FALL 2013 • Volume 34, Number 1

CUR Focus

John R. Brandenberger, *Lawrence University*

Teaching Innovation Through Undergraduate Research

A four-year investigation into the teaching of innovation in the context of undergraduate research has recently been completed in the Department of Physics at Lawrence University. This investigation was prompted by the widely shared belief that a heightened emphasis on innovation both within and beyond the United States is a very important objective (Friedman and Mandelbaum 2011). It follows that demonstrations of successful approaches to the teaching (or at least the encouraging) of innovation among today's undergraduates should be valuable as individuals, institutions, and governments confront major problems ranging from global competitiveness to worldwide issues relating to energy, water, nutrition, pollution, and climate change.

What is innovation? The physicists at Lawrence view it as the *application of new ideas, approaches, or procedures designed to improve products or strategies that usually draw upon antecedents and ultimately provide value to society.* They also embrace the following metaphorical characterization: "Innovation is a slow process of accretion, building small insight upon interesting fact upon tried-and-true process. Just as an oyster wraps layer upon layer of nacre atop an offending piece of sand, ultimately yielding a pearl, innovation percolates within hard work over time" (Rae-Dupree 2008). While there are various views regarding the essence of innovation, most observers agree that a broad range of human activity benefits from innovation of various sorts (Friedman and Mandelbaum 2011).

The primary impetus for this investigation was the highly influential report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* a study commissioned by Congress in 2005 and developed by Nobel laureates, CEOs, and academics in association with the National Academies of Science (Augustine *et al*. 2007). The report contains 500 pages of opinion, data, charts, and analysis that focus upon ten important actions that the U.S. should consider undertaking to better compete and prosper in both the near and far term. The report actually concentrates on four recommended actions judged to be most critical: improving K-12 mathematics and science education, sustaining the U.S. commitment to long-term basic research, training, and retaining top scientists and engineers, and ensuring that the U.S. remains an outstanding place in which to pursue innovation.

Among other things, the National Academies report documents the slippage in global competitiveness that the U.S. has suffered during the past twenty years. The report also asserts that U.S. prosperity depends in large measure on an abundance of *good* jobs, roughly half of which in recent decades have stemmed directly or indirectly from science, engineering, technology, and/or innovation. While the U.S. may have set the pace for innovation and technological developments during the 20th century, it is now ceding much of that leadership worldwide, and the implications of this trend are troubling, calling into question whether future generations of U.S. citizens will experience standards of living comparable to what their parents enjoyed. A sequel to the 2007 report published in 2010 declares that the "gathering storm" has now risen to a "category five" (Augustine *et al*., 2007).

Informative but daunting, the original report nevertheless is encouraging with its assertion that the U.S. might partially reverse its slippage in competitiveness through a heightened emphasis on innovation. In essence the report argues that a substantial stream of research is critical to the creation of new knowledge, and that this new knowledge, when combined with imaginative engineering and innovation, can stimulate further innovation and entrepreneurship and hence the creation of jobs, wealth, and renewed prosperity. We physicists at Lawrence see the report as throwing down a gauntlet regarding the need for greater innovation both nationally and globally. We decided to respond by launching an investigation into how to teach or at least encourage today's undergraduates to be more innovative so that when they join the national or global workforce, numerous societies will benefit.

Can innovation be taught? Many doubt it, although various courses that attempt it have sprung up in recent years. Formal coursework regarding innovation now exists at Stanford University, the Massachusetts Institute of Technology, the University of California-Berkeley, Harvard University, Rensselaer Polytechnic Institute, the University of Cambridge, and Olin College to name just a few institutions. Numerous treatments of the subject also exist in today's business schools. Further, MIT and the University of Cambridge support an exchange program in which students in one of those institutions spend a few months observing innovation at the other (Good et al. 2007).

Most academics involved in the teaching of innovation believe that their courses should engage students actively and directly. Hence courses in innovation tend to be very hands-on and project-oriented, with students spending a significant fraction of their time *doing* rather than *listening*. Lawrence University offers such a course, In Pursuit of Innovation, in which students conceive ventures and create prototypes of products (e.g., an ergonomic desk, a smart bike lock, or a piece of carry-on luggage that recharges cell phones), as well as websites, smart-phone applications, and business start-ups, all in ten weeks. Students report that project-oriented courses of this sort significantly influence their thinking, cognitive behavior, and approach to learning.

