Innovative Methods of Teaching Science and Engineering in Secondary Schools

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ABSTRACT

This article describes the design of an interactive learning environment to increase student achievement in secondary schools by addressing students' preconceptions, and promoting purposeful social collaboration, distributed cognition, and contextual learning. The paper presents the framework that guided our design efforts to immerse all students in a progression of guided-inquiry hands-on activities. Students find compelling reasons to learn by responding to authentic science-based challenges, both in simulations and hands-on activities, based on specific instructional objectives derived from the national science and technology standards.

Keywords: Collaboration, Design-Based Research, Games, Learning, Simulations

1. INTRODUCTION

Schools have numerous responsibilities, including teaching the students observation, critical thinking, mathematical reasoning, communication and problem-solving skills. Science and pre-engineering, properly taught, can help schools fulfill these responsibilities because students can *apply* the knowledge and skills learned in their academic subjects to solve practical problems in their science classes. In particular, developing students' conceptual understanding and analytical abilities through *doing* authentic science-based guided-inquiry hands-on activities enhances students' self-worth and confidence, and consequently improves their school-wide academic achievement [1, 2].

Inquiry-based teaching, however, requires highly structured instructional strategies and, as Cozzens [3] remarks, demands teachers who are knowledgeable about both scientific content and pedagogy. Findings reported by Bransford et al. [4] and Jensen [5] about effective teaching and learning strategies highlight the importance of

- using appropriate just-in-time learning stimuli
- engaging students' preconceptions prior to teaching them new concepts
- providing deep foundational knowledge
- helping students make appropriate connections within the context of a conceptual framework
- organizing knowledge in ways that facilitate information retrieval and application
- allowing students more opportunities to define learning goals and monitor their progress in achieving them.

Learning, defined by Simon [6] as changes that allow systems to *adapt and improve performance*, is influenced by both motivational and cognitive processes. Like Fischer et al. [7], we believe intelligence and creativity are generated and sustained through active collaboration, interactions, dialogue, and shared interests between individuals and their socio-technical environments.

However, facilitating the learning and development of students' purposeful social collaborative skills in classrooms during team-based, guided-inquiry hands-on problem-solving activities presents perennial challenges for several reasons. The first author during his 17 years of teaching science and technology in secondary schools (middle and high) has found the following challenges to be the most demanding:

- Motivating *all* students
- Increasing the cognitive skills of resource-deprived students
- Sustaining student engagement
- Addressing students' preconceptions
- Creating time to participate and contribute effectively during individual teams' discussions and building activities (with 7 – 10 teams typically in each class)
- Promoting greater social collaboration within and between teams
- Resolving problems with group dynamics
- Coping with students' "Been There, Done That" attitude
- Inducing students to build well thought out designs while advancing their metacognitive skills
- Constantly developing genuinely interesting challenges and activities.

Etheredge and Rudnitsky [8] observed that fully implementing findings from research and coping with classroom reality has often been overwhelming for teachers and students.

This paper describes our preliminary efforts at addressing these challenges using a design experiment to inform both theory and practice. The conceptual framework (section 3.1) describes the theory. Concurrently, we developed a prototype and necessary instruction for teaching the concept that "electrical circuits require a complete loop through which an electrical current can pass" [9, p. 127] to middle-school students.

2. STRUCTURED-SCENARIO ONLINE GAMES

2.1 Why Structured Scenario Online Games?

The middle-school wonder years are critical periods in the personal, emotional, social, and cognitive development of students. During this period, students have a tendency to rush through building activities without much reflection. Bransford and Donovan [10] observe that this is due to students' preconception of experimentation as a way of trying things out instead of *testing* their *ideas*.

Balasubramanian and Wilson [11] describe students' enthusiasm for learning and sharing their experience after playing the promising educational games designed by the Nobel foundation. We define a game as an *engaging interactive learning environment that captivates a player by offering challenges that require increasing levels of mastery*. The Laser Challenge Game [12] designed by the Nobel Foundation exemplifies this definition. In our classroom study, we found that all middle-school students, disaggregated by gender and ethnicity, made significant learning gains after playing the challenging Nobel games.

