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Accelerated Integrated Science Sequence: An Interdisciplinary Introductory Course for Science Majors

Newton H. Copp, Kersey Black, Scot Gould

W. M. Keck Science Department, Claremont McKenna, Pitzer, and Scripps Colleges, Claremont, CA 91711.

We report here on our development of an introductory science course sequence that integrates biology, chemistry and physics in order to foster an interdisciplinary perspective in future science majors. Accelerated Integrated Science Sequence (AISS) is a two semester, double credit sequence co-taught by a biologist, a physicist and a chemist to first year undergraduates who plan to major in a natural science field. Topics are organized within a thematic framework. The course sequence also features integration of various pedagogical approaches as students shift from one type of activity to another within the

same class session. The presence of AISS in our curriculum over the past five years has been correlated with increased recruitment and graduation of students in science majors and a perception within the department that AISS has helped improve the culture of learning. These benefits outweigh the difficulties of developing such a course and encourage us that interdisciplinary introductory courses can make important contributions to training versatile scientists.

Key words: interdisciplinary, biology, chemistry, physics, introductory, undergraduate, teaching.

Given the remarkable variety of disciplines from which neuroscientists draw their work, it would seem appropriate to instill at the earliest opportunity in future neuroscientists an interdisciplinary perspective. This effort would dovetail with calls for more attention to integrated science in undergraduate education (Alpern et al., 2009; Brewer and Smith, 2009; AAC&U and PKAL, 2011). We describe here an interdisciplinary introductory course sequence that has been offered in our department since 2007 to help students gain the skills, knowledge, and perspectives needed to address complex problems in a variety of fields including neuroscience. One of us (NC) presented this work at the Faculty for Undergraduate Neuroscience workshop on undergraduate neuroscience education held at Pomona College in July, 2011.

Our course, a two semester sequence entitled Accelerated Integrated Science Sequence (AISS), combines introductory level work in biology, chemistry, physics and computer modeling for prospective science majors. AISS is team taught by three faculty members, one each in biology, chemistry, and physics, as a “double course,” such that students earn two course credits for each of the two semesters. Four credits of AISS, i.e., two semesters, meet the department’s prerequisites for upper-division course work and major programs in biology, chemistry, physics and related interdisciplinary majors such as neuroscience. AISS, thus, allows students to complete in the equivalent of four semesters the prerequisites that would otherwise require six semesters, hence the use of the term “accelerated” in the course title.

One of our major goals in developing AISS was to improve our recruitment and retention of science students and increase the number of students who graduate with BA degrees in a STEM (science, technology, engineering, or math) field. Although it is difficult to measure the contribution of any one factor to changes in recruitment and retention of science students, we have seen improvement in a number of key parameters, including

number of science graduates, over the years in which we have offered AISS. These results and other benefits, as well as the trials and tribulations we experienced in designing and teaching an interdisciplinary introductory science course, are described briefly below. A more complete account will be presented elsewhere.

COURSE DEVELOPMENT

AISS is offered within the curriculum of the W. M. Keck Science Department that is co-sponsored by three of the undergraduate colleges in The Claremont Colleges consortium: Claremont McKenna, Pitzer, and Scripps Colleges. This department comprises 27 tenured or tenure-track faculty members: 14 biologists, nine chemists, and four physicists. As a substantial subset of these faculty members met to plan AISS, we confronted what we expected to be our major problem, i.e., deciding what course content from each discipline would be included. Clearly, AISS could not simply be the sum of everything taught in our three disciplinary introductory courses. First, we selected course material from each discipline that lent itself easily to substantive integration while illuminating major scientific principles. Photosynthesis, for example, is discussed in the context of energy transformations. A second category of course material consisted of ideas, topics, and methodologies that are not typically offered in one or more of our disciplinary introductory courses but that effectively advance the integrative nature of the course. An introduction to the physics of diffusion, for example, is not typically included in our introductory physics courses but in AISS helps deepen the discussion of this important phenomenon. A third category is related to course material deemed important for students who intend to do more advanced work in that discipline but may not lend itself so easily to integration. Examples of this third category include nomenclature in chemistry and taxonomy in biology. The result is a course in which the disciplines come together frequently but may

also be separated on occasion for their own sake. The analogy that helped guide us was that of three streams that intersect in various combinations for some stretches but flow separately over others.

The second and much more difficult problem concerned the sequencing of the topics we had selected. Introductory courses in each of those disciplines typically unfold in a particular way honed over many years and evident in the sequence of topics in typical introductory texts. If we were to achieve even a modicum of integration in AISS, however, we couldn't follow any one of the standard stories. We had to create our own. This proved to be our most difficult challenge, but also the one that carried the greatest reward.

