The Development of an Interdisciplinary Data Visualization Course with an Ongoing Community-Based Project Component

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Abstract

This paper describes an interdisciplinary data visualization course established in part through a National Science Foundation (NSF) course/curriculum/laboratory improvement (CCLI) grant. The course and accompanying lab are intended for upper-division biomedical, civil, computer, electrical, and mechanical engineering students, as well as chemistry, computer science, mathematics, and physics majors at The University of Memphis. A service learning component of the course introduces undergraduates to civic engagement through work with high-school teachers. Undergraduates participate on interdisciplinary teams to implement and subsequently extend and maintain a repository of contextually-relevant visualization applications which support inquiry-based learning opportunities for high-school students. In addition, as part of the course, students develop visualization applications that have utility in research projects.

Introduction

Nationally, forty-four percent of undergraduate students complete a community-based experience as part of their curricula. At The University of Memphis (U of M), only twenty-eight percent of undergraduates participate in a community-based experience that is linked to their studies. One goal of this project is to provide an opportunity to address this shortcoming for engineering and science majors through a data visualization course.

In this paper, visualization refers to the processes of exploring, transforming, and viewing higher-dimension data as computer images to gain insight into the underlying phenomena represented by the data. Our approach to a visualization course and lab is inherently interactive by involving the student directly in the process of extracting the data from its source, transforming, viewing the data, and forming, defending, and critiquing hypotheses about what the data represents. Our course also provides students exposure to developing custom software to construct a simulation environment in which data is obtained through calculation for exploration.

Our course teaches visualization techniques and related applications, as well as pragmatic skills required to process scientific and engineering data and build custom software applications using the Visualization Toolkit (VTK) [1] to students in an interdisciplinary, team environment. A key objective of the NSF/CCLI Adaptation and Implementation (A&I) program is to improve undergraduate science, technology, engineering and mathematics (STEM) education through adaptation and implementation of effective materials, techniques and practices to result in a positive change at an institution.

Our course adapts exemplary materials, applications, and code that have been developed and tested at other institutions that converge into two distinct categories:

1. Adaptation from materials originally developed for integrating visualization

techniques into a comprehensive undergraduate, computational science across the curriculum (CSAC) program. Sources include, but are not limited to, materials that were developed via grants provided by the NSF (DUE 9952806), Battelle Memorial Institute, and W. M. Keck Foundation and directed by Capital University [2-3].

2. Adaptation of materials for use by undergraduates from materials originally intended for beginning graduate students and working professionals. Sources include, but are not limited to, those developed by the School of Informatics at The University of Edinburgh [4] and The University of Groningen in The Netherlands [5] for graduate programs and professional workshop short courses.

Our project is adapting, integrating, and testing these exemplary materials and practices for use in an interdisciplinary course and lab consisting of students, end users, and software languages that are significantly different from the ones for which the materials were originally developed. Moreover, the project adopts a constructivist-based and student-based, self-regulated approach to learning [6-7] with the assistance of an educational psychologist who serves as a co-principal investigator (Co-PI) on our project. The combined technological and instructional approaches are complementary in that they are based around active, student-centered learning environments designed to mirror the types of professional environments students will encounter after graduation.

The project has the following supporting objectives, each with specific, measurable outcomes assessed through both formative and summative evaluation metrics:

1. Increase undergraduate students' comprehension of data-intensive phenomena by reducing the cognitive load required when extracting meaning from multi-dimensional data. This objective is being accomplished in part by leveraging software, which has been constructed using a three-dimensional visualization toolkit, in the problem-solving process to exploit the superior visual recognition ability of most students.

2. Increase undergraduates' ability to implement a custom, visualization application. This objective is being accomplished by requiring students to work on interdisciplinary teams to design, implement, and test software applications built using a visualization toolkit based upon a group approach involving end-user constituents.

3. Introduce undergraduates to civic engagement within their professions by having them work on development teams, which include high-school teachers, to implement and subsequently extend and maintain a repository of contextually-relevant visualization applications to support inquiry-based learning opportunities for high- school students.

4. Increase awareness and readiness of high-school teachers to integrate custom visualization tools into their own classrooms by linking tools developed by undergraduates at the U of M to relevant experiments and studies which could be conducted within the teachers' pedagogical activities.

