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STEM inSight: Developing a Research Skills Course for First- and Second-Year Students

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STEM inSight: Developing a Research Skills Course for First- and Second-Year Students

Introduction

We describe the design, implementation and revision of an honors research seminar developed to introduce first- and second-year undergraduates to research in STEM (Science, Technology, Engineering, Math). This seminar includes numerous hands-on, inquiry- and problem-based learning activities, and is rooted in Vygotsky's theory of social constructivism.[1] Open to undergraduates from all majors, this year-long seminar brings together a group of students with faculty mentors to explore a specific topic or theme and gain familiarity with some of the tools and processes of STEM research.

The seminar has been offered two times (in 2010-11, and 2012-13) and has included a total of 14 undergraduates, from majors including Supply Chain Management, Astrophysics, Mathematics, Education, Human Biology, Physiology, Packaging, and several Engineering disciplines. All student participants were members of the University's Honors College and completed the course in their first or second year on campus.

In the initial offering, the course focused on a single problem: how to increase the sustainability of the supercomputer center on campus? Students enrolled in this **problem-based** research seminar learned about the problem area through in-class instruction and homework assignments, and then worked with the instructors to develop individual projects examining various solutions to the shared research problem. In the second year the course was offered, the focus shifted from a specific problem to the broader topic of image analysis workflows, which are used in many STEM disciplines to analyze data from photos and videos. In this **workflow-based** seminar, students learned about image analysis through lectures and assignments and were paired with faculty mentors to research the use of image analysis workflows in various STEM disciplines.

This paper compares these two approaches – problem-based and workflow-based – for developing a STEM research skills course for first- and second-year students. In particular, we discuss: (1) the role of topic and approach on students' interest and engagement in research; (2) the benefits and challenges of integrating novices from various majors in STEM research experiences; (3) the impacts of this experience on the research skills of first- and second-year students; and (4) the pros and cons of a problem-based vs. workflow-based course design.

Background

The research training activities designed for this seminar are grounded in two complementary educational frameworks: constructivism and socioculturism. At its core, constructivism is the idea that learning is an active process where students create meaning from information and experiences.[2,3] Similarly, socioculturism is founded in the idea that "learning is enculturation, the process by which learners become collaborative meaning-makers among a group defined by common practices, language, use of tools, values, beliefs, and so on."[4] In the context of scientific research, this enculturation includes background knowledge of the data, terminology, tools and research methods of the discipline; analytical and technical skills for developing and evaluating experiments; and meta-cognitive skills to review progress, assess challenges and plan future explorations.[5,6]

Both constructivism and socioculturism are rooted in the social constructivism theory developed by Vygotsky,[1] who argued that knowledge and meaning-making activities cannot be divorced from the context in which the learning takes place. Building on the idea that knowledge is constructed in a sociocultural context, this research seminar for first- and second-year students includes both inquiry- and problem-based learning activities that immerse students in the theory, content and practice of STEM research. Inquiry-based activities may include making observations, developing hypotheses, using reference materials, generating and analyzing data, and communicating results.[5] Engaging in inquiry-based activities helps students learn the content of the problem area they are exploring, as well as essential skills for effective investigation processes.[6–10] Problem-based learning approaches challenge students to focus their efforts on understanding and solving a specific problem by synthesizing existing knowledge, applying investigative processes, testing possible solutions and evaluating results.[11–13]

Course Structure

These undergraduate research seminars were offered at Michigan State University (MSU) as a single three-credit course, with class requirements spread across two consecutive semesters (Fall and Spring) totaling 28 weeks. In the first semester, students meet as a group with the instructors once per week for 60-90 minutes. During these weekly meetings, students explore the content and process of research in STEM through lectures, small-group activities, and individual presentations and progress reports. The first-semester activities and homework assignments were designed to guide students through the process of preparing their individual research projects. Sample topics from the first semester include: understanding project goals; completing scaffolded research exercises to gain key skills; selecting individual research project topics; and developing a research work plan.

During the second semester, students continue to meet with the instructors for guidance through the research process. However, the focus of these individual and small-group meetings shifts from instructor-based content to student-led presentations and problem solving. Students develop research posters and presented their work at a campus-wide forum at the end of the second semester.[14] Prior to this forum, students' hosted a practice presentation for class members, instructors, and research mentors, as depicted in Figure 1.

