# Interdisciplinary Science Courses in a Global Context

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**ABSTRACT:** A review of interdisciplinary science curricula at a cross-section of international tertiary institutions is presented, using document analysis and interviews to determine the goals and outcomes of such courses as they shape student learning. The role of interdisciplinary or integrated science in the institution is also reviewed, as well as the dynamics of teaching in a multi-instructor interdisciplinary environment. A variety of methods for quality control of pedagogy, development of assessments, and calibrating grading practices are found, as well as techniques for training faculty and creating well-functioning teaching teams in interdisciplinary courses. As interdisciplinary science courses become more common, the practices within the diverse cohort of integrated sciences courses can help inform practice to adopt the most effective methods for deploying instructors, and assessing learning in interdisciplinary contexts.

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## Motivation for Interdisciplinary Science Courses

In recent years, the most pressing and urgent issues of science and technology are inseparably complex problems that draw from multiple disciplines. Development of new sources of energy, studying the effects of global warming and sea level rise, and the effects of human population increase on rapidly evolving microbial communities and decreasing biodiversity in the natural environment are all interdisciplinary problems that demand solutions. Training students to effectively contribute to solutions in these areas, either as scientific professionals, or as informed policymakers and citizens, requires a retooling of our science education beyond the single subject elective course or disciplinary curriculum.

The urgency of interdisciplinary science education for training the next generation of STEM practitioners has been recognized by a number of societies and academies. The American Cancer Society report entitled *The Role of the Private Sector in Training the Next Generation of Biomedical Scientists* states:

> "In the postgenomic era of research, multidisciplinary and interdisciplinary research will command center stage, requiring team approaches and the collaboration of many individuals from vastly different fields, ranging from computational mathematics to clinical science."
> (American Cancer Society 2000)

The National Research Council also noted that the changing needs for biomedical and behavioral scientists required new approaches in STEM education and recommended that the "NIH should expand its emphasis on multidisciplinary training in the biomedical sciences (National Research Council 2000). The Bio2010 report, *Transforming Undergraduate Education for Future Biologists*, suggests that new approaches for higher education should consider "building a strong foundation in mathematics, physical and information sciences to prepare students for research that is increasingly interdisciplinary in character." (National Research Council 2003). A 2004 AAMC report on Medical Education in the United States highlighted the importance of interdisciplinary education for future medical practitioners, and noted these professionals need to be ensured to have the "knowledge, skills, attitudes, and values needed for medical practice as members of an interdisciplinary health care team, and the ability to perform the complex, integrative tasks required to provide high-quality health care to patients who seek their help." (AAMC 2004). The AAMC-HHMI report *Scientific Foundations for Future Physicians* strongly endorsed a movement toward more interdisciplinary STEM education, stating that "it is the committee's belief that at both levels – medical school and undergraduate schools – interdisciplinary approaches are an important component of the needed new directions in science education." (AAMC 2009). The AAAS report *Vision and Change in Undergraduate Astronomy Education* noted how interdisciplinary fields have produced many of the most exciting discoveries in biological sciences. The report states:

> "Emerging interdisciplinary fields such as genomics, proteomics, metagenomics, synthetic biology, biochemistry, bioinformatics, computational biology, and systems biology are leading to new discoveries, and some are changing the ways we think about and engage in biological research and explore established biological fields (such as evolutionary biology). These new integrated fields, spread across the diversity of life sciences, are opening up a vast array of practical applications, ranging from new medical approaches, to alternative sources of energy, to new theoretical bases in the behavioral and social sciences."
> (AAAS 2011)

The Global Research Council, in its report on Interdisciplinary Research advises that governments and universities encourage interdisciplinary research "by setting and articulating 'grand challenges' that require interdisciplinary solutions" The report highlights that the National Science Foundation has supported "bold interdisciplinary projects in all NSF-supported areas of science and engineering research" but also notes that "A cultural shift in the mind-set is required to promote interdisciplinarity both within the research ecosystem and within academia" (Global Research Council 2016).

## Interdisciplinary Curriculum – Definitions and Terminology

The dominant method of STEM instruction within higher education is rooted in disciplines, resulting in well-known "silos" where instruction adopts the methodologies and terminologies of each of the disciplines and generally focuses on applications of the science in isolation of other STEM disciplines. This approach results in divergent and linear curricular paths, where each of the STEM subjects run in parallel, with little overlap or cross-connections. A slight improvement on this situation is what might be called a "multi-disciplinary" approach, in which each of the STEM disciplines are taught, but instructors build into the curriculum intentional cross connections between disciplines, allowing for the usual parallel and silo-ed instructional paths to intersect on a key case study or application. Interdisciplinary education, as opposed to multi-disciplinary education, includes instructional paths that are interwoven around common topics or themes that can be studied with multiple disciplines, building deep understanding of the connections within and across disciplines (Bloom 2004).

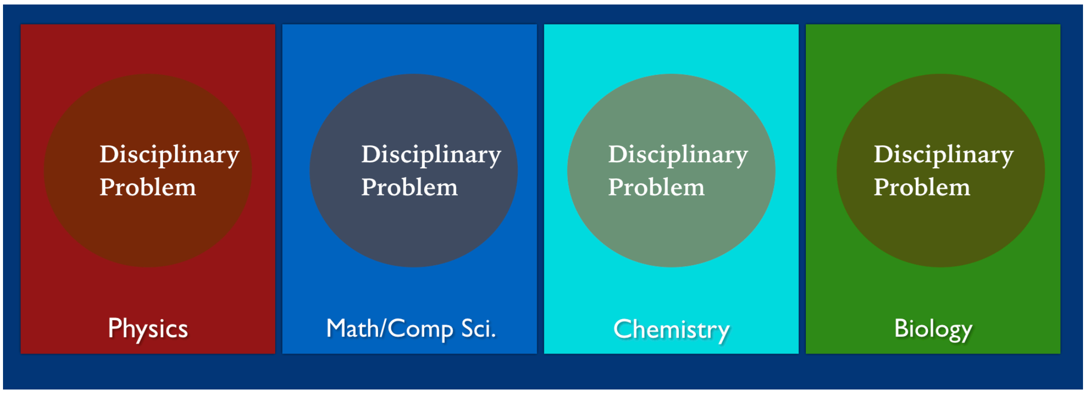


**Figure 1:** Schematic of a Multi-disciplinary curriculum (top) in which a series of disciplines are sequentially engaged to solve disciplinary problems and to give students exposure to multiple disciplines.

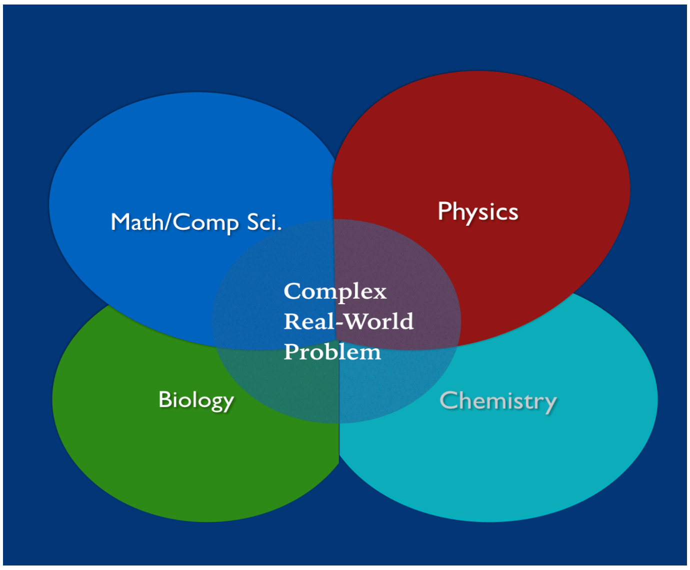


**Figure 2:** Schematic of an Interdisciplinary curriculum, which enables multiple disciplines to converge on a complex problem simultaneously using multiple modes of inquiry to solve the problem.

Within an interdisciplinary curriculum, there are also distinctions to be made between interdisciplinary, and integrated curriculum. An interdisciplinary approach will develop the processes, skills, and concepts from two or more disciplines at the same time, using common themes or modes of inquiry to form interdisciplinary connections. An integrated or integrative approach would bring those same interdisciplinary elements together within a curriculum, but include a strong emphasis on inquiry-oriented pedagogy, and raise the theme or topic considered as the primary element within the curriculum, to which the disciplines are secondary, and in which the exact role of each discipline is "lost" to the search for answers to larger questions that are intrinsically non-discipline specific (Mathison and Freeman 1998).

The interdisciplinary approach may be likened "to a seamless woven garment that stands in contrast to the patchwork quilt of multidisciplinary work." In such an environment, "a concatenation of disciplinary perspectives is replaced by integration of those perspectives (Lattuca 2001)."  Some have also made the distinction between *instrumental interdisciplinarity*, in which the interdisciplinary techniques are pragamatic problem-solving approaches, or *conceptual interdisciplinarity*, which emphasizes the synthesis of knowledge, which becomes an "epistemological enterprise involving internal coherence, the development of new conceptual categories, methodological unification and long-term research and exploration (Salter, 1996; cited in Lattuca 2001)."

A coordinated interdisciplinary science program can provide for deeper mastery and engagement for students and can bring within the students a valuable awareness of how previously disconnected facets of information can apply to complex problems through integrative learning. The development of this type of integrative learning within a curriculum has been recommended by the American Association of Colleges and Universities (AAC&U), who describe this form of learning as "an understanding and disposition that a student builds across the curriculum and co-curriculum, from making simple connections among ideas and experiences to synthesizing and transferring learning to new, complex situations within and beyond campus." (AAC&U 2010). The same organization has provided rubrics to help guide development of both courses and multi-course programs with suggestions of how to foster the integrative learning through aligned learning objectives within multiple courses.

## Curricular Integration within Interdisciplinary Science Programs

Without careful management, an extended STEM curriculum across a multi-year program with multiple instructors and disciplines has been likened to a "jigsaw puzzle," which for students "the curriculum is a pile of jigsaw puzzle pieces without a picture." (Beane, 1995). Curriculum integration has been accomplished in a variety of ways which allows for the educational experience to provide more coherence and which can enable linkages between disciplines and thereby allow for higher order learning. Examples of successful integration within professional degree programs in pharmacy (Pearson and Hubball, 2012) and in medical education (Harden, 2000) provide useful principles that can guide planning for multi-year interdisciplinary STEM curriculum. The sub-field of Scholarship of Curriculum Practice (Hubball and Gold, 2007) studies the diverse contexts in which undergraduate programs are developed and provides for application of findings within the domains of teaching and learning, course design, faculty development and institutional strategy for developing an integrated curriculum. Just as in the case of an interdisciplinary course, an awareness of the distinctions between multidisciplinary, interdisciplinary and transdisciplinary curriculum is needed to provide for effective discussions about blending disciplinary methodologies, case studies and pedagogical approaches. The integration of the curriculum also can be considered within the axes of horizontal integration (across disciplinary lines) and vertical integration (where various sciences are applied and more advanced topics and cases are introduced to transfer skills) (Pearson and Hubball, 2012).

Several authors have developed suggested models and frameworks for integration that considers the learning context, and the interrelations between planning, assessment and programming (Hubball and Burt, 2015). Taxonomies of curriculum integration have been developed to describe how a curriculum progresses in phases from "fragmented" to "threaded," "integrated," "immersed," and "networked" integration (Fogarty, 1991). The "integration ladder" can be used to visualizes stages of integration from isolated disciplinary perspectives toward transdisciplinary approaches (Harden, 2000). Progress toward integration requires instructors to be aware of what is discussed in other courses; harmonization, where teachers responsible for different courses collaborate and discuss frequently to enable multiple connections to arise. The integration can then proceed from a "sequenced" set of courses toward "nesting", in which instructors draws from skills developed in other courses in their subject, or toward "temporal coordination," in which separate disciplinary topics are taught in parallel and students can uncover the relationships between the topics. Figure 1 shows a schematic of these initial curriculum integration levels, based on the taxonomies described in Harden (2000) and Fogarty (1991).

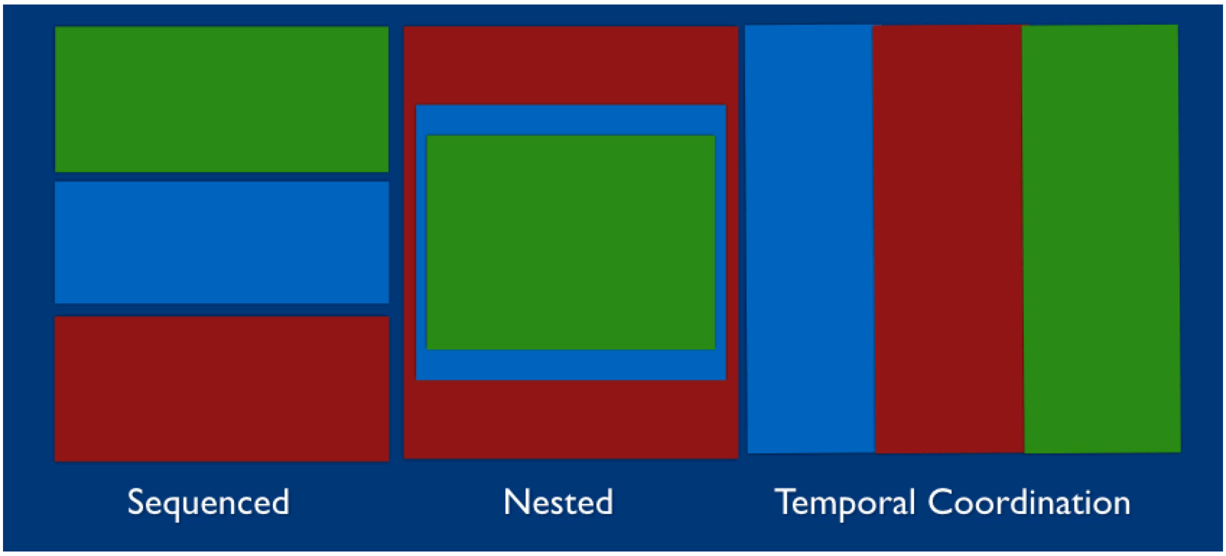


**Figure 3:** Schematic of Curriculum Integration taxonomies where multiple disciplines within a program are arranged in a sequence (left), in a "nested" configuration with multiple disciplines integrated within a course or program (center) or taught in parallel with "temporal coordination" (figure based on Harden (2000) and Fogarty (1991)).

More intensive curriculum integration models include correlation, where disciplinary topics are discussed but time is set aside weekly or at the end of a semester for an integrative case study; complementary programs, where a theme connects multiple disciplinary courses and disciplinary experts to merge in solving an interdisciplinary problem. Integrated courses can provide approaches that range from multi-disciplinary program to interdisciplinary or even transdisciplinary, depending on the degree of emphasis on the connections between disciplines and their applications toward real-world examples that defy disciplinary classification (Harden, 2000). Figure 2 provides a schematic of these more intensive forms of curriculum integration.

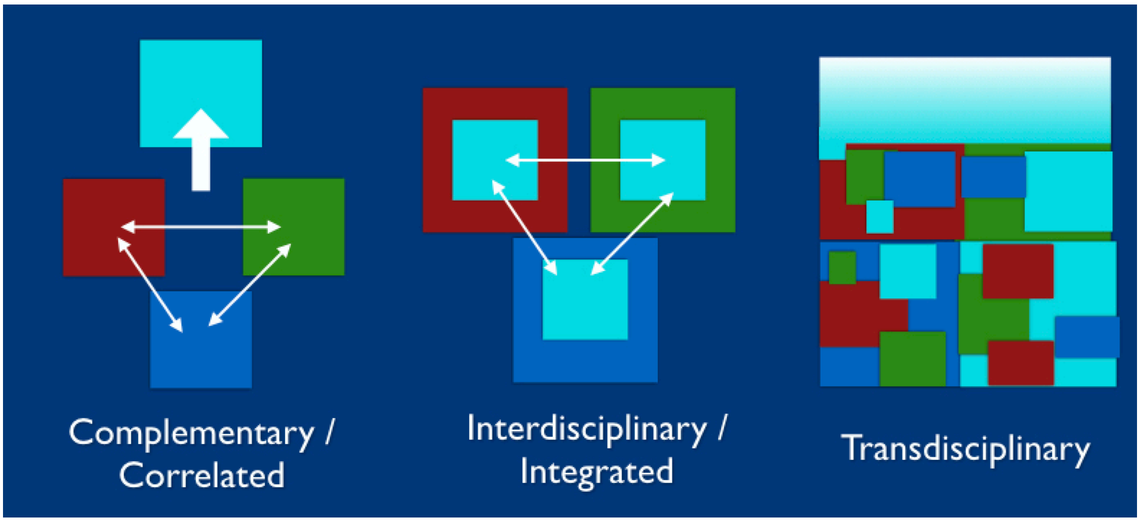


**Figure 4:** Schematic of Curriculum Integration involving more frequent or intensive integration of disciplines including complementary or correlated integration (left) where interconnected disciplines are brought to bear on a case study, interdisciplinary integration whereby interconnections are reinforced throughout a course or program (center), or transdisciplinary integration (right), where the boundaries between disciplines are removed (figure based on models from Harden (2000) and Fogarty (1991)).

