A STEM Incubator to Engage Students in Hands-on, Relevant Learning: A Report from the Field

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ABSTRACT

This paper describes the development of a STEM Incubator program to engage students in hand-on, relevant projects that draw student interest toward computer science and other STEM fields. The program is implemented via one-credit courses allowing students to collaborate on projects in various areas (such as digital sound and music, 3D design, robotics, digital image processing, bioinformatics, and mobile and pervasive computing) and around multiple application domains (e.g. internet of things and security, apps for college campus life, 3D printing and art, wearable sensors for disabilities, and sensors and unmanned vehicles for conservation). An apprentice/leader learning environment is created to sustain student involvement in ongoing projects. The evolution of the program is reviewed, including successes and challenges. We report on the demographics of students who have participated in the program so far, and on the success in attracting enthusiastic interest, notably among female students. The STEM Incubator program, like other similar programs described in this paper, attempts to put into practice the evidence-based teaching practices in active learning that have gained credence over the past decade. The paper is of interest to those considering a similar program or wishing to compare other programs to their own.

CCS Concepts

collaboration in software development, collaborative and social computing, multimedia content creation, interaction devices, sensor devices and platforms, network experimentation, ubiquitous and mobile computing

Keywords

hands-on learning; situated learning; collaboration

1. BACKGROUND

The value of engaging students in hands-on, relevant projects has largely been agreed upon in education of the 21st century. An overview of keywords in SIGCSE and ITiCSE conference papers of the past ten years gives evidence of this (Table 1). Hands-on STEM learning also has strong federal support, demonstrated in a 2014 conference, co-organized by The White House Office of Science and Technology Policy. In the conference report, "early experiential learning" and "active learning methods" are promoted, and STEM educators are urged to realize the "evidence-based teaching practices" that have emerged out of research [1].

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It falls to educators now to create the best hands-on experiences for their students, and to integrate the experiences into the computer science curriculum in a way that not only attracts students but also retains them in the program and teaches useful concepts, skills, and ways of solving problems. Our STEM Incubator program, which vertically integrates participating students in small teams through a leader/apprentice model, is an effort in this direction.

Table 1 Common keywords in SIGCSE and ITICSE papers of the past decade

	SIGCSE	ITiCSE
active learning	100	32
situated learning	4	0
computational thinking	79	31
problem-based learning	9	11

SIGCSE: Conference Proceedings of Special Interest Group on Computer Science Education

ITiCSE: Conference Proceedings of Innovation and Technology in Computer Science Education

To our knowledge, among the first to create robust active learning programs were the University of Texas and Georgia Tech. UT's Freshman Research Initiative involves students in research with faculty and graduate students in integrated course and lab work over a period of three semesters. This program involves chemistry, biochemistry, nanotechnology, molecular biology and computer science. Georgia Tech's Vertically-Integrated Projects Program also spans three years and engages teams of 30 cohorts. The "vertical" movement arises as entry-level students learn from more experienced student leaders and then progress to leadership positions themselves [2]. Both UT's and Georgia Tech's programs have engendered other initiatives. UT's model appears to have been adopted by Iowa State and SUNY Binghamton. Georgia Tech's program has grown into a Vertically Integrated Programs Consortium that includes approximately 14 schools (by our recent count) and has strong private funding. Other similar programs have sprung up, including the University of Central Florida's LEARN (Learning Environment and Academic Research Network), which has a 12 week apprenticeship; and the University of Wisconsin's STEM Innovation Pipeline Project, which extends to pre-college students.

Our STEM Incubator program has similarities to and differences from those just mentioned, in particular with Georgia Tech's VIP program. However, the environment in which it is implemented is fundamentally different as our institution is a small liberal arts university without the benefit of an engineering program.

2. METHODOLOGY

2.1 Motivation

The initial motivation of our STEM Incubator program was to attract more students into STEM disciplines, particularly women, and specifically into computer science. This was at a time when the number of computer science majors had greatly declined (pre-2013). However, as the demand for workers educated in science and technology has grown in the past four years, computer science enrollments have surged, and attracting students is no longer a unique focus. The value of hands-on, relevant projects as an important component not only of attracting but also of retaining computer science students and providing them with an up-to-date education has increasingly been recognized.

