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ScienceDirect

Procedia Computer Science 20 (2013) 541 – 546

Procedia Computer Science

Complex Adaptive Systems, Publication 3
Cihan H. Dagli, Editor in Chief
Conference Organized by Missouri University of Science and Technology
2013- Baltimore, MD

Rethinking STEM Education: An Interdisciplinary STEAM Curriculum

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Abstract

The State University of New York at Potsdam, with support from Lockheed Martin, has developed a multidisciplinary program intended to foster creative thinking by combining studies in the arts, humanities, and STEM fields. The College has a long tradition of innovative education in the arts, natural and social sciences, computer science, and mathematics. This “STEAM” approach will support the development of versatile professionals for the evolving workplace. To develop this program, a team of STEAM faculty members examined existing literature on the development of creativity as well as multidisciplinary models in industry, business, and education. Through academic restructuring of traditional educational models, this curriculum will be at the forefront of engaging learners in team-based multidisciplinary problem solving through mentoring, learning communities, research projects, and partnerships with outside agencies. The program is a model for the education of scientists who will be able to create innovations in modern science and technology necessary to address the complex problems facing human society.

Selection and peer-review under responsibility of Missouri University of Science and Technology

Keywords: STEM; STEAM; undergraduate; science education; curriculum; creativity; innovation;

1. Creative Scientists Needed

In a world with greater population, global interconnection, technological advancement, and large-scale problems than ever before in human history, complex problems require sophisticated problem solving skills and innovative, complicated solutions. In the United States, colleges train scientists in a manner similar to the way they were trained decades ago, while these new challenges place different demands on science. Traditional science training provides a solid foundation of facts and basic science technique, but rarely examines how to foster scientists’ creative, cross-disciplinary problem identification and solving skills. Industry leaders, such as Haden Land, VP of Engineering and Chief Technology Officer for the Information Systems & Global Solutions, Civil Product Line at Lockheed Martin, are interested in identifying ways to foster creativity in the context of science to encourage the kind of visionary innovations that will be needed to solve complex problems [1]. The goal of this project is to develop a curriculum that integrates scientific training with creativity development to promote innovative cognitive skills in undergraduate science students.

The State University of New York at Potsdam is an ideal setting for this curriculum development. The oldest teacher education school in the state university and the birthplace of music education, it has a long history of curricular innovation in education and the arts. In addition, it has strong science programs which focus on providing students with the opportunity to engage in significant authentic scientific research in collaboration with faculty members.

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Selection and peer-review under responsibility of Missouri University of Science and Technology
doi:10.1016/j.procs.2013.09.316

A team of faculty members worked together to develop an interdisciplinary problem-based curriculum structure from the perspectives of their disciplines, which included biology, computer science, mathematics, music education, psychology, theatre, visual arts, and vocal performance. The curriculum structure was developed empirically, through both an examination of scientific literature on fostering creativity and through exploration of models in higher education and industry. This paper briefly describes the research basis and the emergent student outcomes, structural design, and pedagogy of the proposed curriculum.

2. Science of Creativity

A scientific approach has been used to develop this curriculum structure, including reviews of the literature on the nature of creativity and how to develop it. One conceptualization of creativity involves distinguishing divergent and convergent thinking. Convergent thinking is following a process to reach one solution to a problem, whereas divergent thinking involves exploring many possible solutions to a problem. Programs designed to foster creativity often focus on teaching students strategies to promote divergent thinking. Divergent thinking, and therefore creativity, is defined in terms of fluency, flexibility, and originality of cognitive processes. Much of the existing literature has focused on training elementary school children. However, older students are better able to engage in divergent thinking [18], which makes a post-secondary program an ideal vehicle for promotion of creativity.

Other conceptualizations for creative involve fluency, which is operationalized as the number of responses to a problem; flexibility is the number of different types or responses; and originality is the uniqueness of the approach [2]. Other research differentiates "big C" and "little c" creativity: "big C" is creative genius, creativity in terms of widespread thinking about a problem; "little c" is an individual's creative notions that are unique to the individual but not necessarily to humanity at large [3].