An integrated curriculum can benefit from curriculum mapping (Oliver et al, 2007), which visualizes includes needs analysis, existing courses, suggested modifications, and the status of renewed courses and approved changes, along with the alignment of learning outcomes from multiple courses. Medical education literature emphasizes training for staff and faculty to enable consideration of the scope and level of integration, and to foster awareness of the need for both horizontal and vertical integration (Malik and Malik, 2011). Particular techniques could include the use of working groups or faculty learning communities to divide work and ensure involvement from a wide range of stakeholders to develop learning outcomes and skills, to provide meaningful links between disciplines, and to set a timetable to assure completion (Hubball and Burt, 2015). Several authors stress the need for strategies and timetables for assessment, communication, and re-evaluation and revision, as well as for providing sufficient resources (including incentives for faculty) and a method for documenting improvements (Pearson and Huball, 2012; Richlin and Essington, 2004). Networked Improvement Communities can guide and visualize the curriculum development and integration, using an "improvement map" to limit the tendency to offer multiple and competing interventions, and offer an "end to end description of the challenge space" with "driver diagrams" linking the targeted improvements with causes for underperformance, and with specific assessable solutions (Bryk, Gomez and Grunow, 2010).

## Overview of Global Interdisciplinary Science Curricula

Over the past decade, several institutions have responded to the need for interdisciplinary training with new curricula designed to foster interdisciplinary science practitioners. The Claremont Colleges W.M. Keck Science Department offered its Accelerated Integrated Science Sequence (AISS) from 2007 to 2017, funded initially by an NSF STEP grant to prepare students interested in medicine or science more efficiently in their introductory courses. The AISS course combines three one-year courses in physics, chemistry and biology into a single double-credit course. The three instructors within the course provide a form of Just-in-Time Teaching (Simkins and Maier, 2009), by sharing duties within the classroom and trading off each other's expertise in answering questions and describing interconnections between the disciplines of physics, chemistry and biology. Further details of the AISS program can be found in Purvis-Roberts, et al (2009), and Copp, et al (2012). Princeton University has developed the venerable Integrated Science program, where a small and select group of 20-30 students experience a three-year integrated sequence that includes over 20 instructors who teach high-level physics, math, computer science, molecular biology, and genomics. The Princeton program is designed as an elite cadre of future researchers, and has one of the most intense programs available. In recent years however, the scope of the Princeton program has been reduced, and now has been recast as an intense first year experience that fulfils the first-year requirements for chemistry, physics, computer science, and molecular biology (Princeton University 2017).

Other programs have been devised to create either a single year or multiyear interdisciplinary science curriculum for more general audiences of students, which may include future engineers or non-science majors. These programs include the Virginia Tech Integrated Science Curriculum, which includes a two-year double-effort course sequence to give fundamentals of biology, chemistry, physics and math. The course is a gateway to Science majors, and is intended to provide an accelerated and enhanced "active-learning environment stressing multidisciplinary modes of thought" that can enhance science education but also make connections between science, law, engineering and art (Virginia Tech 2017). Northwestern University has an Integrated Science Program, which offers accelerated and smaller disciplinary courses and a dedicated Integrated Science Program house where students can interact with each other and with program staff (Northwestern 2017). James Madison University offers an ABET accredited Integrated Science and Technology (ISAT) program in which science, mathematics, technology, and management and manufacturing engineering prepare students for careers that blend science, technology and business. The ISAT program includes courses that provide the social context of technology and sciences, as well as a four-course Holistic Problem-Solving Spine that allows students to apply system thinking to complex problems. (James Madison University 2017). At the University of Massachusetts, Amherst, a program known as iCons (Integrated Concentration in Science) provides a selective integrative undergraduate science program within the university that focuses on two theme areas – Renewable Energy and Biomedicine/Biosystems. The program extends over the full four years of the undergraduate program and supplements the existing STEM majors with "opportunities to engage with real world issues as part of interdisciplinary teams. (UMassAmherst 2017)."

Throughout Asia and the Middle East several entirely new universities are being created, while in Hong Kong the undergraduate degree programs were recently expanded from three to four-year durations. These changes have created many new innovative interdisciplinary science courses and course sequences. Within the Core Curriculum at NYU Shanghai is the Foundations of Scientific Inquiry program, which includes a three-year sequence of disciplinary courses that starts with Quantitative reasoning, and progresses through Core science courses in Physical Science and Life Sciences that are designed to provide broad perspective on current topics and concepts in both subjects. The Physical Science courses discuss broad topics such matter and energy, climate, particle physics and dark energy, while Natural Science courses explore the intersection of neuroscience, information science, and genetics in the life sciences (NYU Shanghai 2017). Chinese University of Hong Kong has designed a single semester course entitled "In Dialog with Nature" that explores the methods of inquiry in science and mathematics from Euclid and ancient Chinese science to readings from Charles Darwin, Rachel Carson, and James Watson (Chinese University of Hong Kong 2017). University of Hong Kong offers a Fundamentals of Modern Science course, which is designed to give an "an overview of the giant web of knowledge that makes up science." The course integrates physics, astronomy, earth sciences, chemistry and biology in two semesters, with ambitious units that outline the "universal principles and unifying concepts of science", and apply them to the fundamental structure of matter, atoms, DNA, cells, organisms, earth, solar system and cosmology (University of Hong Kong 2017).

Yale-NUS College in Singapore was founded by Yale University and the National University of Singapore with a core curriculum that was designed to answer the question "what must a young person learn in order to lead a responsible life in this century?" (Yale-NUS College 2013). The answer is an ambitious core curriculum that includes courses in Quantitative Reasoning, Scientific Inquiry, and additional interdisciplinary science courses taken by all of its students. In its initial years, the Yale-NUS College STEM curriculum featured an intensive interdisciplinary science course known as Integrated Science taken by science majors, and a year-long interdisciplinary science sequence entitled Foundations of Science. Both courses were taught by teams of faculty and all Yale-NUS students would take at least four full semesters of STEM courses, which were geared toward interdisciplinary problems related to the theme of "water" in Integrated Science and "Grand Challenges" of civilization in Foundations of Science.

Other interesting programs within Canada and Britain include the Honours Integrated Science program at McMaster University, an interdisciplinary, research-based science program targeted toward future researchers. The program includes levels that progress in each year toward more complex research questions, starting with supervised inquiry-based learning, based on projects, followed by thematic modules emphasizing overlapping content between disciplines. The final stage is a fourth year Honours Thesis project (McMaster University 2017). The University of Leicester offers the Centre for Interdisciplinary Science, which includes innovative courses that incorporate research and culminate in a Natural Sciences degree (University of Leichester 2017). The University of British Columbia offers a program known as Science One, which is an integrated first-year science experience taught by 8 instructors, that offers 75 students integrated courses in biology, math, physics and chemistry, including a Marine Biology research experience at their own Bamfield Marine Sciences Centre (The University of British Columbia 2017).

From this wealth of sources comes a strong base of experience in best practices within the integrated science and interdisciplinary science context. This leads to an appreciative inquiry (AI) methodology (Shuayb, et al, 2009), in which telephone interviews and examination of course syllabi and web sites provide a basis for evaluating curriculum design and learning objectives. The AI interviews are the key element that can help "identify, anticipate and heighten positive potential" through an "appreciative cycle" that asks questions that help share best moments within a group to help "maximize participation, energize the participants, and thus accelerate positive change." (Shuayb, et al, 2009). As such, these complexities are best studied using a methodology based on a social constructivist approach (Chick, 2014). By reaching out to this group of science educators, it also is a possibility that the common interest among the group in developing this form of science education could be the basis of a community of practice (COP) in integrated science curriculum development and educational leadership. Such communities of practice are essential for scholarly communication about pedagogy between and within institutions (Roxa et al 2008) and are typified by groups of people who "share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis" (Wenger, 2002). One potential byproduct of the interviewing could be the creation of a network of interdisciplinary science curriculum leaders – which could continue with ongoing conversations about our common concern and passion for integrated and interdisciplinary science teaching. It is also hoped that particular lessons learned within the COP for interdisciplinary science can be codified and disseminated to help others implementing this type of curriculum to learn from the experiences of these institutions and help increase the quality and number of integrated science courses globally.

## Methodology

A set of thirteen interviews were conducted with leaders of twelve interdisciplinary science curriculum efforts in five countries to determine how they have responded to the common challenges in organizing scientists with various disciplinary skills and vocabularies into a unified teaching team. Within the team-taught environment, it is desirable for instructors to create common types of assessments for students based in research-informed pedagogy that emphasizes assessable learning outcomes (Biggs and Tang, 2011; Handelsman, et al, 2007). Our interviews were designed to survey what techniques were used for this kind of course and faculty development, as well as how each team fosters active learning strategies, and assesses student learning. Inherent challenges exist in "making teaching visible" which can be addressed through portfolio development and peer observations of teaching (Bernstein, 2002; Bernstein and Bass, 2005). The interviews were intended to discern how the teams of instructors within each institution agree upon curricular goals and teaching strategies, and then once these "espoused" curricular goals are set, how teams are able to "enact" the curriculum in a consistent way, and how they are able to assess the student's "experience" of the course, and use these observations of student learning and teaching quality to improve the course.

The ways in which student experiences are assessed, and methods for assessment of teaching will all vary in the different institutional contexts, and the study was interested in learning how the mix of student feedback, curriculum review, and peer observations of teaching were used in the assessment of teaching and learning. The most effective assessments include a mix of all of these elements (Trigwell, 2013; Trigwell, 2001), and our study was hoping to determine how this mix ranged across institutional and international contexts. An additional research goal within the interview is to help ascertain how an interdisciplinary team is able to work together and obtain consistency in teaching quality and assignments within various international institutions. After studying the literature on integrated science programs, a list of leading programs was compiled, and curriculum leaders in each institution were identified. The list of curriculum leaders was contacted by email and a subset of the group agreed to phone and Skype interviews during 2015-2016. Within the request for the interview was an assurance of a compact interview of 20-30 minutes to assure the interviewees that the interview would make a minimal imposition on their time, with a standardized set of interview questions to enable comparisons between the programs and institutions. The list of interview questions was included with the email and these questions appear below. For completeness, the interdisciplinary Foundations of Science course at Yale-NUS College was also included in the study, and answers to the same interview questions are provided by the author to compare with the other programs.


**Figure 5:** Global Distribution of Interdisciplinary Science programs considered in this study.

**Table 1:** Interdisciplinary Science Professors Contacted for this Study

| Interviewee/Reporter | Institution | Country | Interdisciplinary Course/Program |
|---|---|---|---|
| Joshua Shaevitz | Princeton University | USA | Integrated Science |
| Scot Gould | Keck Science Department | USA | AISS |
| Katie Purvis Roberts | Keck Science Department | USA | AISS |
| Eric Maslen | James Madison University | USA | Integrated Science and Technology |
| Scott Auerbach | University of Massachusetts | USA | iCONS |
| Darryl Yong | Harvey Mudd College | USA | Probing the Inverted Classroom |
| Michel Pleimling | Virginia Tech | USA | Integrated Science |
| Christopher Addison | University of British Columbia | Canada | Science One |
| David Scicchitano | NYU Abu Dhabi | UAE | Foundations of Science |
| Jan Gruber | Yale-NUS College | Singapore | Integrated Science |
| Shaffique Adam | Yale-NUS College | Singapore | Integrated Science |
| Adrian Lee | NUS | Singapore | Special Programme in Science |
| Bryan Penprase | Yale-NUS College | Singapore | Foundations of Science |
| JCS Pun | University of Hong Kong | Hong Kong | Fundamentals of Modern Science |
| Carolyn Eyles, Chad Harvey | McMaster University | Canada | iSci |

## Structured Interview Questions

To provide efficiency and consistency of the interview, each of the interviewees was given the list of questions below in advance which are summarized below in Table 2, according to categories relating to the interdisciplinary courses. Their responses were tabulated and are summarized in the next sections.

**Table 2**– Questions posed to course leaders within structured interviews.

| Course Feature | Questions |
|---|---|
| Faculty Preparation | How do you prepare faculty to teach in a multi-instructor and multi-disciplinary environment? |
| Faculty Collaboration | How do you share information on what each instructor is doing in their section both for graded assessments and content?<br><br>What techniques work best for professors to share pedagogical approaches used in each course? |
| Faculty Grading Consistency | How can you evaluate the consistency of grading within each section? |
| Assessment of T&L | How do you assess the quality of teaching within each course?<br>How do you assess the quality of learning for students within each course? |

## Overview and Results from Interviews

### Keck Science Department, Claremont Colleges – AISS

The Claremont Colleges W.M. Keck Science Department offers an Accelerated Integrated Science Sequence (AISS) to prepare pre-medical and science majors for physics, biology and chemistry in an integrated year-long double course sequence. Funded by an NSF STEP grant, and now the Keck Foundation, the AISS program is now offered to students from Claremont McKenna, Pitzer, and Scripps Colleges. The course is team-taught by three professors, representing the disciplines of physics, chemistry and biology, who offer an intense immersion into all the three sciences to their small class of 25-32 students. The course has two-hour meetings 5 days a week, and a separate 4-hour lab - giving a total of 12-14 hours per week of class time. A typical class is taught "studio mode" - with in-class lab exercises mixed seamlessly with lecture and discussion.

The AISS course includes topics such as waves (which leads to discussion of the ear, electromagnetic radiation, and quantum mechanics), molecular structure (which leads to discussion of the physics of electrons, chemical bonding, and the shape of macromolecules) and energy within thermodynamics, organisms and cells. The topics within the AISS course have been refined over the 10 years to include those that work well in the team-taught "studio" mode, and that naturally integrate the different science disciplines (Purvis-Roberts, 2009).

In AISS, all three instructors are in the class at the same time, and frequently hand off discussion of phenomena to each other to allow a discussion of how each of the various disciplines (physics, chemistry and biology) apply to the topic. In one class, for example, students used the bioinformatics.org database and the RCSB Protein Data Bank on laptops to study biological macromolecules. The biology professor led the class, but the physics professor often would jump in and explain how electron polarization contributed to hydrophobic and hydrophillic parts of macromolecules. Additional information from the chemistry professor clarified how these macromolecules are formed and found in cells. Throughout the class students would break into teams to find and render large molecules on their computers using the databases and a three-dimensional visualization program in MAPLE.