Rationale

Data visualization has become a ubiquitous tool in professional practice to reduce the cognitive load that is required to extract meaning from extremely large data sets; however, interdisciplinary undergraduate courses and accompanying laboratories for gaining the knowledge to create custom software to visualize application-specific data did not exist at the U of M or at any university in the Mid-South region. Nationwide, very few institutions offer undergraduate courses related to the general field of computational science [8]. Partially in response to this need, the NSF and Keck Foundation recently funded the CSAC program managed by Capital University that has produced materials of which a subset is being adapted for our course and laboratory.

Advances in data acquisition and storage have dramatically increased the size of data sets from which meaning must be extracted by researchers and practitioners of a wide variety of disciplines. For example, it is not unusual in biomedical engineering for a routine cardiac mapping experiment (in which the electrical and mechanical activity of the heart are recorded) to gather several gigabytes of data in just tens of seconds of recording [9]. Such advances have exacerbated problems associated with scale: How are these massive data sets extracted, displayed and analyzed in a way that gives the investigator insight into their own data? Therefore, it is essential to integrate visualization methods early on into the undergraduate classroom.

Our interdisciplinary course and lab is important because it emphasizes problem-solving techniques and a team approach to building applications while providing opportunities for students to acquire fundamental visualization techniques that can be integrated into subsequent engineering and science courses, capstone and research projects, as well as undergraduate honors theses. Our course eliminates the void in applications of visualization technology that exist throughout the engineering and science curricula at both U of M and within the Mid-South region. The course complements the software development courses that many of our students already take by reinforcing programming techniques and having students contribute to applications that will provide insight into phenomena captured in large data sets.

Our pedagogical approach adopts a combination of constructivist-based psychology and student-based, self-regulated learning originating from the work of Piaget [10] and Vygotsky [11]. Constructivist-based educational practices encourage students to be active learners and to seek solutions for themselves as opposed to traditional teaching methods where students “learn” by imitating the teacher or by demonstrating minimal competency levels through testing. The emphasis is targeted towards learning content through direct experience with materials and tools in which the students themselves construct knowledge based on collaborative learning strategies and subsequent applications.

Emphasis on Community

Our project strongly encourages students to develop or enhance visualization tools that may have utility in the local community via the high-school classroom. Few high-school teachers and even fewer high-school students have any exposure to visualization software used by engineers and scientists. As stated by Beattie et al. [12]: “Visualization of scientific processes offers a new dimension in communicating the excitement of science and vividly introducing K-12 educators to both the richness and perplexing complexity of natural and technological processes.” Preliminary discussions of these ideas with several teachers from our local high schools confirmed this statement, and subsequently, the high-school teachers themselves became active participants and researchers in the project as well as facilitators to their own students.

By promoting interactions between undergraduate students and high-school teachers to build or enhance custom visualization applications, our project seeks to have a broader impact in that the imaginations of students and teachers will be influenced in understanding the physical world. Enlisting a significantly larger number of engineering and science students and faculty in collaborations with high-school teachers is an additional outcome of the project.

Visualization provides an interactive means for infusing enthusiasm and excitement into traditional paper-pencil techniques that are often perceived as boring particularly by minority and female students. Too often, underrepresented groups lose interest in science and engineering at an early age and write off careers in these fields before they are engaged by the subject matter [13]. Therefore, it is critical to provide strategic opportunities for underrepresented students to use visualization tools, to bring those tools into their perception of science, and to develop a passion and the confidence to pursue careers in science and engineering. Since the demographics of the Mid-South region provide a large pool of underrepresented students, their potential career choices, attitudes, and preparation may be influenced through educational opportunities like this program involving local universities such as the U of M at an earlier point in their educational development.

Course Organization

The course and supporting lab are intended to include interdisciplinary participants; therefore, computer graphics, which is often the prerequisite of visualization courses in traditional computational science programs, is not required. The following are the course prerequisites: 1) mathematical maturity consistent with junior standing in engineering, computer science, math, physics, or chemistry; 2) previous programming experience in at least one high-level language and; 3) familiarity with elementary data structures and algorithms. These course prerequisites are structured such that students from other disciplines outside of CS, with an interest in visualization, are qualified for the course. Most engineering students at U of M are required to take an introductory programming class that is similar in many aspects to the first computer science course (CS1), although a variety of languages including C/C++, Java, Fortran, or Visual Basic are used depending on the specific course and major.