While the research on creativity suffers from some limitations, in that much is anecdotal and systematic research often has selection biases, measurement issues, transferability of skills, and demand characteristics, [4, 5, 6], there are some trends to guide program development. Research shows that fostering creativity in students is beneficial. Various studies have shown that students involved in creativity programs display more advanced thinking [7]; ability to cope with stress [8]; enhanced self-awareness [8], life skills [3,9]; social skills (i.e., communication, team work, confidence, autonomy, motivation) [9]; connections with their community [10]; and are generally more open and eager to thinking creatively [5, 18]. Furthermore, there is evidence that involvement with courses on creativity may enhance faculty satisfaction and possibly retention, through interaction with colleagues and diversification of pedagogical practice and enhanced collaborative learning [10].

The descriptions of training programs certainly contain some common elements. Such programs start with a core knowledge base as a springboard for future creative endeavours [11, 12, 13] and focus on providing ample opportunity to practice what is learned [14]. Knowledge and skills developed include communication of all types, negotiation, and problem solving, with application to authentic problems [15]. Habits are cultivated, such as documenting through notes, designs, or journals and even maintaining physical fitness [14]. Students are encouraged to become active problem solvers [16], and to "take ownership of ideas, processes, directions, and engage with motivation" [15, p. 491). Because collaboration with other professionals and with the constituencies being served is so important, there is a great emphasis on providing experiences to enable students to work in communities. Building communities with other students is important, through living together and spending time outside of class, fostering communal incubation of ideas [3, 12]. Learning to appreciate the advantages of groups is vital, to appreciate that "group members have diverse backgrounds, are open to new ideas, constructively challenge one another, effectively communicate and provide feedback, successfully manage conflict, trust, and help each other, and share a commitment to their work" [17, p. 155]. Nevertheless, time for individual reflection is also important to allow students to take responsibility for their own learning [15].

The literature shows that creative individuals are engaged, active learners, excited, intrinsically motivated [13] and have positive attitudes towards creative thinking [18]. A unique higher education structure would allow students to construct their own curriculum in consultation with advisors who ensure rigorous academic standards. Thus, coupled with time for incubation, inquiry based learning in which students dictate the problems within domains in which they are interested, while working with an interdisciplinary array of instructors, will cultivate dispositions related to creative problem solving (i.e., creative self-efficacy, persistence or perhaps even obsession, and ability to tolerate ambiguity can be promoted [3, 12, 14, 17]. The job market is evolving at an exponential rate, with interconnections among a variety of fields. Since the prospective career path for students is unknown, students will need the ability to understand multiple domains as well as to creatively make connections among a variety of disciplines. A single area of study (*i.e.*, major) has become antiquated.

Faculty who are successful in these programs also have some common characteristics, which are vital for programmatic success. "The effectiveness of any program depends on the interests, enthusiasm, and involvement of the teachers" from a variety of disciplines [5, p. 522]. Just as reflection is important for creative students, instructors must engage in professional reflection. The work of faculty must include time for such reflection to develop their creativity and connect and collaborate with other instructors [10, 19]. The facilitative role of faculty is emphasized. They promote student-directed learning and autonomy, providing constructive, nonjudgmental feedback [3, 9, 15].

Instruction is inquiry based and oriented around problem solving in which students and faculty work to identify problems of study. Faculty will model problem solving and encourage reflection, communication skills, autonomy, and self-monitoring. They teach students to see problems as opportunities and model the notion that interaction among colleagues is important for creative problem solving [19, 20, 21]. Faculty need to be "good communicators and able to set clear direction without being controlling" [17,

p. 156] and they must display “genuineness, empathy, and unconditional positive regard” [21, p. 152]. The benefits for faculty will be numerous (*e.g.*, developing their own creativity as teachers [16], increased knowledge of other disciplines, and renewed enthusiasm.)

Thus, the goal is “not to teach ‘creativity’, [but rather to] isolate creative thinking strategies and introduce metacognitive thinking” [7, p. 17]. This requires a shift from thinking about teaching content within a domain to a domain-driven application of course content, asking how knowledge can be used. The teaching of creativity is integrated into all instruction, with learning activities that are engaging and relevant, and promote student ownership of their own learning, including development of the curriculum [15, 16]. Creative students influence curricula and modes of instruction [19].