Figure 1: Students Practicing Research Poster Presentations

While the overarching structure and tasks was the same for both offerings of this course, the focus of the classroom activities and student research projects was different for the problem- and workflow-based seminars. In the problem-based seminar, the first-semester activities were designed to introduce elements of the common research problem (how to increase the sustainability of the supercomputer center on campus?). A combination of in-class lectures, hands-on activities and homework assignments was used to help students develop a fundamental understanding of the problem area, including basics of fluid dynamics, thermal regulation, and high performance computing.[15] The individual student research projects were developed in consultation with the course instructors and explored various solutions to the shared research problem of sustainable supercomputing.

During the workflow-based seminar, the in-class activities and homework assignments introduced students to fundamental concepts about image analysis workflows, which are used in many areas of STEM research. A series of scaffolded learning activities was used to engage students in increasingly-complex image analysis tasks. After gaining a basic understanding of the process and content of common image analysis workflows, students were matched with faculty mentors from a variety of STEM disciplines to develop an individual research project. While all of the students applied the same general approach – image analysis workflows – to their research project, the specific questions, content and process of their research projects varied depending on their interests, skill sets, and research domain.

Course Descriptions and Prerequisites

This seminar was limited to Honors College members in their first- or second-year at Michigan State University, and most of the advertising and recruiting was handled by Honors College advisers during freshman orientation or sophomore course-planning appointments. For the initial, project-based seminar (dubbed "Cyber Green") the course description focused more on engineering aspects of the research problem:

> **UGS 200H: Sustainability in Super Computing**
> This seminar will introduce students to conducting research using High Performance Computing. In the first semester, students will learn how to use Computer Aided Design and High Performance Computing to study and model the energy consumption of a modern supercomputer. This honors research seminar will also allow the students to use the knowledge they gained to explore their own research projects to invent and research ways to make the ever-growing need of bigger and faster computational resources sustainable into the future.

Although not required, a recommended prerequisite for the problem-based seminar was prior experience in computer programming, such as would be acquired through high school or advanced placement programming coursework. It was expected that this programming experience would assist students in developing computational or engineering solutions to the sustainability question at the center of the problem-based seminar. Six students enrolled in the Cyber Green seminar during the 2010-11 academic year; their majors included Supply Chain Management, Astrophysics, Mathematics, Education, Packaging, and Engineering.

For the second, workflow-based seminar, referred to as "STEM inSight," the course description focused on a broader exploration of research methods and image analysis workflows in STEM disciplines:

> **UGS 200H: Study of Scientific Measurement using Digital Images and Video**
> Students will explore scientific methodologies that use digital imaging techniques for experimental observations. Students will be introduced to a variety of tools and methodologies that can be used to annotate and extract useful observational data in digital images. In-class experiments will include research from datasets in engineering, biology, zoology and forensics. Students will walk away from this class with a fundamental knowledge of how to use digital images and video for scientific measurement, and develop valuable research skills applicable to many scientific research projects on campus.

For the STEM inSight seminar, no prerequisites were required or recommended. Eight students enrolled in this workflow-based seminar during the 2012-13 academic year; their majors included "No Preference" (students who have not yet declared a major focus), Human Biology, Physiology, and several Engineering disciplines.

In-Class Lectures and Activities

Since these seminars were designed to introduce first- and second-year students to basic principles and techniques for research in STEM, the instructors developed a number of lectures covering topics relevant to both instances of the seminar (problem-based and workflow-based). Example lecture topics include:

- The scientific method and the general process of research in STEM
- The responsible conduct of research,[16] including overviews of authorship, intellectual property, software licensing, human/animal subjects, data integrity, and appropriate use of University resources
- Developing an effective research poster and giving research presentations; students were also coached on the development of an "elevator speech" – a brief (30-60 second) description of their research project and its potential impact, which can be used to introduce their research poster and/or invite further conversation about their project
- General tools for supporting research, such as bibliography management software

In addition to these general topics, the instructors also provided more detailed and technical information to students in each seminar. For the problem-based Cyber Green seminar, the first semester was largely devoted to learning about the basic engineering principles involved with the research question (how to improve the sustainability of the campus supercomputing center?). Through in-class lectures and assignments, students learned that supercomputers generate heat and that power must be expended to cool the server room to safe operating temperatures. Students were also introduced to principles of fluid dynamics, the process of scientific measurement, and the use of CAD (computer aided design) software and CAD-based models.

