Course

For More Information Please Contact:
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Interdisciplinary Science Program