Innovation and creativity are closely linked, and some experts believe that most individuals, especially young people, are innately quite creative (Wagner 2012). Hence the task at hand may be more unleashing, unlocking, or inspiring innovation and creativity than attempting to teach it formally. Nevertheless, at Harvard's Technology and Entrepreneurship Center, Tony Wagner teaches creativity with a special focus on how young people learn through failure. He claims that creative, youthful play leads to deep-seated interests that often blossom into careers and life goals, and that play, passion, and purpose are the main forces that drive young innovators. Along similar lines, Edward Burger of Williams College believes that "individuals need to embrace the realization that taking risks and failing are often the essential moves necessary to bring clarity, understanding, and innovation." According to Alexander Hiam, innovation can be characterized by its emphasis on five specific actions: initiative, imagination, inquiry, invention, and implementation. And Dan Edelstein of Stanford argues that innovation can be taught, but perhaps more effectively and naturally in the humanities than in the sciences.

Whatever the case, we physicists at Lawrence have chosen to explore whether we can use ongoing faculty research programs as incubators of innovative behavior among undergraduates. Our belief in this approach stems from the conviction that innovation, even if only incremental, must occupy center stage in an ongoing research program, and that innovation constitutes the life blood of a sustainable research program. Hence we believe that ongoing research programs in colleges and universities should naturally provide rich, instructive, and contagious environments that stand a good chance of stimulating innovative behavior among undergraduates. We have been exploring this thesis for four years.

Structure of the Investigation

The Lawrence approach to teaching innovation in the context of undergraduate research is straightforward: As the summer research students begin to grapple with their chosen research endeavors, their weekly activities are further enriched by collective readings and discussions that focus upon innovation and major innovators. Students read assigned passages from an immense literature on innovation and discuss them with faculty members during noontime luncheons. Fifteen character traits thought to be characteristic of many successful innovators are also discussed during these luncheons. As the summer unfolds, students are encouraged to conceive modest innovations in the agendas and/or approaches of their respective research groups and to attempt some initial prototyping. Students are also urged to embrace various character traits (Finke et al. 1992) that the innovation literature and the department associate with successful innovators.

During the summers of 2009 through 2012, the Lawrence physicists used ongoing research programs in astrophysics, biophysics, laser spectroscopy, surface physics, plasma physics, quantum optics, and cold-atom physics to conduct the investigation. Eight or nine undergraduates and six faculty members were involved each summer. This investigation, which enjoyed extensive support from the National Science Foundation's Transforming Undergraduate Education in Science program and other sources, was conducted during ten-week summer research periods, onto which innovation-stimulating activities were superimposed as described above. The schedule for each of the summers was:

Weeks 1-2: Students began by viewing and discussing *Deep Dive* (Koppel 1999), a video featuring the highly regarded innovative design company IDEO. Students also discussed scientific advances and revolutions (Kuhn 1970), strategies for pursuing innovation (Gelb 2007, Husick 2011), the importance of Silicon Valley and other sites well known for innovation (Grove 2010, Shurkin 2008), and various lectures viewed during weekly lunch sessions (www.TED.com). As the students became better acquainted with their chosen research programs, they participated in weekly brainstorming sessions without the presence of faculty members, debated the maxim "fail often to succeed sooner," and discussed fifteen character traits believed to be important for successful innovators.

Weeks 3-6: As the students became more deeply engaged in their respective research programs, they were encouraged to conceive modest changes that might strengthen existing approaches in these programs. They were also required to deliver short but frequent progress reports on their research efforts and to engage weekly in brainstorming sessions that focused on problems confronted in the research groups.

Weeks 6-8: Students continued to identify and propose changes or improvements (incremental innovations) in their groups' research activities. Brainstorming shifted to a focus on the merits, strengths, and shortcomings of these student-conceived changes.

Weeks 8-9: Serious consideration was given to the implementation of the student-conceived changes, the constructing of prototypes of these innovations, and the incorporation of the more successful innovations into the various research programs.

Week 10: Students made final presentations at summer science symposia and were interviewed by panels of visitors who attempted to assess the successes and shortcomings of the program.

Evaluation

Overall, this approach to the teaching of innovation worked quite well. The expectation was that a careful monitoring of the approach would confirm that the teaching of innovation can be superimposed upon existing research programs, and that such overlays can be effective in stimulating innovative behavior. Judging from the experience of four summers, the department finds that this approach does heighten students' innovative inclinations considerably, especially among the more able and confident undergraduates. As a major indicator of the program's success, faculty members looked for tangible evidence of innovative advances developed by the students over the course of the summer. But since evidence of this sort would likely emerge only late during each summer, faculty supervisors also searched for indirect signs of success. For this purpose, they used questionnaires, rubrics, student presentations, student notebooks, and a panel of visiting experts.