Curricular features involve projects and applied learning, reducing fear of evaluation, combining different approaches to training, and flexibility. The curricular reliance on applied projects identified by students and faculty is important. Projects should engage students in useful application, real-life problems, and interdisciplinary work to promote deep engagement [15]. Frequently the projects impact local, campus, or societal issues [2]. Both numerous hands-on short-term activities and long-term projects are used, sometimes in timeframes not restricted by the traditional academic calendar, such as continuing between semesters and through summers [20]. “Creativity, innovation, flexibility are rewarded, mistakes [are] viewed as opportunities [and] learning is ongoing [22, p. 63]. Removing fear of evaluation of ideas is especially important in early stages [6, 23]. This suggests that a program might start by asking students about interests to build the curriculum, to stop thinking of students as passive recipients of knowledge, and instead allow them to actively mold the curriculum. Curricula “build on experiences and existing relationships with people and places [by] collaborating [on] tasks, contributing to curriculum planning” [10, p. 44].

Students are encouraged to reflect on their creative process and to understand that the “process is dynamic but non-linear [and]…learning should be a reflective and iterative process” [15, p. 489]. Journaling, exposure to creative thinkers, and opportunities for students to plan, monitor, and evaluate their own processes can foster creativity [7]. Teaching techniques that encourage students to reconceptualize established ideas and behavioral patterns, along with interdisciplinary work, promote creative thinking [2]. For example, there is evidence that studying the visual arts does improve scores on tests of visual creativity [24]. Some research also suggests that combining different approaches to training programs may be crucial to suit the preferences of diverse students [5].

One study that specifically assesses the development of creative and critical thinking in a college curriculum reports that faculty believe that teaching practices that stimulate creative thinking involve active learning, with high levels of engagement in course material, applications to real problems in and outside of the classroom, and interdisciplinary work. In the same study, students indicated that interactions with faculty and other students, both in and out of the classroom, and writing assignments fostered creative thinking, whereas reading assignments did not [25].

Thus, programs need to create “communities that provide stimulation, diversity, and richness of experience [as well as] adequate time for creative thinking, rewarding creative thoughts and products; allowing mistakes; imagining various perspectives; questioning assumptions; identifying interests and problems, and generating multiple hypotheses” [16, p. 610]. Collaboration is promoted by mentoring programs, environments with social reciprocity, and shared residences [23].

Research also identifies some issues that can cause difficulties for students that must be considered as the program is implemented. “Creativity [is] a subversive act since it disturbs and disrupts existing patterns of thought” [16, p. 608]. There is some evidence of a bimodal distribution in response to such programs, i.e., students seem to either love or hate the training [8]. In the absence of thorough research, the most effective modes of creativity instruction are ambiguous and both students and teachers report feeling uncertain [9, 15]. In one study, students reported not having enough time to complete goals [9] and in another, students were reluctant to alter direction when needed [3]. Addressing these potential concerns will facilitate programmatic success.

3. Models in Higher Education and Industry

Conversations with industry leaders discussing characteristics they wish were cultivated in students suggest that they are looking for people who can “think outside the box,” work in teams with people with diverse expertise, and approach problems both divergently and convergently. As specific learning outcomes are developed, further conversations with industry leaders will inform the discussion. There are also movements to encourage legislators to support the arts because of their role in fostering innovation. In fact there is a United States Congressional Caucus on STEAM co-chaired by Representatives Suzanne Bonamici and Aaron Schock. Recently a briefing by a number of arts organizations addressed integrating arts education with STEM in order to stimulate creativity in students in K-12 [26].

Exploration of programs in higher education suggests that no one is developing a program quite like the one proposed herein. A number of programs are initiated by art and design schools to demonstrate how their curricula can benefit sciences. The Rhode Island School of Design mentions STEM to STEAM with partnered studies, structured group problem solving, and use of established international education programs. The Maryland Institute College of Art has a STEAM Graduate Research Focus Area, and integrated informal education for art and STEM, along with centers for design practice, design thinking, and art education. Other institutions focus on creativity in certain areas such as business or engineering. Bryant College in Rhode Island addresses creative problem solving, teamwork, and the innovation process in a core with a focus on global business, along with mandatory study abroad. Rensselaer Polytechnic Institute offers programs in electronic arts, games and simulation arts and sciences, and design, innovation and society, with explicit discussion of STEM to STEAM projects and a performing arts center designed to support technical art development and display. Others focus on broader interdisciplinary applications of arts and sciences to focus on problem solving.