Engineering students must follow up the programming course with at least one applications-oriented course that requires extensive programming. For example, Electrical Engineers take Matrix Computer Methods that requires extensive C/C++ programming, while many Civil Engineers take Engineering Analysis that requires extensive programming in Fortran. Several math, physics, and chemistry students take both CS1 and CS2 in Java from the Computer Science Department to acquire fundamental programming skills. For example, approximately 38% of CS2 students in the Fall 2002 semester at U of M were non-CS majors.

All students of the course perform several minor experiments, including using data and applications outside their given discipline. These minor assignments include tasks to familiarize the students with visualization libraries, the visualization platform, as well as fundamental concepts such as data types (e.g., polyline, triangle, tetrahedron, voxel, etc.), fundamental visualization algorithms (e.g., scalar, vector, tensor, texture, volumetric methods, etc.) and advanced modeling techniques (e.g., polygon reduction, mesh smoothing, contouring, triangulation, etc.). Minor assignments are designed to provide students with basic experiences in using height fields, contour plots, univariate/bivariate color maps, etc., which are often required to complete a significant assignment.

For more substantial assignments, a student team is provided previously measured or extracted source data and/or methodology to generate the data via computation. The data must then be transformed into representation types used by the VTK. This step involves students writing custom software and deciding on the form of the visualization data to use. The next step often includes students creating visualization mappings for models corresponding to physical structure within the data (e.g., polygonal surfaces corresponding to organs within the human body, spheres of atoms, computational surfaces of flow boundaries, etc.). The final step involves combining the remaining application-specific data (e.g., electric field potentials in three-dimensional space) with the modeling components (e.g., human thorax) to display an image that aids the end user in interpreting the data. Figure 1 provides an overview of this workflow based on the VTK pipeline process [14].

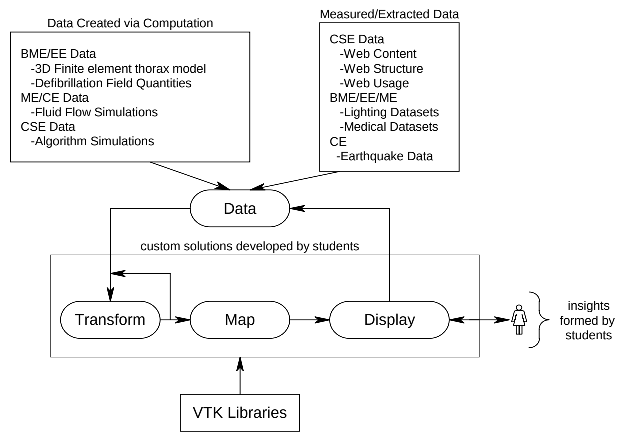

Figure 1. Data Visualization Workflow.

Assignments provide an opportunity for students to partition then delegate responsibilities to team members. Students must define the functionality required and how each functional module will interface with the other team members' contributions to achieve a working system that satisfies the requirements. Students must then formulate and defend their insights about the supplied or generated test data using images generated from their tools.

Course Projects

Students are required to design and implement a final course project that supports one of two goals: 1) an application that may support a research experience for undergraduates (REU); or 2) an application that may have utility in the high-school physics classroom.

For example, Dr. Amy de Jongh Curry, an Assistant Professor of Biomedical Engineering at U of M and Co-PI of our project, conducts research in cardiac defibrillation efficacy. She provides a variety of three-dimensional data that is used in course assignments and projects.

Three-dimensional finite element human thorax models are widely used to simulate defibrillation field quantities such as voltage, potential, gradient, and current density. These quantities are computed at approximately 10^5 spatial nodes that comprise the model, making comprehension of simulation output difficult [15, 16]. Therefore, the objective of one particular course assignment is to display a subset of the geometric model of the human thorax in which the nodal information associated with the geometry of the model meets a specified threshold value (i.e., minimum gradient). The model that is used includes data of surfaces representing intravenous electrodes, chambers of the heart, epicardium, great vessels, lungs, skeletal muscle, the thorax surface, etc. Simulation results from the model include nodal data associated with the <x, y, z> coordinate points of the thorax volume. Students develop a custom visualization application to process the raw data, resulting in views of both the geometry and the nodal data of the model. The geometry of the model is most often viewed by rendering triangulated surfaces within the thorax volume. Nodal data, such as potentials or current densities, are represented by a legend that relates a color with a mean numerical value. The colors are then be mapped to the rendered object indicating the nodal data of the geometry.