Students of the current generation have grown up in the midst of a head-spinning digital revolution that has popularized things that were only imagined a few short years ago – voice recognizers that actually understand us and answer our far-flung questions, truly immersive virtual reality goggles, ubiquitous and wearable sensors that seek to anticipate our needs, wristbands that monitor our every move, smart phones, smart prostheses, constant worldwide connectivity, and an app for everything. It seems that computer science education has had to scramble to keep up. While we, with admirable deliberation, have taught our data structures and theory of computation courses, the world has raced forward with transformative, game-changing, even disruptive innovations. Students who grew up in the digital world are likely to be uninspired by computer science programs that don't give them a tangible, visible connection with today's digital innovations, and a sense that they can contribute something of their own. Thus we have embraced relevance, applications, collaboration, and hands-on learning.

Another aspect of our vision for the STEM Incubator was related to social relevance, a theme which has received attention in the computer science education literature [2] [3] [4] [5]. Thematically, we initially described our vision for the STEM Incubator program as *socially-inspired learning* – learning *in* and *for* a community, motivated by collaboration, caring, creativity, and competition [6]. These elements have remained integral to the program as it has developed. In practical terms, the theme has been manifested in team-work; relevant applications, particularly for those with special needs; interdisciplinary project efforts that extend to music and the visual arts; and light-hearted competitions that help to make the projects more fun.

2.2 The STEM Incubator Courses

The centerpiece of our STEM Incubator program is a continuing series of one-hour courses on a wide range of topics, as described in the abstract. The topics may vary each semester according to the interests of the professors who teach them. Professors are allowed a great deal of flexibility in how they conduct their individual courses. The shared concept is that the courses offer students an interesting, non-threatening introduction to STEM and, in particular, computer science, by means of hands-on projects that seem timely and relevant to today's students.

Some course topics – robotics and drone development, for example – are more hardware oriented. Others – like digital image processing, bioinformatics, and app invention – may involve more software (application programs) or introductory level programming. While the courses have clearly defined learning goals, the outcomes are specified by the professor, constrained so that the projects can realistically be completed in a one-hour, one semester course. Some courses are more open-ended, allowing the students to discover the outcomes and to specify milestones around a significant challenge set by the instructor. The students set about on an exploratory path to prototype and test along the direction of their final goal.

2.3 Leader/Apprentice Model and Vertical Integration

The STEM Incubator courses implement a leader/apprentice model, with entry level students (apprentices) learning from more advanced students (leaders) in small teams and in projects that can progress in successive semesters. A student can take the course three times if the topic varies, twice as an apprentice and once as a leader, or vice versa. The courses are graded pass/fail. The three STEM Incubator credits can count toward a minor or BA in computer science degree. To receive a pass, the students must have shown participation in all activities, including teamwork, oral presentations and demonstrations, as well as kept track of their work in electronic or paper-based journals.

Significantly, it is the students rather than the professors who serve as primary project leaders to their teammates. Leaders are expected to have some experience in a previous STEM course similar to the one they are currently taking, or relevant knowledge (like programming ability) from another computer science course. The professor's role as the academic mentor is to inspire, guide, facilitate, and provide additional information and instruction when required.

The leader/apprentice model has proliferated both in academia and business/industry and it is a key component of the type of vertical integration proposed by Parslow [7]. Similarly, the "cognitive apprenticeship model" emphasizes mentoring of abstract thinking and problem solving skills [8]. The thrust of our program is to integrate computational and algorithmic problem-solving with hands-on skills.

2.4 Project Continuity

An outgrowth of the apprentice/leader model is an effort towards continuity – i.e., fostering projects that can evolve and grow in successive semesters. Our goal is to foster projects that continue from one semester to the next, with apprentices graduating to leader level and then bringing entry-level students up-to-speed with on-going projects.

2.5 Space and Resources

We began our STEM Incubator program with some departmental resources and no support in the form of grants or university funding. We had to use our already-limited space in the Computer Science Department to make room for the additional number of students attracted by the program and by the type of hands-on projects involved. With this "can do" attitude, we developed our course structure and passed it through university approval, reconfigured a classroom as our STEM Incubator Lab, and spent some of our departmental budget on equipment such as drone components, Raspberry Pis, Arduinos, Makey-Makeys, Kinect Cameras, a 3D printer, and so forth. Some faculty members were able to use grant money when their STEM courses related to their research.

We discovered that lack of resources was not a bar to the initial success of the program. The STEM courses themselves and the excitement and buzz about our program circulating among the student population is helping raise awareness and recognition of our efforts in our institution.