As an illustration of the types of in-class activities integrated into both versions of this seminar, consider the following sequence of activities from the problem-based, Cyber Green course. In the first few weeks of class students were given room diagrams, measuring tapes and digital thermometers. Using these tools, students were asked to take time (during class) to make measurements inside the server room and compare these measurements to the existing room diagrams. The goal of taking these measurements was to provide a physical basis for building a CAD-based drawing of the room. The activity also immersed the students in the server room environment and the process of scientific measurement, giving a physical context to the broader sustainability problem students were trying to solve. After measuring the sever room, students developed CAD drawings that incorporated their own physical measurements and reinforced the hands-on experience of gathering this data. For instance, while making the CAD drawings many students realized that some of their measurements were incorrect, and/or that they were missing key measurements needed to complete the drawing. Follow up visits to the server room allowed students to complete their CAD project and gave them a better understanding of the detail needed to develop and model a physical system. Providing time and guidance during class for these measuring and modeling activities allowed students to work and learn iteratively, and to benefit from the shared experience of their classmates.

In the workflow-based STEM inSight seminar, the technical lectures focused on key topics in image analysis, such as how cameras work; how images are stored in data files; how to convert between image data types; and what tools are available to help researchers process image and video data. An example of an in-class activity is the exploration of binary versus ASCII data. For this exercise, students were shown the underlying, ASCII-based data that comprises an image stored as a .png (portable network graphics) file. After exploring this basic file format, students were given the opportunity to modify and create images by manipulating the ASCII data using simple text editing tools, such as the various “notepad” features available on standard computing platforms. This hands-on activity gave students a concrete example of how changing ASCII text in a data file impacts the image that data encodes, and sparked discussions about various ways that information can be represented, including binary, ASCII and other formats.

In the second semester, there were few lectures or in-class tasks in either seminar. Instead, students met regularly with the instructors – both individually and in small groups – to provide progress reports, receive feedback on their research process, and troubleshoot problems they encountered. Students were coached to give effective presentations and had several opportunities to practice giving oral and poster presentations of their research.

Scaffolded Learning Tasks

In addition to the weekly class meetings, students completed homework assignments during the first semester of the course. These tasks were designed to scaffold students’ development of essential research skills and domain knowledge, and prepare students to complete their individual research projects during the second semester. Time was allocated during class sessions for students to work on their homework assignments in small groups and receive input from the instructor.

For the project-based Cyber Green class, the homework assignments focused primarily on building a CAD model of the supercomputing center's server room. The initial goal was to have students use the model to run (very) basic fluid dynamic simulations of heat transfer in the server room, with the assumption that students might choose to extend these simple models as part of their individual research projects in the second semester. However, the goal had to be adjusted to accommodate students' need to spend more time developing basic skills. For example, the first step in the modeling process was for students to take physical measurements of the server room. While this process seemed like it should be straightforward, in reality these novice students had difficulty understanding concepts like accuracy and precision, and had to repeatedly measure and re-measure the same dimensions before mastering the tools and generating consistent results. Once the server room was measured, the dimensions had to be input into CAD in order to generate a room model. Again, this task proved to be surprisingly difficulty for some students, who had difficulty translating numerical measurements into a 3-dimensional model. The instructors provided additional group instruction on topics that were confusing to many students, and worked individually with students who needed more assistance with the measuring and modeling process. Eventually, all of the students completed a CAD model, but not everyone completed the simulation before the deadline for selecting a research project topic. In the end, none of the individual research projects required fluid dynamics modeling, and the instructors relaxed the original plan of utilizing the CAD simulation in favor of providing more one-on-one help for the individual research projects students chose.