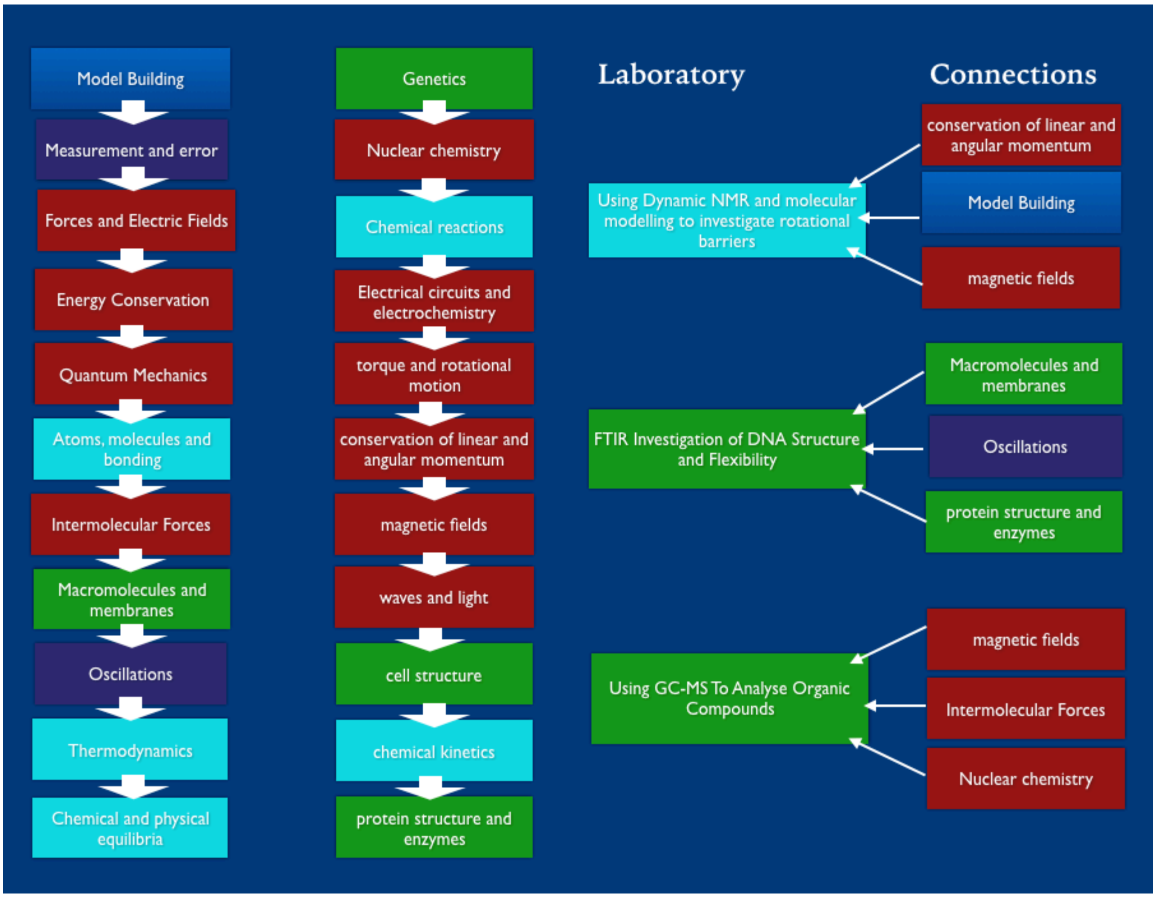


**Figure 6:** Flow Chart for topics in the Claremont Accelerated Integrated Science Sequence (AISS) classroom (left columns), and a sampling of lab topics in the course with connections to topics in class (right). Disciplinary topics are color-coded with red indicating physics, green biology, and light-blue, chemistry. [adapted from Purvis-Roberts, et al 2009]

As an example of an exercise in class, students were asked to find the exact sequence for a gene in a micro-organism, and then were charged to design their own macromolecule to perform a particular job - in this case to create a macromolecular vessel to hold a particular atom within a cell. The students went off in teams and presented their designs at the end of the class. Throughout the AISS class, the mix of hands-on learning, discussion between the students and the team of professors, and project-based learning provides a rich and exciting context in which to learn about the unity of science.

The first interview was with Scot Gould, a physics professor from Keck Science Department of the Claremont Colleges. Scot is one of the three professors teaching in the Claremont Colleges' AISS program, and has over five years teaching in the program. Scot described how all three AISS instructors are in the classroom in the same time, and how this allows each professor to play off each other during the class. The presence of all three instructors within the classroom makes it easy to communicate what each is doing, and they can naturally communicate and learn from each other about their various pedagogical approaches in real time while teaching. The AISS teaching team still has some challenges in creating assignments since different disciplinary approaches and material is introduced by particular members of the three-person teaching team, making it complicated to jointly author and grade assignments. They have solved this problem by introducing a system where the instructor who introduces concepts in the course is responsible for creating and grading assignments for the students based on these concepts. The team cycles through assignments designed and graded by one of the individual instructors, rotating regularly through all three of the teaching team. Since all three instructors are alternating in a sequence (typically with assignments on T/F), the variations in grading practices average out within the AISS program. This system has worked well for them as they do not have to negotiate and blend their approaches in creating assignments and grading, and evens out different philosophies of assessment. In addition to homework assignments, they have weekly midterms or quizzes.

We discussed how it is difficult to find instructors for this type of interdisciplinary teaching. Some instructors are known to be very fixed and rigid in their disciplinary approaches, and so something of a recruitment process exists for AISS, seeking instructors flexible in their approach to teaching. To prepare for the course the instructors meet during the summer to select the students for the course, and to also lay out the course together. The summer meetings before the semester begins include about 6-10 hours of discussion. This process took much longer in earlier years, and Scot described how it took "five long afternoons to lay it out" in the first year. In the second year, this fell to only a few afternoons. Now with long experience, the process boils down to about 6 hours. In these meetings, the instructors will study what topics they want to emphasize – sometimes repeating topics from the standpoint of each discipline. Once the class starts, the more experienced instructor starts off on a few topics and the new instructors learn as they go. They are "always seeing each other" so during the semester formal meetings are typically not necessary, and only a few 15 minute meetings are needed.

One key point that came out in the discussion was how teaching in an innovative course requires an open-minded approach to teaching. Scot feels strongly that each component of the course, laboratory schedule, topics to cover, and assessments have to be questioned and the purpose of each identified. The approach of questioning everything prevents instructors from repeating past practice without the deeper rationale for why each element exists within a class. Such efficiencies are necessary for AISS, which is working to create a single year-long double-credit course that compresses three full-year introductory science courses. It is interesting to note that even if three instructors are teaching together, they may not always agree on the best way to teach topics; this requires gentle communication to convey alternatives during a class in front of the students. With the three teachers in the room often one of the instructors can raise their hands to provide an alternative viewpoint, and to also share a different way to teach a topic. However to enable these discussions, a faculty member has to learn how to "give up control" compared to the experience within the more typical solo teaching environment.

The assessment within AISS relies primarily on outcomes for their former students, by studying how the AISS students perform in later and more advanced courses, as well as in their post-graduation success in gaining admission to medical school and other fellowships. This assessment process is supplemented by some information on student attitudes, conducted by a team of educational researchers at the nearby Claremont Graduate University. The AISS team discussed ideas for more detailed assessment that might include pre-course and post-course concept tests (such as a physics force concept inventory test) but these have not been implemented. In the early days of AISS they used the ACS standardized tests to gauge performance, but in recent years since the curriculum is different from the ACS curriculum they do not use these tests.

In final thoughts Scot shared his view of how rich the AISS experience is for students and for faculty. Scot says this AISS is “the single most exciting thing he has done pedagogically, ever.” He is convinced that this program is worthwhile for students entering medical school, as the AISS instruction is much more like the medical school environment which is typically interdisciplinary. The challenge in “scaling up” AISS has prevented them from offering it to a larger group than the current 30 students. Keck Science is challenged to offer AISS – with a very large number of science students needing introductory courses, and the department is somewhat understaffed with professors. This means that each of the three disciplines (physics, chemistry, biology) has to negotiate to free up one of their instructors from the schedule. The department is however committed to offering AISS due to the rich environment it provides to students, and the conviction that it promotes student learning more effectively and efficiently than a traditional introductory science course.

To gain more insight into the origins and early implementation of AISS, I interviewed Katie Purvis-Roberts, one of the founders of AISS, and first author of both the NSF proposal that started AISS, and the publication describing the implementation of AISS (Purvis-Roberts, et al 2009). Katie described how the course was launched and how the founders of the course worked as a team for a year before teaching the class. The year was spent teaching units to each other, and meeting as a group – amounting to over three hours per week teaching together and another 6 hours per week meeting and discussing. The intensive year before offering AISS allowed the teaching team of three professors - Katie Purvis-Roberts (Chemistry), Gretchen Edwalds (Biology), and Adam Lansberg (Physics) - to reconcile some of their varying approaches to teaching and to learn each other’s subjects. An initial plan to have each of them take the other’s courses was not feasible but the large number of meetings and discussions forged the group into a tightly-knit team and built relationships and trust within the team. The team was constantly discussing and negotiating, and were able to agree on formats for exams, grading protocols and the design of the course. When a new teaching team began to offer AISS, Katie described how the new team was unable to have the full year as her team did, and wondered how the negotiations were possible in the shorter timeframe. She also mentioned that the new team (which included Scot) met for the summer and decided to re-invent large parts of the course instead of building upon or adapting the materials developed by the founding team.

When the course was implemented, the intense demands of time became apparent – including 18 hours of contact per week mixed between five days a week of teaching and daily office hours. Katie recognized that preparing faculty for this kind of environment might be difficult without the “inherently interdisciplinary” environment of Keck Science. The Keck Science department already had an agreement to have interdisciplinary seminars and they enlisted nearly the entire department to help design labs for the AISS course. This broadened awareness of the course within Keck Science and also helped the AISS teaching team learn more about different approaches to teaching. Grading within the AISS course was done with individual subject experts grading questions pertaining to their field and the team would pass around exams to reconcile their grades for interdisciplinary questions.

The assessment of teaching and learning consisted of a mid-semester survey for students and end of semester evaluations, and a team from Claremont Graduate University interviewing students about their experience. Katie reinforced Scot's point about AISS graduates having good success in science fields after graduation and improved performance in more advanced classes as an indicator of student learning. The teaching for the course was assessed constantly by the team as they taught and in their weekly meetings. The bonds within the teaching team made it easier to then discuss different teaching approaches and to honestly work out solutions when teaching was not going well in some of their sessions with students.

### University of Massachusetts, Amherst – iCons

The University of Massachusetts Integrated Concentration in Science (iCons) program is hosted at its integrated science center, a newly constructed building dedicated to fostering interdisciplinary research and teaching in science. The iCons program is literally built from the ground up in 2014 to train "the next generation of leaders in science and technology with the attitudes, knowledge, and skills needed to solve the inherently multi-faceted problems facing our world (UMassAmherst, 2017)." The iCons program is organized around two theme areas – Renewable Energy and Biomedicine and Biosystems, areas that aligned with collaborative research strengths at UMass Amherst and societal needs that students considered important and motivating. The program begins in the Spring semester of the first year, with a course entitled "Global Challenges, Scientific Solutions," which trains students to excel in diverse teams on current, real-world problems of the students' choosing. In the second year, students take prerequisite courses in math and biology and other disciplines, preparing them for the iCons 2 course titled "Integrated Scientific Communication," Energy and Biomedicine sections challenge students to communicate effectively to both technical and non-technical audiences. In the Spring semester of the third year, iCons 3 "Team Discovery Lab," again with Energy and Biomedicine sections that teach key lab attitudes, knowledge, and skills relevant to real-world problems in each theme area.The final year involves a year-long iCons 4 capstone, including 6 credits of advanced study – usually in the form of a science-laboratory-based honors thesis – and 2 credits of "Integrative Team Science Seminar" that trains advanced communication and reflection around the advanced study work, and each student's career in college. . The iCons program is notable both for its vertically-integrated curriculum that builds on the disciplinary expertise that a diverse cohort of students bring to their team, and its emphasis on both preparing science practitioners and policy makers, who may go on to an array of possible careers.

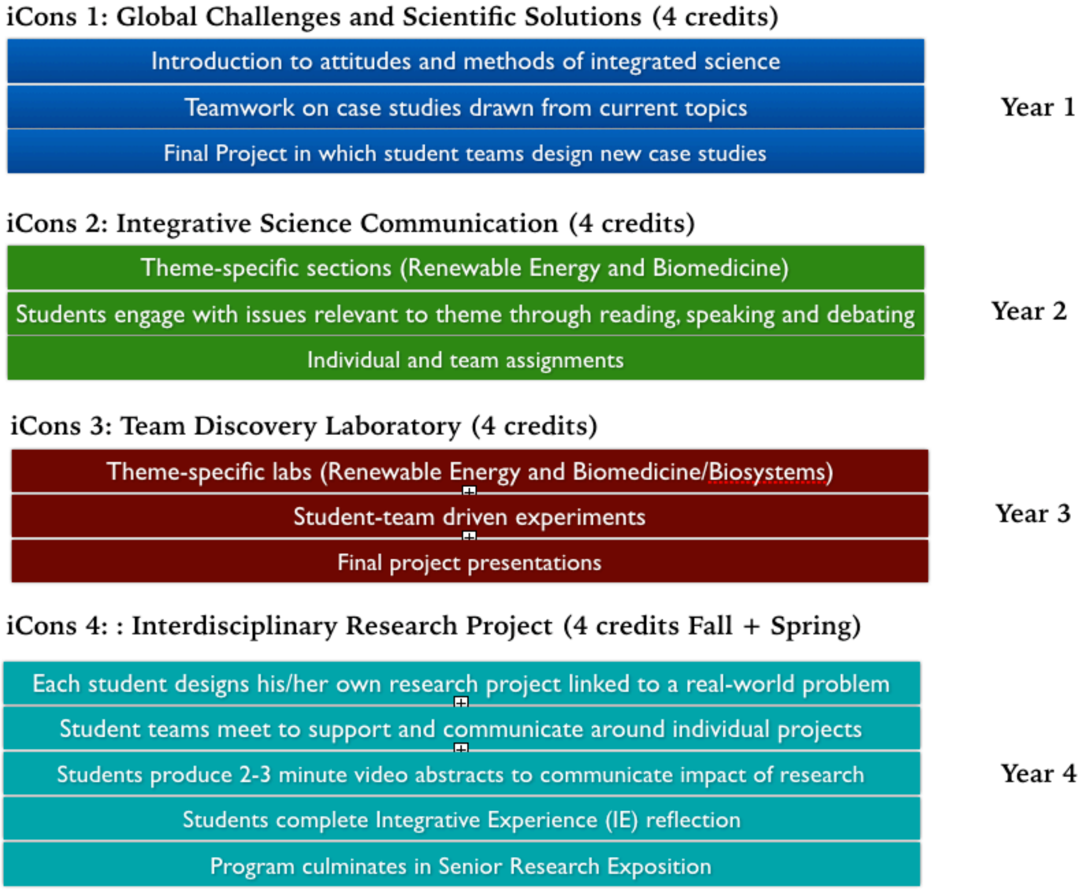


**Figure 7:** Schematic of the U Mass iCons integrated science curriculum.

To determine more about the implementation of the iCons Program, we interviewed Scott Auerbach, the founding program director (2009-2016) for the iCons program at UMass Amherst. Prof. Auerbach began by describing how his program differs from some of the other interdisciplinary science programs. The iCons team visited Princeton University and Olin College in the early days and were very impressed with both of these institutions and their approaches. In particular, Scott indicated that the Olin visit was "transformative," but in both cases the iCons team recognized the need for their program to help heal the "splintered" nature of academia which is dominated by disciplinary approaches. Breaking out of disciplinary approaches is really a "sociology problem" according to Scott. The iCons program is one that reaches about 60 students each year, in an institution with 22,000 undergraduate students. The UMass students apply to iCons and of the typically 160 or so who apply, 60 are accepted. This small fraction of students who apply could also be part of a larger trend in which predictable and traditional approaches may be easier to accept for both students and faculty.

The teaching within iCons is designed with active learning in mind via the "Guide on the Side" approach built into the course design, which focuses on case studies and student-initiated research questions. The iCons program includes two tracks that study health/biomedical topics and energy/environmental science topics, mappng on to research strengths of the UMass Amherst campus. The two tracks begin together in iCons 1, but are split in the iCons 2 and iCons 3 courses. Within iCons 2 and 3, a "boot camp" stage gives intensive training in communication or laboratory measurement for several purposes – persuasive speeches, effective Powerpoint presentations, and proposal writing; precision, reproducibility, and fundamental experimental design. These early skill-building phases pivot early in the semester to fully student-driven activities, where teams of iCons students actively identify the problems on which they will work and the methods best suited to meeting their goals. Scott explained how the student-written proposals enter into a competition to form teams which then together take on the student-proposed research projects in a six-week unit. A feature of each iCons course is a so-called "Divergent Design Problem," namely, students are tasked with "greening" the infrastructure of the UMass Amherst Campus. Student proposals (and later) projects can go in any direction under this umbrella, hence the name "Divergent Design." In only six weeks, students are asked to go from idea, to research, to design, to the final assignment – a public debate open to all iCons students and faculty to determine the best design idea.

The intensity of the iCons course sequence is based on an awareness of the need for students to take charge of their learning, and an acceptance of the role of challenge and even failure in promoting deep student learning. For example, in the iCons 3 Energy Lab, students design and conduct two research projects within a semester, and in both cases are required to reflect on what they learned, and in cases where the research fails to discuss why this happened and what they would do differently given a second attempt. Since the ambitious projects are being conducted by inexperienced students, the instructor team fully expects many of the projects to fail and recognizes the importance of this element in learning despite this bringing a certain tension and anxiety into the course. The idea is that even if activities "crash and burn," students will learn more deeply if they reflect on why it happened. iCons faculty will often discuss how "constructive failure" is planned into iCons activities to provide more valuable opportunities for transformative learning.