Believing in our five guidelines [11] that are necessary for games and simulations to be meaningfully integrated into classrooms, we designed STRuctured-scenario ONline Games (STRONG, in short) as modular, self-contained, easily accessible, multi-player, online *interactive learning environments*, to direct, facilitate, and assess students' conceptual science, technology, engineering, and mathematics (STEM) understanding through deliberate reflection.

STRONG scenarios and challenges are designed to promote a deliberate *STOP → REFLECT → THINK → ACT* approach to rekindle students' intentionality and inherent preference for goal-oriented actions. Besides, as Balasubramanian [13] discussed, such deliberate thinking fosters self-organized learning. Schön [14] remarked that such "reflection-in-action" situations also foster new ways of thinking and coping with surprises.

The engaging scenarios in STRONG unfold as cliff-hanger chains of events to captivate students' attention, stimulate their motivation, and provide meaningful contexts for learning. For instance, a dialogue between Peggy and Cassandra (fictitious names for students' online avatars, Fig. 1) in our STRONG prototype under development, sets the tone for students finding compelling reasons to design a warning device after they have suddenly fallen into a dark cave during a hiking adventure.

Peggy: Oh great! Now what are we going to do?
Cassandra: Sweet! Let's play cops and robbers.
Peggy: We need to get help quick.
Cassandra: Are you kidding me? This is freaking awesome.
Peggy: Are you kidding ME? This is freaking . . . FREAKY.
Cassandra: No way, this is the ultimate opportunity to play the best, the most extreme, the greatest game of cops and robbers known to humankind.
Peggy: OK, just one game, but after that we're getting help.
Cassandra: Deal! I'm the robber, you try to find me.
Peggy: OK, go. (a couple of minutes pass)
Peggy: Uh Oh! I can't find you. This is scary. Where are - - (cut off because she fell). I tripped on a rock. Help me.
Cassandra: HA HA HA, you tripped. I mean . . . are you okay?
Peggy: Yes, I'm fine. I tripped on this rock.
Cassandra: That's not a rock. It's a treasure chest from the old Captain Willy.
Peggy: I don't think we should open it, there could be something dangerous in there. Let's get help first.
Cassandra: Oh yeah! I have my cell phone, we could just call my mom.
Peggy: Why didn't you think of this before?
Cassandra: Uh oh . . .
Peggy: What?
Cassandra: No signal, I hate my phone service, it never works
Peggy: We're doomed. Well, I guess we could open the box to see what's in it . . .
Cassandra: It's not a box. It's a treasure, but let's look inside. (open the box)
Peggy: It's some wire and . . .
Cassandra: Gold?
Peggy: No a light bulb and . . .
Cassandra: Gold?
Peggy: No a battery. We can put this together to make a signal to get us out of this eerie place.
Cassandra: We could scream for help, someone might hear us as well.

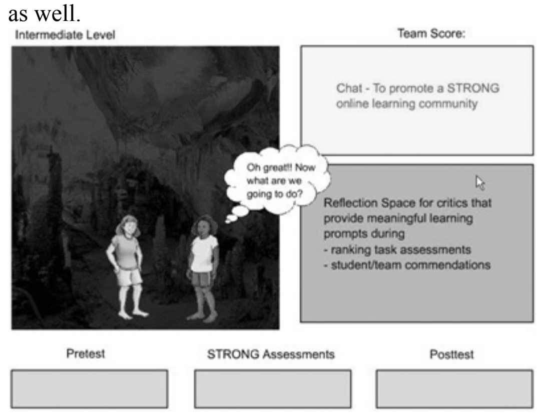

Fig. 1 The STRONG Interface

Then a circuit construction [15] Java simulation pops up on the screen for students to experiment with and build circuits for a warning device using wires, three light bulbs, two batteries, and switches in a safe and non-threatening environment. When students use two batteries, they learn that there is a right way and a wrong way to connect batteries. Using three light bulbs leads to a better understanding of series and parallel circuits.

In summary, STRONG scenarios are designed to enable more students to view surprise and failure as potential opportunities that help them develop good critical thinking, mathematical reasoning, and problem-solving skills as outlined in the *Benchmarks for Science Literacy* [16].

2.2 Curriculum-centered design

From their review of educational gaming literature over a period of 28 years, Randel et al. [17] concluded that games could be used effectively to provoke interest, teach domain knowledge, and shore up retention in math, physics, and language arts when *specific* instructional objectives were targeted.

