Complex adaptive systems and quantitative reasoning in an interdisciplinary STEM mathematics classroom

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Overview

In this presentation we will share outcomes from the Real STEM project, which provides professional development for rural teachers in the Georgia Coastal Plains supporting implementation of interdisciplinary STEM courses as well as STEM modules in mathematics and science courses. Real STEM includes a number of innovative student-active strategies for teaching including: Understanding by Design (UbD) approaches to teaching for understanding, problem-based learning (PBL), place-based education (PBE), complex adaptive systems (CAS) thinking, and quantitative reasoning (QR). QR is the mathematical underpinning of the projects. The projects are ongoing so we will report our results on impact on teacher practice and student learning to this point. We will conclude with a discussion of how the projects may address issues of engagement for rural, low socio-economic status student populations in STEM in Central America and the Caribbean.

Key words: STEM education, quantitative reasoning, complex adaptive systems thinking, problem based, place based

Introduction

Real STEM is a collaboration of four rural school districts in the Georgia Coastal Plain with Georgia Southern University and multiple research institutes. The research institutes include the Skidaway Institute of Oceanography, the Sapelo Island National Estuarine Research Reserve, the Southeastern Natural Sciences Academy, the Ossabaw Island Education Alliance, and the Gray's Reef Marine Sanctuary. The purpose of the collaborative is to develop interdisciplinary STEM courses and modules for implementation in the partner high schools. In spring 2013 the collaborative developed modules which were integrated into existing high school classes. The modules provided an opportunity for the teachers to test out implementing interdisciplinary STEM approaches. In summer 2013 the teachers participated in field campaigns with STEM faculty from Georgia Southern University and the research institutes, to determine complex adaptive systems problems which would drive an interdisciplinary STEM research course to be offered in the 2013-14 academic year. Interdisciplinary STEM professional learning communities of teachers were established at each of the partner school districts to collaborate on development of the course. The expectation is that this course will impact not only the interdisciplinary course, but the mathematics and science courses of the teachers in the professional learning community.

Why should a program being conducted on the Georgia Coastal Plains be of interest to this program? The Central America and Caribbean education systems and the United States education system seem to be vastly different entities; however, many of the barriers impeding students in Central America and the Caribbean from continuing their education (poverty level, rural issues of access and transportation, academic skill, and relevance) are similar to the barriers to education in the rural areas of the United States, particularly in the Southern U.S. The common question for us is how do we make STEM education relevant to these traditionally under-represented populations in rural areas? How do we encourage more students to pursue STEM careers and become STEM literate citizens who can make informed decisions about grand challenges facing their generation? How can we improve the quality of life for students in rural areas of the United States, Central America, and the Caribbean?

Literature review

A desired outcome of student learning is the apt and effective application of content in complex, real-life situations. Only through use does translating knowledge to solve practical problems become efficient, spontaneous, and effortless (Arndt, 2006). Integrating systems thinking into learning has gained traction as a major movement in education, especially for understanding physical phenomena. It has been applied in the fields of engineering, health behavior and education, medicine, and science with documented efficiency and sustained benefits (Swanson et al., 2012). Its inclusive, cyclic design allows holistic visualization of problems and solutions relevant to many disciplines and communities (BeLue, Carmack, Myers, Weinreb-Welch, & Lengerich, 2012). Systems thinking is inherently interdisciplinary, with mathematics (QR) playing a central role in allowing students to make data-informed decisions.

According to Paul West, writing for the Jamaica Gleaner (2013, p. 4), an "essential component [to improving STEM education] should be education and training," of both teachers and students, from the primary level through the tertiary levels of education. This training would have to be focused on math and science and should emphasize ways of making these topics relevant to students. This is not just applicable to Jamaica but to students across Central America and the Caribbean. We propose that in order to make learning relevant it must begin by teaching for understanding (UbD) and not skill acquisition, be driven by problem-based learning (PBL) involving students in exploring authentic real-world problems, and engage students through place-based education (PBE) which ties the problem to their community or place (Figure 1). While PBE ties the problem to place, we look for connections to grand challenges that require the student to explore connections with regional or global problems. For example, the eight grand challenges in environment identified by the National Research Council, includes biogeochemical cycles, biological diversity and ecosystem functioning, and hydrological cycles. Such grand challenges are by nature interdisciplinary, complex adaptive systems (CAS). Complex Adaptive Systems have also been applied to learning since the mid 1980's (Dodder and Dare, 2000; Davis and Simmt, 2003); however, its implementation has not been widespread.