Figure 2 illustrates a tool developed by students using de Jongh Curry's data to view the human thorax. In this particular application, students provided the ability to select which major tissues are displayed and the characteristics of the tissue. Figure 3 illustrates the visualization of the weak fields corresponding to one particular electrode configuration. The goal of this particular application is to assist users in tracking the flow of electrical activity in regions of the heart, which may improve investigators' comprehension and understanding of mechanisms of defibrillation shocks. Several students have been involved in both the development of the tools via our course and directed individual study, as well as the investigation of electrode placement, design, configuration and the efficacy of different impulse waveforms as part of a REU program.

Another aspect of our project includes teachers from the Memphis City Schools to determine how medical visualization applications developed by engineering and science students can be best integrated with classical high-school physics and anatomy topics. Some of the teachers participating in our program have also benefited from summer workshops offered by the VaNTH research center and are attempting to utilize applications developed by our students with VaNTH teaching modules [17].

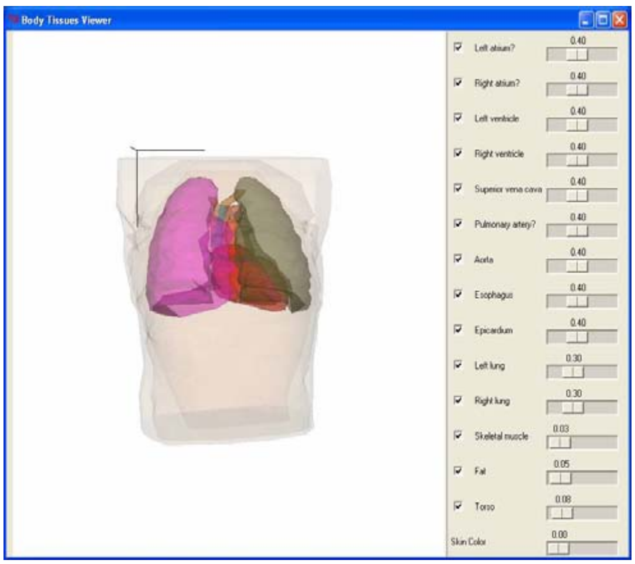

Figure 2. Torso Model Visualization Tool.

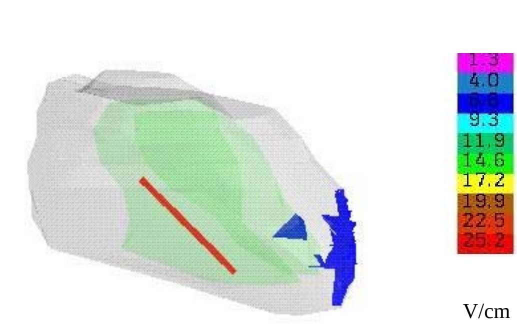

Figure 3. Visualization of the weak fields of one particular electrode configuration.

Figure 4 illustrates a tool developed by students of the course that uses a geometric rendering of a torso to select slices of data from a magnetic resonance image (MRI). Some of the biomedical-oriented tools developed by students of the visualization course have received excellent evaluations by de Jongh Curry's team in that, in their opinion, they are easier to use than comprehensive packages like Matlab and further enhancements to the tools are being specified for future assignments and projects.

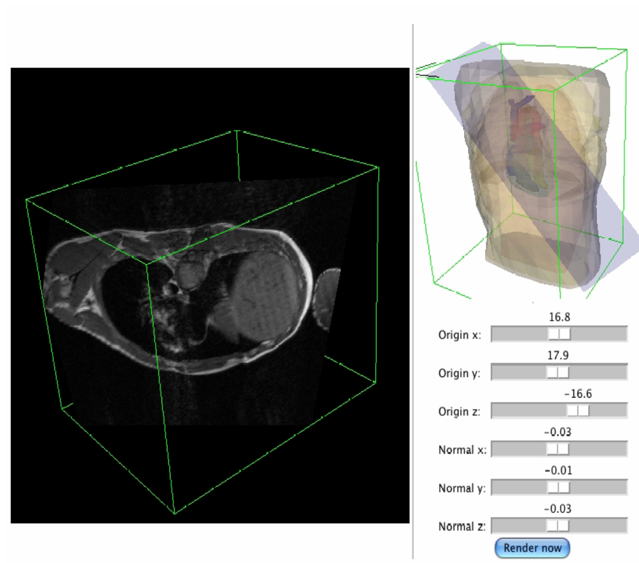

Figure 4. MRI Image Viewer from Geometric Model.