In our early design of STRONG, students learn, use and understand *one* concept from the *National Science Education Standards* [9], "electrical circuits require a complete loop through which an electrical current can pass" (p. 127), while building simple electrical circuits for a warning device. Along with this concept, players of STRONG will learn and use the knowledge and skills in three labeled strands in the *Atlas for Science Literacy* [18]: lines of reasoning, failure, and interacting parts.

There are four levels in STRONG: beginner, intermediate, proficient, and advanced to correspond with the primary, (K-2), elementary, (3-5), middle, (5-8), and high, (9-12) school grades in the Benchmarks [16]. The outcome variables in these four levels of STRONG are the developmentally appropriate STEM knowledge and skills tabulated and color-coded at http://www.GamesToLearn.us/ConceptForSTRONGPrototype.htm. Using appropriate scenarios, these Benchmarks [16] are packaged as appropriate challenges for students in the different levels of the game, to interest both resource-deprived and resource-affluent students in their preparation for active inquiry learning.

For instance, at the intermediate level of the game, players demonstrate understanding of how a simple circuit is connected by wiring a warning device using only one light bulb, one battery, and one wire and answering assessment questions correctly. The corresponding Benchmark [16] on failure, 11A/E2, requires students to know that "something may not work as well (or at all) if a part of it is missing, broken, worn out, or misconnected" (p. 264).

3. CONCEPTUAL FRAMEWORK

3.1 The STRONG Plus Model

Hands-on inquiry learning without domain knowledge merely entertains students and results in their inadequate conceptual understanding. Many resource-deprived students reach schools with limited cognitive skills and are consequently less motivated. Wilson [19] observed that direct instruction to impart domain knowledge in sterile learning environments left students unenlightened and unable to see its real-world relevance. To cope with this dilemma, we describe the STRONG Plus framework that seeks to immerse all students in a progression of guided inquiry hands-on activities to facilitate their conceptual STEM understanding, starting with STRONG and proceeding to less guided forms of inquiry learning (see Fig. 2).

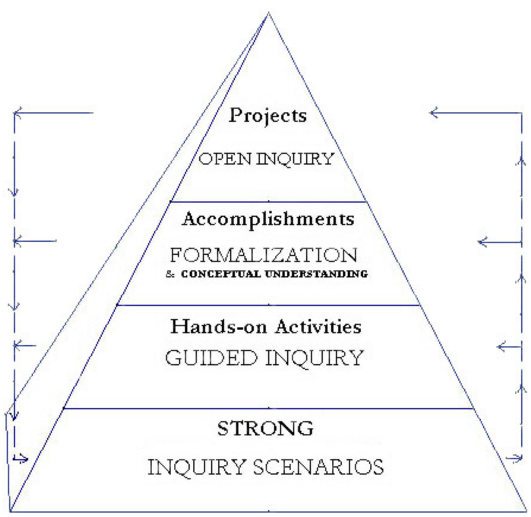

Fig. 2 The STRONG Plus Model, illustrating our conceptual framework.

The pedagogical strategy underlying this conceptual framework is adapted from Vygotsky's model of developmental teaching. Giest and Lompscher [20] propose three stages in Vygotsky's zones of student development: *learn-by-doing* in students' zone of actual performance (ZAP), *learn-by-inquiry* in their zone of proximal development (ZPD), and *learn-by-developmental teaching* where they construct and develop their understanding when their ZPD becomes their new ZAP and so on.

Although designed to be pre-reflective of the formal subject matter, STRONG elicits, first of all, students' rudimentary and incomplete conceptual understanding and prior knowledge in their ZAP. Students work in teams (of two at differing abilities, preferably) to solve challenging problems and accomplish various goals embedded in the game. The small-team setting promotes greater sharing of ideas among young adolescents without fear of negative judgment by their peers, and helps elicit their preconceptions and fragile conceptual understanding during their social interactions and peer mentoring.

McDonald and Hannafin [21] noted that web-based games promote higher order learning outcomes and understanding because they increase meaningful dialogue among the students and help identify students' misconceptions, both of which are not easily obtained in traditional classrooms without conscious teacher mediation. Bransford and Donovan [10] refer to the success of a computer-based DIAGNOSER in increasing students' understanding of high school physics concepts when the program helped teachers elicit students' preconceptions.