One of the assessment tools was a set of fifteen rubrics. Based on character traits that the department and the professional literature on innovation associate with major innovators (Finke et al. 1992), these rubrics helped the department judge whether students were showing signs of heightened *creativity/imagination, curiosity, ambition, competitive spirit, productivity, divergent thinking, willingness to take risk, tolerance of ambiguity, insightfulness, cooperativeness, articulateness, strong engagement, self-reflection, the acquisition of new skills,* and *an inclination to become more promotional* as the summer unfolded. These rubrics were administered three times each summer by faculty supervisors in one-on-one discussions with their student researchers. Following are two examples of the fifteen rubrics on which students were rated using a 5-point scale with 1 the lowest and 5 the highest rating:

Creativity/imagination rubric: Innovators have strong predilections to conceive creative or imaginative ideas, approaches, or processes. Numerical ratings mean:

5. Frequently conceives creative or imaginative ideas, approaches, or processes.
4. Often conceives creative or imaginative ideas, approaches, or processes.
3. Sometimes conceives creative or imaginative ideas, approaches, or processes.
2. Rarely conceives creative or imaginative ideas, approaches, or processes.
1. Never conceives creative or imaginative ideas, approaches, or processes.

Being promotional rubric: Successful innovators have the confidence to promote their ideas to associates and/or third parties. Numerical ratings mean:

5. Frequently exhibits the confidence to promote his/her ideas.
4. Often exhibits the confidence to promote his/her ideas.
3. Sometimes exhibits the confidence to promote his/her ideas.
2. Occasionally exhibits the confidence to promote his/her ideas.
1. Never exhibits the confidence to promote his/her ideas.

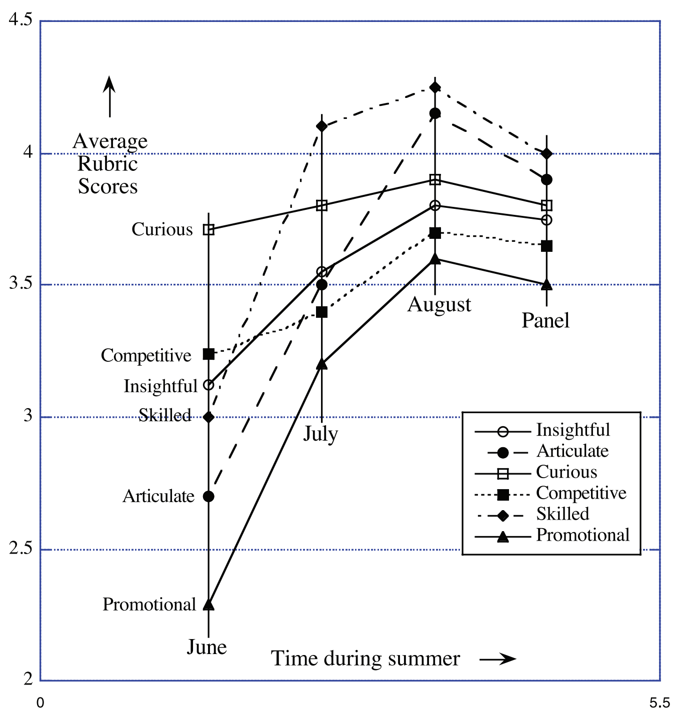
The plots in Figure 1 summarize the *average* scores for seventeen students on six of the rubrics administered during the summers of 2010 and 2011. These results pertain only to the summers of 2010 and 2011 when the rubrics remained unchanged. For the summers of 2009 and 2012, the rubrics varied slightly from those of 2010 and 2011. We made several changes because our use of the original set of rubrics in 2009 prompted a slight shift in the choice of innovative character traits that we sought to track. The initial changes were made after the summer of 2009 but prior to the summer of 2010. Then for the final summer, we once again changed several of the rubrics to test a few more attributes. All in all, these changes amounted to fewer than 20 percent of the total number of character traits, and the results for the summers of 2009 and 2012 closely resemble those shown in Figure 1. In the figure, "June" scores are those that were collected at the beginning of the summers, "July" and "August" scores at the middle and end of the summers.

The upward trends in virtually all the plots suggest moderate success in influencing student attitudes and behavior. Of course the plots with the steepest slopes indicate the traits in which faculty members observed the greatest change in students. Two traits, namely becoming more *promotional* and *articulate,* showed the greatest increases: The average student scores for these two traits increased by substantial amounts in the summers of 2010 and 2011, 57 percent and 53 percent, respectively, in only ten weeks. Apparently the research students responded quite enthusiastically to the program's emphasis on better speaking, not only better speaking in general, but also speaking more promotionally when presenting research progress and results.