We considered adopting a topical or case study approach, as featured prominently in the integrated science courses offered at the University of British Columbia (Benbasat and Gass, 2002) and Louisiana Tech University (Ramsey et al., 1997) before finally settling on a framework built from a small number of themes, each of which transcends the disciplines of biology, chemistry, and physics. We moved away from the more topical approach, thinking that the development of topics was likely to be idiosyncratic to the extent that it would discourage new faculty members from rotating into the course. We hope that our thematic approach makes it easy for faculty members to see how their expertise can fit into AISS and offers greater flexibility than perhaps characterizes a strong topical or case study approach. Over the past three years, the organizing themes for AISS have been (i) Randomness, (ii) Structure, (iii) Energy, and (iv) Dynamics (Table 1). A somewhat different thematic structure prevailed in the first two years of AISS when it was staffed by different faculty members. The focus on states that predominates in the first two themes gives way in the last two themes to a focus on the processes underlying transitions between states. These themes help us sustain a coherent rationale for juxtaposing apparently disparate topics from different disciplines as they help students appreciate transcendent ideas in science, a fundamental element of an interdisciplinary perspective.

It may be difficult to discern from Table 1 just what topics from disciplinary introductory courses are or are not included because subject matter that often receives its own block in a disciplinary course may be distributed throughout AISS. This seems to be true more often for topics in physics than for topics in either of the other two disciplines. Many particle mechanics topics, for example, are found throughout the course. Force and descriptive properties of kinematics are emphasized in the structure sequence. The consequence of force over time is an example of dynamics modeling. Properties of waves, e.g., physical and electromagnetic, form the basis for discussing the fundamentals of quantum mechanics. Students in AISS are required to relate traditional physics topics to the outcomes observed in bio-chemical experiments. In the end, they expect that bio-chemistry topics in upper division courses should be understood through fundamental physical laws, an expectation that we consider a major positive outcome of the course.

Themes and Topics	
Part I: Randomness	<p style="text-align: right;"><i>Entropy: statistical definition</i></p> <p style="text-align: right;"><i>Measurement: randomness & statistics</i></p> <p style="text-align: right;"><i>Mendel, genetics, and probability</i></p> <p style="text-align: right;"><i>The Boltzmann distribution</i></p>
Part II: Building structure: matter and interactions (fundamental forces)	<p style="text-align: right;"><i>Structure: water</i></p> <p style="text-align: right;"><i>Building structure: matter and interactions</i></p> <p style="text-align: right;"><i>Organization within matter: atomic structure</i></p> <p style="text-align: right;"><i>Idealized behavior and interactions between gas phase particles</i></p> <p style="text-align: right;"><i>Covalent bonds: the foundation of structural complexity</i></p> <p style="text-align: right;"><i>Properties reflect interactions</i></p> <p style="text-align: right;"><i>Forces: building blocks of bulk properties</i></p> <p style="text-align: right;"><i>Chemical bonds and the stability of structure</i></p> <p style="text-align: right;"><i>Irreversible chemical reactions</i></p> <p style="text-align: right;"><i>Chemical equilibria: connecting structural states</i></p> <p style="text-align: right;"><i>Biological molecules: lipids</i></p> <p style="text-align: right;"><i>Biological membranes</i></p> <p style="text-align: right;"><i>Fields: continuous distribution examples</i></p> <p style="text-align: right;"><i>Biological molecules: amino acids</i></p> <p style="text-align: right;"><i>Biological macromolecules: proteins</i></p> <p style="text-align: right;"><i>Biological molecules: nucleic acids</i></p> <p style="text-align: right;"><i>Origin of structure: protein synthesis</i></p> <p style="text-align: right;"><i>Cells</i></p> <p style="text-align: right;"><i>Power of a structural approach: molecular evidence for evolution</i></p> <p style="text-align: right;"><i>Acid-base equilibria</i></p>
Part III: Energy	<p style="text-align: right;"><i>Structure and energy states</i></p> <p style="text-align: right;"><i>Waves</i></p> <p style="text-align: right;"><i>Quantum mechanical approach to atomic and molecular structure</i></p> <p style="text-align: right;"><i>The energy principle</i></p> <p style="text-align: right;"><i>Energetics of chemical phenomena</i></p> <p style="text-align: right;"><i>Biological energy transformation</i></p>
Part IV: System Evolution: Dynamics	<p style="text-align: right;"><i>Basics of rate equations</i></p> <p style="text-align: right;"><i>Chemical kinetics: rates of reaction</i></p> <p style="text-align: right;"><i>Dynamics: Newton II</i></p> <p style="text-align: right;"><i>Multiple order evolution of single entity systems</i></p> <p style="text-align: right;"><i>Non-constant rate problems</i></p> <p style="text-align: right;"><i>Systems that evolve toward equilibrium</i></p> <p style="text-align: right;"><i>Combining dynamical systems</i></p> <p style="text-align: right;"><i>Electrical systems: electro-chemistry and circuits</i></p> <p style="text-align: right;"><i>Control of molecular and cellular systems</i></p> <p style="text-align: right;"><i>Natural selection</i></p> <p style="text-align: right;"><i>Ecosystems and boundaries to regulation</i></p>

