Chapter 5: The New Age of Active Learning and Scientific Teaching

The ACE fellowship can sometimes be described as an "anthropological field study of administrators." Like an anthropologist, one travels to a foreign land and adopts the foreign customs, vernacular and culture of the world of administration - in this case wearing suits, attending meetings about strategic planning, and using terms like "value-added" and "faculty development." In my ACE year of "field study" thinking about science teaching was like returning to my own tribe. The classroom experience of making a subject come alive, finding new opportunities for undergraduates to conduct research, and innovating in teaching were topics that all of us strived for at Pomona College, and this effort constituted over 20 years of my career teaching physics and astronomy.

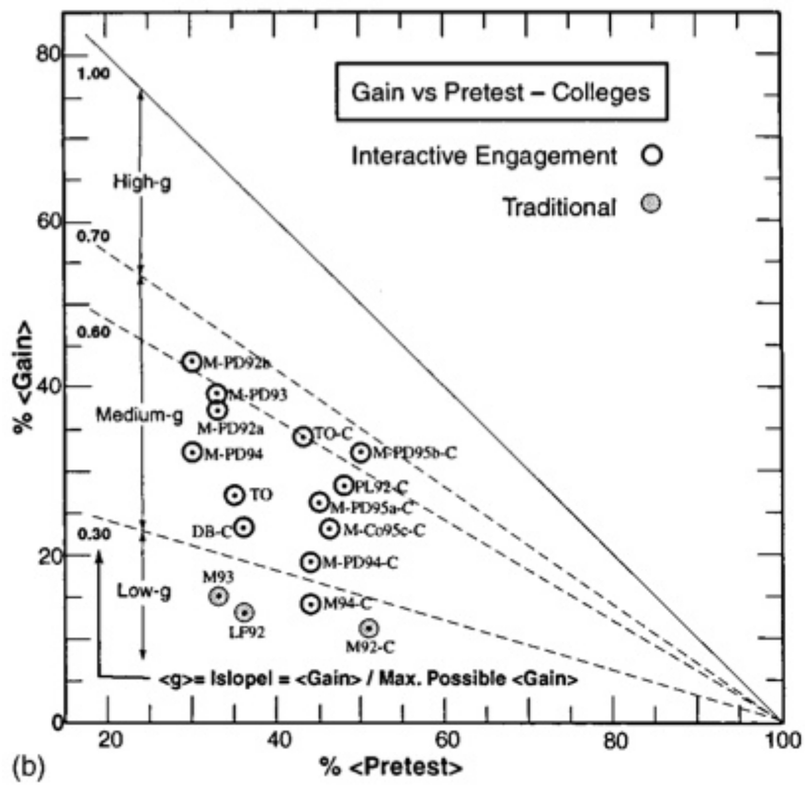
Just as your home town looks different after a long journey, however, I began to notice that what I thought was familiar - science teaching - was changing very rapidly. Other colleges and universities were striving for the same objectives, but finding diverse ways to improve the quality of instruction and undergraduate engagement. More remarkable to me was the way in which a convergence of psychology, cognitive science, and educational theory had actually created a new scholarship of teaching. The results of hundreds of experiments at the institutional, disciplinary, and course level are now documenting quantifiable advances in the quality of experience for students - and many of these institutions, majors and courses were very different from the familiar ways I thought were best from my own experiments at Pomona.

I began also to learn about how the science of teaching has arisen and transformed what is possible in a classroom. By using new course design principles such as "Scientific Teaching" or "backward course design" or "Constructive Alignment" instructors can create courses that are well-designed mechanisms for enabling learning. Using well defined learning outcomes that are assessable and based on practice, students and instructors can see their progress through the course. After seeing how much progress has been made, I had something of a Copernican moment when I realized there is much more to teaching than one's own classroom, one's own subject and one's institution. Just as one can collaborate in science research, it is entirely possible to collaborate on course development, assessment, and learning outcomes. By having access to a large community of scholars in teaching, it is possible to be liberated from the "tyranny of own's own experience" which is necessarily limited to small numbers of students, courses and outcomes. The exploration of this world is described below.

Peer Learning and the Force Concept Inventory of Physics

Within my home institution of Pomona College, my colleague Tom Moore has been a leader in physics education with his "Six Ideas That Shaped Physics" curriculum, and his approach of having students work problems within class. Years before clickers were invented, Tom was gathering feedback in class with cards showing multiple choice answers (A,B,C,D or E), or small whiteboards for equations. Tom's efforts have created a widely adopted curriculum for introductory physics that not only features advanced topics usually only seen in later courses (quantum mechanics, relativity, and thermodynamics), but also uses most of class time for students to work on problems instead of listening to lectures. When Tom began doing this work in the early 1990's it was revolutionary, but new research has shown that this approach results in large learning gains over a traditional course. Tom's own results confirm the effectiveness of the class, as his "problem based learning" teaching style gives larger gains in the widely used physics test known as the Force Concept Inventory than traditional classes (The 'Six Ideas' site is http://www.physics.pomona.edu/sixideas/sisuc.html)

The "Force Concept Inventory" and also the "Mechanics Baseline Test" are two powerful assessment tools developed by physicists to measure the degree of student physics insight. The use of this tool has greatly advanced physics teaching, since it has been widely used in all forms of physics courses - big classes, small classes, interactive classes, studio physics classes, lab classes - enabling comparisons in learning gains using this same test. In cases of different student populations, the difference in learning from the beginning to end of the course allowed the rare chance to quantify the "gain" students experience from a particular course.



Percentage gains on Force Concept Inventory tests from a set of College students, showing larger values of gains than in "traditional" lecture courses (shaded circles). This sort of quantitative assessment of learning in physics has helped validate a number of new approaches to learning the subject, including peer learning and other forms of interactive teaching. (From Hake, R., 1997)

Physics and Astronomy has several large groups actively developing new techniques in peer and problem-based learning, and finding ways to engage even large lecture classes with interactive discussions. Eric Mazur from Harvard is one main pioneer of this technique that he calls "peer instruction." The technique allows for large classes to have small groups of students working on problems during the class and reporting their results back to the instructor. One key tool in this approach is the "clicker" - infrared remotes attached to a control unit that can instantly record and display the answers coming from the class. The software and hardware has matured to a point where they are very easy to use, and now classes of several hundred can be fully as interactive as Tom Moore's small Pomona classes using the combination of peer learning groups and clicker technology. In our work at Pomona we have tried several systems and have used the "iclicker" units which we have found are the most versatile and cheapest. Even in smaller classes of 40, having the instant feedback about student opinions and answers to questions greatly improves the interactivity of the course.

By monitoring the performance of particular students on in-class questions, Eric can now identify the higher performing students, and dynamically assign groups to mix skill levels and enable students to teach each other during the class and assure that all the group members understand the exercises. Eric Mazur has expanded the community of instructors using this technique with an international Peer Instruction Network (http://blog.peerinstruction.net/), which has over 2000 members across the world who are able to share ideal peer learning exercises that optimize the experience and learning in physics classes.

Another influential force in the move away from lectures and toward active learning in class is Carl Wieman, 2001 Nobel Laureate in physics, and director of science education initiatives at the University of British Columbia and the University of Colorado. His journey as a teacher is described in a very thoughtful article in Change magazine. Carl describes what he calls the "learning puzzle:"

> *"When I first taught physics as a young assistant professor, I used the approach that is all too common when someone is called upon to teach something. First I thought very hard about the topic and got it clear in my own mind. Then I explained it to my students so that they would understand it with the same clarity I had. At least that was the theory. But I am a devout believer in the experimental method, so I always measure results. And whenever I made any serious attempt to determine what my students were learning, it was clear that this approach just didn't work."*
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> Carl Wieman, "Why Not Try A Scientific Approach to Science Education?", Change, Sept, 2007, p. 9.

Carl described his shift in thinking about teaching after examining the results from the Force Concept Inventory, and from physics student focus-groups. He observed very little learning during undergraduate courses for most students, and noticed that most students moved from "novice" to "expert" only when they were advanced PhD students working on experiments. Carl realized that active learning from these experiments integrated disconnected bits of information of physics into a "coherent structure of concepts that describe nature and that have been established by experiment." The trick is to create this same type of experience for students in the classroom, instead of waiting 7 years for them to become advanced graduate students!

Carl identified a series of steps toward new and better teaching, that are validated by educational research as more effective for promoting learning. The first step is to "reduce cognitive load" in students, who suffer when their short-term memory is overloaded by a content-heavy lecture. Slowing down, using well-designed and concise figures and less jargon, all help in making sure that students learn. The second step is to "address beliefs" that students bring to class. Instead of thinking that students are blank slates, their preconceived ideas and misconceptions actively resist concepts that contradict this "private universe." Instructors should motivate a topic by connecting the topic to things students already are familiar with, and with applications in the real world. Within the classroom environment, instructors should "stimulate and guide thinking" by designing activities to ensure students think about the processes, with frequent assessments to help them improve. And finally, Carl advocates "using technology" to make classroom more active - clickers and interactive computer simulations are two examples.