Scott discussed how challenging it was for him to enter into the environment of iCons at first, requiring a lot of effort to learn new ways to teach. He also appreciated the team-based nature of the course which includes 2 faculty and a TA in iCons 1, and a pair of instructors in iCons 2 and 3. Their teams are also well served by a very talented staff director of iCons, who Scott considered a "Secret Weapon" of the program.

To communicate what is happening within iCons, it is necessary for the entire group of iCons affiliated faculty to meet in a retreat, which is typically conducted both just before and just after the Spring Semester. Typically in the first week of January, the 8-10 iCons instructional faculty along with other interested faculty meet to discuss the goals of iCons for the coming semester, and then debrief at the end as well. These meetings in some years are a weekend retreat (as was the case for their 5-year review this year), but in other years are simply long lunch-based meetings. The iCons program recognizes that iCons instruction is not "ordinary teaching" so the iCons director aims to select only tenured faculty so as to not risk junior faculty losing tenure from lower course evaluations. This is due to the innovative approach within iCons which can get lower course evaluations in some of the traditional categories of the UMass standardized teaching evaluation form. However, since Scott (and now the present director, Dr. Justin Fermann) look for the best faculty, they sometimes approach faculty within months after receiving tenure to bring them into the group!

iCons also employs an unusual approach to assessing student learning. Part of the academic assessment consists of students engaging in "generative" interviews, explaining their learning process in an interview with another student. While one student speaks, the other student records the speaker's impression on how they have progressed in each of the chosen learning goals for the course. Each student then synthesize these answers into a cogently written piece that describes how well they have learned within 3 of the most important learning goals. The students are then graded, in part, on their piece based on both how much they have improved, and how they as students can document this learning. Training students to take agency in their learning and even in assessing their own learning requires a different type of culture – and the iCons program works to train students in managing these expectations from "Day 1" in their orientation program. The program tracks students after graduation and are proud that 98% of their graduates have been placed in good jobs or postgraduate work within one year after graduation. The iCons faculty are also proud of an alumni group that has formed, called "iCAN" for the iCons Alumni Network, which works to bring the iCons form of learning to high schools across the Boston area.

## Princeton University, Integrated Science

Princeton has traditionally offered one of the most demanding integrated science programs, that spans three years of the undergraduate curriculum. The course has a unifying theme of the mathematical models used to describe nature. Princeton Integrated Science is exceptionally rigorous, and develops a very solid grounding in all aspects of quantitative modeling, including dynamical models, chemical kinetics, population growth, and also probabilistic models found in genomics and thermodynamics. In the first, year, Students get a full year of Chemistry, Physics and one semester of Computer Science and a substantial amount of Biology. The first-year course meets five days a week for an hour, and has a 3 hour lab and 3 hour computational "precept" each week, and counts as a double class.

In the original formulation of Integrated science, the second year included mix of chemistry and biology which was closer to a traditional biochemistry curriculum. Topics of organic and biological chemistry were covered, as well as crystallography, and dynamic models of cell metabolism, which mixed the disciplines of biology, chemistry and physics. In Spring of the second year, students worked with genome sequencing, genetic engineering, mutational analysis, genetics of populations, and neuroscience. In the third year, students chose a major, and all of them took a Project Lab (its official title is "Experimental Project Laboratory in Quantitative and Computational Biology"). In the lab course, students designed and executed their own experiments, giving them extensive experience in research with one of the many participating Integrated Science professors.

Staffing of this ambitious course required a large number of faculty - in both the Fall 2010 and 2012 syllabus, 12 professors were listed, representing the departments of Physics, Ecology and Evolutional Biology, Computer Science, and Chemistry. Many or most of the faculty were based in the Lewis-Sigler Institute at Princeton, which is dedicated to "Integrative Genomics" and "Quantitative Biology," and the sequence leveraged the research activity and expertise of this institute. A good amount of computation was also part of the curriculum, and students made their own programs and models using Java in the first semester, and by the second semester were working on advanced topics of computational biology. The large time investment from both faculty and students seemed to be worth it, and in the words of one of the Princeton students who completed the program, Michelle Ward '10:

> "The course taught me to not limit my questions to a particular field. Rather, by asking questions about the chemistry and physics behind a biological system, I can learn about the biology from a more complete perspective" (Princeton ISC, 2017)

The professors also felt strongly that including such a broad range of sciences provided stronger preparation for scientific research. In the words of David Botstein, one of the founders of the Integrated Science program, "Any budding researcher needs a foundation in several fields to be able to work on the most important problems confronting scientists today" (Botstein, 2017).

To learn more about Princeton University's Integrated Science program, we interviewed the current Integrated Science Director, Joshua Shaevitz. The program has evolved since its founding over a decade ago by David Botstein. The original program was a 3-year curriculum that included an intensive first year of physics, chemistry and computer science, followed by a second year of biology and biochemistry, and then a third year Project Lab. The current program has been restructured into a freshman year program that integrates computer science, biology, biochemistry and physics, with a very high level of mathematics applied throughout the curriculum. The intensive first year double course meets five times a week, as half of a student's four courses, and fulfils the introductory year-long course requirement in chemistry, physics, and semester credit for introductory majors-level courses in Computer science and molecular biology. Students can separately complete a certificate in quantitative biology, but this is no longer part of the Integrated Science curriculum.

Josh mentioned that the program has capacity for more students than its current 30-40 who are accepted currently. These students are selected to have high math proficiency (at the AP AB calculus level), and are expected to be comfortable with the high level of mathematics. Josh suggested that the program could grow to 60-70 students if it were redesigned to be more flexible with the math requirements, and a bit less of a workload to allow students to have more balanced schedules. Despite the high workload, which is "just over the edge for some Princeton students," the program has attracted some of the best undergraduate students in the country, who usually go on to do advanced research while undergraduates, and obtain doctoral degrees after Princeton.

The first semester course is taught by three science professors, and one computer science professor, who trade off their teaching duties according to a schedule which might include science classes and computer science classes on alternate days. On any given day, one faculty member is lecturing (the primary mode of instruction) and the material to be taught is agreed upon in advance. Since the pedagogy is primarily lecturing, and the curriculum has been in place for a long time, many of the Princeton faculty are well aware of the topics and approaches in the class, reducing the need to communicate about the events within the classroom. The assessments have been set previously, and the preceptors are responsible for setting the problems to be worked, and grading these problems, again removing differences between the various professors. Professors are however intimately involved in both the teaching of the class and in helping students with problems. Some of the problems are worked in groups on Wednesday nights, and the TA's and faculty will drop into these gatherings to help the students along and also to get to know them better. Some of the problems within the curriculum are legendary, and are often simple to describe and very difficult to solve. One example was the "basketball problem" – a simple problem involving accurately solving for the ranges of the force, angles, spin and other variables that will allow for a basketball to travel through a hoop from a given distance. The problem involves physics, computer science, and some advanced mathematics to solve accurately and to handle error propagation of the many factors. The small size of the student cohort, and the intense involvement of the faculty in teaching and mentoring students ensures that there is a good connection to help assess the learning of students in the course.

Despite the great success of the program, Josh is hoping to expand the numbers of students enrolled in integrated science by reducing the workload and mathematical sophistication slightly. He is hoping to export this program since he believes that the program offers a unique form of science education that is valuable for two reasons. First, the way it makes all the sciences equally quantitative helps students see that they are not different. Second, the ways in which the sciences overlap each other and can be unified by key concepts helps students learn science more deeply and see the influences from one field upon another.

## Harvey Mudd College, Probing the Inverted Classroom

The inverted classroom project at Harvey Mudd College arose from a National Science Foundation grant which provided for a four-year study in which instructors in Engineering, Biology, and Mathematics were brought together to perform a controlled experiment in the ways that students learn in either a flipped classroom or traditional classroom environment. Their study found that when the presentations were precisely controlled so that the slides and assignments in both a flipped and traditional course were the same, the student performance on tests were identical in both environments. These findings have been reported in the educational literature (Yong, Levy and Lape, 2015), and have helped quantify whether the flipped format of instruction by itself promotes learning. The degree of coordination within the Inverted Classroom Study had many parallels with a team-taught interdisciplinary program, and while students were not expected to take all of the courses, the dynamics of the instructor team were very similar to those within an interdisciplinary program.

Darryl Yong was a Co-I on the NSF Inverted Classroom project, and also led the development and implementation of a course in Applied Math for Engineers, which is a team-taught course between the Harvey Mudd Math and Engineering Departments. Darryl was interviewed for this study, and he reported how the work within the Inverted Classroom project required an extraordinary level of coordination with his team, as they wanted to remove the bias of one instructor form another in paired math sections. The effort required absolute standardization of the material, from the use of the same Powerpoint slides, the same equations discussed in class, and scripted class sessions to insure the flipped and in-person class experience was the same. Achieving this level of coordination with his co-instructor, Rachel Levy, was extremely difficult and required large amounts of time and negotiating to agree on the best strategy to teach. Darryl noted that at first 4-5 hours per week were required for this coordination, in 2-3 separate meetings in each week. This intense process enabled them to learn a lot from each other about teaching, and Darryl found the experience both very challenging and very rewarding. After many weeks, the co-instructors were able to find ways to divide the effort, with Rachel specializing in modelling problems, and Darryl working to align objectives, content and assessment within the course. The development of these complementary specialized working roles helped leverage the strengths and interests within the teaching team, making the end product better, and also making the development of classes, edited videos, and common assignments more efficient.

The conclusions from this study, according to Darryl, "showed that when everything is controlled so carefully except for the delivery of the content (interactive lecture versus videos), student learning outcomes were the same. The fact that other people have found learning outcomes from inverted classroom teaching strongly suggests that it is the added active learning that makes the difference, not the delivery of the content itself."

## University of Hong Kong, Fundamentals of Modern Science

The Fundamentals of Modern Science course at Hong Kong University (HKU) is a course designed to provide a broad view of science that emphasizes the interconnections between disciplines, and surveys the history, fundamental concepts, and impact of science on civilization and society. The course arose from the recent (2012) restructuring of Hong Kong University curriculum that increased the undergraduate education from three to four years. The extension of these undergraduate degree programs opened new spaces in the curriculum that provides for courses such as Fundamentals of Modern Science. The course is organized around a theme of scale – and begins at the smallest spatial scales considering the fundamental structure of matter. After two weeks on particle physics, the course transitions toward atoms and nanoscience for 3.5 weeks, and then includes 3.5 weeks on "living organism: its mechanism and origin and interaction with its environment," to explore science at the scale of the cell and larger sizes. After the biology unit, topics in energy and heat are considered which leads toward a discussion of earth and its environment, and finally a two-week unit on Planet Earth and the universe to conclude the course.

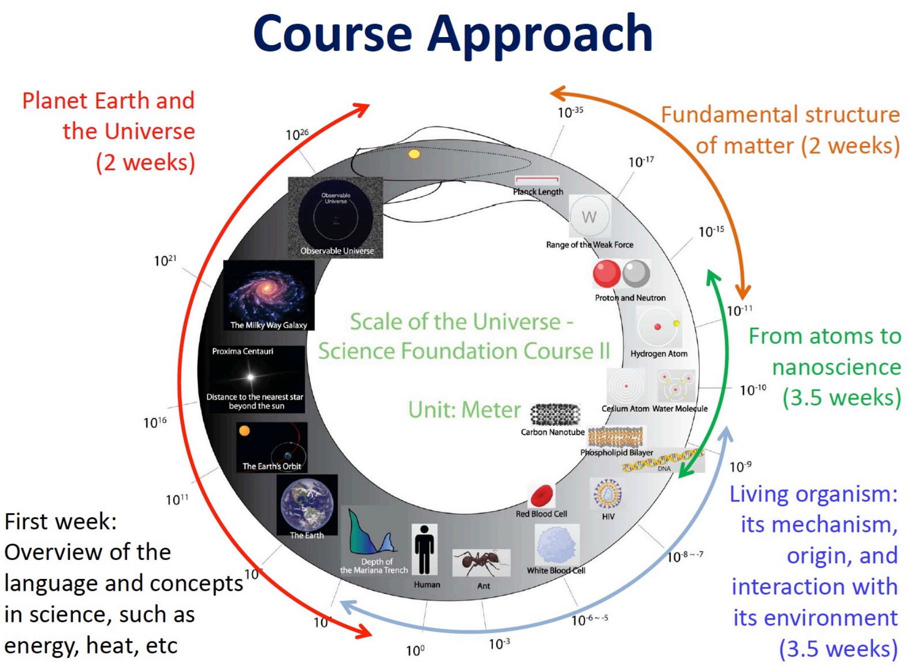


**Figure 8:** Schematic of the HKU Fundamentals of Science course (courtesy J.S. Pun, HKU).

The course is directed by astrophysicist Jason C.S. Pun, who was interviewed for this study. The HKU Fundamentals of Science course is offered to 280 students each semester, and is taught by a teaching team of 3 lecturers from diverse scientific disciplines, and a team of 3-4 tutors. The course meets 3 hours per week for lecture, with an additional 2-hour tutorial session and 2 hours of laboratory each week. Within the course are 4-5 assignments, which explore open-ended questions about science, and these questions are answered by groups of 4-5 students. A team-based project, selected by groups of 4-5 students is conducted to conclude the course, with student presentations in the final weeks of the course. Exams include a midterm and final exam, giving a mix of assessments that are both exam-based and project-based.

Dr. Pun discussed the motivations and development of the course. According to Dr. Pun, “We thought about a lot of different approaches but at the end we used the movie *Powers of Ten* as an inspiration to cover all different natural phenomena linked by the length scale.” The quantum nature of matter was discussed, along with the Heisenberg Uncertainty principle, and then chemistry – with a strong emphasis on water and also carbon – as manifested in nanotubes, and other interesting nanotechnology contexts. Dr. Pun also pointed out that the transition to the largest scales of astronomy and cosmology links back at the end of the course to the smallest scales. As Dr. Pun explained, “environment would lead us earth science and astronomy topics and universe, and completes the circle. We always bring up the idea that what's happening in the largest scale in the universe is also related to the what's happening at the smallest scale of the universe.”

Dr. Pun discussed some of the challenges of the course, which includes the large range of topics to be covered in a single semester, which often are not covered at the level of depth he would like. He also acknowledged the challenges of the size of the course – which includes 550 students each year, broken into two sections of about 280 students. Since the science faculty at HKU are divided into separate departments, the Fundamentals of Science course is staffed with a large team of professors drawing from nearly all of the departments. According to Dr. Pun, the course is taught with “three separate teachers for the lectures each semester.. one teacher focuses mostly on the physics and the astronomy earth science topics the other mostly focuses on chemistry and the other on biology.” Dr. Pun describes the staffing as the best compromise possible to provide broad expertise, without taxing the departments too heavily. The team of three lecturers are complemented by a group of experienced tutors (not graduate students), who supervise groups of 25 students in tutorial sections, with more individualized instruction. In the tutorials, the tutors emphasize “the interconnectedness of the various disciplines of science” and Dr. Pun stresses that “we try to break the barriers in the tutorials.” During the course of the semester, each of the three lecturers will trade taking the lead of the teaching team. During the first times the course was offered all of the lecturers attended lectures throughout the semester to learn more about the other lecturer’s approaches. Now, with experience of several years, instructors typically meet once or twice per semester to coordinate and schedule their lectures.

In the first few years, listening to the others lecturing and studying the lecture notes was used to “smoothen out the differences” and provide more consistency between the instructors. In four years the course has been evolving and is continuing to improve in the consistency between lecturers. To provide consistency in grading from the teaching team, Dr. Pun describes their system: "For oral presentations we usually grade with more than one person but for written assignments we try to keep uniformity by having one person grading all the problems in that particular part. And this actually means one person grading 200 assignments… and of course that is a huge amount of work..." Typically "the lead instructor works really hard for about four weeks," according to Dr. Pun, as they are in charge of all of the lecturing and grading, but they are able to hand off to the other instructors. When instructors are not the lead, they transition to providing other support such as setting up exam questions, consulting with the lead instructor, and giving feedback on the course.

In the coming years, Dr. Pun hopes to improve the "dialogues between different portions of the course by different lecturers; dialogue between materials and lecturing tutorials." The teaching team is also developing strategies to increase student motivation - especially those with less background in mathematics. According to Dr. Pun, "the diversity in academic background is the biggest challenge that we face.. it's a huge amount of effort to try to help this sort of weaker student."