Table 1: Sequence of themes and topics as taught in AISS during the 2010-2011 academic year. Details of subjects taught under each topic are omitted for the sake of brevity.

As in the lecture/discussion part of the course, the laboratory for AISS includes some exercises adopted virtually unmodified from each discipline (e.g., titration from acid-base chemistry), as well as more than a dozen new integrated labs developed specifically for AISS. Some of the laboratory exercises feature open-ended experimental explorations, while others are more highly structured to focus on fundamental skills and techniques for measurement, analysis, and data presentation.

We further promote integration of the disciplines by having all three faculty members attend all class sessions and labs, although in a typical session only one faculty member leads the class. This makes AISS somewhat more expensive to teach than our other disciplinary introductory courses, but we believe the added cost carries distinct benefits. Students regularly cite the unexpected insights that arise from the “real time” interaction among the three faculty members and among faculty members and students as a particularly valuable element of the course. In order to secure this benefit, the department's three sponsor colleges have agreed to hire temporary faculty to make up any shortfall in an individual discipline caused by a faculty member teaching in AISS. (Any shortfall that has occurred is a fraction of an FTE and has been combined with other needs in hiring full-time visitors.)

In addition to selecting and sequencing course topics, we thought about how students would become engaged with these topics and how we could best put an integrative perspective into practice. We decided to teach AISS in larger blocks of time than are typically used in our other courses, thinking that the extra time would encourage us to range widely within a single class session and permit a variety of class activities. AISS meets five days, for a total of 12 hours, each week: three two-hour blocks and two three-hour blocks. Activities include lectures, discussions, student presentations, problem-solving sessions, computer modeling exercises, and laboratory exercises. A typical two-hour session starts with a brief lecture followed by some combination of group work on problems, a modeling exercise, discussion of research papers, or a brief hands-on exploration. More extended laboratory exercises are done during the three hour sessions.

Group work predominates in AISS. Not only do we want students to become familiar with the collaborative nature of science, but students bring different strengths to the class, and we want them to respect and utilize the strengths of others even as they learn from them to improve their own abilities. In computer modeling, for example, one student may be adept at conceptualizing a model while a group partner may be more skilled at developing equations to express the model, and a third at converting the equations into computer code. As they work together on a problem, each begins to expand her or his skill set. Similarly, when doing interdisciplinary exercises students who have a stronger background in physics than biology, for example, will help and be helped by students whose strength lies in biology.

Finally, we needed a classroom that would facilitate the way in which we wanted to teach AISS. Fortunately, our science center had a large room with moveable tables,

each of which can accommodate four students, and basic laboratory infrastructure. This space allows us to make quick transitions from one type of activity to another and thus integrate pedagogies as well as course material. Only when the laboratory work requires a fume hood or specialized instrumentation does the class need to move into another lab.

Enrollment in AISS is restricted to first year students. We reasoned that our students would gain the greatest benefit from AISS if they took it at the beginning of their college careers. We also hoped that a common experience in AISS would promote a bond among students that would increase retention in science majors. Students must apply to enroll in AISS. We seek students who have strong high school backgrounds in biology, chemistry, physics, and math and who have indicated a strong motivation for taking an integrated course. Because of limitations in space and staffing, we have limited enrollments to 28-30 students per year.