Adopting these new approaches can be difficult for professors, however, as Carl acknowledges in his article "The Curse of Knowledge - or Why Intuition about Teaching Often Fails." (APS News, November 2007). Many professors who have advanced knowledge have a very difficult time seeing the subject from the perspective of someone who does not. Brain scans show that the cognitive patterns within "experts" are substantially different from the "novices" and instructors need to recognize the profound differences in thinking of their students. In Carl's words:

> *"This fundamental difference between the novice and expert brain explains many of the findings reported by those who study student learning of physics. Students can think about a topic in ways quite unimagined by the instructor, and so a lesson that is very carefully thought out and is beautifully clear and logical to experts may be interpreted totally differently (and incorrectly) by the student. Another example is that the standard lecture demonstration has been shown to have negligible impact on learning. Many teachers find this hard to believe because the demonstration attracts students' attention and usually demonstrates an important idea in a compelling fashion....*
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> *This "curse of knowledge" means is that it is dangerous, and often profoundly incorrect to think about student learning based on what appears best to faculty members, as opposed to what has been verified with students. However, the former approach tends to dominate discussions on how to improve physics education. There are great debates in faculty meetings as to what order to present material, or different approaches for introducing quantum mechanics or other topics, all based on how the faculty now think about the subject. Evaluations of teaching are often based upon how a senior faculty member perceives the organization, complexity, and pace of a junior faculty member's lecture. In the pages of the APS news, this same expert-centered approach to assessing educational experiences has played out recently in the debate over the use of interactive simulations vs. hands-on labs."*
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> Carl Wieman, "The Curse of Knowledge - or Why Intuition about Teaching Often Fails." (APS News, November 2007)

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Gordon Conference on Astronomy Discoveries and Physics Education

To see some of the innovations in physics and astronomy education in action, I attended a Gordon Conference at Colby College in Maine in June 2012 on the topic of “Astronomy’s Discoveries and Physics Education” organized by Charles Holbrook and Peter Shaffer of MIT. The meeting was a great showcase for the wide range of innovation in astronomy and physics teaching, and the ways in which research-based instruction can inspire and motivate students. Research talks on cutting edge topics of astrophysics were given by the leading groups at Harvard, MIT, Caltech, and the ways in which these topics can be integrated into the curriculum in engaging ways was discussed. Bob Kirshner of Harvard discussed Dark Energy, David Charbonneau of Harvard and Sara Seager of MIT discussed exoplanets, and advanced telescopes were described by Tony Tyson of UC Davis (I also had a role at the conference, presenting research and teaching of nucleosynthesis, quasars and gamma ray bursts!). These research-based talks included a discussion of how best to integrate this exciting research in astrophysics in undergraduate physics and astronomy classes.

Other talks featured presentations by the leading workers in physics and astronomy education. Some of the physics education groups include the University of Colorado Physics Education group (established by Carl Wieman, and represented by Noah Finkelstein), the University of Arizona Astronomy Education Research group, led by Ed Prather, and the University of Oregon Physics Education project led by Greg Bothun. Additional talks described new ways of using remotely operated telescopes in Chile (a project known as Raptor run by Dan Riechart of UNC Chapel Hill), using vast datasets in the undergraduate curriculum. One notable example was from Andrew West of Boston University, who described how to detect and trace the history of thousands of sun-like and smaller stars in the galaxy with students in introductory astronomy classes.

The University of Colorado Physics Research group, led by Noah Finkelstein, helped frame the issues facing STEM education. Noah presented the challenge facing all of higher education - our institutions are "under threat" by being perceived as being in a "bubble" where the parents and students are faced with rising costs, and are rebelling against what appears to be an unresponsive and overpriced higher education sector. In Noah's words, universities and colleges need to "evolve or die," and providing a more engaging, interactive and effective forms of physics and astronomy teaching is his answer for how to evolve. Noah cited data from the PISA rankings, where the US ranked 21/30 in science and 25/30 in math. Helping reverse the decline of US students in science and math is the "Grand Challenge in US Education" and requires a theory of change. Somehow our colleges and universities have to be more effective in producing STEM graduates from less prepared entering students, and with fewer resources - this is the "Grand Challenge!"

The University of Colorado group is facing this challenge with a "scholarly approach to teaching," where new technologies, new curricula, systematic reform, faculty development are combined with this "theory of change" and an assessment regime. The goal is to escape the old paradigm of education which sees the student as an "empty vessel" to fill with content. Instead the students need to be actively engaged to construct knowledge, based on a curriculum that draws on the student's prior experience, and enables this "construction" of knowledge to occur through active learning exercises - the basic steps that Carl Wieman advocated.

The new scholarship of teaching carefully analyzes which curriculum and which processes in the class produces the best learning outcomes. The content for this new form of teaching is strategically chosen based on an assessment of a student's prior knowledge, attitudes, and other attributes. One tool very helpful for this assessment is known as CLASS - the Colorado Learning Attitude Science Survey, available at http://per.colorado.edu, is able to measure prior attitudes before the class, enabling instructors to tailor their classes to the students, and to monitor how the class changes students conceptions about science. The University of Colorado group has produced a vast number of papers, assessment tools and studies about physics education, which are all available at http://www.colorado.edu/physics/EducationIssues/research/papers_talks.htm.

Another example of a more active form of physics and astronomy education was provided by Greg Bothun of the University of Oregon. Greg has developed interactive applets and web sites for many years, has an extensive educational web site (http://zebu.uoregon.edu/), and is now working with technologies that make the classroom like a research laboratory for students. Rather than complaining about students looking at their laptops during class, Greg requires these laptops for students to use to answer questions in class. Greg compiles and shares students' in-class research "on the fly." By leveraging this technology, Greg is able to provide a data-centered and inquiry based class instead of lecture. As students are answering questions based on their own in-class research, conversations and debates in class provide a lively and engaging atmosphere. Greg's class is also taught without a textbook (Greg regards those as "unnecessarily authoritative"), as he prefers to promote "synthesis" within a class based on student-led inquiry.

Greg also presented a few examples of software that he has found effective in his physics and astronomy classes. One is a realistic simulation of the actual observations possible with Galileo's telescope, that allows students to answer the question: "why didn't Galileo derive Kepler's laws?" By taking their own simulated telescopic data, students are able to see precisely how the observational uncertainties prevented Galileo from obtaining the needed precision for finding Kepler's laws. Another computer exercise uses actual stellar and galaxy spectra to measure wavelengths and Doppler shifts, and then uses these measurements to attempt to detect an extrasolar planet. The simulations provide realistic amounts of noise and uncertainty, and use statistics and fitting programs to lead students in a realistic simulation of exoplanet detection. Additional "Dynamical Astronomy" applets from Chris Mihos of CWRU (http://burro.astr.cwru.edu/JavaLab/) enable students to crash galaxies together using an n-body simulation, and measure dark matter content in galaxies by simulated measurements of galaxy rotation curves. (I have used both of these approaches in my classes at Pomona, and can vouch for the way these simulations can transform a class from a passive to an active experience for students, where they are conducting their own numerical experiments to derive exciting physical models.) Greg is also a strong advocate for creative writing assignments within science courses - having students write reflective essays, policy "white papers," press releases about their "exoplanet discoveries" from the simulations, and collaborative video reports. The mix of inquiry, writing, and original projects livens up the class, and engages the students' talents and creativity better than simply working through equations.

The seamless interchange between astrophysics research and physics education was explored throughout the meeting. Bob Kirshner's presentation reviewed the 100 year history of the discovery of the expansion of the universe, from Edwin Hubble to the Nobel-prize winning groups of the past decade. The discovery of Helium and other exotic elements in astrophysics was described by Peter Parker of Yale University (who turned out to be a "suite-mate" of mine during the meeting!), and Steryl Phinney of Caltech described how LIGO and space missions will enable a refinement of our picture of gravitational waves, and "Dark Energy."

Scientific Teaching at Yale University

Being at Yale provided a great opportunity to explore science education with some of the leading minds in the country, and being an ACE fellow allowed me the rare chance to step outside my discipline and learn from how biology and other disciplines approach STEM education. One of the most celebrated of Yale's science educators is biologist Jo Handelsman, leader of Yale's Scientific Teaching group. In Jo Handelsman, Yale is fortunate to have the rare combination of an excellent laboratory scientist, top level teacher, and science education scholar, as well as a co-chair of the working group that wrote the science education report "Engage to Excel" for the President's Council of Advisors on Science and Technology (PCAST).

Jo described her role in the PCAST report, which makes the case for the need for a million new STEM workers by 2020. Jo is concerned about how the current climate of STEM education is extremely inefficient, causing many students to abandon their interests in science both before getting to college, and after enrolling. Fully 60% of students intending to major in STEM fields abandon these interests in college, and the numbers are even higher for some demographic groups, with fully 80% of African American students leaving STEM fields after college! Jo described how a “weed out” mentality exists within some science departments, as many scientists feel a need to educate only the “smartest” students. An over-emphasis on facts instead of process in STEM classes, poor math preparation from students, and particularly high attrition among women and under-represented minorities make the problem even worse.

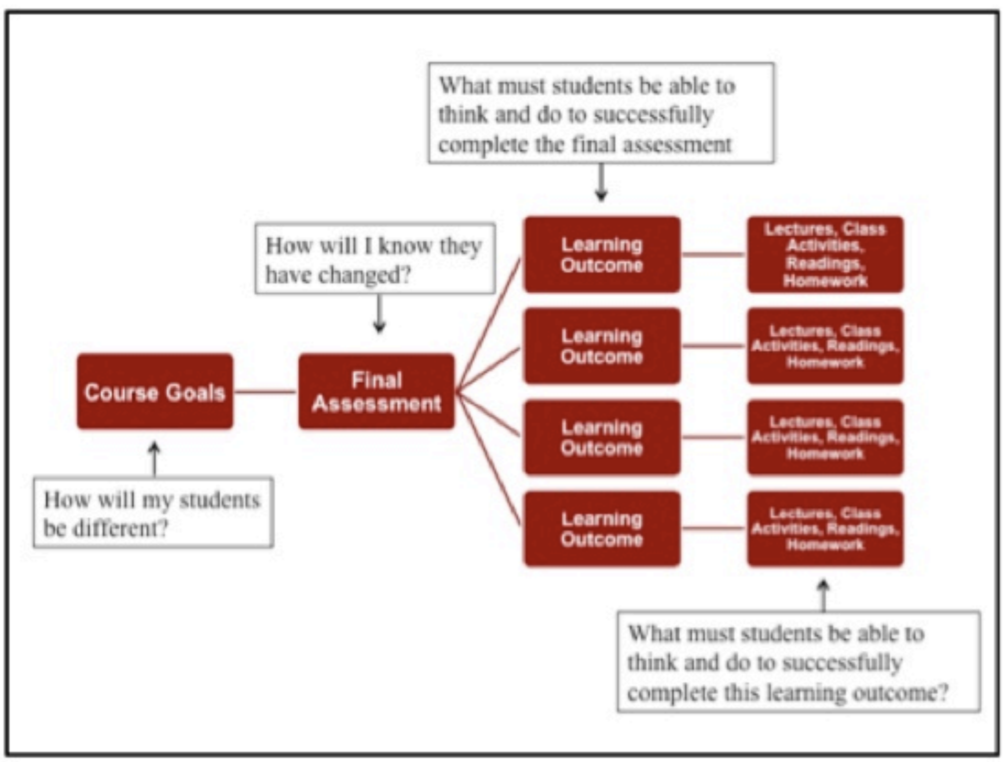
Jo explained how scientific advances are made with diverse teams, all contributing to an investigation and how the active interplay of a group both fuels scientific discovery and a good classroom. The approach Jo and her Scientific Teaching group uses blends inquiry and conceptual work to motivate content. Education research is showing that this approach leads to more effective learning and content retention. Traditional lectures result in only 10-20% of material being retained, according to Jo, but if instead if a professor chooses to “teach concepts and engage minds, they will get the content.”