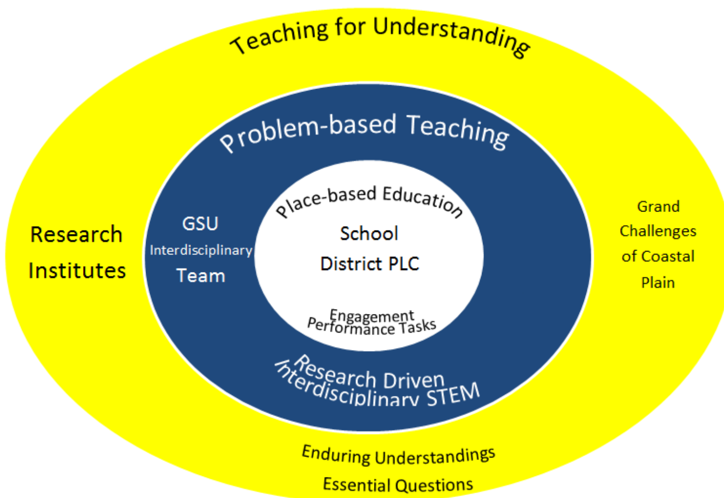

Figure 1: UbD, PBL, and PBE Focus

The grand challenges that serve as the driver for real-world problems in the Real STEM project require students to work within complex adaptive systems. CAS approaches to education are described as "balanced between order and anarchy," consisting of a "network of agents…working in parallel" and "evolving with [in their] environment" to produce an emergent flexible order with "a future that is hard to predict" (Dodder and Dare, 2000, p. 2) and allows for "global patterns of behavior to become apparent" (Lansing, 2003, p.185). Unfortunately, the change to systems thinking in education has been slow, as we still teach in subject silos rather than across curriculum with truly interdisciplinary and relevant learning for all students (Jacobson and Wilenksy, 2006). Lack of systems thinking across curriculum leaves students struggling to find unifying links between the individual elements within a curriculum (Jacobson and Wilensky, 2006). The result is that students turnoff and tune out to STEM, including mathematics. They simply do not see the importance of mathematics in their place.

As a subsystem within a system a classroom becomes a multidimensional set of interactions where the students interact and cooperate to solve problems and understand the world (Mennin, 2007). According to Davis and Simmt (2003) in order to learn to think from a systems perspective five conditions must be met in the classroom: "a) internal diversity, b) redundancy, c) decentralized control, d) organized randomness, and e) neighbor interactions" (p. 147).

Internal diversity

In order for the system to function well there must be a diversity of experiences present within the classroom. This allows for "variation" among the disparate parts (ie: the students) (Davis and Simmt, 2003, p 148) which lends itself to the novel solving of problems. Internal diversity allows for classroom activities to be adapted by students to focus on their interpretations (Davis and Simmt, 2003). Interdisciplinary problems allow students with diverse interests and abilities to interact within STEM and see mathematics through QR as having utility.

Redundancy

At first glance it seems that redundancy and internal diversity are at odds with one another. As internal group diversity focuses on the variety of experiences that students bring to the classroom, we speak of redundancy as a "sameness among [the student's]…experience, expectation, and purpose" (Davis and Simmt, 2003, p. 150). Having a shared community allows for "interactions among [the students] and allows for some students to "compensate for others' failings" (Davis and Simmit, 203, p. 150). Shared community is essential in solving real-world interdisciplinary problems and provides peer support and motivation for mathematics.

Decentralized control

In order for an understanding of systems thinking to permeate student learning, the teacher must give up control and allow students to self-manage their learning, individually or in groups (Davis and Simmt, 2003). It is the capacity to "disperse control" rather than "maintaining control" (Davis and Simmt, 2003, p. 153). This allows for learning to be neither fully teacher-centered nor fully student-centered but rather becomes a "shared insight" (Davis and Simmt, 2003, p. 153). The teacher should focus on establishing a "classroom collective" (Davis and Simmt, 2003, p. 164) rather than a set of individual learners or small groups of learners. Real STEM allows students to select problems within a frame of grand challenges, providing them the opportunity to engage in shared insight with their teachers. In addition we bring scientists into the conversation to assist teachers and students in refining their research questions, methods, and analysis.