## New York University, Abu Dhabi – Foundations of Science

NYU Abu Dhabi (NYUAD) was founded to pioneer "a new model of higher education for a global world… with a distinctive focus on intercultural understanding and leadership." Part of the NYU Abu Dhabi mission is to support "innovative research and graduate education programs that push forward the frontiers of knowledge and respond in powerful and interdisciplinary ways to vital global and local challenges (NYUAD 2017)." The NYU Abu Dhabi Foundations of Science course "provides a fundamental yet rigorous overview of science, focusing on the interrelationships among physics, chemistry, and biology" (NYUAD 2017). The Foundations of Science course is required for science and engineering students, and consists of six different courses taken during three semesters, which begins in the first semester of the first year for most of the science students.

The Foundations of Science program spans multiple years and covers disciplines in physical and biological science in an interdisciplinary manner. *Foundations of Science 1: Energy and Matter* is a team-taught physical science year-long sequence that has been offered since 2011, and includes integrated discussions of matter, energy, physics and chemistry in the first semester. *Foundations of Science 2: Forces and Interactions* studies fundamental forces in a unified way, and spans courses that typically are separate mechanics and atomic physics courses. *Foundations of Science 3: Systems in Flux* unifies topics within physics, chemistry and biology in an elegant way, using analogies between basic circuits to explain flows of energy within chemical reactions, and then applying these chemical reactions toward the physics and chemistry of biological molecules such as DNA, RNA and proteins. The final course in the sequence, *Foundations of Science 4: Form and Function* discusses shapes of physical entities in a general way – and applies concepts of electromagnetism, and chemistry toward the shapes found in nature of molecules, crystals and other naturally occurring symmetries.

To learn more about Foundations of Science at NYUAD, I interviewed Professor David Scicchitano, who is the Dean of Science for NYUAD. Prof. Scicchiatano has been involved with NYUAD since its founding in 2006, and led much of the faculty recruitment effort at NYUAD while directing the Foundations of Science course from the beginning. Prof. Scicchiatano describes their Foundations of Science as “intense” as it has a high level of rigor, and is offered to only 10-15 students per year, who have all applied to take the course. As Prof. Scicchiatano put it, “We used a different philosophy which was that we felt every science student should have rigorous integrated experience where big concepts in science are learned by everybody.” This means the future biology majors are learning a full course in physics along with physics majors, and vice versa. Prof. Scicchiatano pointed out that the design of the course recognizes that “a lot of the great questions in Biology are being addressed by Physicists; but you can’t ask the questions if you don’t have some kind of a concept of what something is." Prof. Scicchiatano recognizes that students don’t always appreciate this mix of disciplines while they are starting out, but later in their academic careers can appreciate the strength of this approach. As Prof. Scicchiatano describes, “I don’t think they’re necessarily convinced, till they start to hit their fourth year. And many become convinced when they actually go out into the world of graduates in the job market. That’s where we get feedback from the one saying, ‘I now get it. I can actually say sit through something at work or a seminar or whatever that involves a gene, even though I'm a physicist and I understand what the heck they are talking about.’”

The NYUAD Foundations of Science course opens with a course on Energy and Matter – which includes discussions of Motion, Energy and Thermodynamics. In each section of the course, Chemistry and Physics are mixed together. The course has a lab as well – which in early days of NYUAD were offered at a separate facility 15 miles away. Now the Foundations of Science labs are offered within their new campus at Saadiyat Island. The Foundations of Science sequence includes six separate semester-length courses, which each are taught by teams of between 2-5 instructors. To help the team learn more about teaching and to help blend their expertise within the sequence, the team is required to attend each other’s lectures. Having the team present in class can often add to the course, as it allows the experts from different disciplines to trade ideas. Often within a class one of the instructors will pitch in a perspective from Physics or Chemistry to provide different takes on the same phenomenon being discussed by a Biology instructor. For example, a physicist may describe how a capacitor can explain cell membrane potentials, while a chemist can provide different terms and perspectives to explain thermodynamics.

In addition to viewing all the lectures, the teaching team also meets frequently and creates sheets for each topic that describe detailed learning outcomes and other details of the course sessions. Frequent discussions about grading also help to align grading practices between he different sections. The many challenges of teaching in a team environment requires a different approach to faculty training, and many of the new faculty spend time at the home campus in New York sitting in on classes, attending training sessions, and studying syllabi of other instructors. The NYUAD faculty learn quickly in this intense environment, and are aware too of the role of student letters in their tenure review - which helps to incentivize good teaching, according to Prof. Scicchiatano.

## Yale-NUS College, Integrated Science

Yale-NUS College (Singapore) was founded in 2013 with a mission to "redefine liberal arts and science education for a complex, interconnected world." The Common Curriculum at Yale-NUS includes 10 different courses across the entire spectrum of disciplines and is designed to "integrate knowledge from across the disciplines and around the world." Science and Math courses within the Common Curriculum include a course in Scientific Inquiry, Quantitative Reasoning, and a sophomore science track. In the first three years of Yale-NUS College, the sophomore science courses included two tracks - Foundations of Science (intended for non-majors) and Integrated Science (intended for Science majors). The Integrated Science sequence included three semester-length courses, which included one semester in the first year of study, and a pair of courses in the second year.

The first of the Integrated Science courses was intended to merge all of the scientific disciplines within a framework of a common theme related to "The Science of Water" and was offered to the inaugural first two classes of students at Yale-NUS College in 2014 and 2015. The first semester integrated science course was intended to prepare students for science majors, by exposing them to a "big problem" based learning strategy, and to also include rigorous mathematics, computational science, biology, physics and chemistry. The course facilitators recognized that the breadth of the course and its expansive aims created some inevitable tensions which were hoped to be remedied by offering topics designed to pique scientific curiosity. These topics were covered with the same level of depth as a disciplinary introductory course for majors, without the same extent of content coverage as a traditional disciplinary introductory course. To accomplish this goal, imaginative assignments were developed and a team-based teaching approach was used that included five professors within the classroom to teach approximately 37-40 students. All five of the "disciplinary content experts" were present in the classroom for each class – and represented the five disciplines mentioned earlier. Other pedagogical innovations included an online journal, where students wrote pieces on topics related to the course, a TEAL-style active learning classroom, and seamless integration between labs and lectures. A schematic of the course topics and applications is shown below.

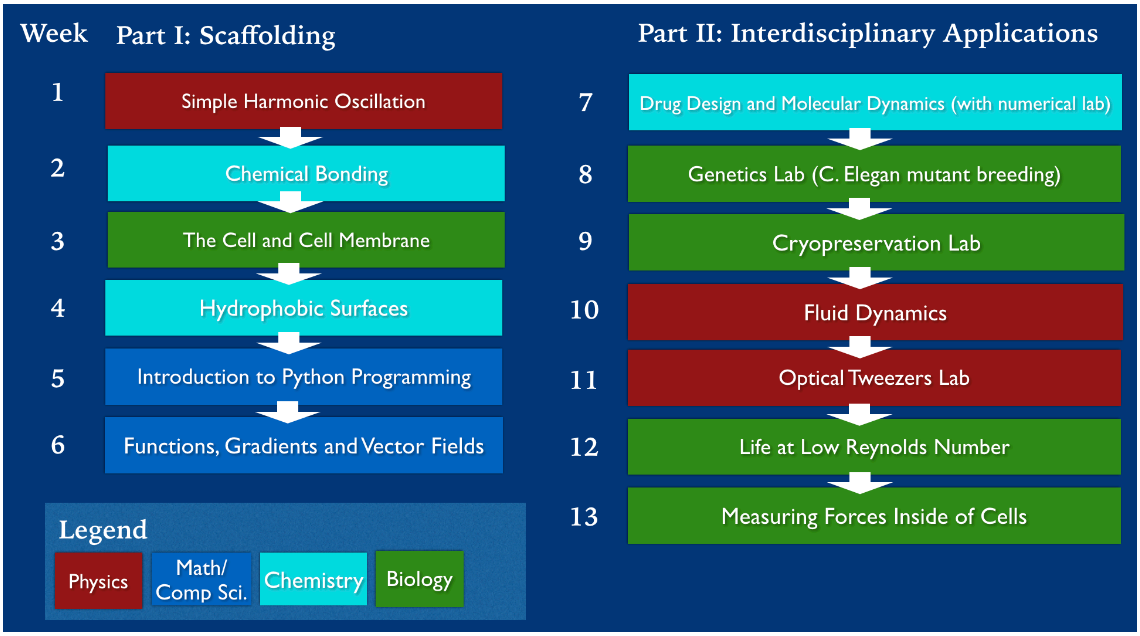


**Figure 9:** Outline of the Yale-NUS College Integrated Science semester-long interdisciplinary introduction to Science for science majors (figure adapted from materials provided by Shaffique Adam).

The Integrated Science course was developed during a year before the Yale-NUS College curriculum was first offered in 2013-14. According to Shaffique Adam, one of the course leaders, the teaching team met (on average) for two hours each week for an entire year, and the earlier discussions were determining whether to use a "top-down" (math/physics) or "bottom-up (biology/earth-science) pedagogical approach. The theme that was finally chosen was "water" and viscosity, which allowed for ample ranges of examples and applications in the fields of Mathematics (Navier Stokes partial differential equation), Physics (fluid dynamics), Chemistry (chemical and Hydrogen bonding) and Biology (life and circulation within organisms). Viscosity unified all of these fields, and included bacterial motion, hydrogen bonding, Reynolds number and other topics. In addition, larger interdisciplinary questions could also be addressed within the course, such as "why is water necessary for life on Earth?" and "what is water and where does it come from?" and "how do living systems use water?" The teaching team included five instructors, who were in the class together – with 4-7 hours of contact time per week, along with a 2 hour teaching team meeting and 2 office hours each week.

To learn more about the implementation of the Integrated Science course, two of the founding faculty members, Jan Gruber (Biology) and Shaffique Adam (Physics) were interviewed. As Professors Gruber and Adam described, "We had the mandate to give the science introduction to all science majors. So we designed something that was a real science course… We would give real math with the math majors who've learned it, real physics with the with the physics majors who've learned it and real so on and so forth." When asked about how they were able to align the course within the theme of the "Science of Water" the professors explained, "the big problems were water based. So we didn't make an artificial effort of bringing in the water where it wasn't natural. The problems included fluid dynamics, freezing life and re-starting it, and drug design, which is driven by hydrophobicity." All five instructors were tasked with the challenge to describe, "what does water mean to your discipline and what are exciting current issues related to water in your field of study?"

Within the course were many cutting-edge topics of science, such as drug design, molecular graphics, and studies of how molecules can bind in the presence of hydrophobic forces. Professor Gruber described the approach: "we expose them to some molecular graphics, they can draw three dimensional structures of proteins, they can look at drugs binding, they can try to see drugs that are going... Then you realize that you need to understand molecular forces e.g. from charged to charge interaction – and in water you especially need to understand hydrophobic interactions. And then we mixed in cell biology of the whole assembly of the cell membrane by hydrophobic interactions." The exploration of hydrophobicity led to lab experiments with hydrophobic and hydrophilic surfaces and this in turn led to understanding cell membranes (which self-assemble driven by hydrophobic interactions). Discussion of trans membrane proteins inserted into these membranes then led to students re-discovering and developing models of the harmonic oscillator and simulating it with Python programming. The Integrated Science course explored cryobiology, showed computer simulations of water freezing, and combined molecular simulations and lab experiments. One unit discussed "Life at Low Reynolds Number" which was inspired by a physics paper by the same name (Purcell, 1977). This unit developed fluid dynamic models, which were tested by experiments with small toy submarines in viscous corn syrup, and by stirring ink and corn syrup together to study the fluid dynamics. These experiments were designed to get students to think about the interplay between physics concepts and actual systems in biology. As Professor Gruber describes, "you can't use a propeller if you're in a highly viscous fluid – a propeller works by preservation of inertia in pushing water backwards and pushing yourself forward; it does not work in a fluid far from turbulence – where inertial forces are small relative to viscosity. That's why bacteria use flagella - so we actually asked the students - if twisted it this way would it move forwards or backwards and most students actually got it wrong."

Some of the challenges within the course came from the variation in preparation of students, especially in Math, and also in the diverse interests of students, who in some cases were less interested in learning about science topics outside of their intended major. The professors described how each of the disciplinary experts would lead a portion of the course, and then take the lead on grading those sections of the course that aligned with their disciplines. This would enable all of the students to receive consistent grades, as "There was no single student of us graded more by one professor than another." When asked how to prepare faculty to teaching in this kind of environment, the professors offered the suggestion that faculty be ready to have discussions in front of the students – and to "riff" on the topics from the perspective of their disciplines. These kinds of discussions require faculty to be comfortable with each other, and so the team needs to form a tight-knit group.

### National University of Singapore, Special Programme in Science.

One of the earliest curricular experiments at NUS with an integrated science curriculum was the Special Programme in Science (SPS), which began in 1996. SPS is a two-year interdisciplinary science curriculum designed to foster research skills in undergraduates in their first years at university. The program serves 80 students over two years, and involves four faculty who offer a mix of courses across Physics, Math, Life Sciences and Chemistry with a special emphasis on communication and programming skills. The program is structured around four key courses, that are sequenced in order of scale of the phenomena considered. The first course is "Atoms to Molecules" which covers physics and chemistry, followed by "The Cell" which is an introductory biology course, and then in the second year the courses called "The Earth" and "The Universe" cover earth science, and astronomy and astrophysics, respectively. Parallel to these thematic courses is the "Discovering Science" course in the first year, where students develop proposals for research projects, which they complete in the second year, and the "Integrated Science Project" – a research experience for second year students.

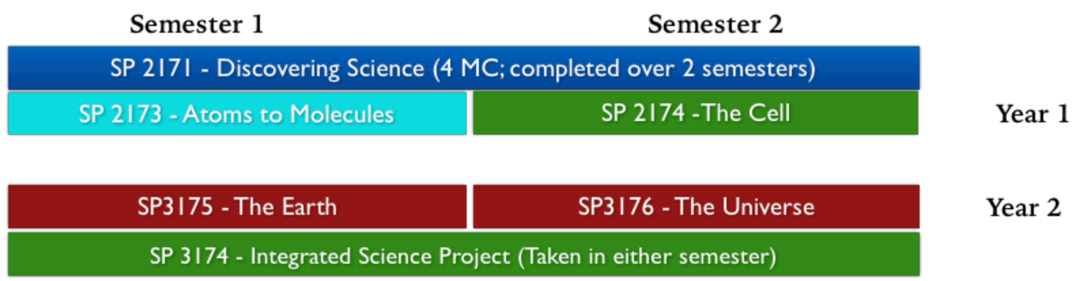


**Figure 10:** Schematic of the NUS Special Programme in Science, showing the multi-year sequence of courses, culminating in an Integrated Science project, which is a research project chosen by students.

As described by SPS Director Dr. Adrian Lee, the program is research oriented, and focuses on the skills practiced during research with a seamless integration of mathematics and communication skills in the curriculum. Dr. Lee summarizes,

> *"We have what we call four thematic modules and two research modules... We give them training during research, in writing a research proposal, in communicating their ideas. Computer programming underpins all of the modules. So they get trained in using Python to do programming. And there are laboratory exercises and mini projects that have been integrated into the thematic modules where they have to apply their knowledge of Python."*[i]

Dr. Lee also summarized how the SPS makes use of student mentors, who are able to supervise first and second year students in a group research project. The current cohort in SPS benefits from the participation of over 30 of these more advanced students, who also can help mentor the younger students in their coursework. The SPS program is also located in a dedicated space, which includes flexibly configured seminar/lecture rooms, a small library and computer lab, and a wet lab and a dry lab. The labs include instrumentation for cellular biology, as well as scanning tunneling microscopy, and spectrometers for physical science. The students in their classes are able to explore more advanced topics than in a typical introductory science curriculum, such as quantum mechanics, cosmology, relativity, and computer modelling. Lab exercises include using video to record cell development, and developing computer programs to track the cells which integrates computing skills into the life science thematic module. The students conduct laboratory experiments in the wet and dry labs, and also participate in a field lab experience in earth science, where students visit the NUS Marine Reserve and study the distribution of fauna on the beach at low tide. Since the SPS is designed to train research skills, in many of these lab exercises, students design their own research programs, such as a field research study at the Marine Reserve.