To engage a class, it helps to challenge a class with a problem they can’t solve before the class, and work with a class to help them figure it out. The classroom should reflect the process and “spirit” of science, including all the students, engaged in exercises of active learning that enable students to construct knowledge. Jo led a workshop of Yale-NUS faculty meeting in New Haven in a cleverly designed demonstration that created this “spirit of science.” A video was shown in which very pure water is lowered in temperature to -6 or -8 C, and a special bacterium is added - *pseudonomis synringi* - which triggers a vial of water to freeze instantly. The video is dramatic, and was reminiscent of Kurt Vonnegut’s “Ice 9” (one example is at www.youtube.com/watch?v=SenJud3cHLc). Our group was transfixed by the video, which was presented without explanation, and then we were asked to describe what happened, and come up with hypotheses of why the water froze so quickly. The animation and engagement of our group of Yale-NUS professors was tangible and we spent about 30-40 minutes debating and discussing all the ramifications of this demonstration in cloud seeding, nucleation of ice, and how this phenomenon might be used to regulate the environment. As it turns out, the size of this bacterium and a protein on its cell wall shaped something like the spacing of an ice lattice makes it nearly perfect for nucleating ice. This bacterium is found in nature growing on leaves, and may be transported up into the atmosphere naturally where it may play a key role in regulating climate. The bacterium is also used by humans for snowmaking, seeding clouds, and industrial processes that require quick freezing. Our discussion roved over all of these topics, and was a great demonstration of active learning.

Jo recommends “backward course design” for building an entire class that fosters engagement and learning. One begins identifying broad concepts that you want to teach, and finding a set of “assessable learning outcomes” that can be reached through processes of active learning. A pair of assessments are used to document learning gains - the “formative” assessment at the beginning of the class, and a “summative” assessment at the end of the class. The combination of active learning within each individual class, and an architecture of assessment and learning outcomes makes for a powerful and effective learning experience within such classes. Jo has written up the full prescription for "Scientific Teaching" in an excellent book with the same name, and in a concise journal article in *Science,* which are cited below.

Many of the ideas that Jo advocates arise from decades of developments of educational theory. Since the 1920's, John Dewey promoted experience and context as necessary for students to learn new things. From his work came the motivation for a proliferation of laboratory experiences that were attached to lecture classes in science, and formed the basic structure of undergraduate science classes. Backward Course Design takes Dewey's approach several steps further, by combining course design, classroom experience, and assessment to give a complete learning environment where student experiments and inquiry are not just in the lab section. The Backward Course Design can also be summarized by three questions, which should be asked in the following order:

1. *"How will my students be different?"* [here you choose course learning goals based student outcomes]
2. *"How will I know if they get there?"* [here you choose assessments - which can include tests, portfolios, presentations, and other demonstrations of competency]
3. *"What will students do to get them there?"* [here you design learning activities - which should include case studies, problem based learning, peer learning exercises, concept mapping, analytical challenges before class, computer simulations, games, and hands-on activity]



Backward Course Design Flow Chart from http://citl.indiana.edu/resources/teaching-resources1/teaching-handbook-items/designing-your-course.php.

Jo Handelsman, Jennifer Frederick, and her entire Scientific Teaching group (http://cst.yale.edu/) have been sharing this teaching approach nationally, with a series of Summer Institute workshops (http://www.academiessummerinstitute.org/). These workshops are sponsored by the National Academies and HHMI, and are offered 2-3 times per year in all parts of the US. The workshop includes a week-long immersion into the Scientific Teaching technique, demonstrations of hands-on activities, and a chance to redesign a course using "backward course design." Jo and her group ran a workshop on the New Haven campus during summer of 2012 for a group of 24 Yale faculty and instructors (including 16 ladder faculty and 3 science department chairs). This workshop has had profound effects across all parts of Yale's campus. During a series of lunch meetings in the academic year 2012-13, these faculty reflected on how they have been able to redesign their course, and the ways in which the new approach have improved their classrooms.

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Two Taxonomies of Learning

Many professors have intuited or discovered from their personal experiences teaching some of these same concepts without reading educational literature. For this reason, having a look at the new theories of learning can be very helpful to those of us in the teaching profession. Theories can help inform what we are doing in the classroom, and give us vocabulary to describe what we have already seen in our students. Cognitive studies, psychology, and educational research have produced new and more sophisticated descriptions of how people learn. These new descriptions can inform the new type of science and engineering education being introduced across the country in innovative classrooms. During the ACE fellowship, I visited MIT's Learning Laboratory to learn more about educational theory from Janet Rankin, the associate director. Her references to a number of topics in educational theory are discussed below, including new "taxonomies of learning."

The basic “taxonomy of learning” was developed by Benjamin Bloom in 1956. Bloom’s taxonomy describes a ranked set of cognitive activity levels that reflect increasing amounts of sophistication within a student. The most basic form of activity is simply remembering “Knowledge,” or content. The “rote” form of learning and the traditional lecture works heavily on this level. One step above this is “Comprehension.” At this level, students can demonstrate “Comprehension” of facts and how they connect together. The next level of sophistication is “Application” which enables students to apply their knowledge to actual situations, such as in a laboratory section. “Analysis” enables students to de-construct a situation into smaller parts that connect to to general principles and knowledge gained earlier. The top two levels of learning, according to Bloom, are “Synthesis” - where students can compile facts and come up with entirely new solutions or concepts, and “Evaluation” - where students can make reason-based decisions about a set of facts on their own, drawing from previously learned knowledge and outside information. This highest level of cognition or learning is often labeled “critical thinking” and is one of the main goals of most liberal arts colleges and universities. Science courses (and all education for that matter!) should aim to reach these higher levels of cognition, by creative assignments, independent projects, and hands-on experiments.

Bloom’s taxonomy of learning (1956), represented in a pyramid diagram, with the highest levels of synthesis and evaluation (or critical thinking) at the top.

Among the very helpful readings that Janet Rankin gave me during my visit to MIT was an alternative taxonomy of learning known as the Feisel-Schmitz taxonomy. In this science and engineering learning taxonomy, a student moves from an understanding of basic definitions of concepts toward computations using those quantities, then toward being able to explain these concepts. The highest two levels of the Feisel Schmitz taxonomy are to solve a problem by applying these skills - “characterize, analyze and synthesize to model a system” and then to judge - “critically evaluate multiple solutions and select an optimum solution.” These steps are described more fully at the MIT TLL web site, and are illustrated above.

Quality of student learning
Feisel-Schmitz Technical Taxonomy

Judge:	To be able to critically evaluate multiple solutions and select an optimum solution
Solve:	Characterize, analyze, and synthesize to model a system (provide appropriate assumptions)
Explain:	Be able to state the process/outcome/concept in their own words
Compute:	Follow rules and procedures (substitute quantities correctly into equations and arrive at a correct result, "plug & chug")
Define:	State the definition of the concept or is able to describe in a qualitative or quantitative manner

The Feisel Schmitz Technical Taxonomy, an alternative to Bloom's taxonomy for science and engineering courses., showing the increasing levels of sophistication in science and engineering students (figure by Janet Rankin, MIT).

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CONSTRUCTIVE ALIGNMENT

Another very useful concept for course development is known as "constructive alignment." It is based on the idea that students "construct knowledge" and that our courses need to assist this process as a primary goal. This concept is described by one of its main proponents, John Biggs, in summary form:

> *"Constructive alignment' starts with the notion that the learner constructs his or her own learning through relevant learning activities. The teacher's job is to create a learning environment that supports the learning activities appropriate to achieving the desired learning outcomes. The key is that all components in the teaching system - the curriculum and its intended outcomes, the teaching methods used, the assessment tasks - are aligned to each other. All are tuned to learning activities addressed in the desired learning outcomes. The learner finds it difficult to escape without learning appropriately."*
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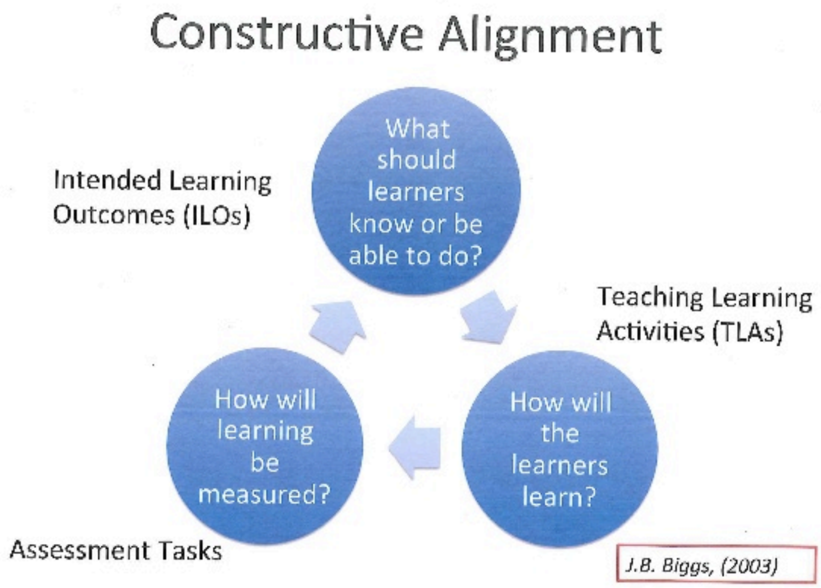
> John Biggs, "Aligning Teaching for Constructing Learning," The Higher Education Academy, UK.