Next come ten traits for which the students' average rubric scores increased between 20 percent and 40 percent over ten weeks. These traits included becoming more *skilled, ambi-*

tious, self-reflecting, fully-engaged, productive, creative/imaginative, divergent in one's thinking, tolerant of ambiguity, risk-taking, and *insightful*. These increases, while not as large as those for promotional and articulate, are substantial and statistically significant; the program appears to have been reasonably successful with respect to advocating these traits. Following this group are two traits on which students' scores increased only 15 percent—becoming more *cooperative* and *competitive*. And last, the innovative trait that showed the least increase over the summers of 2010 and 2011 was *curiosity*, on which students' scores rose only 5 percent.

Figure 1: Average rubric scores for six of the innovative traits for seventeen research students during the summers of 2010 and 2011. The rubrics were administered three times, namely in June, July, and August. The "Panel" scores are averages of estimates provided by the visiting panelists in late August.



While there seems to be no obvious reason why students should embrace certain traits more than others, it does appear that the traits that showed the larger increases concerned behavioral activities that garnered substantial reinforcement (more accolades, compliments, and encouragement from faculty supervisors) in connection with students' daily or weekly research progress. In other words, one suspects that students' day-to-day advances in their research activities and the consequent faculty accolades that they received probably persuaded the students that certain traits (such as becoming a *better speaker* or more *skilled* in the research lab or more *fully-engaged* or *productive*) were more important than others. Apparently the program provided little incentive in regard to students becoming more *curious*.

Late during each summer, a panel of three visitors (mainly physicists but sometimes academics from other fields) interviewed our summer research students. While these end-of-summer visits proved to be valuable, and our visiting panelists were very conscientious, we came to recognize that even hand-picked visitors spending only one day "on the ground" and having to interview nine students individually in only eight hours imposed limits on what we could learn from this method of outside assessment. Nevertheless, the following items represent recurrent themes from the panelists' reports: Students valued the requirement that they deliver frequent presentations and engage in weekly brainstorming sessions; students also came to accept the importance of the maxim, "fail often to succeed sooner"; and they derived considerable inspiration from various TED lectures and the *Deep Dive* video.

The visiting panelists concluded that while these ten-week programs were highly compressed and hence quite challenging for the students, nevertheless a majority of the students did come to appreciate the importance of innovation. The students also reported to the panelists that they benefitted from periods of greater autonomy when the research supervisors were absent. And finally, student attitudes toward risk, failure, tolerance of ambiguity, and creativity improved substantially. The far right column in Figure 1 records the average rubric scores as judged by the panel of visitors. In most cases, the panelists' judgments comport reasonably well with those of the department.

By the end of each summer, members of the department identified tangible advances in their research programs, some of which were attributable at least partly to student-conceived contributions or innovations. In several cases, major achievements and noteworthy innovative contributions by students to ongoing research programs led to faculty publications with student co-authors, papers that appeared in professional journals such as *The Physical Review* and *BioTechniques*. Of course not all of the student/faculty collaborations generated journal articles, but roughly 25 percent of the student researchers over the four-year period did deliver strong poster presentations at professional (national) meetings. Another 25 percent of the students attended regional undergraduate science symposia where they reported on their work and/or presented posters. All in all, most of the students made notable contributions and grew substantially through their participation in the program. The development and contributions by only about 25 percent of the involved students turned out to be disappointing.

Conclusion

In summary, members of the physics department at Lawrence believe that ongoing research programs augmented by innovation-focused overlays can serve as reasonably effective incubators of innovative thinking and behavior among undergraduates. While this investigation did not meet all expectations, the physicists at Lawrence believe that they know why: The combined research and innovation emphases were simply too much for most students to handle in only ten weeks. Hence the students more or less had to choose which to emphasize, and most ended up focusing more on research than on innovation. By the end of the first summer, the department's physicists recognized that they had failed to appreciate the excessive demands of this dual program. To temper their expectations for 2010 and 2011, students were advised to concentrate on only selected parts of their chosen research programs. This approach improved matters somewhat and helped free up more time for students to think about innovations. A second change in 2010 and 2011 involved the use of seminars or journal clubs in the spring term prior to the summer research activity. This modification helped students hit the pavement running in June and hence provided more opportunity to focus on innovation.

Based on our own reflections and students' comments about our investigation, it appears that three major conclusions

Call for Abstracts
Posters on the Hill
Spring 2014, Washington, DC

Nothing more effectively demonstrates the value of undergraduate research than the words and stories of the student participants themselves. In spring 2014, the Council on Undergraduate Research (CUR) will host its annual undergraduate poster session on Capitol Hill. This event will help members of Congress understand the importance of undergraduate research by allowing them to talk directly with the students involved in such studies.