2.6 Faculty Participation

Seventy percent of our full-time faculty in computer science have offered STEM courses since its inception, all of them more than once. This is in spite of the fact that the course is a one-hour addition to their usual teaching load. There appear to be three motivations for teaching the STEM courses. First, the department as a whole is always looking to update and enhance the students' learning experience. The attraction of hands-on, relevant projects – the ability to build something or "make something happen" – is clear among our students. Second, faculty can be equally interested in doing hands-on work to update their knowledge and supplement their more abstract research. A third motivation is that STEM projects sometimes relate to or evolve into the faculty member's ongoing research. We have excellent, high-achieving undergraduate students at our university, some of whom end up collaborating on publications by their senior year. A good number of our undergraduate students continue in our Master's program as well. Thus, the STEM Incubator gives faculty an opportunity to prepare students for increasingly advanced research.

2.7 Participation of Other Disciplines

From its inception, we planned for the STEM Incubator program to involve collaboration with other STEM departments and even art and music at our university. The Biology Department and the Center for Innovation, Creativity and Entrepreneurship have been our primary collaborators thus far. Two professors from the Biology department have participated for the last two years as faculty mentors, bringing their expertise as well as their own students to the program. We have also had conversations with Physics and Art Departments, and they have expressed interest in developing one-hour hands-on type courses of their own. We continue to pursue these collaborations.

3. EXAMPLE COURSES AND OUTCOMES

Out of the various topics initially offered by participating faculty, the following four STEM courses and their outcomes, through various semesters of instruction, are described. These courses offer project continuity and maturation, and students indicate high enthusiasm and a high level of perceived learning according to our survey data (presented in Section 4).

3.1 Bioinformatics and Game-Like Algorithmic Problem-Solving

The most successful version of the Bioinformatics STEM course provided students the opportunity to gain insight into how computer algorithms are being used to solve complicated biological problems, while also getting the students to exercise creativity in determining how to teach others how to think about algorithms. This version, held in Fall 2015, started by exposing the students to the complex problem of whole genome DNA sequence assembly. Students examined this problem as if it was a complex combinatorial puzzle to be solved. The concept of algorithms was then introduced, with examples provided of algorithms that can be used for sequence assembly. In the second half of the course, the students focused on creative activities – designing a game to teach young students, in a fun way, the ideas behind sequence assembly. The students examined aspects of game play and mobile app creation, as well as exercised creativity in assembling a physical version of the game. The course concluded with the students leading their peers through the motivation for and actual play of the physical version of the game.

3.2 Robotics and Fun Competition

The challenge of the Robotics STEM section (roboSTEM) is to enable a robot to navigate autonomously through an obstacle course. Students learn about simple robots, controls, sensors, algorithm development, simple machine learning and AI, and basic Python. Since programming experience is not required, the emphasis is on algorithmic development. Apprentices are placed in teams of two, each team equipped with all the necessary hardware. Leader students assist with programming, and apprentices learn some basic Python in the process, some becoming reasonably proficient in the fundamentals. Students learn about sensors and must design and execute experiments to calibrate an ultrasonic range sensor. A competition is held at the end of the semester for fastest navigation through the obstacle course. Students have generally been very enthusiastic about this section, enjoying the fact that programming results in a physical manifestation of their algorithm. Interviews with female students after the course revealed that they particularly enjoyed the "freedom to fail," the hands-on, experimental nature of the work, the collaboration, and the fun of the final competition.

Figure 1 Working with robots

3.3 STEM and Artistic Experimentation

Some STEM courses have sought a relationship between computation and the arts. One course challenged the students to strip the sound track off a silent movie (without listening to it first), choose a dramatic portion of the movie, and create their own sound track for it. Another section introduced students to 2D image processing, particularly filters and convolutions. The students were challenged to apply filters at the application program level, and learn the basics of how these filters operate as mathematical convolutions. Their project was to apply their knowledge creatively by creating an illustration for Roald Dahl's BFG ("Big Friendly Giant") in which the giant captures dreams in a jar. More recent art-related STEM courses involve creative 3D modeling and printing.