The constructive alignment approach emphasizes a "systems-based" approach to learning that includes integration of activities in the classroom, the department, and across the institution. The goal is to construct an array of meaningful experience through learning activities. Integrated Learning Outcomes, teaching/learning activities, assessment, and grades are all aligned so that a student "finds it difficult to escape without learning what he or she is intended to learn."



The Constructive Alignment approach to course design, as proposed by John Biggs (2003) (figure by J. Rankin, MIT).

The "Integrated Learning Outcome" (or ILO) a central part of Constructive Alignment. These ILO's are designed to produce "functioning knowledge" instead of the more rote-based "declarative knowledge." Functioning knowledge is developed when students "reflect, hypothesize, solve unseen complex problems, or generate new alternatives." Achieving the functioning knowledge requires instructors to choose appropriate Teaching and Learning Activities (TLA's) that otherwise might be described as "active learning." These TLA's require students to "apply, invent, generate new ideas, diagnose and solve problems." (Biggs and Tang, 2009). TLA's are combined with assessment, to lead students toward iterative refinement that converge on the desired outcomes. Assessment (from the student's view) is the first, instead of the last, step of this iterative process of improvement in functioning knowledge.

Constructive alignment also works with a taxonomy of learning known as SOLO ("structure of observed learning outcome"). Students are led through higher SOLO levels toward more advanced "functioning knowledge" that should be the goals of the Integrated Learning Outcomes. Below is a table from Biggs and Tang categorizing the activities associated with each of the SOLO levels. The left column provides elements of declarative knowledge found on traditional exams (memorize, identify, recite, compare and contrast). The right column includes terms that describe "active learning" SOLO activities that build functioning knowledge. Within class, students can achieve functioning knowledge through sorting tasks, developing illustrations, performing computations, and constructing models and solving problems. The SOLO levels provide a third taxonomy of learning that progress from specific or *unistructural* tasks toward more complex or *multistructural* and *abstract* tasks.

Some typical declarative and functioning knowledge verbs by SOLO level

	declarative knowledge	*functioning knowledge*
unistructural	memorize, identify, recite.	count, match, order.
multistructural	describe, classify.	compute, illustrate.
relational	compare and contrast explain, argue, analyze.	apply, construct, translate, solve near problem, predict within same domain.
extended abstract	theorize, hypothesize, generalize.	reflect and improve, invent, create, solve unseen problems, predict to unknown domain.

ILOs need to be written at both programme and unit levels. ILOs of both kinds contain three essential elements: a statement of what the student is supposed to be able to do at the end of the programme or unit, a *verb*; the *content area* to which the verb applies; or *the levels of understanding* or performance in those content areas that are to be achieved.

SOLO taxonomy of learning, with a set of tasks for declarative knowledge (left) and functioning knowledge (right), from the article "Applying Constructive Alignment to Outcomes-Based Teaching and Learning" by Biggs and Tang (2009).

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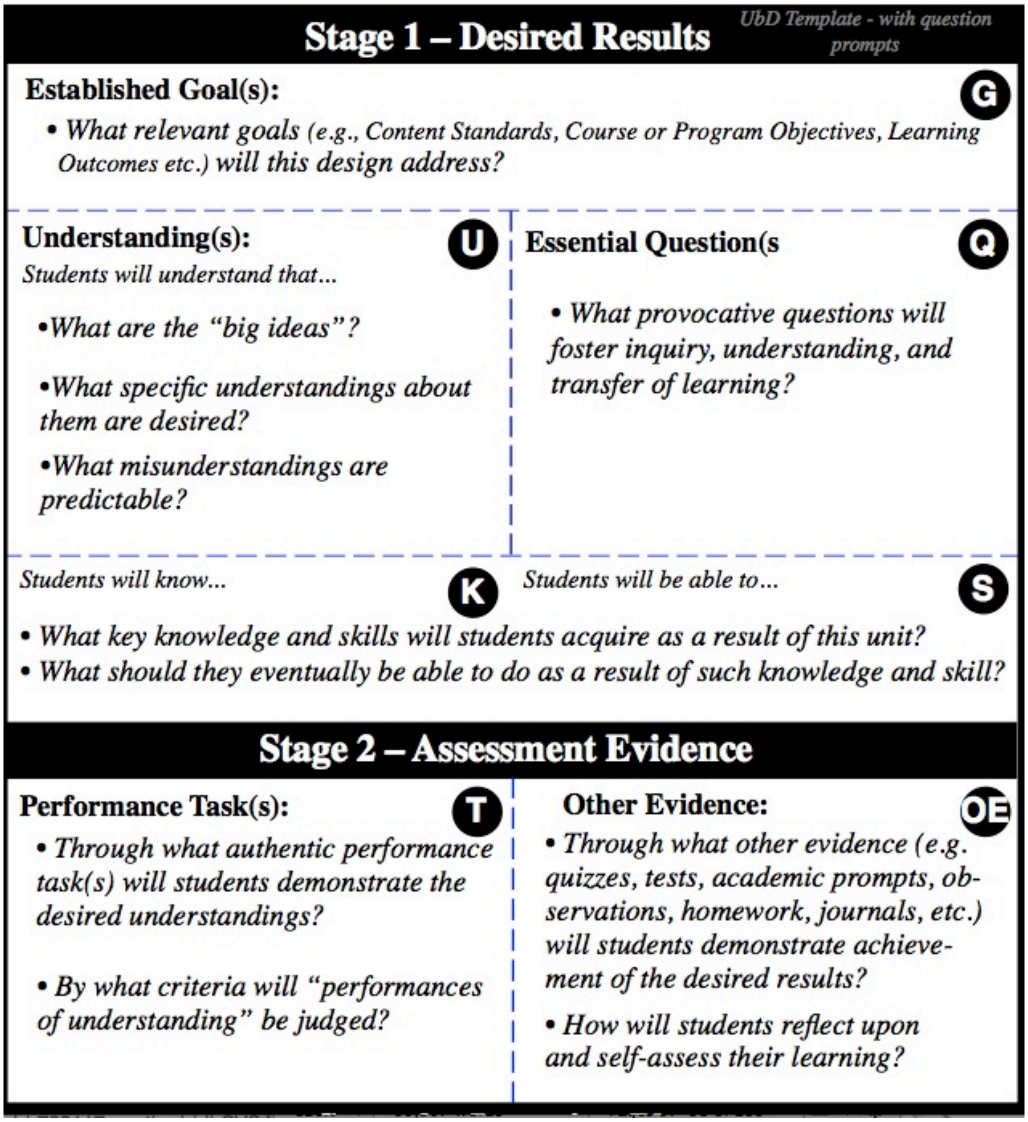
UNDERSTANDING BY DESIGN

A third valuable part of the toolkit of a modern STEM educator is Understanding by Design (UBD). Much like the Scientific Teaching or Constructive Alignment techniques, UBD starts with Learning Outcomes but tries to construct a series of essential questions and big ideas that underly a course. These essential ideas are sometimes called "clarifying concepts." Once these big ideas are identified, the instructor will anticipate some of the misunderstandings and needed tasks to overcome misconceptions while designing the course. A series of "provocative questions" will help frame the big ideas to help "foster inquiry, understanding, and learning." Like the other two techniques, UBD requires instructors to translate these abstract ideas into specific outcomes that finish sentences phrases such as "Students will know..." or "Students will be able to do.." These outcomes are then assessed with "Performance Tasks" and an instructor will answer the questions - "Through what authentic performance tasks will students demonstrate the desired understandings?" and "By what criteria will these performances of understanding be judged?" By framing the assessment in terms of specific "Performance Tasks" an instructor can select the right sort of active tasks to promote the desired performance, thereby locking in both the course activities and content around these assessable outcomes.


Stage 1 – Desired Results *UbD Template - with question prompts*

Established Goal(s): G
- *What relevant goals (e.g., Content Standards, Course or Program Objectives, Learning Outcomes etc.) will this design address?*

Understanding(s): U
Students will understand that...
- *What are the "big ideas"?*
- *What specific understandings about them are desired?*
- *What misunderstandings are predictable?*

Essential Question(s Q
- *What provocative questions will foster inquiry, understanding, and transfer of learning?*

Students will know... K
Students will be able to... S
- *What key knowledge and skills will students acquire as a result of this unit?*
- *What should they eventually be able to do as a result of such knowledge and skill?*

Stage 2 – Assessment Evidence

Performance Task(s): T
- *Through what authentic performance task(s) will students demonstrate the desired understandings?*
- *By what criteria will "performances of understanding" be judged?*

Other Evidence: OE
- *Through what other evidence (e.g. quizzes, tests, academic prompts, observations, homework, journals, etc.) will students demonstrate achievement of the desired results?*
- *How will students reflect upon and self-assess their learning?*

Figure from G. Wiggins, "Understanding by Design" (2005)

After developing the assessment plan, the instructor then develops a learning plan, which is a set of learning activities answering the question WHERETO? This clever acronym is intended to lock in the essential elements of UBD teaching. The first letter refers to Where is the unit going? What should the students expect? The H refers to something used to "Hook all students and hold their interest." The E refers to "Equipping" students with experience enabling them to explore the issues. The R refers to opportunities to Rethink and Revise their understanding. The E refers to Evaluation of their work and its implications. The T reflects an approach that is Tailored to the different learning styles and needs of students in the class, and the O is for the organization to maximize “initial and sustained engagement as well as effective learning.” (Wiggins, 2005). With this clever acronym, instructors can use UBD to create both individual sessions within a course or the entire structure of a semester-long course. A more complete description of this process, with many examples of a complete set of stages in course design, is available at the link below (Wiggins, 2005).

