An Integration of Chemistry, Biology, and Physics: The Interdisciplinary Laboratory

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Background and Course Philosophy

Our Interdisciplinary Laboratory—an integration of chemistry, physics, and biology—is a new venture to integrate research and education. Here integration of research and education has two meanings: first, an investigative style of laboratory more representative of research, and second, a situation where most of the experiments conducted are directly derived from the results of research by Harvey Mudd College faculty.

Interdisciplinary study is increasingly common in the undergraduate curriculum. The character of interdisciplinary courses, however, can vary widely in terms of the disciplines integrated, the audience focus (nonmajors versus majors, introductory versus advanced), and the mode of instruction (lecture or classroom versus laboratory). Many courses combine a basic science with a humanities or social science discipline, commonly with a unifying theme, to examine historical, philosophical, or societal perspectives of a scientific field. These courses are often designed for nonmajors and do not involve a laboratory component. A Science and Technology course described by Markham and McKone is one such example (*1*). Other courses integrate two or more technical disciplines to reflect a broader scientific view, such as a lecture-based course described by Lattanzio, Natural Science 100, Evolution of the Cosmos, which integrates biology, geology, and astronomy for the nonmajor (*2*). Two further examples of this approach are an introductory course combining chemistry and zoology for education majors detailed by Caple et al. (*3*) and a nonmajors Science and Inquiry course blending chemistry, biology, and physics (*4*); both have laboratory components. As an example of an interdisciplinary course focusing on the laboratory experience only, Boersma et al. described an introductory science and mathematics projects-based course for nonmajors called How the World Works (*5*). An advanced lecture course for science and engineering majors is a capstone course focusing on interdisciplinary relationships among biology, chemistry, and physics (*6*); course topics are systematically presented in increasing size regimes, from elementary particles to cosmology. Another example of an advanced course involves a collaboration between chemistry and geology to introduce computational chemistry in mineralogy (*7*), with four computational laboratory exercises designed to complement the traditional mineralogy laboratory experiments. Still other interdisciplinary courses combine fields within the same discipline such as organic and polymer chemistry (*8*), analytical and organic chemistry (*9*), or biochemistry and molecular biology (*10*).

Our Interdisciplinary Laboratory (ID Lab) uses a unique approach aimed at introductory science or engineering majors. This first-year laboratory sequence was introduced at Harvey Mudd College during the 1999–2000 academic year to blend laboratory experiences from biology, chemistry, and physics for the first-year student. It aims both to illustrate the commonalities of investigative methods and laboratory techniques in these sciences and to introduce discipline-specific principles. Concepts and skills from at least two disciplines are blended into each of the experiments. Any missing connections to the third discipline are made in the laboratory manual and during discussions in the laboratory. The ID Lab features an investigative approach based on formulating and testing questions or hypotheses. Each pair of students is provided with a laptop computer for real-time data recording and analysis in the laboratory. Students use these same computers to assist in preparation of their laboratory write-ups.

The pilot sections of this course were team-taught by Biology, Chemistry, and Physics faculty. There were 36 students during each of the 1999–2000, 2000–2001, and 2001–2002 academic years. Students substitute the ID Lab for the fall-semester General Chemistry Laboratory and the spring-semester General Physics Laboratory, both of which are required courses at the college; they are concurrently enrolled in separate general chemistry and general physics lecture courses. During the spring semester, a small proportion of the students are also enrolled in an introductory biology class.

Students were chosen for enrollment in the ID Lab on the basis of interest expressed on a questionnaire sent to all incoming students. In the three years of our experience, almost half of the entering class of 180 expressed interest in the laboratory. Only 36 were selected owing to current limitations of equipment and faculty. Since we view the laboratory as a yearlong course, students are assigned to it for both fall and spring semesters, and transfers out of the course have not been allowed. While it would be possible to allow students to transfer to a traditional course, the reverse exchange would be very difficult because of the quite different nature of the laboratory. A practical consideration is to keep the enrollment number even to assure teams of paired students.