The key piece within SPS is the "discovery science module" – in which students propose a research project for the second year of the program. The course is completed over two semesters and goes by the title "Discovering Science." After students propose a project, a panel selects which projects are to be pursued, and each year about a dozen of these research projects are completed by students in groups of 2-3. These student research projects are supervised by a wide mix of faculty across NUS in multiple departments. These faculty mentors then become involved in the SPS assessment, and provide grades for a written report, as well as from a poster presentation and a group presentation of the results. The combination of written and oral presentation is part of the program design to enable students to develop more advanced communication skills.

Each course in the SPS sequence (Discovering Science, Atoms to Molecules, The Cell, The Earth, and The Universe) expands upon the previous course, with topics that are based on phenomena occurring within various distance scales in the universe. The faculty teach separate courses, and have appointments in different departments, but a floor of labs and offices are dedicated to the SPS program, including faculty office space, which allows the instructors to frequently interact and share information. Dr. Lee described how the four SPS instructors share information on their separate sections of SPS. At the beginning of the term the team would "buckle down" and meet for most of a week to review and plan the courses. The faculty team then meets on a weekly or bi-weekly basis during the semester, where they are "constantly talking about the pedagogy that we are employing." In the team meetings faculty discuss specific strategies for linking their separate courses. For example, the carbon atom is discussed at length in The Atom course, which links to the material discussed in The Cell course, which links to a discussion of carbon cycles in The Earth course. In the team meetings, some of the instructors provide specialized expertise so that in each unit they can contribute ideas or help in designing laboratory exercises. Dr. Lee describes how the team provides a "real community" where there is a lot of "mixing." As Dr. Lee puts it, "there's no sharp line – you know, 'This is my territory'" which helps integrate the separate courses."  In the many years of refinement, SPS has evolved to provide the right balance between content and breadth. In the first two years, the typical realization was that too much content was "stressing out the students needlessly." As Dr. Lee described it, "The content which was not seen as being critical was taken out" in an effort to "focus on quality as much as possible."

To get consistency in grading, the entire teaching team participates in grading the student projects (which include a student-designed research experiment), and the faculty also interview the students in an oral examination about their final projects, which in some European universities is called the *viva* or *viva voce*. These oral examinations allow the faculty team to understand in depth both about the achievement of students, and the ways in which their curriculum has produced solid understanding of science. The grades from these interviews and other work is also discussed among the team and with the mentors, and at the end the grades are "moderated" – which at NUS includes an independent review of the distribution of grades within a course. These grades are based both on the final project and oral exam but also on group projects and presentations that provide continuous assessment during the semester.

Preparing faculty for working in this environment requires active recruiting, according to Dr. Lee. In their recruitment, the SPS faculty look for others who have a strong sense of interdisciplinarity, and Dr. Lee described how they selected some faculty on the basis of their PhD research being based on interdisciplinary topics. Once the new faculty arrive, the SPS director worked to give them "ownership" of the material, and to make sure that their unique expertise can be incorporated into new laboratory or classroom exercises. When instructors try out new things in their course, sometimes other instructors will sit in on the classes, or they will discuss afterwards at a meeting. As Dr. Lee describes it, "Everyone is very aware of what I was doing."

For assessing the quality of teaching and learning in SPS, Dr. Lee described how they are now assessing how well the SPS sequence connects to the program learning outcome which is "to train researchers." They have observed that the students who complete the SPS sequence in their first years, have high grade points at NUS for their third and fourth years, but the SPS program is interested in trying to independently assess the research ability of students, after removing the effects of their grade point averages. Since many of the SPS graduates return as student mentors, it is also possible for the faculty team to review with them how their undergraduate research careers are progressing.

## James Madison University, Integrated Science and Technology Program

James Madison University College of Integrated Science and Engineering (CISE) houses three departments that includes Engineering, Computer Science, and a Department of Integrated Science and Technology (ISAT). The ISAT Department awards M.S. degrees in Integrated Sciences and Technology and Environmental Management and Sustainability, as well as a range of undergraduate programs that include a B.S. in Integrated Science and Technology (ISAT), B.A. or B.S. in Geographic Science, a B.S. in Intelligence Analysis (as JMU is close to the CIA headquarters), and a B.S. in Biotechnology. The program was initiated in 1992, at the request of the Virginia state legislature, who had convened a Commission in 1989 to develop "innovative approaches to education" and to also respond to an increasing demand for higher education within the state. The first class of 65 students arrived in 1993, and additional degrees were added in 1996 (Geographic Sciences) and in 2008 (Intelligence Analysis). Engineering and Computer Science was merged with the program in 2012 to form the present College of Integrated Science and Engineering.

Eric Maslen was the Department Head for the Department of Integrated Science and Technology from 2010-2016, and has presided over the program which now consists of over 800 undergraduate and about 22 graduate students, and a group of 59 faculty. The interview with Dr. Maslen began with a discussion about the program itself which was created 23 years ago. Dr. Maslen indicated that the design for the program would "require kind of a melding of social sciences and technical sciences so that students would learn how to solve problems that probably had science or technological solution but then had very strong social economic context." Dr. Maslen emphasized the diversity of the faculty within the program: "So I've got Historians, anthropologists, and nuclear physicists, and chemists and you name it. They're all in here - and next door to me is even an attorney!" Unlike some programs with such diverse expertise, these faculty were not borrowed from separate departments, but instead were hired into the same department with the understanding for the need for the diverse expertise to solve "contextualized problems" with all the complexity and interactions between the problem and society. Dr. Maslen gave the example of a course on the Global Water Crisis. He described how "the students were basically confronted with water shortages in various geographic regions of the world and asked, 'What's the source of this problem and how might you solve it without any reference to geology or to plumbing, or to politics, or to policy?'" The students "spent a year perusing that question" and the faculty were impressed by how committed the students were to this course, which had "high value" because the students were able to "define social context in a way that maybe wasn't what the faculty would have chosen." Dr. Maslen is hoping that "students will drive the curriculum at that point, they'll realize that the things that they're focused on and their concentrations can contribute to solving these problems."

The ISAT course sequence builds these social contexts along a "spine" which includes an introductory course entitled "Technology, Science and Society" and a second-year course entitled "Political Economy of Technology and Science." The ISAT sequence begins with first year courses in Environmental Issues, and Math, Applied Physics, Biotechnology, and Applied Physics, and second year courses in Telecommunications, Applied Statistics, Energy Issues, Instrumentation and Measurement, and an Introduction to Systems Thinking for Complex Problems. After these courses, students take third year courses in two "Strategic Sectors" which include Applied Biotechnology, Energy, Engineering and Manufacturing, Environment, Information and Knowledge Management, and Telecommunications, Networking and Security. The fourth year includes a year-long senior capstone project and additional concentration courses in one of the three Strategic Sectors.

The ISAT courses are often taught in teams, such as a recent course on Transportation, which was offered by a team of four instructors. These faculty are also involved in teaching one or two other courses in a semester, as well as in supervising capstone projects. When asked how JMU recruited faculty to teach in this environment, Dr. Maslen indicated that many came as "refugees from disciplinary life" and welcomed the chance to "work with people that have kind of a different perspective." He emphasizes the non-disciplinary or interdisciplinary culture of ISAT to new faculty when they arrive. Because the faculty are recruited for this environment, it becomes much easier to achieve close collaborations across disciplinary boundaries. Faculty are also given a chance to participate in team teaching where they learn more about how other people teach, and also get mentoring from other teaching teams.

Within the JMU ISAT program, faculty share information on their teaching by exchanging tests, and working from shared syllabi, as well as frequent conversations. The Department Chair also looks for comments from students that indicate lack of consistency between courses, and if this happens, the chair can help even out such discrepancies. To share innovations within the large range of courses requires some effort but the JMU teaching awards and a classroom visits to excellent teachers allows for sharing of ideas. The teaching is mostly evaluated by student letters, and sometimes when faculty are having challenges they are paired with an instructor with very high ratings to help provide mentoring. To assess the student learning, the ISAT program works with the JMU centre for assessment research, a graduate program at the institution which provides a structured assessment of curricular progress. All of the ISAT courses are assessed in collaboration with this institute, and they mix the results from the structured assessment with accounts of classroom experience from student letters and classroom observations to help revise the courses and improve the teaching and learning within the ISAT program.

## Virginia Tech, Integrated Science Curriculum

Virginia Tech offers an Integrated Science Curriculum (ISC) that allows for students to have a "alternative gateway to majors in the College of Science." The ISC is a two year "double-effort" course sequence that includes 6 hours of lecture and 6 hours of lab, for four semesters. The sequence includes the "fundamentals of college-level chemistry, physics and biology integrated with each other and with the mathematical sciences." The program stresses interrelationships of sciences, and the students are able to have laboratory exercises that are closely integrated with lecture material and with data collection methods that blend statistical and computational modeling. The students also experience a large number of team-based projects, and written and oral presentations during the program. The program is relatively young, and has graduated a total of 101 students in its first five cohorts. The pilot class launched in Fall of 2011, with 11 students, and has expanded to 34 by Fall of 2014, and 67 incoming students by Fall of 2017. The program also has been integrated into an Academy of Integrated Science, which was established in Summer of 2013. The Academy offers undergraduate degrees in three newly approved majors – Computational Modeling and Data Analytics, Nanoscience, and Systems Biology, and has enrolled students in those majors starting in 2015.

The program is staffed by 8 professors, and led by Michel Pleimling who is the ISC Program Leaders and Director of the Academy of Integrated Science. He was interviewed to learn more about how the program is structured. Dr. Pleimling described how the program began in 2009, when a group of faculty began work on a new systems biology degree program, which had a large component of physics integrated into it. The Dean was very supportive of the effort, and helped by providing resources such as summer salaries, and helping provide course releases and funds to get staff dedicated to the program. After three years, according to Pleimling, they began to hire faculty specifically for the Integrated Science Program, with their tenure in a tertiary department but the large fraction of their teaching duties in the ISC. They were able to have researchers who can bring interdisciplinary research into the classroom. In addition to faculty selected for the program, the ISC also has a separate admissions process for students. Students apply and write a short essay explaining why they are interested in interdisciplinary science, which assures that "they understand what they are going to get into" according to Pleimling. Students are selected both for their interests and for their math preparation, which is a very important component in the curriculum. Once admitted, the students are part of the Academy of Integrated Science, which was a "structure" given to the students, without having a department. The ISC has a dedicated, state-of-the-art lab space in a new classroom building. This new building provides students with a large amount of open space to enable them to work together outside of classroom time. The classes are taught in an active learning environment provided by SCALE-UP classrooms located in the same classroom building.

Dr. Pleimling described how the program is taught – typically with team of two faculty in the classroom and one TTA. The two faculty are from different disciplines and are able to share their perspectives in "real time" during the course. Since the ISC includes several different courses, and a fairly large group of instructors, coordination is important. The faculty as a group develop a master syllabus, and each year this is reviewed by the entire group that is teaching the ISC. This group of faculty meet and adjust the syllabus each year, typically in a large group meeting at the beginning of the year, and since the program has been offered several times these meetings are typically an "adjustment" and not a time to "reinvent the wheel." An oversight committee of faculty meets twice a semester, and this group is separate from those faculty teaching in the classroom. Additional meetings of the teaching team occur on at least monthly frequency, and more often for faculty new to ISC. Their key accomplishment in pedagogy, according to Pleimling, is the integration of labs with the course, and to expose students into a "research-like environment." These labs are based on four-week "modules" which are themselves integrated explorations of science with a theme, such as a unit on water pollution which includes biology and chemistry integrated together.

Achieving consistency in grading is an "issue" that they are solving by pairing a new instructor with someone who has already experienced the ISC. In order to improve consistency, they also try to have at least one person teach the entire year. In each year the team works closely with each other and with Pleimling to review the grades and to achieve consensus on procedures for grading and distributions of grades. Bringing faculty into this sort of interdisciplinary environment is made easier by hiring professors who in their research are already working in interdisciplinary teams. During the summer before the class, the new faculty work closely with their partners in ISC to develop course materials and to interact intensively to understand the course in depth. Pedagogical innovations in the course are shared in discussions they have for the entire team at the end of the semester, when they discuss what worked, what didn't work, and both the content and implementation. Within "every classroom" the team works with an active pedagogy, which includes only a "little lecturing" and projects, where students are "actively collaborating." Sharing this pedagogy in the early days of ISC involved a set of very detailed notes, compiled to share with the next generation of teachers. This set of notes has been updated with new innovations, and some projects that students have done. From the mix of meetings and written materials the faculty, spread out in primary appointments in four or more departments, are able to share what they are learning while teaching ISC.

Teaching quality is assessed through university teaching evaluations, and by watching how well students are doing in other classes after ISC. The junior faculty in ISC are also observed by peers in the classroom as part of their tenure and promotion review. Student learning is assessed through analysis of grades, and also to look at what sorts of courses and research students do after ISC. Since their program has been around for six years, they also can look at the careers for students after ISC, and compare that with comparable students outside of the ISC.

## University of British Columbia, Science One

Science One is a single 27 credit course offered at the University of British Columbia (compared to a 36 credit full course load), which is offered to 75 first-year students by a team of 8 instructors. The Science One instructors include faculty from four disciplines, representing both include Educational Leadership track faculty and research-active faculty. Science One is described in its promotional materials as a "community, a place where you can immerse yourself in science." Science One is an intensive first-year introduction to science that integrates biology, chemistry, mathematics and physics. The Science One program includes a dedicated classroom and study area, and makes use of the resources of UBC and adjacent field stations to provide "the highest level of first-year science offered at UBC." Examples of the high-level work includes a field trip to the UBC Bamfield Marine Science Center, a nearby marine biology research station, team research projects designed and conducted by students, and special guest lectures by a wide range of distinguished scientists. As described on the Science One web site, "Science One was founded on the idea of giving first-year students an advantage by giving them access to the best teachers and researchers."

The Science One program has a very long history that goes back to 1991, when the Faculty of Science at UBC decided to develop a program to develop graduates who can "tackle problems that require tools from more than one discipline (Dryden, et al, 2012)." The "value-added" of the program analyzed in terms of grades for students at UBC and show increased grade point averages for Science One students, even when controlling for the GPA within High School (Dryden, et al 2012). To learn more about the program, I interviewed Chris Addison, the current Director of Science One.

Chris describes how he is able to recruit faculty from across the different disciplines for Science One, by stressing to the faculty the unique opportunity to learn how different disciplines approach subjects and teaching. The additional value, according to Addison, is that the Science One faculty can then come back to their disciplinary home with new perspectives. Prof. Addison explained how the team shared information on their work while teaching. The Science One teaching teams all meet weekly and spend about a week in May when they are fresh to go over things. Each discipline in Science One has 2 instructors - one "Educational Leadership" track instructor and one research-active faculty. The instructors learn organically about teaching approaches by attending a wide range of classes, with most or all of the instructor team members attending most of the classes. The Science One instructors will commit to a multi-year segment (3 years) to insure continuity. Chris is always on the lookout for good candidates for teaching and stresses that this environment is an ideal laboratory for new types of pedagogy. The grading is also separate for each discipline and is determined by the faculty teaching each year. Within one year, for example, the physicists preferred 2 midterms while the chemists and biologists preferred a single midterm. Each discipline within Science One is allowed to have their own assessments, and they adopt diverse teaching styles within their sections. In the team meetings they discuss with the group how they approached individual topics, and the progress of individual students. These meetings are also able to determine the topics to cover in tutorial sessions which are offered weekly. Often these discussions also give ideas for new topics to stress in the class, such as entropy and enthalpy with DNA.

The long track record of Science One makes it relatively easy for faculty to get to know the aims and approaches of the course. Prospective Science One faculty are brought in to watch courses, and then observe the process which involves a large block of time during a week – some 14 contact hours of class time each week, with an additional 2 hours of tutorial time and 6-9 hours of laboratory time on top of the classroom sessions. One key feature that helps the faculty share pedagogy and ideas is that the Science One teaching team is co-located in the same place with offices near a student study space. This co-location assures that the teaching team is easily able to see each other and to provide feedback on the teaching as they are all watching the classes together. Even the research-active faculty have a shared office space in this location to improve interaction. The frequent observation of teaching by peers, and weekly enable the group to become familiar with both the goals and methods in each other's teaching. The 8 instructors in the Science One team deploy diverse forms of pedagogy, ranging from Team-Based Learning (TBL) in a chemistry section to more traditional board work in a math section. The constant observing and interaction within the team assures a steady flow of ideas on pedagogy and feedback on effectiveness, and sharing between disciplines. The teaching team tries to develop a high level of trust and mutual respect to enable each instructor to describe how someone from their discipline sees things, and then to add this diversity of perspectives to enrich the course.