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EXAMPLES OF EXPERIENTIAL LEARNING IN YALE SCIENCE COURSES: RAINFORESTS AND MICROBES TO MOLECULES

Yale University offers a wealth of exciting courses by professors practicing all of the new forms of experiential science teaching. One famous example is the MB&B 230b “Rainforest Expedition and Laboratory” taught by Scott Strobel at Yale (https://webspace.yale.edu/rainforest/Site/Home.html), funded by grants from NSF and HHMI. The teaching team includes Scott Strobel, who is also Yale’s Vice President for West Campus, two lecturers, and a leading South American botanist. The 15 lucky students in this course collect samples in the rainforest, and then spend the rest of the semester and summer identifying the *endophylic micro-organisms* within the samples. The “rainforest” course has three components. The Rainforest course begins with a lecture course during Spring semester, where basic ideas of botany, microbiology, and chemistry are presented. The second component is a Spring Break rainforest expedition to Ecuador. The Ecuadorian sites visited include the Belavista Cloud Forest Reserve, the LaSelva Jungle Lodge, and the Cerro Blanco mangrove forest. The third component is a full time laboratory job during the summer to carefully study the samples collected in Ecuador, and to discover new endophytes that may be able to produce new antibiotics, chemotherapeutic agents, or agrochemicals (for a review of endophytes see https://webspace.yale.edu/rainforest/Site/Endophytes.html). Students in the course have a chance to discover entirely new species of bacteria, since rainforests harbor thousands of undiscovered species of creatures of all sorts - insects, birds and micro-organisms! It is hard to think of a more engaging and exciting experience for a young scientist; the course includes hard science, travel to exotic locations, and potential for a scientific discovery. As might be expected, the course is highly popular, and receives near-perfect student assessments. Graduates of the course have great persistence in STEM fields, with 80% continuing on with an independent research project based on the course, and 95% majoring in STEM fields.

A second example of a Yale experiential STEM course is the “Microbes to Molecules” course at Yale, taught by Jo Handelsman and her group, and with Andy Phillips and his Chemistry group over two semesters. The goal of the course is to enable first-year undergraduates to answer the question “Why do antibiotics kill bacteria and not us?” while learning the whole range of introductory biology skills and content. Students apply their knowledge throughout the course in collecting samples, and in attempting to discover new antibiotics. New antibiotics are desperately needed, as many patients suffer and die from bacterial infections of resistant strains. Jo is particularly motivated to help find new antibiotics, since her own mother died from an infection due to an antibiotic resistant strain 10 years ago.

Instead of traveling to Ecuador, students in Jo's and Andy's class visit sites around New Haven, where they gather soil samples that they bring back to the lab to culture. The cultured samples are studied to detect spots where bacterial growth is inhibited, which can indicate the presence of antibiotic compounds. In the second semester, students isolate and characterize the molecules that appear to inhibit bacterial growth, which could perhaps lead to a discovery of a new antibiotic! The group hopes to be able to use this course "to create a transferable model that can be used worldwide." During the semester these students also give an "expert presentation" on their bioassay techniques, read primary literature, and present their results in a poster fair. I attended this poster fair, and can vouch for the tangible excitement in the group of students, who were eagerly describing their sampling, culturing and isolation results.

The Rainforest and Microbes to Molecules courses are just two examples of a growing set of courses at Yale that recreate scientific research in the classroom. Additional field intensive courses at Yale include EEB 273 (Laboratory for Ornithology), where students travel to Ecuador at Spring Break and identify more than 400 unique bird species), EEB 251 (Laboratory for Terrestrial Arthropods) where students do several field trips to identify and classify terrestrial arthropods (or "insects and spiders" to non-biologists!) and Geology and Geophysics 100 (Natural Disasters), where students visit sites of major volcanic eruptions during Spring Break. In all of these courses, the experiential field components are the primary activity and vehicle to promote student engagement, and the content of the course is designed carefully to arise naturally from the field work, so that students are more motivated to learn the materials as they will use the concepts and facts in their daily work collecting samples and visiting field sites.

Yale is not the only campus offering such cutting-edge courses like the Rainforest course, and Microbes to Molecules. A wave of new courses are being offered across the nation that offer advanced biology research as the primary activity for first-year students. The SEA-PHAGES program enables colleges and universities across the US to build research intensive courses. SEA-PHAGES is an acronym invented by Graham Hatfull at the University of Pittsburgh, standing for the Science Education Alliance (the "SEA") to hunt for Phages and sequence their genes in undergraduate biology classes. The program is sponsored by HHMI, and according to their proposal announcement document, it has reached a wide range of institutions:

> *"Since 2008, over 73 schools and over 4,800 undergraduates have participated, 97 student-annotated phage sequences have been deposited in GenBank, and 7 peer-reviewed papers have been published on mycobacterial phage genomes and science education. Three of these publications have student authors."*
>
> HHMI SEA-PHAGES associate proposal document

HHMI workshops gather teams of faculty from across the country for training in a summer workshop. The program provides course materials and sponsors an end-of-year SEA-PHAGES symposium. Other institutions, such as the University of Utah, are opening up advanced gene sequencing facilities for use in undergraduate classes and describe how even introductory students can use the PCR amplified sequences from samples easily prepared in lab for research projects.

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The Yale Center for Innovation and Design

An exciting new element in engineering education are hands-on centers where students can design and build their own inventions, with help from skilled staff members and using advanced equipment. Stanford operates *d.school*, an intensely cool place that is intended to foster the type of creativity so abundant in Silicon Valley startups (http://dschool.stanford.edu/). In 2011 Harvard opened an Innovation lab, which has the cute acronym of "hi" and is known on campus as the "i-Lab." The i-Lab is huge, with 30,000 square feet of space outfitted like a startup, and where, according to Joseph Lassiter, the faculty chair of the i-Lab, "People can try out their ideas and see if they are worth putting to use." Yale's entry into this new type of center was opened during my ACE year, and is known as the Yale Center for Engineering Innovation and Design (http://ceid.yale.edu/), or CEID.

The Yale CEID is intended to be more than a place for students to work on projects. Its central location, at the base of "Science Hill" and close to the undergraduate colleges, provides convenient access that ties together the campus and forms an architectural mid-point between the science and humanities parts of Yale's campus. Large windows line the exterior walls, allowing pedestrians walking by to look in and see what is happening at the CEID, in its open, light-filled space. The Center's cafe features a huge wall to ceiling LED display that streams interesting patterns and images. The Center's interior is stocked with the shop benches bristling with tools and electronics, advanced 3D printers, laser cutters, a chemistry lab, and a fully CAD-CAM compatible machine shop.

Kyle Vanderlick, Dean of the Yale School of Engineering and Applied Sciences (SEAS), described how the Center is part of the resurgence of Yale's engineering program. Kyle described how Yale's engineering program was the first program to award an engineering PhD in the United States in 1860. Yale engineering in the 1930's had grown into six different departments, and in 1932 was constituted as the "Yale School of Engineering." However during the 1960's Yale decided that engineering was "too vocational" and not sufficiently connected to the mission of the University. It chose to disband the School of Engineering, leaving behind just a token, non-accredited, effort in engineering in the form of one single department within the Faculty of Arts and Sciences. Engineering undergraduate degrees awarded shrank from over 200 in the 1950's to a low of 16 by the early 1970's. In the following years, this "pile of ashes" as described by Kyle, fissioned back into a few small disciplinary engineering departments (each regaining accreditation) only to find the engineering programs on the chopping block once again in the late 1980's when Yale was considering eliminating selected academic programs to close a budget shortfall. The decades lost (70's – 90's) cost Yale dearly as these were years when most Universities in the US were investing heavily in building up their engineering programs.

The resurgence of the program began in 1993 when Richard Levin became president. To revive the program, Levin appointed nuclear physicist Alan Bromley as Engineering Dean. Bromley was a former White House science advisor, who returned to Yale to become Dean from 1994-2000, and revived the program. From the 1990's onward, Yale's engineering program grew and developed into a small, interdisciplinary type of engineering school that leverages Yale's strengths in medicine and humanities. In a Yale daily news article from 2009, Kyle pointed out the advantages of Yale Engineering:

> *"We have certain strengths because we are small. We are more interdisciplinary, we're more nimble; we have better connections to other parts of campus that other departments of engineering don't have. It's just not that seamless, it's just not that collaborative, at all places."*
>
> Kyle Vanderlick, Yale Daily News article (2009), "A Small School with grand ambitions"
> http://yaledailynews.com/blog/2009/09/22/a-small-school-with-grand-ambitions/

The new Yale Engineering is interdisciplinary with non-traditional degrees such as biomedical engineering and environmental engineering, and is connected to many other parts of campus, the schools of management, forestry, medicine, and even the humanities. Yale Engineering offers non-traditional courses like "Appropriate Technology in the Developing World." This course enables students to retrofit motorbikes or take surplus gears and sprockets to build devices that can be used by farmers in Africa to generate electricity, pump water, or grind corn and flour.

Kyle describes Yale's strong emphasis on "bridging" between humanities and sciences on the SEAS web site:

> *"Though rarely described this way, engineering is the bridge between the sciences and humanities. Simply put, engineers apply scientific principles to advance the human condition. Their success relies as much upon an understanding of physics and math as an appreciation of history and psychology."*
>
> Kyle Vanderlick, Dean of Yale's School of Engineering and Applied Sciences, from the SEAS web site (http://seas.yale.edu/).

The CEID is perhaps the centerpiece of the Yale Engineering school's strategic plan, which also includes new and remodeled buildings, an expansion to perhaps 20 new faculty and new technology enabled (TEAL) classrooms. More than infrastructure and equipment, the CEID is hoped to catalyze interdisciplinary work and community among the students. Any Yale undergraduate or graduate student can join the center, can come in 24 hours a day to build, to prototype, and to explore possibilities in a welcoming and fun space. From the Center's web site, the Center is described as a combination of a "physical space," "a bustle of activity," "a diverse community," and "a shared mission" that hopes "to empower students to improve human lives through the advancement of technology."