Course Mechanics

The ID Lab features four 3-week-long experiments each semester. Two experiments are conducted in parallel for groups of 18 students (9 pairs) each. After each section has completed an experiment, the groups switch to do the paired experiment. After six weeks everyone has completed two experiments, and the rotation through the next two experiments begins. The laboratory sessions last four hours. The first two weeks of each experiment are devoted to laboratory work and the third week involves in-class data analysis, data compilation among students for statistical comparisons, individual laboratory write-up, and often brief oral presentations of results to the class. All procedures, data, and analyses are recorded in a bound laboratory notebook. When original data are directly and manually entered into a computer, the data sheets are printed and permanently attached to the laboratory notebook. Computer data analyses, including graphs, are also printed and permanently bound in the laboratory book. Laboratory notebooks always remain in the laboratory and are graded by the faculty.

As many of the investigations involve topics and systems that are new to the student and are not necessarily discussed in an accompanying lecture course, the in-house laboratory manual provides extensive introductory material. Before each experimental session, students complete a prelab exercise available on the course Web site and submit their answers to a designated instructor via email. The prelab exercises are designed to ensure that students understand the background information necessary to conduct the experiment and analyze the results. Students are encouraged to submit in writing any remaining questions on the experimental procedure. The instructor may choose to address these questions individually via email or collectively at the start of a laboratory session. Each student is assigned a different laboratory partner for each experiment, but prelab assignments and laboratory reports are completed individually.

The Experiments

Overview

Tables 1 and 2 list the eight experiments that comprise the fall- and spring-semester schedules of the ID Lab. Each experiment integrates at least two disciplines. The background material assisted the student to see the role of the various disciplines and to make connections to other fields. By the second semester of the course, students were able to delineate the chemical, physical, and biological concepts involved in an experiment. However, the faculty found that the beginning student's awareness of the interdisciplinary nature of an experiment was greatly enhanced by specific discussion of these concepts in the laboratory manual and in class.

The objectives of each experiment are discussed below. All experiments are original and were designed by the initial faculty team (the coauthors). Experiments 1, 3, 6, and 7 were inspired by the results of HMC faculty research and provide excellent examples of the integration of research and education. We plan to publish a more complete description of each experiment in the near future.

Fall-Semester Experiments

Thermal Properties of an Ectothermic Animal

The concept of scaling is important to engineering, physics, chemistry, and biology, as the students demonstrate in "Thermal Properties of an Ectothermic Animal". In the first week, students determine the cooling rate of aluminum cylinders of various dimensions and analyze the dependence of cooling rate on the mass, surface area, and volume of these objects. In particular, they analyze their data using Newton's integrated law of cooling, $\ln(T_b - T_e) = -Ct + z$, where T_b and T_e are the temperatures of a body and its environment, C is the cooling constant equal to the overall thermal conductance of the body divided by its specific heat capacity, t is time, and z is a constant related to scaling (*11*). The temperature and time data are entered directly into laptop computers for analysis by Kaleidagraph and MathCad software.

In the second week of the experiment, students repeat this procedure with lizards of various sizes collected in the nearby San Gabriel Mountains (species *Uta stansburiana*, *Sceloporus occidentalis*, *Sceloporus magister*, and *Sceloporus graciosus*). The analogous approach to the analysis of the cooling rates for these two seemingly disparate systems is a startling realization for most students. As the lizards are immobilized during heating and cooling, no regulation of body temperature is allowed through such behavioral activities as location and posture changes. Students discover that in the absence of behavioral thermoregulation, the laws of physics governing heat transfer apply to both inanimate and animate objects—aluminum cylinders and immobilized lizards. Moreover, by looking at the cooling rates of cylinders and lizards of different sizes, the students learn that the laws of scaling apply to both inanimate and animate objects.

Table 1. Fall Laboratory Schedule

Time Period	Experiment	
	No.	Title
First 6 weeks	1	Thermal properties of an ectothermic animal: Are lizards just cylinders with legs?
	2	Molecular weight of macromolecules: Is molecular weight always simple?
Next 6 weeks	3	Mechanical resonance of a high-rise building: Are seismic nightmares avoidable?
	4	Carbonate content of biological hard tissue: Of what are shells composed?

Table 2. Spring Laboratory Schedule

Time Period	Experiment	
	No.	Title
First 6 weeks	5	Using digital logic to time a simple pendulum: What makes a good clock?
	6	A structure-activity investigation of photosynthetic electron transport: How does a biological system convert physics into chemistry?
Next 6 weeks	7	Synthesis and characterization of liquid crystals: Or, when are liquids not?
	8	A genetic map of a bacterial plasmid: Where are the restriction sites located?