RESULTS

Two Examples

Under the theme of Structure, the voltage-gated potassium channel serves as an interesting and important illustration of the relationship between structure and function at the molecular level in biology. By the time that this topic enters the course (under “Biological macromolecules: proteins,” see Table 1), the students have been steeped in the physics of forces, including forces in charge-charge interactions and how those forces vary with the nature of the charge, e.g., dipoles vs ions, and the distance between charges. They have also learned a great deal about the electrostatic interactions of atoms in a molecule, with water as a major example, the enthalpy of hydration, and the chemistry of amino acids. In concert with their growing knowledge of forces, they come to appreciate why the carbonyl oxygens lining part of the potassium channel pore carry partial negative charges and why there are differences in hydration of potassium and sodium ions. In addition to listening to lectures and discussing original research articles on this topic, the students develop their understanding by accessing online databases of protein structure to visualize the potassium channel and other proteins in various ways. Then, rather than lecture the students on the selectivity and through-put of ions through a potassium channel, we simply ask them to work in groups and develop plausible explanations for why the potassium channel allows potassium ions to pass so much more freely than sodium ions, as well as for the forces involved in moving the potassium ions through the channel. The students “light up” as they “discover” the knock-on explanation for potassium ion conduction through the channel. Not only is the biologist able to engage the students with this topic at a deeper level than is typical of a disciplinary introductory biology course, but the students are thrilled as the insights offered by an interdisciplinary perspective dawn on them. The connections enrich their understanding of an important phenomenon and help them feel empowered to develop compelling hypotheses.

Similarly, physics, chemistry, and biology come together later in the course (under “Electrical systems: electro-chemistry and circuits,” see Table I) in a laboratory exploration of biological membrane potentials. Students explore aspects of the electrical properties of membranes (time and space constants) by working with breadboard equivalents of the circuit model of a neuronal membrane (Wytenbach et al., 1999). They also learn about electrochemistry and the Nernst equation in lecture and lab. Having been prepared by this work, the students then work in groups to make intracellular recordings from crayfish muscle cells and determine the effects of altering the extracellular potassium concentration on the resting membrane potential (Wytenbach et al., 1999). By integrating lab exercises in this way, the students come to appreciate other aspects of neuronal function, such as the conduction of the action potential along an axon, in greater detail than is typical of an introductory biology course.

These two related examples illustrate different, but not mutually exclusive, strategies for integration. In the case of the potassium channel, principles from separate disciplines are presented in series to build a foundation for exploring a particular phenomenon. The laboratory example, however, features a more parallel integration in which principles from several fields converge in the exploration of a phenomenon. Alternatively, the suite of “membrane potential” laboratory exercises can be viewed as a juxtaposition of topics in different disciplines to illustrate common underlying principles. AISS combines both of these strategies, the serial and the parallel, with an important third strategy consisting of using common tools to cope with apparently disparate problems across disciplines. For example, throughout the course sequence students learn computer modeling, using differential equations in MatLab or Maple, to model a wide variety of physical, chemical and biological phenomena. Examples related to the teaching of chemistry in AISS have been published elsewhere (Purvis-Roberts et al., 2009).

Assessment

Outside experts contracted to conduct formative and summative assessments of AISS during its first five years (Ulsh and Drew, 2011; Ulsh, 2011). Some of their findings are reported below. A more complete account of the results of that effort will appear separately.

To date, approximately 140 students have completed AISS. Retention of students across the two semesters of AISS is higher than in our disciplinary introductory courses, each of which is also a two-semester sequence (approx. 90% vs approx 75%, respectively). This result, encouraging as it is, may reflect more the process by which we select students for AISS than the course itself. Students who have completed both semesters of AISS, however, go on to take more upper-division science courses than students with similar backgrounds in high school science and math but who have taken our other introductory science sequences. Furthermore, AISS students earn grades at least as high, if not higher, in these advanced courses than students in a control group who did not take AISS. This helps assure us that the sacrifice of some

disciplinary course content to achieve integration does not leave AISS students ill prepared for advanced work in the various disciplines. We are also encouraged that a large number of AISS students have gone on to succeed in interdisciplinary research under summer research fellowships at our own institution and others.

Students report in interviews that their experiences in AISS have increased their level of interest in science and their confidence in pursuing science majors and careers. Anecdotal evidence indicates that AISS students tend to stand out in upper-division science courses for being openly inquisitive, perhaps a sign of confidence, and also for pushing to extend discussions beyond typical disciplinary boundaries. As we had hoped when we launched AISS, students who experience this rigorous two-semester gauntlet form a lasting bond that adds to their sense of belonging in the department and improves their retention in science majors.

Faculty members who have taught in AISS also report benefits. Because we chose not to organize the course around specific topics or case studies, we were forced to rely entirely on the fundamental principles shared among biology, chemistry, and physics to make our story coherent. As AISS faculty members developed a richer understanding of the diverse implications and applications of concepts such as entropy, thermodynamics, kinetics, waves, and others, they began to change the way they teach upper-division courses in their own fields. They knew in detail what students were learning in the other disciplines’ introductory courses and how to link those ideas with their own field. This is one important way in which the impact of AISS ripples through other parts of our curriculum. Another way is that some of the labs developed for AISS are now being adopted by the other introductory science courses.