3.4 STEM Pro Humanitate

Following the motto of our University (For Humanity), one sequence of STEM courses since our Incubator program inception has focused on problems and projects with high social relevance [4], namely focusing on people with special needs as well as the environment. In particular, a number of student teams in this STEM course have focused on design and development of Arduino-based wearable sensors and the exploration of related pervasive technology for people who are visually or hearing impaired. A watch-like device, dubbed H.E.L.P. by the students (Human Echo

Figure 2 H.E.L.P device to inform user of obstacles

Location Partner), uses sonar and vibration on the skin to inform the user of obstacles in the scene [9]. The device has been tested with over 25 people and a second version is currently under development. Similar STEM work is being done for the hearing impaired and other conditions, such as Guillain-Barré syndrome. Another group of student teams has been focusing on the development of unmanned aerial and underwater vehicles for the collection of data related to ecology and conservation. A prototype developed by students last Fall 2015 will be taken to the field in 2016 for observation of coral life in Belize. A Senior Honors project that explored visualization of sound for the hearing impaired was also born out of STEM incubator course. Faculty mentors for these STEM courses include professors from the Computer Science as well as Biology Departments.

4. ASSESSMENT

4.1 Enrollment and Demographics, and Assessment

We have been collecting demographic information about our course and major/minor enrollments since the inception of our STEM Incubator program, Fall 2013. To date, 205 students have enrolled in the courses, as indicated in Table 2. The percentage of female students has grown, and in the most recent semester, more than 50% of the students are female. The number of female computer science majors and minors has also grown. In our first report on the program, the percentage of female majors or minors was 26%. It is now 32%.

Among the students who have taken a STEM Incubator course since Fall 2013, 76 took a computer science course (other than STEM) before or during the same semester as the STEM Incubator course. Importantly, 14 students have gone on to take CS1 after the STEM course. Twenty-two students have taken two or three STEM Incubator courses.

Table 2 Demographics of STEM Incubator course

Semester	# students	African-Amer	Hisp	2 or more races	M	F	Freshmen
Fall 2013	30	3 10%	3 10%	NR**	18 60%	12 40%	
Spr 2014	49	1 2%	4 9%	NR	27 59%	19 41%	19 39%
Fall 2014	47	2 4%	3 6%	NR	30 64%	17 36%	25 53%
Spr 2015	23	1 4.5%	2 9%	NR	11 48%	12 52%	2 9%
Fall 2015	30	2 7%	2 7%	NR	15 50%	15 50%	19 63%
Spr 2016	26	2 7.7%	0	2 7.7%	12 46%	14 54%	3 12%
total*	177						

*In each row but the last, the totals are total course enrollments. Students may take the course multiple semesters. In the last row, the total is the total number of individuals who took a STEM course.
**Not reported
The totals in the last row are not the sum of the columns above because students who took more than one STEM course are counted only once in the last row.

Table 3 Demographics of computer science majors and minors at our university

	# students	African-Amer	Hisp	2 or more races	M	F
CS Major	89	2 2%	7 8%	5 6%	66 74%	23 26%
CS Minor	52	3 6%	2 4%	2 4%	30 58%	22 42%
Total	141	5 3.5%	9 6.3%	7 5%	96 68%	45 32%

4.2 Pre- and Post-Course Surveys

We have conducted pre- and post-course surveys since the inception of the program, measuring students' changing interest in a STEM or computer science major and the extent to which the course had an influence. We reported on the period from Fall 2013 to Fall 2014 in a previous paper [6]. In 2015 (Spring and Fall), out of 56 students who took the courses, 37 completed post-course surveys. The tables below show the results of two questions in the post-course survey. (The "increased interest" numbers may be deceiving because some students already had a high level of interest going in, resulting perhaps in "not much increase.") The "increased confidence" results – where 54% of the students responded with a 4 or 5 – show good results regarding the effect of the STEM courses on student perceptions.

Table 4 Answers to the question "To what extent has the STEM course increased your interest in a major in STEM?"

Increased interest	5	4	3	2	1
Spring 2015	4	2	4	0	1
Fall 2015	13	6	2	5	0

Table 5 Answers to the question "To what extent has the STEM course increased your confidence in your logical problem-solving ability?"

Increased confidence	5	4	3	2	1
Spring 2015	3	3	5	0	0
Fall 2015	7	13	3	2	0

The 2015 survey results also showed that nine students – seven of whom were freshmen – settled on computer science as their major in the post-course survey, where that was not their first choice in the pre-course survey.