Molecular Weight of Macromolecules

The concept of a distribution is fundamental to science. Gaussian distributions, the Boltzmann distribution, and so many others are used daily to analyze and interpret data. Polydispersed macromolecules, whether natural or man-made, follow a distribution of molecular weights, as students seek to understand in “Molecular Weight of Macromolecules”. Students physically separate molecular-weight fractions of a synthetic polymer (polyvinyl alcohol, PVA) and employ viscosity measurements to determine the molecular weight and size distribution of the polymer. An aqueous solution of the polydispersed sample of the PVA polymer is fractionated into relatively monodisperse samples by adding increasing amounts of isopropanol. This approach takes advantage of the more limited solubility of higher molecular weight PVA macromolecules in isopropanol. Aqueous solutions of the various fractions are then prepared, the viscosities of these solutions are related to the intrinsic viscosity of each fraction, and a viscosity-average molecular weight is calculated.

Since no two pairs of students obtain the same fractions, a class molecular weight distribution is prepared by sharing data during the write-up and analysis laboratory session. The dependence of a macromolecule’s physical properties on molecular weight and polydispersity is discussed. The calculations and necessary graphical treatment of the data are accomplished using the laptop computers and MathCad software.

Mechanical Resonance of a High-Rise Building

The concept of resonance is a major instructional theme in physics today and clearly has widespread applications. For chemists, nuclear magnetic resonance is perhaps the prime example. Of course resonant circuits are fundamental to communications and other electronic applications, but resonance is also applicable to the transference of energy in mechanical structures, as the students discover in “Mechanical Resonance of a High-Rise Building”.

Students measure the vibrational resonance of a model building and explore the effect of various structural features on the building’s resonance response. The “high-rise building” is constructed of aluminum rods and plates and mounted on a granite slab. Variable voltage, displayed on one channel of a dual-channel oscilloscope, is supplied to a dc motor mounted on the top floor. The frequency of rotation of the motor is detected by a frequency counter whose output is connected to the other channel of the oscilloscope for measurements. The acceleration of the building in a given direction (measured with an accelerometer) is recorded as a function of stimulating frequency. A resonance curve is constructed by plotting the displacement of the building measured by the accelerometer versus frequency using Kaleidagraph software.

For the second week of the experiment, students propose a hypothesis that they would like to test regarding mechanical resonance of the model high-rise buildings, and they outline an experimental protocol for doing this. The protocol is submitted via email to the instructor, who makes certain the proposed experiment is feasible with the apparatus that is already on hand or can be made available before the next laboratory meeting in one week. For example, students might test how the building’s resonance is affected by the number of floors, the floor height, or even the presence of a simulated swimming pool (modeled by a pan of water) on one of the floors. Presentations of results occupy much of the laboratory time during the final week of the experiment.

Carbonate Content of Biological Hard Tissue

When are two pieces of data statistically the same? Answers to this question are crucial to virtually all scientific studies. The opportunity to make such statistical inferences is afforded in “Carbonate Content of Biological Hard Tissue”. The object is to determine whether the mineral-containing shells of oysters, hen’s eggs, and the skeletons of reef-building corals contain statistically different amounts of calcium carbonate. We employ a simple acid–base titration technique in which the sample is dissolved with excess hydrochloric acid and the unreacted HCl is titrated with a strong base. Students formulate a hypothesis to test a question of interest, such as “Do eggs of different sizes differ in carbonate content?” or “Do the various calcified structures of different organisms (coral skeleton, mollusc shell, bird egg) differ in carbonate content?” They use the laptop computers with the MathCad software to determine if the average percentages of carbonate in the various samples are statistically different from one another.

During the final week of the experiment, students present their findings to the class, discussing which carbonate sources are the same and which are different and making suggestions as to why. This is an interesting case in which the formulation of a hypothesis for the origin of any differences has to rely on first answering the question whether differences do exist statistically.