Although rudimentary, the STEM content- and context-specific student discussions necessitated through play in STRONG, empowers students with new ways to talk, think, and act in secondary schools (cf. Roth [22]).

After engaging all students using the game, teachers could use the student performance data to provide formal explanations, promote further reflection, and use guided-inquiry hands-on activities to develop students' knowledge and formal conceptual understanding in their ZPD, before formally assessing student accomplishments. Students' flexibility in thinking and performing hands-on activities, beyond the rote and the routine, could be used as one measure of their understanding (cf. Perkins [23]).

Finally, students learn through developmental teaching using projects and problem solving. Observing both, students' creative and imaginative solutions to problems, and their attitude and engagement towards challenges encountered during hands-on activities are other authentic metrics of students' understanding. Following this developmental teaching, students' ZPD in the second stage becomes a new ZAP. This *iterative* process continues through the three stages as students' transition to higher levels of learning and become more active self-directed learners.

In summary, the STRONG Plus model shown in Fig. 2 illustrates our preference for engaging all students with the game first, then providing them with formal explanations and opportunities for hands-on investigations, and concluding with formal assessments and projects to promote conceptual STEM understanding.

3.2 Reflection and Collaborative Problem Solving

Deliberate reflection and collaborative problem solving are two cornerstones in all four stages of the STRONG Plus model. Starting with a well-designed game increases the domain knowledge and motivation of all students. The game provides more students with an opportunity to participate in stimulating and thoughtful conversations in a non-threatening high-challenge small-group gaming environment, before engaging in less guided forms of hands-on inquiry learning.

Reports from classroom observations [24], show that the weakest elements observed in science and mathematics classrooms are the limited time, opportunity, and structure for students to engage, ask questions, and understand all the material. Tools, like STRONG, provide a basis for more doing, testing, reflection and metacognition among middle-school students. Bransford and Donovan [10] describe how using *ThinkerTools*, a physics inquiry curriculum, the low-achieving students from inner-city schools have shown a deeper conceptual understanding of physics because of the metacognitive component in the reflective assessments.

STRONG requires little or no teacher intervention during play. However, students' typed responses in the assessment fields are recorded and processed continuously during the 15-20 minutes of play. Students receive instant feedback on their performance, in the assessment windows and reflection space, from embedded critics in the game.

Critics are agents that provide context-specific advice to users based on their inputs in a computational environment. As observed by Cios et al. [25], the dynamic feedback students receive, based on the embedded fuzzy logic and machine learning techniques in the STRONG system architecture, promote students' active learning.

4. PROTOTYPE OF STRONG

4.1 Design-Based Research

Section one in this paper discussed the complexities and challenges associated with STEM teaching and learning. Section two described how STRONG uses backward design [26], an outcomes-oriented approach requiring identification of desired learning goals and then working backwards to develop meaningful learning opportunities and assessments to promote learning. The STRONG Plus model elaborated on in section three described how the dilemma of "informing" through direct instruction and "doing" in inquiry-based learning might be reconciled.

We considered the development of our prototype as a design experiment because it afforded us opportunities to theorize and address the complexities associated with learning. Cobb et al. [27] recommend that the primary goal of facilitating learning is to improve initial designs by repeatedly testing and revising conjectures. These recommendations have guided us in the development of the STRONG Plus framework and we subsequently used this theoretical model to design a prototype that facilitates student learning.

In addition to teacher observations and feedback, tools like STRONG will help researchers gather real-time data on student learning and performance. Besides, student performance on their diagnostic assessments (their online pre-tests) and post-tests are used to test and improve the design of our prototype.

In summary, our research agenda has a two-fold purpose. The STRONG Plus model depicts our early efforts at developing a theory. Designing a prototype as we developed assessments and necessary instructional support materials to improve practice is another.

4.2 Contextual and Experiential Learning

The case study by Yeo et al. [28] and our personal experiences show that interactivity and animated graphics in games and simulations, by themselves, do not help students learn basic scientific and engineering concepts. Students need additional supports to promote deep conceptual understanding. The Flash animated scenarios in the game not only provide a context and purpose but they also motivate students by enabling them to *do* science.