In designing the second offering of this seminar (the workflow-based "STEM inSight" class), the instructors lowered expectations for students' prior knowledge and developed more granular scaffolded learning activities that started students with very basic concepts and skills. Students were initially given a manual data analysis tasks that reinforced key concepts and processes in image analysis. For example, students were asked to create accounts on Zooniverse.org[17] and contribute to one of the "citizen science" projects administered by the site. One of these projects – Moonzoo[18] – uses input from "citizen scientists" to measure and catalog craters in thousands of images of the surface of the Moon; students could participate by viewing images of the Moon and clicking on craters. This task was an ideal introduction to image analysis workflows for the first- and second-year students in this course because: (1) students were introduced to the idea of using image data for scientific research; (2) students had the opportunity to make a contribution to ongoing scientific research in the first few weeks of the course; and (3) the Zooniverse project interfaces are designed specifically to engage and educate novice users (data integrity is maintained by automatically comparing results from multiple users and seeking additional input as needed). As part of this early assignment, students wrote short, blog-style reports about on the image analysis workflow and their experience using Zooniverse, documenting the time and effort required to complete the task and offering ideas for improving the analytical workflow.

Individual Research Projects

During the first semester, students spent time in class brainstorming ideas for their individual research projects, and spent time outside of class conducting background research to refine their ideas. In the problem-based Cyber Green course, all students were addressing the same research question (how to increase sustainability in the supercomputing center), and the class spent time developing a list of possible solutions. With guidance from the instructors, students outlined the general parameters of several individual research projects that could be completed during the second semester. In some cases, students conducted background research or hands-on experiments to estimate the viability of an idea. After refining the project list, students ranked their top three choices and the instructors assigned projects based on students' interests and skills. Although students were encouraged to recruit their own mentors for these research projects, none of the students had developed relationships with other faculty members in time to identify external mentors; instead, the course instructors continued to mentor all of the individual research projects for the Cyber Green class.

For the problem-based Cyber Green seminar, the six students each explored one of the following topics in their individual research project:

- cost benefits of using the local water table to cool the server room
- alternative heat conduction by submerging a compute node in mineral oil, a project known as the "Deep Fried Server" and shown in Figure 2
- using thermoelectric generators to recycle the excess heat generated by the supercomputers (data collection shown in Figure 3)
- using an automatic window vent to cool the server room in the winter; Figure 4 depicts the student's analysis of variations in outside temperature
- cost benefits of using Condor to take advantage of extra CPU cycles on campus labs
- a supply chain management analysis to determine sustainable shelf life for compute nodes past their warranty

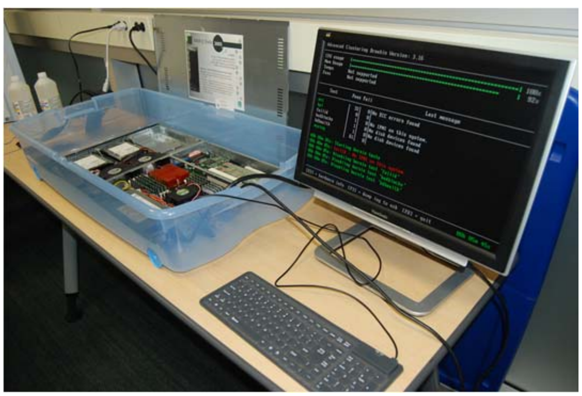

Figure 2: server (in box at left) cooled by submersion in mineral oil, rather than air[15]