Besides using VTK for "sense making" with respect to large datasets, some students also appear to enjoy using the VTK environment to build simulation applications. For example, Figure 5 illustrates an easy to use conservation of momentum tool developed for use in the high-school classroom. High-school teachers, who are team members of our project, provide feedback on how such tools can be improved for subsequent releases. For example, our teachers recommended the following enhancements for the application shown in Figure 5:

1. Add slow motion, stop and step functions
2. Show angles after impact between the two balls

3. Show a right angle sign between the balls after the collision when they are of the same mass
4. Enable the masses of each ball to be varied
5. Add a data table that shows values with units for all variables
6. Provide capability to show all vectors and paths
7. Show values next to vectors as well as in a table
8. Add an equation table
9. Allow variables and values to be turned on/off on the actual animation

Such recommendations are posted with each version of a given tool on the project website for future students who wish to enhance a given application.

Figure 6 illustrates a projectile motion tool also developed for use in the high-school classroom. For this particular release of the tool, the teachers recommended that slow motion, pause and step features be added as well as an option to enter the magnitude and angle of the projectile's velocity.

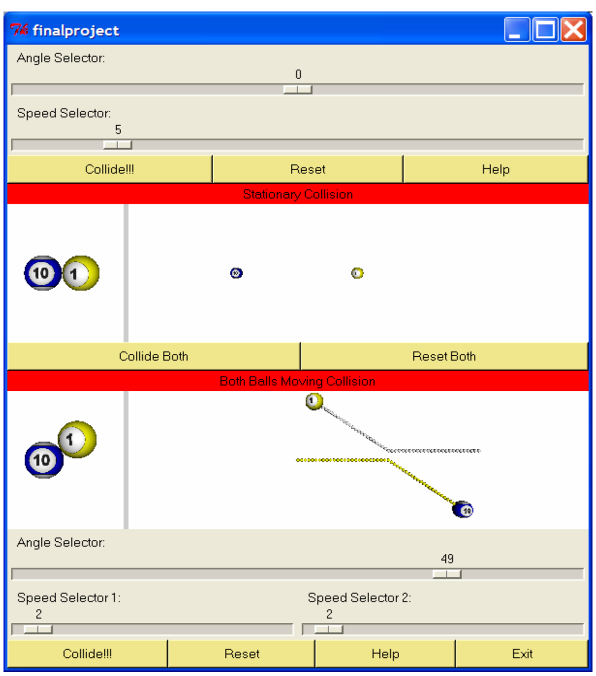

Figure 5. Conservation of Momentum Tool.

Figure 6. Projectile Motion Tool.

Even though an argument can be made that equivalent or superior tools are available in some cases from commercial products, having students participate in the development process with teachers viewed as clients provides valuable practical software engineering experience in joint application design and incremental product improvement. Although anecdotal, undergraduate students appear to be satisfied knowing their tools may have utility in the local community after the semester ends.

Implementation Details

Most of our students use Tcl/Tk [18] for the implementation of the majority of their assignments and projects. Tcl/Tk is a scripting language that is relatively easy for students to learn on their own provided they already know at least one high-level language. Moreover, Tcl/Tk is more straightforward than C/C++ or Java for many students to use for experimenting with visualization techniques and user interface design, and requires significantly less lines of code for most problems. Finally, Tcl provides a neutral "playing field" for an interdisciplinary course for the presentation of the implementation of visualization algorithms and processes in the classroom since students have not used it in a prior course.

Since Tcl/Tk is an interpreted language, students can rapidly test visualization algorithms without having to wait on compilation and linking processes. Students typically use Tk for user interface development since it provides support for push-buttons, text widgets, scroll bars, and other user interface building blocks. In the event that execution time becomes critical, students can port their application to C/C++, but this has not been required for most of the tools developed to date.