Organized randomness

Organized randomness allows for a balance between the redundancy of shared qualities and the diversity of experiences that students bring to the classroom. It allows for rules to determine boundaries but not the "limits of possibility" (Davis and Simmt, 2003, p. 154). Organized randomness allows for classroom learning to be "relaxed [or] rigid" depending on the needs of the students (Davis and Simmt, 2003, p. 155). The Real STEM focus on quantitative data analysis as a means of moving students from qualitative discourse to quantitative discourse is an example of setting rules for both teachers and students in their research.

Neighbor interactions

In order for students to truly learn, they must be able to interact and affect each other's activities and learning. They need to be able to share "ideas, hunches, queries, and other manners of representation" (David and Simmt, 2003, p. 156). This allows for a community to develop within the classroom as concepts cross each other and patterns emerge (Mennin, 2007).

However, it should be noted that the amount of interaction is more important than the type of interaction (ie: pod seating vs. traditional seating). There must be time allowed for depth of interactions to take place in order for students to truly collaborate and cooperate. The Real STEM project requires teachers to use a performance task as a major component of evaluation. A performance task is an open-ended authentic situation that requires the student to demonstrate understanding through a performance, such as a presentation to experts on their findings. This centers learning of STEM with the students as they interact in collaborative groups on the performance task.

In addition, CAS thinking is an ideal platform to expand minority participation (including low socio-economic and other under-represented groups) in mathematics and the sciences in Central America, the Caribbean and the United States. The very nature of CAS thinking encourages the expansion of learning beyond the classroom by moving students from local to global situations. Because students bring a variety of experiences (Mennin, 2007) with them to the classroom, they can "construct beliefs about how things in the world behave" (Jacobson and Wilensky, 2006, p.20). By involving students in authentic, relevant, and engaging projects their understanding of systems becomes much more powerful leading to more collaboration and cooperative learning (Jacobson and Wilensky, 2006).

Mathematics plays a central role in implementing interdisciplinary CAS approaches into STEM courses. A fundamental tenet of CAS is that "the system is not just the sum of its parts, but the product of the parts and their interactions" (Davis and Simmt, 2003, p. 138). As Minnon (2007) further states, if one breaks down a CAS System into its parts it will not "provide an accurate picture of a group that is strongly interconnected" (p. 310). Mathematics provides the tools for building a quantitative account of the connection between the parts of a system. A focus on systems calls for modeling and model-based reasoning, which involves developing and using various forms of representation, feedback, and redesign (Lehrer & Schauble, 2002). Modeling enhances science education by broadening processes beyond conducting experiments. The application of mathematics and statistics within a STEM context is fundamental to a modeling based approach, providing quantitative data-based evidence to support qualitative arguments.

We refer to the application of mathematics within a context, including modeling, as quantitative reasoning. *Quantitative reasoning* (QR) is mathematics and statistics applied in real-life, authentic situations that impact an individual's life as a constructive, concerned, and reflective citizen. QR problems are context dependent, interdisciplinary, open-ended, authentic tasks that require critical thinking and the capacity to communicate a course of action (Mayes, Peterson, & Bonilla, 2013). Mayes, Forester, Christus, Peterson, Bonilla, and Yestness (2013) have developed a learning progression for QR that has four fundamental components:

- Quantification act (QA): mathematical process of conceptualizing an object and an attribute of it so that the attribute has a unit measure, and the attribute's measure entails a proportional relationship with its unit
- Quantitative literacy (QL): use of fundamental mathematical concepts in sophisticated ways to compare, contrast, and combine the quantified variables
- Quantitative interpretation (QI): ability to use models to make predictions and discover trends, which is central to a person being a citizen scientist
- Quantitative modeling (QM): ability to create representations to explain a phenomena

These components interact within a QR cycle (see Figure 2) when students engage in the process of science as model-building. QA is the process of mathematizing the context by identifying objects, their attributes, and assigning measures. The resulting variables can be operated on mathematically or statistically if a student possesses sufficient QL. Citizens are often provided models to support a political viewpoint, requiring QI to make informed decisions. Finally, while citizens may not build models, it is important that students engage in QM so they understand that models are simplified versions of complex systems. Otherwise as future citizens they may fail to question the authority of models.