The importance of the CEID to Yale's community was evident in its opening ceremony during February of 2013. The opening featured a wide range of Yale faculty, alumni, industrial leaders (including the Boeing CEO, W. James McNerney, Jr. - Yale '71), and Yale administrators such as Peter Salovey, Yale's President-elect. In the opening speeches, the leaders stressed the ways in which the center is hoped to bring students in art, physics, engineering, and even psychology together, since engineering and technology requires this sort of interdisciplinary approach to design products that people enjoy using, and that are economically, ethically, and technologically sound.

After the CEID opening ceremony, I met with Eric Dufresne, the CEID director. If any person could embody interdisciplinary science and engineering, it might be Eric. Eric has a PhD in Physics from the University of Chicago, worked as a management consultant for McKinsey, founded his own company to develop "holographic optical tweezers" and is an Associate Professor of Mechanical Engineering and Material Science, with joint appointments at Yale in Chemical Engineering, Physics, Applied Physics and Cell Biology! Eric described how the CEID and his personal philosophy of education align toward promoting student creativity. Yale has long been a leader in humanities, and has innumerable theatre productions in its Colleges, art studios, and music groups. This same type of creativity can now be expressed at the CEID, according to Eric, and he hopes the center can unleash creative energies in science and technology so that students can "realize ideas." Eric believes this type of open-ended, student-driven science education is the future of higher education. By giving students this kind of facility, Yale gives a solid answer to the "value added" of a university in the era of MOOCs and declining research dollars.

Eric proudly described some of the capacities of the new CEID. It includes four 3-D printers, a laser cutter, a small high-tech machine shop that includes 3 CNC mills, electronics shops, and a chemistry lab. The staffing is equally impressive. Instead of a machinist, the CEID employed a former tenured Ohio state professor with a physics PhD who worked in industry for a decade, and who knows machining, scientific theory, industrial manufacturing, and has years of experience teaching. Other staff members are on hand to help students build all manner of contraptions, and realize their creative ideas in acrylic, plastic, aluminum, or wood.

The student-built contraptions were on display at the CEID's Student Design Competition, which I attended during the ACE year. First-year Yale undergraduates were charged with building devices to solve problems using the resources of the CEID and collaborating Yale faculty. Yale College Dean Mary Miller, and a panel of engineers were also on hand to judge the projects. One group designed a housing for to help biologists research water quality in the Mara River (Tanzania). They presented their device in the form of a one act play, that enabled them to dramatize the challenges that such a device faces from being stomped on by hippopotamus, and being clogged by river debris. A second team demonstrated how they designed and built a small and portable blood assay system where injection of a small sample of blood into a tiny capillary channel will enable it to respond to light. Their device made use of both the laser cutting and 3D printing capabilities of the CEID. A third team developed a new sensor and software system to enable the huge LED system in the CEID cafe to register the number of people in the cafe in the form of an entertaining display of bouncing balls. The LED system, according to Yale Deputy Dean of Engineering, Vince Wilczynski, is "the largest low-resolution graphic system" and includes a bank of LEDs in a large display that spans two walls and the ceiling of the cafe. The students designed their system using n-body physics code to realistically render the bouncing balls, infrared sensors, and a sound system that registered when people entered or left the cafe. The excitement and fun of this contest and the engagement of these Yale first-year students provides good evidence both of the CEID achieving its goals and of Yale Engineering reaching out to the Yale undergraduates and the larger Yale Community.

The Yale Engineering program and CEID present a great case study in how an institution like Yale can redesign a school to become more interdisciplinary, more engaged with the mission of the college, and more relevant to student sand to the world. The upward track of Yale Engineering includes an emphasis on "A Sense of Purpose" which is part of the "mantra" of Yale engineering to produce engineers that have "breadth," "depth," and "purpose." Yale Engineering graduates students students that have:

> *"fundamental knowledge of science and engineering, but also a strong understanding of the complex social, political, economic, and environmental implications that must be considered when developing complete solutions to global problems."*
>
> http://seas.yale.edu/about/y-shaped-engineers

Vincent Wilczynski, Deputy Dean of Yale Engineering (and former ACE fellow) described how the convergence of these three factors creates a "Y shaped engineer" that combines all three - breadth that includes liberal arts and other subjects, depth in one discipline, and a purpose to applications that solve problems.

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Cal Poly San Luis Obispo and "Learning by Doing"

One of the institutions most dedicated to the experiential form of learning in science and engineering is Cal Poly Pomona, San Luis Obispo. Their educational philosophy of "Learning by Doing" has guided their curriculum and institution for decades, and has resulted in some of the most impressive graduates in science and engineering in the country. Some Cal Poly programs compete with those like Stanford and MIT in engineering rankings, despite their much lower budgets and tuition rates (in-state annual tuition at Cal Poly is only $5970!). The US News rankings gives Cal Poly the award for the best public master's university in the West and sixth place for the West's Regional Universities. Cal Poly SLO was also ranked as the third best master's engineering program in the country, behind the Air Force and Naval academies. The Cal Poly SLO physics program was chosen by the American Physical Society as one of the best 21 "thriving" physics programs in the country to be studied as part of the "Spin-UP" report, which praised them for being "friendly and open with a broad, hands-on and can-do approach to physics." Understandably, students in California and beyond are clamoring to get into Cal Poly SLO, and they received 45,000 applications for only 4,000 spots in the entering class, giving them a selectivity more like that of an Ivy League University than a Cal State campus!

To learn more about the Cal Poly approach to STEM education, I visited the Cal Poly SLO President, Jeff Armstrong, who helped set up additional meetings with some of the Cal Poly leaders, such as Enz Finken, Provost, Rakesh Goel, Associate Dean of Engineering, Phil Bailey, Dean of Science, and John Keller, the co-director of CESaME - an education center for science and engineering. The visit was timed to enable me to drive all the way up to San Luis Obispo and still make a flight later in the day, so my meetings were tightly choreographed to fit within a few hours.

My first meeting was with Jeff Armstrong, the President of Cal Poly. Jeff comes from a background is in large food animals and their nutrition and reproduction, and is a leading researcher and award-winning teacher in this subject. His practical background is consistent with the engineering and agricultural strengths of Cal Poly SLO. Before coming to Cal Poly SLO in 2011, Jeff worked at Michigan State, Purdue and North Carolina, and was raised on a farm in Western Kentucky. He met with me in his office and was enthusiastic about Cal Poly SLO, since in his words, its "Learn by Doing" philosophy has led to a "renaissance of the practical." Jeff and his assistant Kim Uyttewaal led me through an overview of the institution and its admissions. Jeff is thrilled with Cal Poly SLO's strong alumni network (to the point where some retired engineers volunteer to work on campus), the enthusiasm of faculty and staff, and a strong network of partner companies, and potential donors.

Jeff still does seem some areas for improvement at Cal Poly SLO, which come in main three areas - diversity, development and student success. Cal Poly SLO has a much less diverse student body than the rest of the Cal States, with less than half of the students coming from traditionally underrepresented minorities. To improve this situation, several programs are in place. The Cal Poly EPIC summer program enables junior high and high school kids to explore "Engineering Possibilities in College" (https://epic.calpoly.edu/about/). Minority and first-generation students are also recruited with on-campus weekends (both an "Open House" and "Polycultural Weekend"). A Summer Institute provides a solid orientation to the campus culture to pre-frosh students (http://sas.calpoly.edu/si/), and many of these students are eligible for a wide range of scholarships. As a first-generation college student himself, Jeff has a solid understanding of the importance of improving the experience of minority and first-generation students. Jeff is hoping to further advance the diversity of the student body, and also to implement a more effective development regimen, since the alumni giving, despite enthusiastic and successful alumni, is lower than some of its peers. Student success is also an area for further work, and Jeff hopes to see graduation rates and performance of students improve.

Phil Bailey, Dean of Science at Cal Poly SLO has had a huge impact on student success during his 44 years on campus. Phil helps tie together all the rich academic and programmatic offerings with an emphasis the human side of studying engineering and science. His work has made him a father figure to many of the students, as he communicates regularly with the entire entering class with a series of letters to "give ideas about how to navigate the first quarter of college." Phil has also had many of the students stay in his home, and his warm approach has helped many generations of students feel comfortable and welcome on campus. Phil thinks that student success is one of the best measures of teaching ability, and by stressing this point with the faculty, he has helped them redesign courses to improve the performance of students in intro courses. One example he cited was a re-organization of Math courses, which led to a decrease in the D/F rate in introductory math from 70% to 20%. Phil described how many of the Cal Poly SLO professors are moving toward new types of pedagogy, and that more than 20% of the Cal Poly curriculum is in "non-lecture" format. The Cal Poly "Learn by Doing" approach places a heavy emphasis on lab work, and Phil is proud of the new studio chemistry curriculum, where lecture and lab are integrated in all of the chemistry courses. Even though a lab costs a lot more (more than 3 times more than a lecture course) the gains in learning make it worth it, and Phil is working to maintain and expand the laboratory program, even with decreasing budgets.

Phil believes that students need to be persuaded and taught how to study, and cites an NSSE study that showed that 40% of the students in college study less than 10 hours per week. Phil's mantra is "Study 25-35 hours per week!" Phil has started a "25-35 program" to promote this idea, and has emblazoned the slogan onto refrigerator magnets he cheerfully hands out. Many students are actually not aware of the necessity of longer study hours for success, as their high schools often have not demanded the same level of preparation and work as Cal Poly SLO. Phil's work increasing student success emphasizes not only studying, but compassion and concern for the students. His approach has two key elements - 1). Treat each student as an individual, and 2). Seek out students at risk and find out what is wrong. His second principle has enabled him to find out that in many cases students simply don't have enough money to buy food; by helping them get good nutrition in college he has seen many of them revive physically and academically. Phil believes that many students in such circumstances have long odds of success, but emphasizes to these students that "we are here to help you beat the odds." At Cal Poly SLO, the students also want to help their community succeed, and actually voted to increase their student fees by over $1000 to enable a "student success fund" to support coaches for academic success, and to help recruit a more diverse campus.