AISS has also benefited our science program overall. During the time in which AISS has been offered, the number of prospective science students who have applied for admission to Claremont McKenna, Pitzer, and Scripps Colleges has more than doubled, as has the percentage of the total number of applicants that consists of prospective science majors. The number and percentage of science matriculates has followed suit. The number of graduates with STEM majors has also increased substantially during this period. Given that there has been only one cohort of AISS students that has graduated to date, the cause of the rather steady rise in science graduates remains unexplained. Perhaps the use we have made of AISS in recruiting science students to these colleges has served indirectly to increase retention and graduation of students in science majors. Alternatively, factors other than AISS may be driving the observed changes in admissions and graduation.

DISCUSSION

Developing an interdisciplinary introductory course for science majors has not been easy. There is no integrated textbook for science majors. There are few models of integrated courses for our target audience. We were inspired by the Science One program at the University of

British Columbia (UBC) in which faculty from multiple scientific disciplines co-teach an integrated introductory majors class (Benbasat and Gass, 2002). But the other course that most closely resembles AISS, the one at Louisiana Tech University (LTU), targets future science teachers, rather than a broad spectrum of science majors (Ramsey et al., 1997). Standardized exams, such as the ACS exams and the MCAT, as well as our own upper-division courses and graduate school admissions requirements, are all designed with disciplinary introductory courses in mind, a fact that continues to constrain our thinking about how far to carry the integrative aspects of the course without disadvantaging our students. We repeatedly encounter translation problems in coping with the different languages of the three disciplines: Different terms are used for the same concept, or the same symbols are used to indicate different quantities. Differences in philosophy and pedagogy among faculty members and across disciplines should not be underestimated. Extensive conversations about all aspects of the course, including sequencing of topics, content and style of presentations, examinations (style, number, timing), and lab exercises, have been essential and enlightening. We eventually realized that, rather than force resolution of all differences, we should embrace those differences that remain after our conversations as indicative either of prevailing differences among the disciplines or reasonable differences among faculty members. It is helpful for students to experience both sorts of differences, as long as the rationale for apparent “discontinuities” in the course is made clear.

Finally, even in our multi-disciplinary department, the assignment of faculty members from multiple disciplines to teach in the same course and be present at all class sessions imposes significant administrative problems.

It is in coping with these difficulties, however, that the greatest rewards lie. Although it is labor intensive to have multiple faculty members in the course at all times, for example, the effort produces one of the most important benefits. As reported by faculty members at UBC (Benbasat and Gass, 2002) and LTU (Ramsey et al., 1997) who co-teach integrated courses, the epiphanies that emerge in class from spontaneous interactions among people with different backgrounds and interests provide a high point for faculty members and students alike. The application of physical principles to the behavior of potassium channels, as described above, reliably elicits “aha!” reactions from students. Students are also surprised to learn how many phenomena, such as diffusion and osmosis, can be understood by flipping a coin. Also, the realization of just how much chemistry can be understood in terms of electromagnetic radiation and quantum mechanics commonly triggers an excited “now I understand!”

The ripple effects of AISS through the rest of our science curriculum have already been mentioned, especially in terms of the growth and development of faculty members. In general, AISS seems to have stimulated a productive culture of learning in our department, one characterized by a confident inquiring

attitude and an expectation of working to see the larger picture.

We intend to expand the impact of AISS in our curriculum, but we do not intend that AISS will replace our disciplinary introductory course sequences. We imagine parallel tracks, each of which will appeal to a different segment of our student population. We face difficulties in greatly increasing enrollments in AISS, but additional support that we recently received for developing and teaching AISS labs may allow us to add sections to AISS and thereby increase its impact. An alternative will be for us to use AISS as a model for designing integrated courses that draw on only two disciplines, such as biology and chemistry, as done at some other institutions (e.g., Vogel Taylor, et al., 2009). Our goal is to make an integrated perspective available to more of our first-year students as they begin their studies in the sciences. Our experiences with AISS have convinced us that this is an exciting way to begin the training of versatile scientists in neuroscience and other interdisciplinary fields, and produce a more scientifically informed public.

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Address correspondence to: Dr. Newton Copp, W. M. Keck Science Department, 925 N. Mills Ave, Claremont, CA 91711. Email: ncopp@kecksci.claremont.edu