The assessment of teaching is done through student surveys, which gives an assessment of the performance of all the instructors in the course. Because the course is so interconnected, with pairs of instructors in the class at all times, some students can find this challenging as they are required to separate the instruction from the individual professors. The semester student survey is complemented by an end of year exit survey which allows for more qualitative data about the program and a reflection on the teaching and their learning during the year. To assess the learning of students, the Science One team is developing two unique instruments - one for assessing interdisciplinary attitudes toward science, and another to provide data on a student's approaches to solving problems in science. The first instrument is a different kind of science attitude survey that specifically probes attitudes toward interdisciplinary work, and the second is designed to allow students to divide a problem into different disciplines through sorting cards - and records how students see how pairs or multiples of disciplines would bear upon a sample scientific problem. These two tests are being refined and prepared for publication and sharing, and in addition to the curriculum of Science One, has the potential to make a major contribution to interdisciplinary science instruction. Prof. Addison noted that the philosophy of Science One is to "have our own disciplines, but then find ways to connect those together."

## McMaster University, iSci Program

iSci at McMaster University is an "honours, interdisciplinary, research-based science program" designed to provide graduates with "high level research and communication skills" which as described in their own literature has been developed by an "unconventional group of collaborators, crossing discipline and administrative boundaries." Carolyn Eales, the iSci Program founder and former director, and Chad Harvey, Associate Professor in the School of Interdisciplinary Science, were interviewed for this study.

The iSci program was envisaged in 2007, and began in 2009, and currently accepts 40-60 students each year, selected from over 450 applicants and is operated by 5 faculty and several staff members who create the instructional team. They employ a pedagogy known as "Research-based Integrated Education" which structures the learning around specific research problems. They provide these scaffolded research projects to "motivate learning" and to engage all of the scientific disciplines. Among the topics studied in iSci are interplanetary exploration, pandemics, climate change, medical imaging, sustainable energy, environmental contamination, genetic modifications and "the complex issues facing society" that require "collaboration between multidisciplinary teams of scientists with the expertise to think creatively." The program progress through four levels in each of the four years. The program begins with a Foundations course, which study topics such as explanatory exploration, drugs, sustainable energy and cancer along with labs and science literacy training and additional electives. In the second year, iSci branches into a wider instructional team that develops six research projects with additional laboratory, science literacy and mathematics training. In the third year, the Level 3 program develops three more intense research projects followed by an independent project and concentration specific elective courses. Finally in level 4 students complete their iSci Thesis projects and participate in a seminar. A strong emphasis on scientific literacy is developed throughout the four years and the program is integrated with the university library with a HQ in the Science and Engineering library and the head librarian co-leading the scientific literacy component.

The faculty for iSci were originally selected by the McMaster University Dean of Science specifically for their potential interest and ability for interdisciplinary work from many different departments, at a wide range of ranks. Within the early group of faculty were also two faculty specifically recruited and assigned to teach in the program. Part of their preparation was an extended 8-month design exercise whereby the faculty "deconstructed" the first-year science program and together decided what each of the key essential concepts were from the various disciplines. iSci also incorporated staff members, such a librarian, into the teaching team. The deconstruction was followed by a construction using a deep look at potential research problems, and building up with the "key essentials" from each discipline (including knowledge, skills, experiences, and concepts). Then the group identified big topics – relevant to today - such as sustainable energy and planetary exploration as a unifying element, which provided something of a "interdisciplinary quilt" that structures the first-year program. Within the quilt they integrated fundamental concepts from each discipline and also the research problems that students would work on. New faculty when joining are helped to understand how unique the iSci program is and to be fully involved in the many meetings and discussions.

Once the iSci faculty launched the program, the team also consciously structured frequent bi-weekly meetings and frequent co-teaching opportunities so faculty could share ideas about both teaching strategies and disciplinary approaches to topics. A month before the term begins a master schedule is created for each of the different class sections throughout the term. Faculty collaboration was further fostered by the continuous development and improvement of the course. The iSci program includes iCons seminars which are co-taught by two or more instructors and other courses where more disciplinary topics are covered. Standardized teaching evaluations are completed for each of the faculty (even when co-teaching) which the Director reviews with faculty to help improve in their teaching. An additional channel of communication from students was a dialog between first year and more advanced student mentors, who meet regularly to discuss the curriculum, and to review survey data from students and other feedback. Grading consistency was achieved by considering iSci students relative to "average level of students at grade" – thereby lessening some of the competition within students involved in iSci. In many cases peer evaluation of group projects were conducted, allowing students to have a role in assessing their learning and in assessing the contributions of their peers. These assessments were also discussed frequently in group meetings, and a rich set of conversations across the iSci faculty helped assure sharing about teaching strategies and consistency with grading. Taken together, the iSci program provides a laboratory for teaching, with many from the teaching team has been published (Symons et al 2017).

## Yale-NUS College, Foundations of Science

For completeness, the year-long interdisciplinary introduction to science at Yale-NUS College known as Foundations of Science is described below. This program was organized as part of the Yale-NUS Core curriculum, and was taken by the second year students who were not intending to concentration in the sciences. The author was one of the designers of this course, and taught or led the course during all three years of its implementation – when it was offered as a year-long two semester sequence in 2014-15, 2015-16 and as a one-semester course during 2016-17. The same questions that were asked of our interviewees are answered below, following a brief description of the course.

The Yale-NUS College common curriculum spans two years of undergraduate education in humanities, social science and the natural sciences. One of the key components during the first years of Yale-NUS College was the year-long Foundations of Science course, which was taken during the second year by nearly all of the Yale-NUS students. Foundations of Science (FOS) was intended to be the main science course for non-majors in science, and was designed to be an interdisciplinary exploration of science that built upon the work students have done in the first year of the common curriculum.

Within FOS each of the eight instructors in the teaching team offered a 5-week or 6-week "disciplinary case study" short course in their disciplines. Students took two of these disciplinary case studies in each semester from their instructors, and then groups of students were asked to work on projects that differed from each of the implementation years. The entire teaching team of eight professors met on a bi-weekly basis to plan and review the course. The scheduling of the course allowed for four units to be taught at each of two times, to enable students to sample two of the four offerings during the semester, giving them exposure to four different disciplines through the year.

For the FOS implementation in academic year 2014-15, the disciplinary case studies were merged with an immersive field trip, in which students visited Langkawi Island in Malaysia, and performed observations of ecology, beach erosion, astronomy, and field biology, as well as discussed topics such as mathematics and cancer with the instructional team. For the FOS implementation in academic year 2015-16, the disciplinary short courses were aligned with two themes - Evolution (the study of gradual change within the world through the laws of physics, chemistry and biology) and Revolution (the study of sudden disruptive change through both disasters and disruptive technology). The Evolution theme units were taught by instructors from the disciplines of Field Ecology, Biology, Chemistry and Astronomy, while the Revolution theme units were taught by instructors in the disciplines of Earth Science, Physics, Computer Science and non-technology. A listing of Yale-NUS FOS instructors for the eight units within the two theme areas during 2015-16 is below:

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**Evolution Theme Disciplinary Case Studies**

Antonia Monteiro - **"Novel Traits"** (biology)
Jen Sheridan - **"Biogeography"** (field ecology)
Stanislav Presolski - **"Chemistry of Life"** (chemistry)
Bryan Penprase - **"Finding and Maintaining a Habitable Planet"** (astronomy)

**Revolution Theme Disciplinary Case Studies**

Andrew Bettiol - "**Modern Physics and the Silicon Revolution** " (physics)
Simon Perrault - **"Interaction with Mobile and Wearable Computers"** (chemistry)
Lerwen Liu - **"Nanotechnology and Sustainability"** (nano-technology)
Brian McAdoo - **"Earthquakes"** (earth sciences)

At the end of each semester, groups of four students were brought together to work on a Grand Challenge problem that allowed them to apply and integrate what they learned in the disciplinary case studies. The teams included one student in each of the four discipline areas. The teams were asked to design a technology or research program to address one of two questions:

> For the **Revolution theme:** *"Design a new disruptive technological innovation that can be used to deal with one of the consequences of global climate change."*
> For the **Evolution theme:** *"What are some likely future adaptations of organisms and communities to the anthropocene?"*

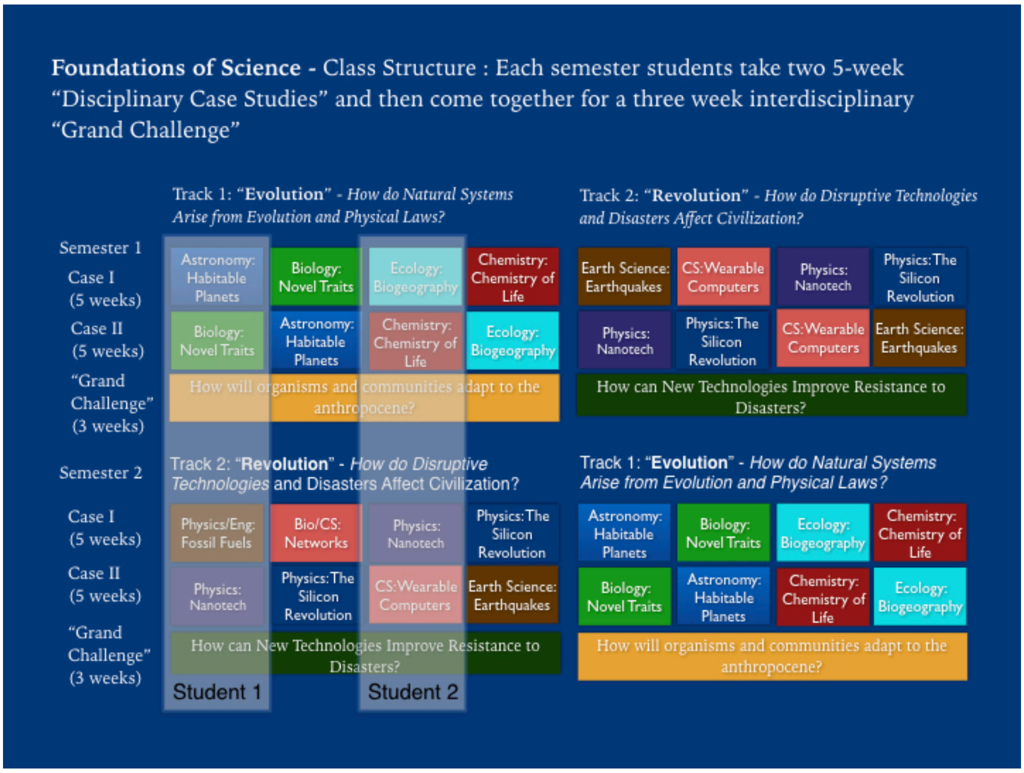


**Figure 11:** Schematic of the Yale-NUS College Foundations of Science course, showing the way in which students would move through two “Disciplinary Case Studies in each semester, followed by a Grand Challenge problem.

Each of the teams were asked to design their own research program or to invent their own "disruptive technology" to answer these questions, and their results were presented in a poster session. During the second semester of FOS, students swapped theme groups and took two additional disciplinary case studies. The second semester included a slightly different mix of instructors and topics, but within the same framework, and with a second Grand Challenge question and poster session. A schematic of the sequence of short courses and Grand Challenge exercises is shown above in Figure 7.

In the final year of Foundations of Science (2016-17), the course was offered as a single semester after the Yale-NUS common curriculum was reduced by two courses. This single-semester offering included just the two disciplinary short courses, and was without the Grand Challenge exercise at the end.

Throughout all three years of Foundations of Science, a large teaching team of 8 or more instructors was used to offer the various disciplinary half courses. This teaching team was very heterogeneous, and consisted of a mix of Math, Physics, Astronomy, Geology, Chemistry, Biology and Computer Science professors, along with several adjunct and visiting professors (including one Engineering visitor from Yale University). In most cases, teaching teams were assigned shortly before the beginning of the semester, and so there was not an extended period for the team to share their pedagogical approaches and grading philosophy. The teaching assignments would also change from semester to semester, with only a few of the teaching team continuing on for multiple semesters or years.

This heterogeneity of the teaching team made the "disciplinary case study" model both attractive and necessary as there was not enough time for a fully integrated course to be developed. Despite these difficulties, the teaching team would meet regularly to have productive discussions eight or nine times during a semester. These were typically lunch discussions, and instructors would update the team on how their short courses were going, share information on grading and plan the common activities within the course (the Langkawi field trip, and Grand Challenge exercise, along with some guest speakers). Information was shared during all of these meetings on what each section was doing and common frameworks for grading projects and units were developed. In some cases, faculty would visit other sections, allowing for some transfer of knowledge about pedagogy, and within the course student evaluations and some focus group interviews after the course were done to assess the quality of teaching.

Because of the heterogeneity and variation within the disciplinary case studies, the Foundations of Science model was modified toward a more common experience type of course within the Common Curriculum at Yale-NUS during 2017-18. The new course, known as Science 2, did retain some of the elements of the old Foundations of Science course. In the new Science 2 course, a larger segment of "common" materials (3 weeks) was followed by a "deep dive" 5-week segment, which differed somewhat based on the instructor's expertise, but was aligned with the common theme of Global Warming. The ending of the course, like FOS, also included an integrative 3-week exercise which in some ways is reminiscent of the FOS Grand Challenge exercise. The strength of the disciplinary case study short course model is that it enables faculty to teach within their expertise, and if combined carefully with common units and a chance for students to apply their knowledge within the short course, can be a very effective model. This model does however require careful coordination of the faculty within the various sections, and ideally a period of continuity of multiple years within the teaching team for it to reach full effectiveness.

## Overview and Analysis of Findings from Interviews

To interpret the results from the interviews and studies of the various courses and programs, I have divided the courses into three groups, based on their durations in number of semesters or years.

### Single-Semester Interdisciplinary Science Courses

The first group considered are the courses which last for a single semester, which includes the courses shown below in Table 2. Within the shorter format, the degree of integration and coordination between the various instructors depends on how the course is structured. For Fundamentals of Modern Science and Integrated Science, a team of instructors conferred frequently and shared the grading within the course so that each instructor would grade the portion of the course that aligned with their expertise. This assured consistency across the whole group of students, but also provided some variability in grading from one assignment to the next. In Foundations of Science, each instructor would be responsible for grading their own disciplinary case study section, but the grades from these sections would be discussed within the teaching team, and a concerted effort was made to assure that the grade distributions were fair and did not have large deviations from one section to the next.

**Table 2:** Interdisciplinary Science Courses for 1-semester, with topics covered, thematic unifier, and number of instructors in the teaching team (N).

| Institution | Leader | Course | Topics | Thematic Unifier | N |
|---|---|---|---|---|---|
| *University of Hong Kong* | *JCS Pun* | *Fundamentals of Modern Science* | *Atoms, Molecules, Cells, Organisms, Earth, Universe* | *Scale - from small to large – with particles and physics, chemistry and biology* | *4* |
| *Yale-NUS* | *Shaffique Adam, Jan Gruber* | *Integrated Science* | *Circulation, Fluid Dynamics, Harmonic Oscillator, Water Molecular physics* | *Water – and viscosity in Chemistry, Biology and Physics* | *5* |
| *Yale-NUS* | *Bryan Penprase* | *Foundations of Science* | *Disciplinary Case Studies - Habitable Planets, Biogeography, Wearable Machines, Networks, etc.* | *Modes of Inquiry - Field Observation / Lab Experiment (2016)* | *8* |

Sharing pedagogy within a one-semester course also varied within the group of courses, with only the Yale-NUS Integrated science course featuring the entire team of 5 instructors in the classroom. This approach provided a lot of collaboration and real-time response from the interdisciplinary teaching team, but required a lot more time from the instructors. The other two courses featured instructors who each would discuss material in their own classroom, but frequent meetings of the instructor team would share ideas in pedagogy.

For all three of these courses, the diversity of students and instructors provided serious challenges. At the University of Hong Kong, and Yale-NUS College, students typically studied within a British-style high school, which caused them to be highly specialized in their science topics before arriving to the interdisciplinary course. This disparity in student preparation provided serious challenges to the instructors and in all three cases have resulted in the courses undergoing a major restructuring.