Since Cal Poly SLO is a practical place, it not only educates students for jobs - it also helps them create new companies and products. A new Center for Innovation and Entrepreneurship (http://cie.calpoly.edu/) is giving students chances to compete for prizes, meet mentors, and work in teams during a 12-week "Hothouse Summer Accelerator" to develop new products. This last year, Cal Poly SLO supported seven student-designed companies in this summer program, including teams that will develop new vegetable snacks, implement software for splitting bills among apartment room-mates, design vertical gardens for buildings, and make a new form of lightweight concrete using cellulose and cement (a complete list is at http://www.calpolynews.calpoly.edu/news_releases/2013/May/hothouse.html).

Two other notable programs at Cal Poly SLO embody the hands-on and high impact approach of this institution include the CeSaME center, and the CubeSat program. Cal Poly's CeSaME center is an acronym for the "Center for Excellence in Science and Mathematics Education." The center runs a number of exciting workshops for teachers, including the STEM Teacher and Research program, which matches high school science teachers with researchers at national laboratories funded by NOAA, DOE, and NASA for a summer project. Over the past six summers, the STAR program has provided 290 research opportunities for high school teachers within 15 different research sites. CeSaME also houses the "Learn by Doing Lab" which is a facility that gives Cal Poly students interested in teaching a space to try innovative new hands-on activities with visiting school classes. Teachers can also check out the facility for use in their classes. The CESaME center also participates in a number of initiatives, including math tutoring for area K-12 students, administering the NSF-funded Noyce scholarship program for students interested in teaching science or math, and participating in the Central Coast STEM Collaborative, and the California STEM learning network. Having an innovation center dedicated to teaching exemplifies Cal Poly's priority in helping assure student success in STEM fields, and the importance to Cal Poly in increasing access to these fields from diverse populations of students.

The Cubesat program at Cal Poly SLO exemplifies the type of cutting edge undergraduate work that is possible in an institution dedicated to Learning by Doing. Over the past ten years, over 100 Cal Poly students have helped develop and launch over 32 "CubeSats" which are tiny cubical satellites (the face is about the size of a CD jewel case -10 cm square) packed with electronics for studying space.

The Cal Poly SLO "CubeSat" being tested in the environment near campus (from http://polysat.org).

NASA has signed a $5-million contract with Stanford University and Cal Poly SLO to help extend the CubeSat program to more universities. CubeSat satellites are launched using innovation known as the P-POD device that integrates these cubes to existing launch vehicles. This device enables students to design and build self-contained space instruments that can piggyback on other NASA launches. The maximum mass of these satellites (also known as "picosats") is 1 kg, making a design challenge for students to devise instruments small and light enough to fit in the compact package. Cal Poly SLO professor Jordi Puig-Suari started this program and described his goals for the program: "CubeSat existed to help students understand spacecraft and the work neeed to craft them. We were trying to develop a very simple spacecraft for students." (Cal Poly Engineering Advantage Newsletter, Fall 2010).

Cal Poly SLO's combination of "Learning by Doing," a commitment to student success, a history of innovation in undergraduate science and engineering education, and outreach to surrounding schools and industry makes Cal Poly SLO a compelling example of a university that is both changing how science is taught and having a big impact on both its students and the state. Cal Poly's practical and effective form of education gives a strong response to those who question the value proposition of higher education.

The Integrated Science Curriculum

The "renaissance of the practical" as exemplified by Cal Poly SLO and Olin College (discussed in Chapter 4), has also been accompanied in recent times with the "renaissance of interdisciplinarity." There are many reasons - the rapid advance of technology enables new inventions from physics to be applied to biology, algorithms from computer science to inform new genomics projects, and advanced imaging and video techniques in biology to inspire new physics discoveries. The expansion of databases have made access to huge genetics sequences available to anyone with a computer, along with troves of new data from the Hubble Space Telescope, NASA missions of all kinds, and even particle accelerator data. With online tutorials and advanced software, it is becoming easier to explore other disciplines online and to learn what previously would have required years of lab-time. Perhaps most importantly, the areas of science which are providing the most opportunities and discoveries - big data, molecular engineering, nano-technology, and genomics, are all interdisciplinary. It is time that our science curriculum at our Universities and Colleges catch up to these new interdisciplinary realities!

In recent years, a number of very effective courses that span multiple disciplines have been developed and are attracting interest and funding. The interdisciplinary or "integrated science" course is one example that attempts to teach multiple sciences at once for undergraduates. Several notable versions of this type of science course have been developed at places such as Princeton, the Keck Science Department of the Claremont Colleges, and at the new Yale-NUS College in Singapore for three examples. The main features of these integrated science courses are described below.

Princeton Integrated Science

Princeton has 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. The second year is a mix of chemistry and biology which is closer to a traditional biochemistry curriculum. Topics of organic and biological chemistry are covered, as well as crystallography, and dynamic models of cell metabolism, which mixes the disciplines of biology, chemistry and physics. In Spring of the second year, students work with genome sequencing, genetic engineering, mutational analysis, genetics of populations, and neuroscience. This second year course only meets twice a week with a weekly precept session. In the third year, students choose a major, and all of them take a Project Lab (its official title is "Experimental Project Laboratory in Quantitative and Computational Biology"). In the lab course, students design and execute their own experiments, giving them extensive experience in research with one of the many participating Integrated Science professors.

Staffing of this ambitious course requires 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 are based in the Lewis-Sigler Institute at Princeton, which is dedicated to "Integrative Genomics" and "Quantitative Biology," and the sequence leverages the research activity and expertise of this institute. A good amount of computation is also part of the curriculum, and students make their own programs and models using Java in the first semester, and by the second semester are working on advanced topics of computational biology. The large time investment from both faculty and students seems 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."*
>
> Profile of Michelle Ward, '10 (http://www.princeton.edu/integratedscience/students/michelle-ward/)

The professors also feel strongly that including the broad range of sciences is a stronger preparation for scientific research. In the words of David Botstein, director of the Lewis-Sigler Institute, "Any budding researcher needs a foundation in several fields to be able to work on the most important problems confronting scientists today." (http://www.princeton.edu/integratedscience/)

Claremont Keck Science Department AISS program

Another interesting curriculum is the Claremont Colleges (Keck Science) Accelerated Integrated Science Sequence (AISS). 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 students. The course has two-hour meetings 4 days a week, and a Friday 4 hour lab. A typical class is taught "studio mode" - with in-class lab exercises mixed seamlessly with lecture and discussion. Links to many documents are in the references section below, including an overview of the curriculum, online versions of the syllabus, and an article on the curriculum published in the American Journal of Chemical Education.

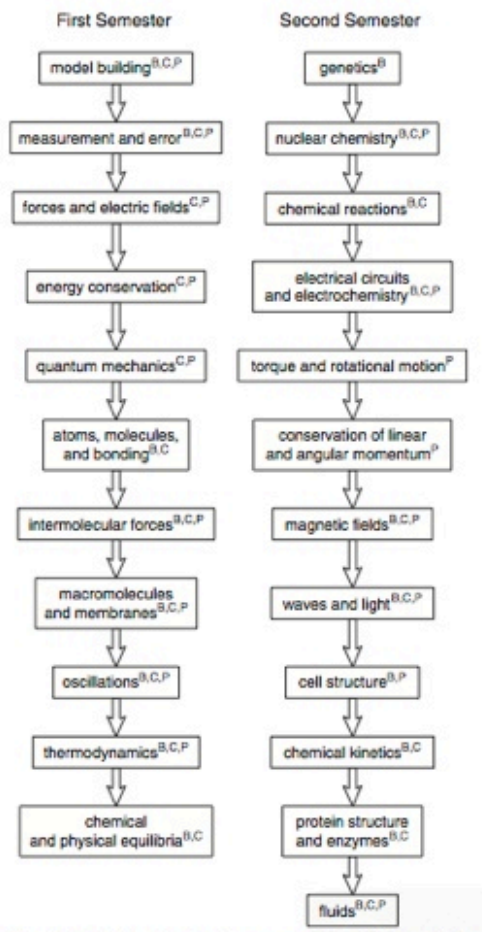

Figure 1. Schedule of main topics covered in the AISS course. The disciplines covered during the section are denoted (B = biology, C = chemistry, and P = physics).

Laboratory	Connection with Biology or Physics
Using Dynamic NMR and Spartan Modeling To Investigate the Rotational Barrier in N,N-DMA	Angular momentum; Magnetic fields; Computer modeling
FTIR Investigation of DNA Structure and Flexibility	DNA structure; FT calculations; Oscillations
Using GC–MS To Analyze Organic Compounds	Magnetic fields; Physical forces; Identifying isotopes

Flow Chart for topics in the Claremont Accelerated Integrated Science Sequence (AISS), and a sampling of lab topics in the course with representative disciplines (right). [From Purvis-Roberts, et al (2009), Journal of Chem. Ed., 86, 11, p. 1296]

The syllabus describes the basic structure of the course, which 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 list of topics is shown below in a flow chart from Purvis-Roberts, et al (2009); these topics have been refined over the 6 years that AISS has been offered to include those that work well in the team-taught "studio" mode, and that naturally integrate the different science disciplines. During the ACE year, our group at Yale-NUS visited Claremont to see the AISS course in action and talk with the instructors, Scot Gould, Emily Wiley, and Kersey Black.

During our visit to the class, all three instructors were in the class at the same time, and frequently would 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 the class we visited, students were using bioinformatics.org database and the RCSB Protein Data Bank on laptops to study biological macromolecules. The biology professor, Emily Wiley, mostly led the class, but the physics professor, Scot Gould, would jump in and explain how electron polarization contributed to hydrophobic and hydrophillic parts of the macromolecules. Kersey Black, the chemist, jumped in and described 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. At one point the class was charged to find the exact sequence for a gene in a micro-organism, and at another they 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.