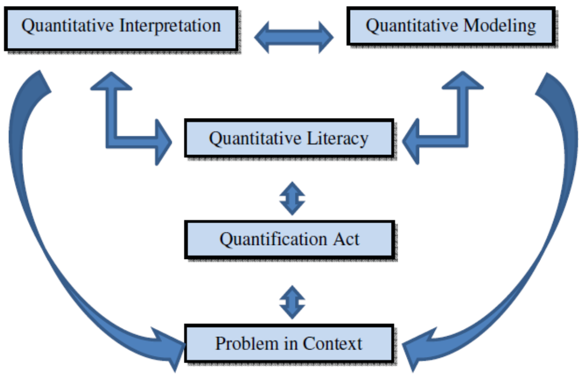

Figure 2: QR Cycle

Mathematics and QR tie into CAS in two fundamental ways. First, model-based reasoning is essential in CAS thinking and developing models is intensely mathematical. This includes quantifying variables from the real-world context, creating representations which are often quantitative such as graphs, statistical representations, and equations, and interpreting quantitative models. Second, the ability to reason quantitatively is essential when developing data-based arguments. Quantitative reasoning (QR) includes the development of quantitative literacy, the ability to interpret quantitative models, and even the ability to create quantitative models. According to Lutsky (2008), there are four major reasons for teaching quantitative reasoning to both teachers and students: QR will improve student reasoning, QR will improve student ability to construct, communicate, and evaluate arguments, relevant QR for students is "primarily simple and non-technical", and QR will bleed over to be relevant across the curriculum.

Pairing QR with CAS is a natural fit because "numbers are a staple of the accounts of world events, environmental trends, financial matters, consumer choices, health decision making, assessments, economics, science, and everyday issues" (Lutsky, 2008, p. 60). In essence numbers are widely used in everyday life and help us, among other things, to grasp complex concepts, see patterns, and facilitate discussions and arguments. Numbers have the power to inform and influence and it is imperative that all citizens of the world know how to understand numbers and think critically about them (Lutsky, 2008). In addition, Jacobson and Wilensky (2006) state that when paired together, CAS and QR become "key conceptual tools" for use in modeling and simulation of systems both real and artificial (p. 13).

Methodology

We believe our Real STEM project could be a model for working with the Central American and Caribbean education systems to improve STEM teaching and learning. Real STEM created a collaborative among Georgia Southern University, regional research institutes and school district partners to develop integrated STEM performance tasks that engage students in applied learning through real-world challenges of environment and energy that impact their local communities. Our goal was to connect students in the classroom with scientists in the field to have conversations about real-world problems impacting the Georgia coastal plain. The students will investigate these problems from their perspective, relating it to associated problems within the place they live. They will then expand their findings from local place to regional or even global grand challenges, using databases compiled by the regional research institute as well as national or global databases. While the intent was to provide teachers and students freedom in selecting the STEM problem to be studied, in collaboration with STEM researchers, a number of expectations for the modules were provided. The expectations include: the module must be interdisciplinary, including science, technology, engineering, and mathematics perspectives; the problem must be place-based, but extendable to regional, national, or global grand challenges; the task must engage students in conducting research in which they collect their own place-based data; the students must complete a performance task as a major component of the assessment in which they report their findings to a group of experts; and students must provide quantitative accounts which provide for data-based informed decisions.

To support the teachers in the project, we proposed three teams of professionals: Team 1 consisted of Research Scientists who identified research being conducted in the Georgia coastal plain which served as potential research problems for students; Team 2 consisted of an interdisciplinary team of Georgia Southern University STEM and STEM education faculty who assisted in transition of those research topics to a level that is accessible by secondary school students; and Team 3, the implementation team, which consists of Professional Learning Communities (PLC) of teachers from multiple STEM disciplines who work together within a school to develop and implement an interdisciplinary curriculum.

Results and conclusions

The implementation of the project consists of three goals: develop integrated STEM modules, implement the STEM modules in an interdisciplinary STEM pathways course, and evaluate the impact of the modules. In Spring 2013 the teachers developed a one to two week interdisciplinary STEM module and implemented it in an existing science course. This provided the PLCs the opportunity to pilot the module and test problem-based learning, place-based education, and Understanding by Design principles. In Summer 2013 the three teams collaborated on identifying research problems that would serve as the basis for the 2013-14 academic year interdisciplinary STEM courses. These are complete courses where students will work in collaboration on real-world authentic place-based research problems from an interdisciplinary perspective. We are currently finishing up the course development and have begun implementation of the courses in Fall 2013. For the course development teachers have had to develop research questions, curriculum, and an open ended performance task for students. Using the Understanding by Design Framework they are working to identify enduring understandings and applying a Backwards Design perspective to develop a curriculum. They have met with scientists from both Research Institutions and the University to hone their plans and develop solid research questions.