Figure 3: measuring voltage generated using a thermoelectric generator

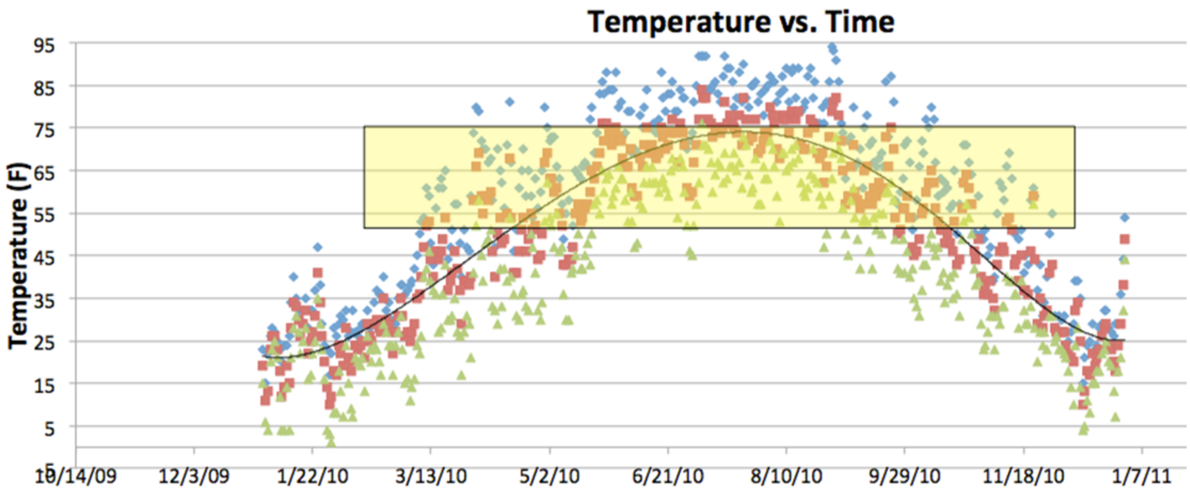

Figure 4: outside temperature vs. time as gathered by sensors outside the server room building

In the workflow-based STEM inSight seminar, students were able to develop basic image analysis workflow skills through the in-class activities and homework assignments, but needed guidance in understanding how this common skill set could be applied to research in very different aspects of STEM. The instructors helped connect students to faculty members across campus who were already using image data in their research. Students were encouraged to explore ongoing research in their own disciplines or interest areas, and the instructors facilitated the matching process – including going with several students to meet with potential mentors. The following excerpt is from an email that an instructor sent to a prospective faculty mentor, and is a good description of how students received guidance from both course instructors and domain experts during the individual research projects:

> *"To help train these undergraduates, I would like to identify small projects that involve manual analysis of image data using existing software/tools. An example project would be the measurement of variations in size between objects of the same type in a large stack of images. Although labor intensive, this project should be reasonable for a novice student to complete during a semester. I would provide weekly training for students to introduce them to computational techniques and image analysis, while you provided students with guidance on the research project within your discipline.*
>
> *The goal for these manual projects would be to help students gain research skills while also helping you work on a small research problem/project of interest to you. As students gain skills, they may work with you to extend the projects to further automate and accelerate your research."*

All of the students in the STEM inSight course were matched with external faculty mentors, and about half of these mentors were previously unknown to the instructors. The eight students enrolled in the workflow-based seminar explored the following topics in their individual research projects:

- correlating size and shape of regions of the brain with age in MRI scans
- streamlining the workflow in CMEIAS Molecular Biology image analysis software
- comparison of MRI brain scans relating to human desire for salty/sweet snacks
- general method of background subtraction in scientific imaging
- face expression analysis based on localized face based anchor points (Figure 5)
- tracking of chameleon eye movements in video (Figure 6)
- measuring the quality of chestnuts based on light/dark regions of CT scans (Figure 7)
- the timing of image analysis in horse gait measurements

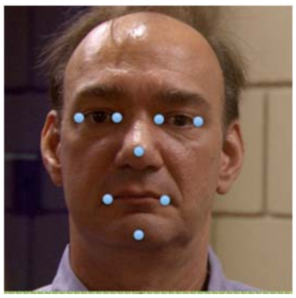

Figure 5: selection of face anchor points; image from Phillips *et al.*[19]

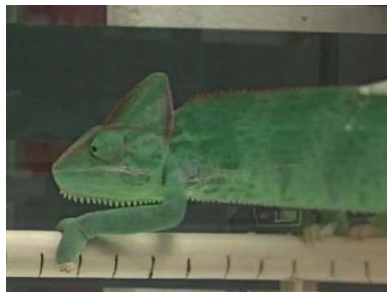

Figure 6: tracking chameleon's eye movements; image from Ingle *et al*.[20]

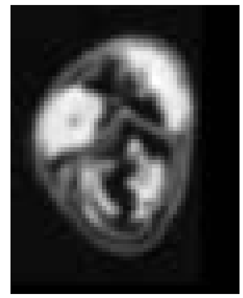

Figure 7: CT scan of a chestnut; image from Donis-Gonzalez *et al.*[21]

Assessment Methods

The seminar was graded on a pass/fail basis, with a course grade assigned at the end of the second semester of work. This seminar was one section of a three-credit honors course at Michigan State University, with each section focusing on a different research topic/project. Instructors for each section were recruited from among the MSU faculty by the Honors College, which served as the administrative home for the course.