Yale-NUS College (Singapore) Integrated Science

The new Yale-NUS College curriculum has a very strong emphasis on interdisciplinary study across all of the divisions. Since the new Singapore college does not have departments, each of the common curriculum courses are team-taught by groups of humanities, social science and science professors. The Yale-NUS science group worked for over a year to take the best features of integrated science programs and apply them to the new common curriculum. The result is not one but three different tracks of integrated science. The entire student body at Yale-NUS will take an interdisciplinary science course entitled "Scientific Inquiry" that is intended to demonstrate the ways in which scientists from all disciplines develop models and theories, test them with experiments, and change their ideas when faced with new data. Some unifying themes connect the units - mathematical ideas of prime numbers and factoring connects with chemists' conceptions of the periodic table, which also provides "irreducible" components of nature. Evolutionary biology and geophysics and a unit on consciousness and perception explore how complexity arises from simple principles and how scientists use observations to describe such systems-based phenomena. The "Freshman Seminar" is a common presence on many campuses to develop writing skills in first year students, but this first semester science course, taken by all the students, serves a similar function for developing scientific literacy.

Integrated Science for science majors that includes a first semester with the theme of "Water" followed by a double course that blends two disciplines together, culminating in a mini-capstone project. The "Water" theme includes sections on the cosmic origin of water, its physics (including the harmonic oscillator for vibration modes), its chemistry, the role of water in life, studies of limnology and the ecology of water, and even the geophysics of water and tsunamis. By bringing all the science disciplines to bear on this one theme, students can explore the unity of science and how the various branches of science can complement each other in describing nature.

Integrated science at Yale-NUS for non-majors is a year-long sequence entitled "Foundations of Science" which has a theme related to the origin and sustainability of life in the universe and on earth. The first semester explores the origin of life-giving elements, the formation of the earth, its early history and climate, and the rise of life and humans on earth. The second semester will cover three main themes related to sustainability - energy, environment and health - using a project-based learning mode where students conduct investigations about the energy generation in Singapore and the region, explore nearby rainforests and wetlands and study human impacts on the environment, and discuss long-term threats to human health from carcinogens, pathogens, and global warming. The entire science faculty (including scientists with expertise ranging from astrophysics to zoology!) will team-teach both of these sequences to provide an integrated approach to science organized along overarching themes.

OTHER INTEGRATED SCIENCE PROGRAMS

Several other institutions offer variants of the integrated science curriculum. The University of Richmond provides an integrated introduction to biology, chemistry, physics, mathematics and computer science for first year students. Funded by an HHMI grant, this course includes a 5-day a week lecture, with 3 hour weekly lab. This gives them the equivalent of five courses with 4 course credits, and a more efficient lab which reduces the number of lab hours by half. The University of Massachusetts Amherst offers its "Integrated Concentration in Science" (Icons) Curriculum. In this four year program, housed in a new Integrated Science Building, students are offered a series of courses that integrates the various disciplines, with an innovative "case study" approach. Northwestern University offers its Integrated Science Program (ISP), one of the first integrated science tracks to bring multiple disciplines into a complete curriculum for advanced students. Northwestern's program requires a diverse combination of disciplinary courses, rather than completely integrated multi-disciplinary science courses. The James Madison University Department of Integrated Science and Technology offers integrated courses which break the traditional boundaries of disciplines, and like the AISS course, give grounding in multiple fields at once. Virginia Tech's Academy of Integrated Science (founded in 2011) selecting students for the Integrated Science Curriculum which runs something like an honor's college on campus. Their program includes a two-year double-effort sequence, with six hours of lecture and six hours of lab per week that integrates chemistry, physics, biology and math. The University of Arizona Integrated Science fosters interdisciplinary work and prepares students broadly for careers in medicine and science, through a carefully selected "Program of Study in multiple disciplines." Most of these efforts began only in the last few years, suggesting that the momentum for integrated science is building across the country.

References and Links for Integrated Science

Princeton Integrated Science:

http://www.princeton.edu/integratedscience/
http://www.princeton.edu/~wbialek/intsci_web/IntSci.html
http://www.princeton.edu/~wbialek/intsci_web/planF08.pdf
http://www.princeton.edu/~wbialek/CUNY_101103.html
http://www.princeton.edu/~wbialek/MFA2011.pdf
http://www.princeton.edu/integratedscience/curriculum/sample-syllabi/isc231.pdf
http://www.princeton.edu/integratedscience/curriculum/sample-syllabi/isc233.pdf

Claremont Keck Science Department AISS course:

Overview of the Claremont AISS program http://www.jsd.claremont.edu/aiss/
Sample Syllabus for the class from 2011: AISS Fall 2011 Syllabus
Article on AISS from the "Journal of Chemical Education"

Yale-NUS College (Singapore) Science Curriculum:

Yale-NUS College Scientific Inquiry Course - http://www.yale-nus.edu.sg/index.php/learning/common-curriculum/common-curriculum-courses/scientific-inquiry.html
Yale-NUS College Integrated Science Course - http://www.yale-nus.edu.sg/index.php/learning/common-curriculum/common-curriculum-courses/integrated-science.html
Yale-NUS College Foundations of Science Course - http://www.yale-nus.edu.sg/index.php/learning/common-curriculum/common-curriculum-courses/foundations-of-science.html

Other Interdisciplinary or Integrated Science Programs:

University of Richmond Integrated Quantitative Science - http://iqscience.richmond.edu/
University of Massachusetts, Amherst ICONS program - http://www.cns.umass.edu/icons-program/academics
Northwestern University Integrated Science Program - http://www.isp.northwestern.edu/
Virginia Tech Integrated Science - http://www.science.vt.edu/ais/isc/index.html
University of Arizona Integrated Science - http://is.arizona.edu/ISP_Program_of_Study.html
James Madison University Integrated Science and Technology - http://www.isat.jmu.edu/

STEM Educational Innovation - A Historic Moment

As I rounded off my year as an ACE fellow and considered the many innovations in science and engineering education, it became clear that the large number of experiments in teaching STEM subjects have yielded a rich harvest. Instructors can now choose from a wide variety of research-validated techniques, theoretical constructs about how people learn, and work at entirely new institutions and centers built specifically for hands-on and active learning. The institutions and new curriculum are the culmination of the post-war investment in science research and technology infrastructure. The new era of STEM higher education can bring the widespread adoption of increasingly sophisticated methods of teaching to increase the "yield" of that infrastructure in terms of excited and motivated students, with classroom experiences that fully embody a spirit of discovery and active inquiry.

All of the STEM educators I have talked with and worked with have been conducting their own experiments both in laboratories and classrooms, but the difference of this moment is that for the first time these many small-scale experiments are being tested, discussed and validated. Many of the conclusions of the educational research confirm the intuition professors who have experimented for decades with new forms of teaching. What formerly were hunches are now validated with data on learning outcomes, and intuition can now be guided by new theories such as constructive alignment, scientific teaching and learning taxonomies. This abundance of results now puts intuitions about teaching on a solid scholarly footing.

In many cases too, we have learned that our intuitions about teaching can be wrong. Teaching as we were taught in the past can simply perpetuate a form of STEM education that only a very few unusual students (such as those who became professors!) can survive. Carl Weiman in his article "Why Intuition About Teaching Often Fails" makes a statement about the wrenching process of abandoning one's past notions about physics education, which applies generally to teaching in all STEM fields:

> *"In much the same way that physicists had to go through the wrenching process of replacing their classical-physics-based intuition with a new, more useful intuition about the quantum world, we need to make a similar step with regard to physics education."*
>
> Wieman, C., in "The Curse of Knowledge" or Why Intuition About Teacihng Often Fails, APS News, Nov. 2007

By taking this new "quantum leap" from traditional modes of teaching, modern STEM educators can create more effective forms of learning for the students that can be validated by testing, from brain scans, and perhaps most importantly, from the obvious joy and creativity of students in an active learning environment! These new forms of teaching are now less of a risk for the professor, and can be guided by the new research in teaching and learning described above. One outcome of the new wave of STEM teaching could be a new *learning* infrastructure that can match the amazing *research* infrastructure of our campuses.

This new wave of STEM teaching enables students to test their scientific intuitions, and explore science in what could be caused a "right-brained" form of STEM education rooted in creativity. As David Oxtoby in his 2012 Colby College address "Chaos and Creativity" points out - creativity of this sort will "rely on the integrative and synthesizing parts of the brain." Modern neuroscience research has verified on a synaptic level that active and creative learning (where students are talking about tasks done in class, or drawing upon imaginative metaphors) results in measurable increases in brain activity (e.g., see book by J. Zull, 2002). We could be at an historic moment where the innovation and advances in STEM teaching and learning in US Colleges and

Universities will leap forward as rapidly as our science research infrastructure has advanced in recent decades.

After the long journey to many centers of this new type of STEM teaching, I find myself returning to the classroom with new awareness of the "science of teaching" that takes some of the uncertainty and doubt out of the more familiar "intuition driven" form of teaching. The return to the classroom should be familiar after 20 years of teaching, and yet in many ways my return to this home is reminiscent of T.S. Eliot's quote about exploration (which applies nicely to those of us exploring new ways to teach!):

> *"We shall not cease from exploration, and the end of all our exploring will be to arrive where we started and know the place for the first time."*
>
> T.S. Eliot

References

David Oxtoby, "Chaos and Creativity" - an address on Liberal Education for the 21st Century from Colby College, April 2012, http://www.colby.edu/news_events/c/n/040813/2705768/transcript-chaos-and-creativity-liberal-education-for-the-21st-century/

Zull, J.,2002, "The Art of Changing the Brain: Enriching the Practice of Teaching by Exploring the Biology of Learning", Stylus Publishing, Sterling, VA.