Spring-Semester Experiments

Using Digital Logic to Time a Simple Pendulum

Biological clocks, oscillating chemical reactions, and pendulums are all periodic time phenomena. The period of the phenomenon must be measured by a clock of some sort. In conducting the experiment “Using Digital Logic to Time a Simple Pendulum”, students learn the basics of digital logic and integrated circuits in order to construct a digital clock to time the period of a pendulum.

In the first week, students construct a clock and measure the length dependence of the pendulum’s period. They then propose a hypothesis to the instructor for approval, perhaps to test the period dependence on such factors as amplitude of swing or weight- or mass-to-volume ratio of the bob. These experiments are conducted during the second week. The constructed clock is accurate enough to show deviations from the small angle approximation typically used to discuss pendulums. Some explorations border on the breakdown of the small-angle assumption, and the validity of this approximation is discussed in the laboratory. In the third week, all data are analyzed and the students present their test results to the class. Periodic behavior in chemical reactions and biological systems is discussed in the laboratory manual to extend the applicability of this concept.

A Structure–Activity Investigation of Photosynthetic Electron Transport

Phenomena that vary with time but are not periodic are characterized by a rate of change. From nuclear decay to photosynthesis, rate phenomena are immensely important in our understanding of the world. The rate of electron transport in photosynthesis is the subject of "A Structure–Activity Investigation of Photosynthetic Electron Transport".

In the first week, students test the effectiveness of a set of substituted quinones as model herbicidal inhibitors of photosynthetic electron transport in spinach chloroplasts. A spectroscopic assay is used to measure the rate of electron transport to an exogenous acceptor, dichloroindophenol (DCIP). DCIP added to the chloroplast preparation positions itself as a terminal electron acceptor in the photosystem II electron transfer chain (*12*). In aqueous solution, oxidized DCIP appears blue and absorbs light maximally at 600 nm but reduced DCIP is colorless. Students use a flashlight to initiate light absorption and trigger the transfer of electrons through the series of naturally occurring electron acceptors. Reduced DCIP is formed after two electrons per DCIP molecule reach this final electron acceptor. Thus, the rate of loss of absorption at 600 nm is proportional to the rate of electron transfer. Substituted quinones bind to a herbicide-binding protein and displace one of the naturally occurring electron acceptors in the electron transport chain. Students use the molecular modeling program Molecular Properties Pro on the laptop computers to examine each quinone and visualize the structural aspects that promote and hinder electron transport inhibition. By correlating quinone structure with inhibitory activity (i.e., the extent to which the rate of electron transport is diminished), the herbicide-binding region in plant chloroplasts may be modeled.

On the basis of their first week results, students form a hypothesis about what substituents and structural features promote inhibition. The second week they test their hypothesis by using a wider pool of quinones including benzoquinones, naphthoquinones, and anthraquinones. In the last week they share their results and see how consistent their predictions were. In addition they suggest the likely features of the active binding site, such as its dimensions and the presence of hydrophobic or hydrophilic regions within the binding pocket.

Synthesis and Characterization of Liquid Crystals

States of matter are gases, liquids, and solids—or are they? Not all liquids are as simple as they seem, for there is a class of liquids whose molecules exhibit order in one or two dimensions. Such materials are liquid crystals, and besides their immense practical importance in display technology, they have fundamental roles in living systems as well. For example, cell membranes can be viewed as a type of liquid crystal. Cholesteric liquid crystals are the basis for many color displays, whose color depends on the pitch of the helical arrangement of the molecules in the liquid crystal phase.

Table 3. Goals, Outcomes, and Related Assessment Questions

Goal	Expected Outcome	Related Question	
		PEQ*n*	PCQ*n*
Promote the excitement and practice of laboratory science with experiments that illustrate the blending of disciplines in real-world problems	Students will learn the commonality of science while recognizing discipline-specific principles.	PEQ1, PEQ4	PCQ1, PCQ2
Promote the excitement and practice of laboratory science by investigative experiments that develop problem formulation skills	Students will confidently explore new areas of scientific study.	—	PCQ4
	Students will better retain new concepts, since they can relate to real problems.	PEQ5a, 5b, 5c	PCQ5
Promote the excitement and practice of laboratory science with experiments that vary in disciplinary perspective and content.	Students will recognize how discipline-specific principles can be quite similar but applied and interpreted differently.	PEQ1, PEQ4, PEQ5e	PCQ8
Introduce experimental protocols, laboratory, computational, communication, and computer skills.	Students will be able to communicate effectively across disciplines.	PEQ5d, 5e	PCQ6, PCQ7