Within the Cyber Green and STEM inSight sections, the pass/fail determination depended on students' performance against a series of milestones, as described in the course syllabus. Examples include:

- Research blog posts (content, style, grammar, appropriately addressing audience, etc.)
- Research progress reports (weekly or bi-weekly written reports and in-person meetings)
- In-class assignments (participation, teamwork, demonstrating skill acquisition)
- Participation in class meetings and discussions
- Homework assignments (correctness, completeness, etc.)
- Research presentations (oral and poster formats, clarity, accuracy, depth, etc.)

The first- and second-year students enrolled in this course had a range of majors, experiences and skills. Given this variety – and the broader goal of helping each student develop research skills and experience – the instructors developed individual expectations for student performance.

This was most evident in the range of sophistication in students' individual research projects. For instance, one student (majoring in Electrical Engineering) came to the course with experience in computer programming. After meeting individually with the student and gauging the prior experience level, the instructors encouraged the student to pursue a project working with a biologist to help the faculty member make improvements to existing image analysis software. This project involved digging deeply into existing code (authored by dozens of students over time); while this was a challenging project, the student had the appropriate skill set and experience to succeed and in the process gained insight into a variety of programming methods and approaches.

In contrast, another student with a major in Mathematics had very limited computer programming experience and domain knowledge at the outset of the course. After meeting with this student individually, the instructors helped develop a project where the student focused on studying the cost benefit of scavenging extra CPU cycles using a Condor system. Although this project was technically less sophisticated than the previous example, for this particular student the research process had substantial challenges and presented many learning opportunities. Although students did not develop the same set of research or technical skills, the individual projects, assignments and in-class experiences were customized to allow each student to make progress in building his or her own set of research skills.

For the most part, the students enrolled in both seminars met or exceeded the instructors' expectations. For a few students, however, the self-directed nature of the individual research projects proved particularly challenging. This is not necessarily surprising, since first- and second-year students may have particular difficulty with time management and adjusting to the expectations and pace of college academics. For instance, one student in the Cyber Green seminar floundered part way through the year and began to have difficulty meeting deadlines and keeping appointments. The instructors followed up by email several times, outlining specific expectations, deadlines and consequences, and in the end the student managed to complete the minimum required to pass the course.

Lessons Learned: Impact of Topic and Approach on Students' Interest and Engagement

The focus on sustainability and the environment made the problem-based Cyber Green seminar more appealing to students initially – this was an accessible topic that proved motivating to novice students, who were eager to engage in research that they felt could have a direct impact on a very specific problem. In contrast, the workflow-based approach of the STEM inSight seminar was more abstract and the instructors had to expend more time and effort to explain the idea of image analysis and how this workflow could contribute to research in various STEM disciplines. Overall, in the classroom portion of the seminar the Cyber Green students were engaged and interested in the course content much sooner than the students in the workflow-based seminar.

In terms of the individual research projects, students proved to be more interested and motivated by the workflow-based projects than those in the problem-based seminar. For the STEM inSight seminar, students developed mentoring relationships with faculty in their own majors or areas of interest. Students found these projects to be personally fulfilling, and had opportunities to engage with faculty, graduate students and researchers in their own domains – relationships that have the potential to continue as students gain more research experience and skills. Students also gained valuable research skills during the problem-based Cyber Green seminar, but their individual research projects were not as closely linked to students' own interests, nor did students have opportunities to explore research related to their major interests.

Although the workflow-based approach required more up-front effort from the instructors to engage students in understanding a more general research process, the resulting individual research projects proved more substantial and impactful to students than in the problem-based approach. Another benefit of the workflow-based approach is that matching students with existing research projects gives greater opportunity for students to continue research after the course ends. For example, as of the writing of this paper, half of the students in the STEM inSight seminar reported that they would continue working with their research mentors after the class has ended.

Lessons Learned: Benefits and Challenges of Integrating Novices from Various Majors

In developing a research skills course for first- and second-year students, it proved important to match course expectations to students' experience and skills. For example, some students (particularly in the problem-based course) had extensive experience in computer programming and were able to complete more technically challenging research projects than other students, who may have little or no technical or research skills. In the Cyber Green seminar, the instructors' initial goal of having students develop a complete CAD model of the server room was adjusted to accommodate students who needed more support for the modeling process.