### Year-long Interdisciplinary Science Courses

The second group of courses considered are year-long courses, which includes the courses shown below in Table 3. It should be noted that the Princeton Integrated Science course after 2016 has also adopted a year-long format, but the research in this study considered the structure of the course before 2016.

**Table 3:** Year-long Interdisciplinary Science Courses with topics covered, thematic unifier, and number of instructors in the teaching team (N).

| Institution | Leader | Course | Semesters | Topics | Thematic Unifier | N |
|---|---|---|---|---|---|---|
| *Keck Science, Claremont Colleges* | *Scot Gould, Katie Purvis-Roberts* | *Accelerated Integrated Science Sequence (AISS)* | *6* | *Integrated Intro Physics, Chemistry and Biology* | *Macromolecules, Physical properties of biomolecules, informatics* | *3* |
| *University of British Columbia* | *Chris Addison* | *Science One* | *2* | *Intro Biology, Chemistry, mathematics and Physics* | *Thermodynamics, Rates of Change, Electrostatics* | *8* |
| *Foundations of Science* | *Bryan Penprase* | *Foundations of Science* | *2* | *Disciplinary Case Studies - Disasters, Biogeography, Wearable Machines, etc.* | *Immersive Field Observations (2014); Grand Challenge Projects (2015)* | *8* |

The group of year-long courses feature large teaching teams who have worked together for various lengths of time. Within the AISS course, a group of three instructors would work together for an entire year, and typically continued for a three-year rotation. This duration of time allowed the team to learn how to work closely with each other in the classroom, and instructors within AISS commented on the importance of the in-class team discussing and debating scientific issues as a major feature of the course. The curriculum within Science One was similarly developed by a large team with years of continuous experience, extending back to 1991, with some instructors, like Chris Addison, with over 8 years of experience in the course, and all instructors in the course committing to a 3-year term to insure continuity. The Yale-NUS Foundations of Science course, by contrast, was only offered for two years in the year-long format, and included a diverse and changing set of instructors that would turn over nearly completely from year to year, and often would include adjuncts and visitors for single semesters at a time. The success of each of the year-long courses seemed to rest on strong rapport within the instructor team, an extended period of planning and discussion before the courses began, and long-term continuity in the teaching team. Any multi-semester program should consider providing the necessary resources and staffing to provide continuity over multiple years to allow for the instructor team to adapt to the interdisciplinary format.

For both the AISS and Science One courses, students elected and applied for selection to the interdisciplinary environment, allowing for the instructors to be sure that the student preparation and expectations are appropriate for the more challenging interdisciplinary environment. For the Yale-NUS Foundations of Science course, all students were required to attend the course and many had little interest or preparation in science, making the interdisciplinary course more challenging to teach. It may be advisable to have students elect for interdisciplinary programs of this kind, and to also be sure they have a uniform level of preparation before they begin the programs.

## Multi-year Interdisciplinary Science Programs

The third group of interdisciplinary science programs considered were multi-year programs, which includes the courses shown below in Table 4. Like some of the one-year interdisciplinary courses, students were selected to the programs after an application program, making for well-prepared and highly motivated students. This is the case for all of these multi-year programs, with the possible exception of the NYU Abu-Dhabi Foundations of Science program, which was the pathway for students intending to major in the sciences.

**Table 4:** Multi-year Interdisciplinary Science Programs with topics covered, and numbers of semesters and years for the Program

| Institution | Leader | Course | Semesters | Years | Topics |
|---|---|---|---|---|---|
| Princeton University | Joshua Shaevitz | Integrated Science | 6 | 3 | Computational Biology, Biochemistry, Molecular Biology |
| University of Massachusetts, Amherst | Scott Auerbach | iCONS | 5 | 4 | Global Challenges, Science Communication, Discovery Laboratory, Research Project |
| Virginia Tech | Michel Pleimling | Integrated Science | 8 | 2 | Fundamental Physics, Chemistry and Biology, and Math |
| James Madison University | Jeffrey Tang | Integrated Science and Technology | 8 | 4 | Technology, Environment, Telecommunication, Complex Problems, Biotechnology |
| NUS | Adrian Lee | Special Programme in Science | 8 | 2 | Discovering Science, Atoms to Molecules, The Cell, The Earth, The Universe |
| NYU Abu Dhabi | David Scicchitano | Foundations of Science | 6 | 2 | Physical Science, Molecular Forces, Shapes of Molecules |

In most cases students had shown prior aptitude and talent within the sciences, and represent an "elite" cadre of future researchers, for which the interdisciplinary environment is a stimulating way to integrate an already sound fundamental science preparation. Recognizing the extra challenges that come to students from an interdisciplinary course, especially in the presence of different preparation levels, is extremely important for program success.

Nearly all of the instructor teams for these multi-year programs were housed and appointed within the same unit. The geographic co-location of faculty in many cases was reported as a significant and necessary element in the success of the interdisciplinary program. Examples include the Princeton Integrated Science program, which featured a group of faculty largely housed at the Lewis-Sigler Institute, the U Mass iCONS program, which included a dedicated Integrated Science Building for the program, and the NUS Special Programme in Science, which houses the faculty and labs within a single building that can be flexibly configured. In cases where faculty are not co-located, having appointments specific to the multi-year program, and an active regime of recruitment and training is essential for success. Examples include the U Mass iCONS program, the Virginia Tech Integrated Science program, and the JMU Integrated Science and Technology program, where faculty were specially appointed and trained specifically for the program. These strong connections between faculty and continuity are essential for the longer-term programs, and in all cases required significant institutional commitment for the programs to be possible.

## Recruiting and preparing faculty for Interdisciplinary Science

Throughout the study, a wide range of motivations for interdisciplinary science were cited, and in some cases interdisciplinary courses arose naturally from themes or problems that were intrinsically interdisciplinary. Having a natural interdisciplinary integrating theme – such as global warming, unified processes over a range of spatial scales, or interconnected problems within environmental science – provided a strong motivation for the interdisciplinary work. In both the iCONs and AISS courses, the interdisciplinary science courses arose from "inherently interdisciplinary" contexts. In both cases the course becomes a vehicle for knitting together a "community of practice" as it is the "artefact" within the community that becomes joint intellectual property. The large degree of difficulty and institutional resources required for interdisciplinary science programs should require that the courses strive for authentic interdisciplinarity and not seek interdisciplinary formulations for their own sake.

Preparing students and faculty for the interdisciplinary environment is crucial. The majority of these programs are offered to a pre-selected "elite" group of students, which allows for the program to succeed, but also raises some troubling questions about access and scale. For such programs to reach a larger fraction of students, or to serve less prepared students, a means for leveling preparation before the course needs to be found. Some general education interdisciplinary courses, such as the Yale-NUS Foundations of Science and University of Hong Kong Fundamentals of Science had no pre-selection, and attempted to serve the more diverse preparation. Such courses may consider some kind of intensive "boot camp" experience to prepare students for the intense interdisciplinary environment and to shore up skills withn the student population before the course begins.

The NUS SPS, iCONS AISS and UBC Science One programs are able to offer active learning and student-driven inquiry in their daily classes, and these principles have been successfully implemented by having the pedagogy drive the content chosen for the course. It became clear that once a strong theme for the interdisciplinary inquiry had been found, having pedagogy as a primary driver of content was a powerful tool in uniting faculty even as they come from different disciplinary backgrounds. The use of backward course design, with clearly articulated and assessable learning outcomes as a primary design principle, was also a powerful tool for unifying and clarifying the curriculum for both students and faculty. Using innovative assessment strategies, such as the iCONs self-assessment by students, enables the instructors to provide more agency within the student population for their learning, further increasing engagement within the students.

In several cases, the interdisciplinary course or program is able to bring together an entire department in the design of curriculum and laboratory exercises, and this strengthened the community of faculty and became a useful vehicle for sharing pedagogical approaches across the diverse spectrum of disciplines. Managing these relationships across an entire department, and sharing the task of development of a course broadly not only can make the course development more effective but can provide greater stability and sharing of course content and pedagogy. The use of extended periods for course design and building a teaching team was in place for most of the programs, and the investment in significant time for planning and discussing teaching strategies strengthened the bonds within the teaching team that enabled them to discuss teaching honestly and openly.

From the interviews with the Princeton and HMC instructors, it became apparent that a wide range of coordination between instructors can exist and still produce excellent outcomes. The Princeton Integrated Science represented a minimalist level of structured and required meetings, because of a high degree of familiarity with the long-established curriculum among the faculty and because the large number of informal contacts between students, faculty and preceptors enabled multiple points of contact and channels of communication within the community. Within the Harvey Mudd College context, the effort to produce standardized class materials required intensive negotiation but the level of detail also enabled both instructors to gain deep insight into subtleties in presenting and conceptualizing math materials in their sections. In both cases, the necessity of clear and frequent communication, and deep personal relationships among the team and their students made the development of a quality interdisciplinary course possible.

From the interviews of the several teaching teams, it is clear that interdisciplinary instructors need to provide frequent negotiation between disciplinary perspectives within a teaching team to give deep insights to the instructors and improve the quality of the course. Regardless of how the courses are designed and maintained, the significant investment of time needs to be made to build a truly interdisciplinary curriculum, to allow the faculty to understand the boundaries and overlaps in disciplinary expertise, and to find areas where synergies from blending disciplines can deepen student learning. This process is difficult but from our study it is clear that it can provide perspectives and understanding in both students and faculty that make it worth the effort.

## Building a Community of Practice in Interdisciplinary Science

Having a natural interdisciplinary integrating theme – such as global warming, unified processes over a range of spatial scales, or interconnected problems within environmental science – provided a strong motivation for the interdisciplinary work in most of the courses studied. In the Claremont AISS, Princeton Integrated Science and Yale-NUS Foundations of Science and Integrated Science courses, the interdisciplinary science courses identified "inherently interdisciplinary" contexts to integrate disciplinary expertise. As such, the interdisciplinary course becomes a vehicle for knitting together a "community of practice" among the science faculty and becomes a form of joint intellectual property that strengthens the curriculum and program. Such communities of practice are essential within institutions (Roxa et al 2008) and are typified by groups of people who "share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis" (Wenger, 2002). The large degree of difficulty and institutional resources required for interdisciplinary science programs requires practitioners within interdisciplinary science to maximize efficiencies within their curriculum, and communicate effectively about the benefits from interdisciplinary courses as they build the strong community of practice necessary for a successful program.

Preparing students and faculty for the interdisciplinary environment is crucial. The majority of these programs were offered to a pre-selected "elite" group of students, which increased the success rates of students, but also raised some troubling questions about access and scale. For programs to reach a larger fraction of students and to serve less prepared students, a means for leveling preparation before the course needs to be found. General Education interdisciplinary courses, such as the Yale-NUS Foundations of Science and University of Hong Kong Fundamentals of Science had no pre-selection, and faced challenges in teaching students with diverse levels of preparation. Such courses might benefit from some kind of intensive "boot camp" experience to prepare students for the intense interdisciplinary environment and to shore up skills within the student population before the course begins.

Most of the studied programs offer active learning and student-driven inquiry, and when these principles have been successfully implemented, the pedagogy can help shape and limit the scope of content chosen for the course. Having pedagogy as a primary driver of content was a powerful tool in uniting faculty from different disciplinary backgrounds. The use of backward course design, with clearly articulated and assessable learning outcomes as a primary design principle, was also a powerful tool for unifying and clarifying the curriculum for both students and faculty. Extended meetings for course design and building the teaching team requires a significant investment in time, but in many cases resulted in strong bonds within the teaching team that improved the curriculum and its assessment.

From analyzing the results from our interviews with leaders from 7 interdisciplinary science programs in 4 countries, we have identified a set of "best practices" in preparing faculty for teaching in the interdisciplinary science program, for collaborating and communicating grading and pedagogy within the course, and for assessing the outcomes of students. These practices were observed in multiple of the most stable and long-running interdisciplinary programs and were reported to improve the quality of the teaching and instruction. A summary of these effective practices is presented below in Figure 10 and tabulated in Table 12.

**Table 5 –** Effective Practices within Interdisciplinary Science programs and courses

| Topic | Best Practices |
|---|---|
| Faculty Preparation and Selection | Faculty selected based on interest and ability in interdisciplinary science; assigned to units or programs for multiple years, and co-located with other interdisciplinary scientists |
| Faculty Collaboration | Frequent meetings including pre-course planning meetings, and regular weekly or more frequent contact to discuss curriculum and pedagogy; having offices and laboratories close together; co-teaching in same class to increase discussions and observations of pedagogy. |
| Faculty Grading Processes | Providing systems whereby disciplinary content experts grade sections relevant to their expertise, and assignments with components graded by multiple faculty |
| Assessment of Programs | Discussing and monitoring performance of students in subsequent classes and in research; developing statistics and input from alumni about their employment and research progress. |

We observed that a wide range of strategies for coordination between instructors can produce excellent outcomes. The Princeton Integrated Science represented a minimalist level of structured and required meetings, because of a high degree of familiarity with the long-established curriculum among the and from multiple points of contact and channels of communication within the community. Within the Harvey Mudd College context, the effort to produce standardized class materials required intensive negotiation and time, which also enabled the instructors to gain deep insight into subtleties in presenting and conceptualizing the materials in their sections. In all cases, the necessity for clear and frequent communication, and deep personal relationships among the team and their students made the development of a quality interdisciplinary course possible.

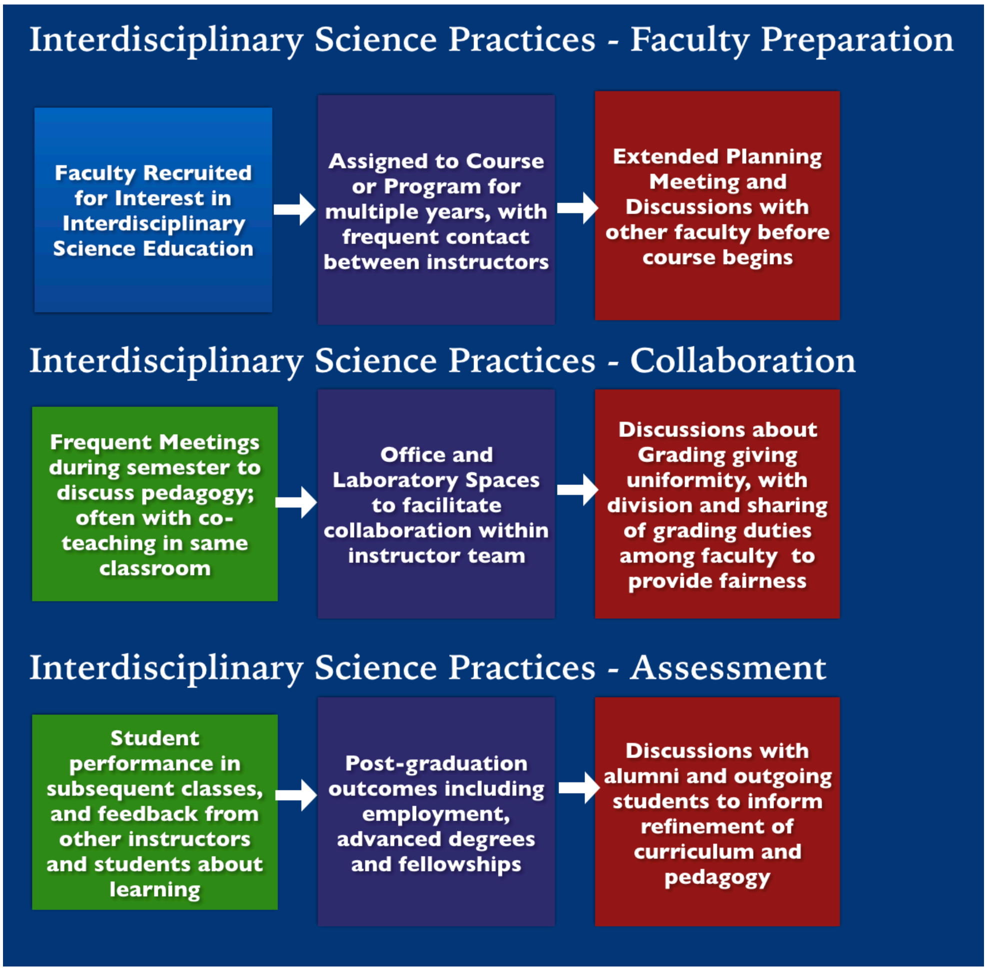


**Figure 12:** Visual representation of "best practices" within interdisciplinary science courses and programs, divided into categories of faculty preparation, collaboration and assessment.

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