Oklahoma State University has an Institute for Creativity and Innovation, which coordinates creative scholarship and innovative instruction, problem solving workshops, and contests for innovative and creative solutions to various problems. Stanford University's d-school (school of design) is a center for innovation, with interdisciplinary teams of students working on the world's problems. Students take one course in creativity and innovation and the d-school also supports an alumni creative camp. The review of the curricula at these and other institutions identified a number of interesting academic components, including intensive first-year sessions, problem solving courses addressing "world problems," structures infusing creativity throughout the curriculum, a study abroad experience in a relevant setting, multiple internships, and equipment such as machine shops accessible to students. None of these institutions present an integrated curriculum, however.

4. Components of Instructional Programs

The proposed program is designed to develop exceptional and creative leaders with six characteristics. First, they will be excellent communicators, who are good at listening and at articulating verbal, written, and visual ideas, and who think and communicate in analogies and metaphors. Second, they will be good organizers who schedule time well, complete tasks, and identify subtasks to reach a bigger goal. Third, they will be managers who can motivate, facilitate, and guide others, both as individuals and as group members who work well with others with differing perspectives. Fourth, they will be discerning learners who have depth of domain knowledge in at least two fields, breadth of knowledge that facilitates cross-disciplinary thinking, and information literacy to seek resources when needed. Fifth, they will be creative and innovative thinkers who can find, shape, and solve problems in ways that lead to innovative and unique applications, who can conceptualize in multiple levels of abstraction and synthesize across multiple disciplines and levels of analysis. Finally, the program will cultivate an understanding of the importance of personal traits including life-long learning; self-motivation; self-efficacy; persistence; learning from mistakes; reflective and flexible thinking; collaboration; and personal, professional, and social responsibility, including the willingness to tackle ethical issues.

The program is designed around student interests yet contains curricular hallmarks that infuse its coursework and activities. Each element includes these hallmarks in some form – communication, collaboration, responsibility, application, reflection, creative learner, problem engager, synthesis, literacy, and dispositional development. For example, in regard to application, applied problems will be addressed in early coursework and as the student progresses towards a culminating senior project, they will work on a sequence of projects that are connected across semesters to lead to the senior research thesis or internship project. In collaboration and responsibility, mentoring and teaching assistant programs will allow upper-level students to work with lower-level students on projects, so that cross-level collaboration is occurring throughout the four-year curriculum. Similarly, every class will address written, visual, and spoken communication or problem solving requirements. The program will be demanding and will include special sessions (winter or summer term) courses that allow for such things as creative activity or in-depth projects that are less possible in the normal semester structure. It will require close mentoring by academic advisors and peer mentors.

5. The SUNY Potsdam Model: An Integrated Curriculum

SUNY Potsdam has an individualized major program called Student-Initiated Integrative Major (SIIM). Each student in the STEAM program will develop a unique SIIM, which generally involves a major area and two minor areas of specialization. This program has been modified so that students will proceed through the major in a cohort of students with whom they will be working on integrative problem solving. The student-directed curriculum model revolves around three sets of activities: Domain Knowledge, Integrated Learning Modules and Problem Solving Workshops. Domain knowledge involves developing scientific expertise, both the basics within a discipline and cognate sciences, clearly essential for student success in industry or graduate school, and meeting the basic communication and disciplinary breadth of the college's General Education Program. In their first semester students will take a course on problem engagement in the 21st century. Students for the STEAM program will be recruited during freshman advising and the pool of candidates for the STEAM curriculum will be identified from participants in the course. This course is followed by a two-week winter term exploration of a problem topic facilitated by faculty. From this discussion, students and faculty work to construct the Integrated Learning Module (ILM) for the following semester. The ILM will involve multidisciplinary problem solving teams working on a particular thematic problem, such as global overpopulation or water shortages. Students will propose course themes and then select related problems to study, so they take ownership over their own projects. There will be at least one Integrated Learning Module offered each semester. In addition, students will take the Problem Solving Workshops, some of which will be held as intensive sessions in winter term when they can immerse themselves completely in a project. Students are required to have an internship and the program will be crafted to allow students to take a semester abroad. The culmination of the student's academic experience will be a significant senior capstone research project applying scientific knowledge to solve a significant problem.

Each student's program will thus include four major components:

- Interdisciplinary Major (25-48%): A student-designed, forward thinking major with at least two different fields of study.
- Integrative Core (42-49%): Problem based multidisciplinary, student-driven applied learning occurring throughout the curriculum.
- Internship Experience (2-10%): Required real-world experience away from the home campus.

- Other Requirements (5-14%): Miscellaneous General Education and liberal arts requirements.