In the second, workflow-based class, the instructors focused more on anticipating and adapting to students' varying technical skills. For example, the STEM inSight seminar asked students to explore various image analysis software tools and their use in STEM research workflows. Installing and configuring this different software can be a significant challenge for novices, so the instructors developed a virtual machine (using VirtualBox[22]) that allowed students to use many different image analysis tools without needing to install and troubleshoot the software on their own computers. This scaffolded approach removed many of the technical challenges of getting started with the software, and instead allowed the novice students to focus on the underlying task of using different software tools to view and modify images.

In addition to being novices to STEM research, students who participated in this course came from a variety of majors. This proved to be a strength for both the problem- and workflow-based seminars, as students were able to integrate their own backgrounds and interests into their individual research projects. By regularly sharing their individual progress with the whole group, the students were able to learn from others' experiences and share ideas across disciplines. For example, a Computer Science student in the course worked with a student majoring in Neurobiology to help debug a technical problem loading data into a virtual machine. Later in the semester, the Neurobiologist was able to explain to the Computer Scientist some terminology used in describing regions of the brain. Although their backgrounds and skills were different, both students were working on individual research projects using MRI (magnetic resonance image) scans of human brains, and by sharing their research with the group they were able to support each other's work.

While the students benefitted by sharing their ideas and experiences, it was somewhat more challenging for the instructors to figure out how to best integrate students' varied interests into the individual research projects. The instructors met individually with each student to discuss ideas and opportunities, and spent considerable time identifying potential projects and external faculty mentors to work with these undergraduates. As discussed previously, the problem-based approach required less up-front effort from the instructors, since all students were addressing the same research question, but required more day-to-day mentoring of students during the research phase. The workflow-based seminars required the instructors to expend considerable effort to match students with external mentors and projects, but resulted in spreading the work of research mentoring across many more faculty members.

In both the problem- and workflow-based seminars, the general topics proved flexible enough for the instructors to identify individual research projects that built on students' existing interests and skills. For example, the Business student who enrolled in the Cyber Green course was able to apply supply chain management principles to explore the effective life cycles of various supercomputer modules, and model a replacement schedule that balanced cost, power consumption, efficiency, and expected operating life. In the STEM inSight seminar, one student expressed a passion for horses and the instructors helped to connect the student to faculty members in the College of Veterinary Medicine and an equine gait analysis project involving video data.

One significant challenge for novice students is a lack of technical skills and content knowledge required for more sophisticated research projects. For instance, in the workflow-based STEM inSight seminar, one student had the idea to explore algorithms for automatically recognizing facial expressions. Accomplishing this would require substantial computer programming skills and graduate-level knowledge of pattern recognition, which the student lacked. As a compromise, the instructors helped this student identify a simpler research project in the same general area: measuring the variations in face-based anchor points in images of different facial expressions. Completing this project introduced the student to this research area, and helped the student develop basic programming skills; however, the students' final project was fairly limited in scope and thus was only able to make a minor contribution to the ongoing research of the faculty mentor. Those students in the workflow-based seminar who had more advanced technical skills were able to engage in more substantial research projects and make more significant contributions to faculty research. For example, one student in the STEM inSight seminar who had significant prior programming experience was able to attempt a fairly complex project to develop a background subtraction algorithm for image analysis. Implementing this algorithm was a small, but important, step in the overarching research project of the faculty mentor, and this student's advanced skills allowed for a more substantial research contribution.

In another example, a student (majoring in Mechanical Engineering) was concurrently enrolled in an introductory programming and was very interested in applying these new skills in the research seminar. After meeting individually with the student and gauging the prior experience level, the instructors encouraged the student to pursue a project in updating a human user interface. This was an ideal project for a highly motivated novice because it allowed the student to dig into existing code and see how other programmers solved problems. In the beginning, this student was frustrated by the challenges of reading and understanding code written by others. However, after spending time on the project and working with the instructors, the student was able to adjust the existing program, test new solutions, and develop a substantial project that solved several software problems for the faculty research mentor.

Similar challenges arose in the problem-based Cyber Green seminar, although in this course students could more easily apply their own domain knowledge to the common research topic – giving them a broader range of expertise with which to conduct the research. For example, the student majoring in Electrical Engineering developed a project to estimate how much thermal transfer could be made by opening a window in colder months. This student came into the seminar with basic computer programming skills and a knowledge of calculus, which gave the student sufficient technical and analytical skills to develop and conduct an experiment and then analyze the results. The resulting project resulted in new information and allowed the student to make a genuine (if small) contribution to this area of research. While not all students chose such technical projects, all of them were able to integrate their existing domain expertise into developing their own solutions to the common research challenge in the Cyber Green course.