Table 4. End-of-Experiment Questionnaire, with Responses to PEQ5

1. How do you think the interdisciplinarity of the lab itself could be improved?
2. What did you most enjoy, or find most rewarding, about this experiment?
3. What did you least enjoy, or find least rewarding, about this experiment?
4. What would you change about the lab? What would you keep the same?
5. Please rate the following items on the extent to which this investigation improved your skills (1 = not improved to 5 = greatly improved), and comment on how.
   a. collecting and recording scientific data
   b. formulating and testing a scientific question
   c. analyzing and interpreting data
   d. communicating scientific results to others
   e. working with a partner

Q	Average Response ± SD (1 = not improved to 5 = greatly improved)							
	Expt 1	Expt 2	Expt 3	Expt 4	Expt 5	Expt 6	Expt 7	Expt 8
5a	3.4 ± 1.0	3.4 ± 0.9	3.6 ± 1.1	3.6 ± 0.9	3.5 ± 1.0	3.7 ± 0.8	3.5 ± 1.0	3.5 ± 1.1
5b	3.2 ± 1.1	2.8 ± 0.9	4.4 ± 0.7	2.7 ± 1.1	4.0 ± 0.9	3.5 ± 1.1	2.8 ± 0.9	3.2 ± 1.1
5c	3.6 ± 0.8	3.3 ± 1.1	3.9 ± 0.8	3.5 ± 1.0	4.0 ± 0.9	4.0 ± 0.8	3.7 ± 0.7	4.2 ± 0.8
5d	3.3 ± 0.8	2.9 ± 0.7	3.9 ± 0.8	3.0 ± 0.9	3.7 ± 1.0	3.1 ± 1.0	3.6 ± 0.8	3.4 ± 0.9
5e	3.0 ± 1.0	3.3 ± 1.0	3.5 ± 0.8	3.5 ± 0.9	3.5 ± 1.0	3.7 ± 1.1	3.4 ± 1.2	3.2 ± 1.1

Students measure the pitch of mixtures in “Synthesis and Characterization of Liquid Crystals”. In the first week they synthesize and purify cholesteryl nonanoate, a compound known to exhibit a cholesteric liquid crystalline phase. They then form binary mixtures of cholesteryl nonanoate and cholesteryl chloride, known to form a cholesteric (i.e., chiral nematic) liquid crystalline phase over the range of 30–80 °C for certain solution compositions (viz., mole fractions of cholesteryl chloride equal to 0.30–0.55 [*13*]). To measure the pitch of the helix formed by the mixture, two measurements are necessary: the refractive index of the phase and the selective reflection of that phase. Since the required refractive index data are too numerous for one pair of students to acquire in the time available, students are assigned mixture compositions and temperatures to study. These refractive index measurements and the synthesis are completed in the first week.

For the second week, the students measure the selective reflection of their mixture using a spectrophotometer equipped with a variable-temperature cell. The chiral nematic liquid crystalline phase is characterized by an arrangement of molecules having an orientational order that describes a helical pattern propagating along an axis known as the optical axis. The helix is characterized by a pitch that represents the physical distance for one complete revolution about the optical axis. For these cholesteric materials that distance is about the wavelength of visible light. The selective reflection that the students measure is the result of the constructive interference of visible reflected light and is the origin of the brilliant colors of cholesteric liquid crystals.

In the third week the selective reflection and the refractive index data are combined to calculate the pitch of the helix as a function of temperature, using MathCad and the laptop computers. The calculations are interesting because the pitch is calculated as a function of temperature from the ratio of refractive index and selective wavelength, each of which is an independent function of temperature.

Box 1. End-of-Course Questionnaire

The two most frequent answers and their frequency are given after each question.