CUR invites undergraduates to submit an abstract of their research that represents any of CUR's divisions (Arts and Humanities, Biology, Chemistry, Geosciences, Health Sciences, Mathematics/Computer Science, Physics/Astronomy, Psychology, and Social Sciences). To ensure proper review of applications, the above are the only disciplines in which students may apply. In the case of research that is interdisciplinary, students should select the division that most closely describes the research.

Directors of undergraduate research, faculty members, and other involved administrators are urged to encourage their students to submit posters. This is a highly competitive program and a very exciting experience for both students and their faculty advisors.

Call will open September 2, 2013. Applications due November 4, 2013.

can be drawn: (1) that the teaching of innovation is more difficult than one might imagine, (2) that partial student ownership in a research effort is important if one hopes to generate student enthusiasm for innovation in a research context, and (3) that when innovative activities are superimposed upon professional-level research efforts, ten weeks is probably insufficient time to address both objectives. Two Lawrence students participated in this investigation for two consecutive summers, and it was quite clear that the second summer provided substantially more opportunity for these students to make greater research contributions and develop a stronger appreciation of innovation. One other conclusion seems germane, however, and that is that programs and efforts of this sort should also be useful in various other disciplines where faculty/student collaborations based on ongoing faculty research or scholarship exist. There appears to be nothing in physics or the physical sciences that would make our findings unique to those fields.

Acknowledgments

The author is pleased to acknowledge NSF/TUES support for this four-year effort. Support was also provided by Lawrence University and funds honoring the late Dale S. Skran, Sr., as well as research grants from NASA, NSF, and Research Corporation for Science Advancement. The author is pleased to acknowledge various contributions by Matthew Stoneking, William F. Skinner, Jennifer Stone, Douglas Martin, and Erlan Bliss.

References

Augustine, Norman R. *et al*. 2007. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future,* and its 2010 sequel: *Rising Above the Gathering Storm, Revisited; Rapidly Approaching Category 5*. National Academies of Sciences. Washington, D.C.: National Academies Press.

Burger, Edward B. and Michael Starbird. 2012. *The 5 Elements of Effective Thinking*. Princeton: Princeton University Press.

Edelstein, Dan. 2010. How is Innovation Taught? On the Humanities and the Knowledge Economy. *Liberal Education,* 96: 1.

Finke, Ronald A. *et al*. 1992. *Creative Cognition: Theory, Research, and Applications.* Cambridge: MIT Press.

Friedman, Thomas L. and Michaelbaum, Michael. 2011. *That Used to be Us.* London: Picador Books.

Gelb, Michael J. and Sarah Miller Caldicot. 2007. *Innovate Like Edison*. New York: Dutton.

Good, David *et al*. 2007. *University Collaboration for Innovation*. Rotterdam: Sense.

Grove, Andrew. 2010. How America Can Create Jobs. Bloomsberg Businessweek, July 01, 2010.

Hiam, Alexander. 2011. How — and why — to teach innovation in our schools, eSchool News, February 1, 2011.

Husick, Lawrence. 2011. What Students Can Learn from Steve Jobs, The Newsletter of the Foreign Policy Research Institute. 16: 8.

Koppel, Ted. 1999. *Deep Dive*. A half-hour television segment narrated by Ted Koppel on ABC's *Nightline*, first aired on August 13, 1999. Now available on YouTube.

Kuhn, Thomas. 1970. *The Structure of Scientific Revolutions*. Second Ed. Chicago: University of Chicago Press.

Rae-Dupree, Janet. 2008. Eureka! It Really Takes Years of Hard Work. *New York Times*, February 3, 2008.

Shurkin, Joel N. 2008. *Broken Genius: The Rise and Fall of William Shockley.* New York: Macmillan.

TED: Ideas Worth Spreading. A website that offers more than 900 video lectures by outstanding and inspiring experts and practitioners in numerous fields, www.TED.com.

Wagner, Tony. 2012. *Creating Innovators: The Making of Young People Who Will Change the World*. New York: Simon & Schuster.

Wagner, Tony. 2012. Educating the Next Steve Jobs. *The Wall Street Journal*, April 13, 2012.

John R. Brandenberger

Lawrence University, brandenj@lawrence.edu

John R. Brandenberger, Chapman Professor of Physics Emeritus at Lawrence University, has served on the university's faculty for more than 40 years. He currently teaches a course on innovation, and he largely conceived and helped direct the four-year investigation described in this article. His research area is atomic/molecular/optical physics and laser spectroscopy. He is one of the original physics councilors for CUR.