Lessons Learned: Impact on Research Skills of First- and Second-Year Students

Based on the case studies described here, both the problem-based and the workflow-based approaches were successful overall in helping first- and second-years students develop key research skills in STEM. While the seminar was graded on a pass/fail basis, the instructors developed specific milestones for students to accomplish in order to receive a passing grade. In the first, problem-based seminar, all students passed the course and most met or exceeded all of the milestones. One student struggled with parameter estimation, but met the minimum requirements to pass the course. In the second, workflow-based seminar all students met the milestones for passing the course, although about half of the students encountered problems working with virtual machines on various operating systems.

Based on the instructors' assessments of students' in-class activities, homework assignments, and final research posters and presentations, it is clear that students in both courses developed or improved skills in:

- analytical problem solving
- effective presentations
- technical communication
- computational understanding
- research ethics

While the sample set of fourteen students enrolled in these two seminars is small, we do know that of the group of six students enrolled in the initial, problem-based seminar (in 2010-11), all are still enrolled at Michigan State University. The eight students enrolled in the second, workflow-based seminar, have just completed their first- or second-year at MSU, and over half report that they intend to pursue additional undergraduate research opportunities.

Lessons Learned: Comparative Discussion of Problem- and Workflow-Based Approaches

Overall, both the problem- and workflow-based classes proved successful in helping first- and second-year undergraduates gain content and process knowledge about research in STEM disciplines. Table 1 summarizes the previous discussions of various advantages and disadvantages of each approach. Ultimately, the decision about which approach to take at a particular institution will depend on the desired research theme or topic and the availability of external mentors and projects.

Moving forward at Michigan State University, the instructors are inclined to continue the workflow-based approach for two reasons. First, the workflow-based seminar allows students to develop mentoring relationships and research skills in their own areas of interest. The potential for students to develop long-term relationships with researchers in their field is valuable enough to outweigh the additional effort required of the instructors in managing the workflow-based seminar (including helping students to identify research mentors and motivating students during the early classroom activities, before students develop an understanding of the way research workflows apply to their own interests). This approach is feasible at MSU given the broad availability of external mentors and research opportunities.

Second, the workflow-based model requires fewer year-to-year adjustments in the course curriculum. Image analysis workflows are used in a wide range of ongoing research projects at MSU, providing tremendous variety and opportunity for students from any major or background. In comparison, the problem at the core of the Cyber Green seminar (sustainability in the server room) has a very limited solution set – particularly within the constraints of novice students' skills and the one semester timeframe of the individual research project. To repeat the problem-based seminar at Michigan State University, the instructors would either need to recycle the same basic set of research projects as a solution to the Cyber Green problem, or identify an entirely new problem to focus on and then update the lectures and assignments that instruct students on key content related to the problem area.

Table 1: Comparison of Project-Based and Workflow-Based Course Structures

	Project-Based (Cyber Green)	Workflow-Based (STEM inSight)
Advantages	• Students were excited about the topic of sustainability, and picked the seminar in part because they felt the research had the potential to "change the world" • Common theme for research projects allowed instructors to develop general lectures on technical skills and common content areas • Students' individual projects each addressed different solutions to the same problem, so it was easy for students to share ideas and offer helpful insights from their own academic backgrounds	• Broad use of image analysis workflows in STEM research on campus made it easy to find external faculty mentors willing to supervise students' individual projects • Easier to match research projects and faculty mentors to students individual / disciplinary interests • Repeating the course is easy, as the existing course content (lectures and assignments) can be reused and new research projects can be readily identified for future students

	Project-Based (Cyber Green)	Workflow-Based (STEM inSight)
Disadvantages	• Fluid Dynamics simulation task proved too difficult for novice students, and instructors had to adjust course expectations • Limited solution set to the research problem, so repeating the course would require recycling projects or developing a new common research problem and revising course content • Difficult to find external research mentors, due to limited connections between students' projects and existing faculty research interests	• Novice students were less enthusiastic early in the course because they did not initially grasp the idea of image analysis workflows and their use in STEM research • Novice students often lack the technical and/or programming for more sophisticated research; consequently many of the individual projects focused on manual image analysis tasks or documentation of existing workflows

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