1. *What was effective in promoting your learning in this course?*
   The pre-labs being due the night before the next day’s lab (10).
   Friendly and enthusiastic faculty (9).
2. *What was not conducive to learning in this laboratory?*
   The length of some labs—unable to focus past 5:30 (8).
   Pre-lab material does not necessarily correlate with lecture material and had to be learned from the lab manual (7).
3. *What could instructors have done differently to promote your learning?*
   Nothing. The instructors were very helpful and answered questions (5).
   Explain more of the practical implications of the laboratory material (4).
4. *What could you have done differently to promote your learning?*
   Prepared better before the lab, read the manual more carefully (19).
   Manage personal time better to avoid fatigue in lab (3).
5. *What are the most important skills you learned in ID Lab?*
   The importance of writing details in lab book, how to write up a lab (13).
   Recording procedure, data analyses, following instructions, time management (8).
6. *What aspect(s) of the ID Lab did you find most valuable?*
   Incorporating different disciplines—broad range of topics (13).
   Developing our own hypotheses (4).
7. *What aspect(s) of the ID Lab did you find most challenging?*
   Sometimes difficult to understand the concepts on which the labs were based—the pre-labs were confusing (11).
   Developing deeper critical thinking skills to analyze data and errors (9).
8. *How has your experience in the ID Lab helped you to grow as an experimentalist? For example, did your concepts of scientific investigation change or become clearer?*
   Take data meticulously and scrutinize it carefully for all possibilities (11).
   Never had any labs before (5).
9. *Would you recommend ID Laboratory to an incoming student? Why or why not?*
   Yes, but it takes getting used to the different format but you do really interesting labs and real experiments (15) .
   Yes, it is a great opportunity to learn and develop critical experimental skills and it is challenging (3).

A Genetic Map of a Bacterial Plasmid

The ability to apply chemical tools to biological systems is crucial to understanding the structures and fundamental reactions of biological systems. In “A Genetic Map of a Bacterial Plasmid”, students use gel electrophoresis to map the restriction sites of several restriction enzymes within a bacterial plasmid DNA molecule.

In the first week they use restriction enzymes to cleave double-stranded DNA molecules at specific sites, producing DNA fragments of specific size. Given three enzymes, students conduct three single-enzyme restrictions and three “double digestions” using pairwise combinations of enzymes. Gel electrophoresis experiments done during the second week permit determination of the size of the resultant fragments in terms of the number of base pairs. During the write-up period in the third week the class data are pooled to reconstruct the entire plasmid and locate the positions where the enzymes digested or cleaved the DNA molecule. In the course of the experiments students have time to explore the molecular interactions between restriction enzymes and their DNA recognition sequences using the molecular visualization program RasMol installed on the laptop computers.

Goals, Outcomes, and Student Evaluations

Methodologies

Working with our college’s assessment officer early in the planning of the laboratory, a number of goals and expected outcomes were set forth. These are presented in Table 3. Assessments were conducted through two methods: questionnaires and a post-course exercise. There were two types of questionnaires, post-experiment (PE) and post-course (PC). Two experiments were evaluated by students at the conclusion of an experimental rotation, that is, every six weeks. In the first semester at the end of the first six weeks, a midsemester course review was conducted to assure the instructors that nothing was completely off track. At the end of each semester the students completed a questionnaire looking at the total semester’s experience. At the end of the year a meeting of all students and faculty was held (with refreshments) to discuss the whole experience.

The questions used for each assessment are presented in Table 4 and Box 1 and will be referred to as PEQ*n* and PCQ*n*. The correlations between specific goals and outcomes and specific assessment questions are shown in Table 3. For example, the post-experiment question 1 (PEQ1) "How do you think the interdisciplinarity of the lab could be improved?" speaks directly to the goal of promoting excitement in laboratory science and the blending of scientific disciplines. The post-course question 1 (PCQ1) "What was effective in promoting your learning in this course?" speaks to developing excitement in the laboratory.

In combination, these assessments not only cover each of the specific goals and the larger goals, but also address the critical question "Is an interdisciplinary approach better than a traditional approach?" To address this question specifically, a special post-course assessment exercise, introduced and discussed below, was given to every first-year laboratory student.

Post-Experiment and Post-Course Student Evaluation Questionnaires

On the end-of-experiment assessment, some questions asked for free-form written answers and others required numerically scaled answers. The results of these assessments are presented here first by discussing the numerical averages for the scaled questions in the end-of-experiment questionnaire, second by discussing the two most common and other selected responses to the questions in the end-of-course questionnaire, and third by offering selected but perceptive student quotations drawn from the questionnaires in Box 2.