In order to compare teacher learning, we have collected and run preliminary descriptive statistics (Figure 3) on the data collected from the Concern, Confidence, and Commitment self-rating rubric from teachers throughout the professional development series this summer. The self-rating rubric is a Likart scale rubric on a scale of 1-Low to 5-High in regards to how teachers felt at the beginning and end of the professional development. It is important to note that the Concern scale is read in reverse of the Confidence and Commitment scale (one would expect higher levels of concern in the beginning and lower levels after the intervention). In regards to place-based education, initially teachers felt higher levels of concern about implementing PBE which led to lower levels of confidence and commitment. After the professional development on place-based education their concern levels dropped on average three points, and their confidence and commitment rose four points. For the professional development on problem-based learning, teachers initially had high levels of concern about implementation but also had relatively high levels of confidence and commitment to implementing. After the training on problem-based learning, concern dropped three points, while confidence rose five points and commitment rose five points. The results on teaching interdisciplinary STEM education were perhaps the least prone to change, with teachers initially feeling moderate levels of concern and afterwards only decreasing in concern two points. Their confidence did rise by five points and their commitment rose by three points, but overall there wasn't much movement on this subscale. For the Teaching for Understanding professional development, teachers showed decreases in levels of concern (from 12 points to 10) while their confidence and commitment each improved five points.

Table 1

Concern, confidence, commitment

	Concern		Confidence		Commitment	
	Before	After	Before	After	Before	After
Place-based Education	9	6	7	12	10	14
Problem-based Learning	12	9	11	16	14	19
Interdisciplinary STEM Teaching	8	6	9	14	11	14
Teaching for Understanding	12	10	18	23	19	24

Source: private survey, 2013

Even though we are only halfway through our project we have had many opportunities to evaluate the project and refocus our thinking. It has become obvious that as we were encouraging systems thinking for students, we took for granted that our teachers were able to think from a systems perspective. This was not always the case. For example, much of the research that is being done on the Georgia coastal plain is on the coast, but some of our school districts are inland (as much as 100 miles). We had to repeatedly stress to teachers and scientists alike that what happens on the coast does impact students 100 miles away as well as vice versa and help teachers learn to tie in the local place to a regional system. In addition, we learned that many of the data analysis techniques that scientists were using were beyond the understanding of the teachers in the project. Due to this there was often a disconnect, for teachers, between reading the data and interpretation of the data. For example, in a discussion with a teacher, we were talking about dissolved oxygen levels in the Savannah River. She was able to discuss learning from a scientist on how to measure dissolved oxygen, but she was unable to discuss why it was important to know those levels. It is essential that the data gathering be associated with a real-world problem in which the student is interested, such as the impact of dissolved oxygen levels on survival of a species. Despite these setbacks we have had great success with teachers in hands-on field campaigns. Encouraging teachers to get out of the classroom to investigate phenomena has been especially exciting.

In addition, with guidance, the teachers have expanded their systems thinking. For example, several schools are designing research questions concerning the health of a local river. Through the professional development, they were able to identify a greater purpose/impact of their study by looking at the role the river plays in the complete watershed. This scaled their thinking up to the system of a watershed (rivers to reefs), not just an isolated river. They were able to find a greater purpose for their original study by applying systems thinking.

The knowledge and skills gained by the teachers through the summer field experiences has reinforced the rationale of utilizing PBL and PBE pedagogy. Numerous times, the high school math teachers commented about appreciating the access to "real life" data that the research institutes collect. No more will they have to use artificially contrived numbers in their mathematics lessons. From the high level of teacher interest and engagement resulting from the field experiences, we expect this to carry over to the students.

Fostering collaboration between research scientists and high school students has not been without its challenges. Because research scientists are trained at a high level in their discipline, identifying appropriate entry points for content and skills for high school students/teachers has taken some work. As conversations have developed between our research scientist teams, our faculty team, and our PLC's, we are starting to overcome the gap. Through ongoing communication, smaller partnerships between experts and the teachers are beginning to develop. Teachers are becoming more comfortable in requesting input from the faculty and the scientists and the faculty and scientists are beginning to designate time and energy to working with the teachers and students.

We will share our experience of working with mathematics, science, and engineering teachers to develop and implement interdisciplinary STEM modules and courses. Intensive data collection on the Interdisciplinary STEM course offerings will take place in the Fall 2013 semester and we will share our most current data on the impact on both teacher practice and student learning. The preliminary teacher interviews and classroom observations indicate positive teacher response to working in interdisciplinary STEM professional learning communities and their interaction with scientists on identifying real-world problems. As the teachers further develop their modules and implement them in the fall, we will continue to track their development towards improved systems thinking and quantitative reasoning.

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