When students are ready to test their understanding of a concept, say, "electrical circuits require a complete loop through which an electrical current can pass," they will answer six questions that promote their higher order thinking. These six questions are generated randomly from a library of twenty-five questions, unique to each level of the game. This will minimize chances of students misusing the online chat to exchange notes with correct answers.

For instance, in one type of question having *several* possible correct answers, a student will have to select all choices that apply. The possible answers might include: The wire is ◯ warm ◯ cold; the light bulb is ◯ on ◯ off; the light bulb glows very bright and ◯ burns out ◯ does not burn out.

Students' wrong, partially correct, and correct answers have pre-assigned fuzzy logic scores from 0 to 1. This is combined with another unique feature in STRONG asking students "How confident are you in your answer?" The *confidence multiplier*, varying from 1 to 10, for "I am guessing" and "I am 100% confident," respectively, multiplies the raw score (with fuzzy values between 0 and 1), before displaying scaled team scores.

In section 2.1, we defined a game as *engaging interactive learning environments that captivate a player by offering challenges that require increasing levels of mastery*. Typically, with numerous genres available, the term "game" has been elusive to define. Glazier [29], Prensky [30], and Rasmusen [31], have described the presence of the following basic components in games: 1) Player Roles, 2) Game Rules, 3) Goals and Objectives, 4) Puzzles or Problems (Challenges), 5) Narrative or Story, 6) Players' Interactions, 7) Payoffs and Strategies, and 8) Outcomes and Feedback. Consequently, our STRONG prototype includes these basic components (Table 1).

Table 1: STRONG Prototype and Basic Components in our Rudimentary Game – Intermediate Level

Basic Game Components	STRONG
1. Player Roles	Players select one of the six online avatars and watch scenarios unfold. Our current design does not give players more freedom and control over their clothes and their environment, but these power-ups will be incorporated in subsequent designs to reward higher team scores.
2. Game Rules	Students take a pretest (hands-on and online), watch engaging scenarios unfold as Flash movies, use embedded electrical circuit construction Java simulations, answer six randomly selected questions, and take a post test (hands-on and online).
3. Goals and Objectives	Players will learn, use and understand at least *one* core concept from the standards, while building simple electrical circuits for a warning device.
4. Puzzles or Problems (Challenges)	Players demonstrate an understanding of how a simple circuit might be connected for wiring a warning device, using only one light bulb and a battery. Each STRONG assessment question is a puzzle or problem or challenge in itself.

5. Narrative or Story	The dialogue about cops and robbers between Peggy and Cassandra when their cave is suddenly engulfed in darkness depicts a typical scenario in STRONG.
6. Players' Interactions	Student discussions, building various circuit designs using hands-on and Java simulations, answering six questions (three for each player) for assessment even as they alternate and collaborate represents expected interactions.
7. Payoffs and Strategies	What kind of confidence multiplier factors might players use? With raw scores varying from 0 to 1, multiplying it with a multiplier could change the final scaled team scores significantly.
8. Outcomes and Feedback (Embodying concepts to be learned	Players learn and demonstrate understanding of the concept "electrical circuits require a complete loop through which an electrical current can pass," after reflecting on the critique and feedback in the STRONG prototype.

As students play the game, real-time data on their performance will be collected into a database. The embedded critics in the game will offer contextual clues, when necessary. For example, a comment in the reflection space could be "Have you considered connecting this circuit in the Java simulation and seeing what happens?" The contents on the STRONG home page http://GamesToLearn.us include relevant Benchmarks [16], sample worked examples, STRONG assessment, and links to the Java simulations in our STRONG prototype.

5. NEXT STEPS

Mitchell and Savill-Smith [32] noted that players' limited pre-existing computer skills, teacher bias towards learning methods, and possible conflict between game and learning objectives could impact the benefits of using a game, but as knowledge engineers of STRONG, we believe the effect of these would be minimal because the five guidelines [11] that informed our design considerations.

The STRONG Plus model has guided our design efforts in developing a prototype to help students explore and understand electrical circuits. While the existing prototype can be played online at http://GamesToLearn.us, we continue testing and improving our initial design.

In conclusion, a tool like STRONG empowers both students and teachers. STRONG meets learner needs because it supports students' preference for *learning by doing*. STRONG is promising for instructors because it supports teachers who engage students with guided-inquiry hands-on learning. A solid foundation in STEM during students' critical developmental years will help them enhance their lifelong learning goals.

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