The answers to the end-of-experiment assessment, question 5a–5e, are presented in Table 4.

Overall the laboratory improved the self-perceived skills of the students. On question PEQ5b, formulating and testing a scientific question, experiments PEQ2, PEQ4, and PEQ7 received somewhat lowered scores—which is understandable because those experiments required the development of considerable technical skills, significant data acquisition, or both, and did not allow the students much freedom. Experiments 3 and 5 scored very high on this scale because the second week of the experiment was devoted to allowing the students to explore. The techniques involved in those experiments were quickly learned and therefore allowed the exploration of new conditions. Experiments 3, 5, and 7 received higher than average scores for question PEQ5d, communicating scientific results to others, most likely as a result of the class presentations and discussions that were held during the data analysis session in the third week of the experiments. Students perceived that all of the experiments contributed uniformly to development of their skill in collecting and recording scientific data (question PEQ5a) and working with a partner (question PEQ5e).

Students evaluated their experiences in the ID Lab many times, always with an overwhelmingly enthusiastic response. The two most-common answers to the end-of-course questions (PCQ*n*) are presented in Box 1. Other responses tended to be individual comments. Most of those single comments not only supported the most-often stated answers but in addition revealed much more of the students' perceptions of their learning in the laboratory. An eclectic collection of perceptive student quotes is presented in Box 2.

Box 2. Student Quotations on the ID Lab

On what promoted learning in the laboratory

Many experiments offered an opportunity to create and test one's own hypothesis. [This] allows for creativity and a personal stake in the laboratory activity.

I enjoyed coming up with my own experiments and hypotheses. I think this is the kind of immersive learning everyone should experience.

The feeling that we were discovering and learning together.

On the most important skills learned in ID Lab

I learned many skills in ID Lab, but, most importantly, I learned to draw connections between the many different sciences and conclusions that were relevant to the findings.

I learned how to approach laboratory from a non-cookie cutter mentality … you had to figure out some of it for yourself … I guess I kinda surprised myself.

On the valuable aspects of the course

Seeing the interaction between the various sciences.

I really liked it when I could see the interdisciplinary nature of the experiments. It felt like I was doing something real, not just what every other frosh in every other college was doing.

[ID lab] was a really good chance to be exposed to labs that were very interesting and more "real-life" applicable. It was so valuable to be forced to think about what we know in many areas of science and pull it all together. I feel very well rounded.

Being a step ahead of chem / phys / bio class. Doing things that were interesting as opposed to monotonous.

On what was most challenging

Dealing with new experimental processes that I had never dealt with.

Combining the varied sciences.

Working with different lab partners.

What was most challenging in ID Lab was to learn how to break down the barriers among the different disciplines because most people apply knowledge from only one particular subject to lab.

I'm beginning to realize that there isn't always a right answer. Also some labs lead to more questions than answers and thus to more refined experiments.

What I found most valuable was also most challenging. Sometimes it was hard to think so critically about certain situations. I really think [the lab] has helped me look at a situation and see that there are so many things going on—physical, chemical, biological.

On the interdisciplinary nature of specific experiments

I think the applications are more interdisciplinary than the experiment itself [in reference to the pendulum / digital clock experiment].

For the faculty to note

Lab can be fun when it's interesting.

Post-Course Student Exercise

An important goal of the laboratory was to better instruct students on how to approach data, formulate hypotheses, and design experiments to test the posed hypotheses. This goal leads to the crucial question of whether the ID Lab experience was better than the traditional lab experience. The post-course assessment exercise was administered to all students in the spring semester Chemistry 26 (General Chemistry) laboratory, a course that also included all ID Lab students during this

Box 3. Post-Course Exercise Questions

1. From the data shown, what can you conclude about the effect of solute concentration on contractile vacuole pulse rate?
2. In what way(s) would you analyze the data to support your conclusion?
3. (a) What are the main sources of experimental uncertainty in this study? (b) How would you estimate those uncertainties?
4. Suppose you were going to have the chance to continue this study in the following lab period. What would you do? (a) State the hypothesis you would test. (b) Outline a brief protocol you would follow to test your hypothesis. (c) How would you analyze and present your data?
5. On a scale of 1–10, how difficult did you find this task? Please explain your rating.