Assessment

The project evaluation team is led by Ms. Anna Phillips (Co-PI). Her training as an Educational Psychologist includes interview techniques, survey and evaluation research. The evaluation plan for our project employs a mixture of quantitative and qualitatively-based instruments for data collection. The evaluation plan is composed of both formative assessment instruments (F) and summative assessment instruments (S) as both types address different stages and benefits of the project. Potential stakeholders include program participants from The University of Memphis, within and outside of the Herff College of Engineering, Shelby County/Memphis City school districts and their high-school math, science, and pre-engineering students, NSF, and associated teacher-training programs responsible for continued teacher development in the fields of math and science along with local/regional/national employers of program participants. Table 1 summarizes the learning objectives, measurable activities, and assessment instruments for our project.

Conclusion

This paper presented the development of an interdisciplinary data visualization course with an ongoing community-based project component. The course is unique in that it is promoting active involvement of undergraduate students in the development of applications that have utility in either high-school classes or research experiences (REU). Although some of the visualization applications developed by students may be inferior in some aspects to other offerings, some of the applications have been more appropriate than comprehensive commercial packages for certain applications due to their simplicity and ease of use. Moreover, the applications developed by students as a part of the course provide valuable experiences in eliciting requirements from end-users (e.g., high-school teachers, university researchers and others) and receiving critiques of their work from evaluators other than the course instructor. Finally, the exposure of high-school students to undergraduate work provides an opportunity for these students to appreciate how some of the concepts they learn in class have applicability in real-world problems, which may motivate them to consider a career in engineering or science.

The course website is located at http://engronline.ee.memphis.edu/eece4731/ and the NSF/CCLI project website is located at http://engronline.ee.memphis.edu/nsf_ccli_0410290/. The course website is updated during each semester in which the course is offered. Also, the project website is updated with meeting minutes and other working notes from workshops held with teachers and other project participants. Some of these materials may be suitable for adoption by others.

Our project began September 1, 2004 and the course was first offered during the spring semester 2005; therefore, significant data for a meaningful assessment is ongoing and results will be disseminated as they become available.

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Table 1. Learning Objectives, Measurable Activities, Assessment Instruments

Learning Objective	Measurable Activities	Assessment Instrument
Increase students' comprehension of data-intensive phenomena by reducing the cognitive load required of them when extracting meaning from multi-dimensional data	Assess background/content knowledge of current data-intensive phenomena; track knowledge based on analysis skills/procedures/bases as applied to multi-dimensional data. Pre/post program case studies as applied to cognitive strategies	(F/S) Pre-post program questionnaire in analysis skills; (F) In-class surveys responding to content/style of sample materials; (F) In-class feedback forms regarding use of visualization tools (S) End-user survey responses
Increase undergraduates' ability to implement a custom, visualization application based on a set of user-defined requirements	Observation/documentation of teacher and faculty guidance/mentoring and modeling on design and implementation of group-based custom visualization applications; development of/evaluation of project presentations	(F) In-class surveys responding to content/style of sample visualization materials; (F) In-class feedback forms regarding use of visualization technology; (S) End-user survey responses; (F/S) Videotape/reviewer evaluations of project presentations
Infuse undergraduates into civic engagement by having them work on interdisciplinary teams, including high-school teachers to produce and maintain a repository of contextually-relevant, visualization applications to support inquiry-based learning opportunities	Active data collection supported with formal technical presentations to disseminate research findings at the 11th-12th grade level; Assessment/documentation of local/regional/national professional conference presentations applications, experience, and hands-on activities to continually expand the program level of knowledge from semester to semester; expert-based evaluation of previous participants will serve as evaluators; end-users will serve as evaluators	(F/S) E-mail entries (S) Longitudinal follow-up via interviews/questionnaires; (S) Engineering-Day presentations; (F/S) Pre-post program questionnaire in visualization and analysis skills; (F/S) In-class feedback/evaluation forms from program faculty, participants, end-users; (F/S)Videotape of presentations
Increase awareness and readiness of high-school teachers to integrate custom, visualization tools into their own classrooms by linking tools developed by undergraduates at the U of M to relevant experiments and studies which could be conducted within the teachers' pedagogical activities	Establish pre/post program levels of awareness as evidenced through current curriculum vs. post-program curriculum; develop visualization tools/projects that can be linked between university students and K-12 students; map areas of potential links between new tools and existing curricular goals	(F/S) Pre-post program questionnaire in readiness/preparation levels of program participants; evaluation of visualization tool projects by multiple stakeholders including program faculty, participants, and end-users.

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