The load within each component will vary based on the student's self-designed curriculum. Here are two sample degrees to illustrate the types of programs students may design:

Limnology Degree

Student-Initiated Interdisciplinary Major (SIIM)
BIOL 151 General Biology I
BIOL 152 General Biology II
BIOL 300 Ecology
BIOL 311 Genetics
BIOL 409 Fresh Water Ecology
CHEM 105 General Chemistry I: lecture & lab
CHEM 106 General Chemistry II: lecture & lab
CHEM 341 Organic Chemistry I: lecture & lab
ARTS 369 Video I
ARTS 395 Video II

Integrative Core
Introductory Course (*Creativity & Problem Engagement*)
Integrative Learning Modules (ILM)
Two 9 credit ILMs
Three 6 credit ILMs
Introduction to Student-driven Curriculum
Three 2 credit Winterim Problem Engagement Courses
Integrative Capstone Project Seminars (ICP)
Two 6 credit ICP Seminars, which includes an Integrative capstone project the student's fields of study.

Internship (or Study-away) Experience

Additional General Education Requirements or Electives

Energy Analyst Degree

Student-Initiated Interdisciplinary Major (SIIM)
GEOL 103 Physical Geology
GEOL 204 Historical Geology
GEOL 301 Sedimentary Geology
GEOL 311 Mineralogy
GEOL 321 Optics and Petrology
GEOL 420/440 Geochemistry/Economic Geology
CHEM 105 General Chemistry I: lecture & lab
CHEM 106 General Chemistry II: lecture & lab
CHEM 341 Organic Chemistry I: lecture & lab
ECON 105 Principles of Microeconomics
ECON 110 Principles of Macroeconomics
ECON 302 The Global Economy
PHYS 325 Energy and the Environment

Integrative Core
Introductory Course (*Creativity & Problem Engagement*)
Integrative Learning Modules (ILM)
Two 9 credit ILMs
Three 6 credit ILMs
Introduction to Student-driven Curriculum
Three 2 credit Winterim Problem Engagement Courses
Integrative Capstone Project Seminars (ICP)
Two 6 credit ICP Seminars, which includes an integrative capstone project the student's fields of study.

Internship (or Study-away) Experience

Additional General Education Requirements or Electives

Existing curricular structures at SUNY Potsdam allowed adaptation of common elements identified in other institutional programs, as described previously. For example, a first-year curriculum that includes writing, speaking, and critical thinking elements provides a foundation for skills to be developed. A well-developed Learning Communities program allows for the grouping of courses to be taken by a cohort of students. A General Education program that already requires students to take two arts courses, one with an experiential focus, and one with a critical analysis focus, provides a greater arts experience than most other colleges require. The possibility of two- or three-week winter and summer term programs allows for a concentrated course to address one problem intensively. Numerous possibilities for study internationally or exchanges with institutions within the United States allow for cross-cultural experiences globally or in locations in the U.S. such as urban settings. A well-developed program to help students find and achieve internships and an undergraduate research program with some funding available will assist with capstone experiences. Most importantly, a faculty culture that focuses on providing individualized student attention and opportunities will assure support for this kind of curriculum.

The design of each course or activity in the program will identify the curricular hallmarks it incorporates and a cross-walk will be created to assure that all hallmarks are adequately addressed throughout the program. Thus, for example, there should be adequate attention paid to collaboration at each level of the program to assure that students practice it in increasingly sophisticated ways as they progress through their college career. At an even more granular level, each course or activity will identify specific learning outcomes related to both disciplinary expertise and the curricular hallmarks to assure that course outcomes are aligned with program goals. Unlike other programs, students' experiences will be integrated and progressive through their college career. Finally, a rigorous assessment of student outcomes with appropriate pre- and post-test measures and development of student e-portfolios will examine the success of the program empirically.

This unique STEAM curriculum will be a model for educating creative scientists who can develop innovative solutions to serious global problems. Once it has been offered and thoroughly assessed, it will be disseminated throughout the higher education community.

Acknowledgements

We wish to thank the Lockheed Martin Corporation for providing funding to support that development of this curriculum. Lockheed Martin's Haden Land and Michael Nance have provided vision and inspiration. We also thank our SUNY Potsdam colleagues who have served as resources for the project: Nancy Griffin, Jenica Rogers, Steven Marqusee, and Peter Brouwer.

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