These data suggests that we have had success in attracting entry-level students, retaining their interest, and giving them confidence in their problem-solving ability. The surveys, along with interviews that have been conducted with five recent female students, give a strong indication that female students are enjoying and benefiting from the program. This is attributable in large part to the type of hands-on projects that we offer in the STEM courses, conducted in the apprentice/leader learning model.

5. CHALLENGES AND FUTURE WORK

5.1 Interdisciplinary Collaboration

Involvement of other disciplines in an overarching STEM initiative can be challenging, given the constraints, existing faculty commitments, and cultures across other departments. We already have an active relationship with members of the Biology Department as well as with faculty in the Program for Innovation, Creativity, and Entrepreneurship. The Physics and Chemistry Departments are open to course collaborations, and possible collaborations with the Art Department are currently being explored. This may entail the creation of a STEM course in other departments with the ability to cross-list interdisciplinary courses. Some departments, such as Biology, are able to use existing courses for handling students who wish to participate in our STEM incubator program but receive credit from Biology. Though challenging, interdisciplinary participation and collaboration can be key to the growth of vertically integrated programs such as our STEM Incubator.

5.2 Space

As noted earlier in the paper, we have had to "make do" with the existing space in our department as we initiated our STEM program. We have refurbished one of our labs (larger than our initial STEM space) and dedicated it as the STEM lab, to be used by students in any of the STEM courses. This gives us an opportunity to see if having groups of students working on different projects in the lab at the same time creates synergy and excitement or distraction and mayhem.

As hands-on learning has gained popularity, maker spaces have been popping up everywhere, on university campuses and within business and industry. Generally these spaces serve multiple disciplines, envisioned as a place where scientists and artists can meet to experiment and collaborate. One of the authors of this paper has attended a workshop in which a variety of designs for open, fluid, interdisciplinary maker spaces were presented [10]. Buildings and spaces such as these are something to aspire to with adequate funding, but the practical situation is that we often have to use the space we have.

As we have explored the creation of a maker space with other departments on our campus, we find that our STEM Incubator lends itself quite well to the implementation of a distributed or hub-and-spokes maker space model. The idea is to engage students in more interdisciplinary projects and make them aware of the many resources and spaces available to them across campus. This takes cooperation, planning, awareness, and deliberateness on our part.

5.3 Pedagogical Challenges

One of the challenges of our STEM courses is to have continuity from one semester to another and cross-fertilization among projects. Centering our program on a one-credit P/F course has the advantage of creating a non-threatening environment for students to be introduced to STEM learning. However, practically speaking, students are not going to spend enough on a one-hour course to be able to produce very impressive results – even given their enthusiasm for the work.

Our vision is to have on-going projects that evolve from one semester to the next, with students advancing from apprentice to leader positions. We have had some success with this, especially as students sometimes move forward from STEM course projects to more complex Senior Honors projects or summer research fellowships (funded by our university). This has happened with 2D imaging and 3D printing projects, among others [11].

Another pedagogical challenge is in the relatively open, experimental nature of our STEM course projects. In the more open-ended, experimental courses, where students have some freedom to follow their curiosity, professors have to be prepared to answer questions about areas that may not be within their expertise. The hands-on nature of the courses leads professors into electronics, Bluetooth communication, Arduino programming, innovative goggles, drone assembly, and all kinds of things that require more than a soldering iron. Our experience is that the projects can turn out to be almost as fun for professors as for students, and they help us to be more in touch with the fast-changing world of digital devices.

5.4 Conclusions

In this paper, we describe the key elements of our STEM Incubator initiative, a vertically integrated approach for engaging underclassmen and upperclassmen students interested in science applications. The data we have collected, as well as anecdotal data provided by students, suggests that our approach based on the leader/apprentice model is increasing interaction among students and furthermore, the work is found to be enjoyable. We base this on the data we have collected as well as the very visible enthusiasm that students communicate to us about the courses and projects that they have been involved in. Interviews with some of the female students have revealed that they came into the STEM course with little understanding of computer science, and emerged from the course thinking it was something they actually liked and could be good at. This was exactly what we hoped for. The hands-on projects have the added benefit of reinvigorating our own interest in our discipline and making us feel more in step with the digital world.

Though we are pleased with the current results achieved by our STEM Incubator, we realize that there are still many challenges that need to be addressed in order to make our effort sustainable. We are striving to refine the STEM Incubator program, to improve our own teaching within the courses, to find more and better ways to assess the program's impact, and to seek collaborations with other units within the university.

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