semester. The assessment was administered in class at the time of the final experiment of the Chemistry 26 course. Students were given a short description of the osmoregulatory behavior of a protozoan (a species of *Paramecium*) and one page of data collected for a short experiment detailed in the handout. Neither prior exposure to the nature of the organism nor concurrent enrollment in a biology course was expected. Students were asked to read the material before the following laboratory meeting. One week later, at that laboratory session, they were given a series of questions to answer. These questions are listed in Box 3; the student, given some data, was to present a data analysis and form a possible hypothesis to test that analysis.

An expert outside of Harvey Mudd (a biology faculty member at Pomona College) read the responses without initially knowing which students were concurrently enrolled in the ID Lab. Numerical scores (on a scale of 1–5) were assigned to the responses to each question to scale the answers relative to each other. Average answers were scored “3”; superior and inferior responses were scored accordingly. For question 3a, the number of experimental sources of error cited was also noted. Question 4 was further evaluated in terms of whether a true hypothesis was posed (rather than a simple question) and whether students merely repeated their original conclusion (Question 1) as the new hypothesis to test. Two subjective scores were assigned for the overall sophistication of the responses and for the creativity in analysis and design of investigations. ID-Lab students were identified after the scoring was complete. Overall summaries and pairwise comparisons of scores for ID-Lab students and non-ID-Lab students were made, including pooled-variance *t*-tests of differences between means. The conclusions from this study support the notion that ID lab students could better handle the exercise and seemed to demonstrate “higher order” thinking skills than their non-ID-Lab classmates. However, we should be somewhat cautious about the conclusions because we have only analyzed one year’s data and the ID-Lab students were not selected for the lab entirely at random.

Assessments Summary

The various questionnaires have already been discussed but two important trends relevant to the goals are worth emphasizing. The questionnaires revealed that students have a more positive attitude toward the laboratory experience than their peers in the traditional laboratory sequence. Students also developed the ability to recognize the interdisciplinary nature of the selected experiments and were more appreciative of the interdisciplinary nature of scientific research at the conclusion of the course. We feel the post-course exercise was revealing and supported our premise that the Interdisciplinary Laboratory did encourage higher thinking skills in comparison to the normal laboratory sequence. As mentioned our original assessment vehicles continue to be refined as does the laboratory itself, but we are certainly encouraged to continue to develop and improve the laboratory.

Sustainability of the Course

This course was conceived and developed by a small core of committed faculty with the support of the three participating departments and our Vice President/Dean of Faculty. A team of undergraduates tested and modified the experiments during the summer prior to the initial offering of the course. From the start we recognized that teaching outside of one’s own discipline would most likely be the most challenging aspect of the course for faculty. To address this concern for those considering participating in this course in future offerings, we held a week-long training workshop during the summers of 2000 and 2001. In these workshops, faculty conducted the experiments on their own to gain familiarity and experience. Workshops in the next few years should add to the faculty base to allow rotation of numerous faculty through the course and permit expansion of the course to multiple laboratory sections.

The faculty believe that the novelty of the experiments enhances their investigative nature from the student point of view. Thus additional experiments should be developed and substituted on a rotating basis to maintain the fresh character of the course.

Offering the course for one typical laboratory section did not cause a great perturbation in the teaching assignments of the faculty in the three departments. However, exploring the increase to two sections has pointed out difficulties in coordinating faculty between departments. It is hoped that continued faculty workshops will generate an ever increasing interest in the laboratory and a concomitant decrease in resistance to the wider introduction of this laboratory concept. Advice to those who wish to try this type of laboratory is to start small, recognize that the laboratory is faculty intensive, and plan around the equipment available. As to costs, these were significant but not enormous and mainly involved equipment. We were fortunate to be well equipped to start and the AIRE award funds provided our remaining needs. Laboratory size was determined by pairs of students, the number of pieces of specialized equipment available (pH meters, spectrophotometers, etc.), and how much rotation through experiments was desirable. We had equipment for 9 pairs of students to simultaneously conduct any one experiment, which led to our design of two parallel experiments, each conducted by 18 students.

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