Innovative Methods of Teaching and Learning
Science and Engineering in Middle Schools

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ABSTRACT

This paper describes design of an interactive learning environment to increase student achievement in middle schools by addressing students' preconceptions, and promoting purposeful social collaboration, distributed cognition, and contextual learning. The paper presents a 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 from the national standards.

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

1. INTRODUCTION

Schools have a multitude of responsibilities, including teaching the students observation, thinking, 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 and pre-engineering classes. In particular, developing their 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.

Inquiry-based teaching, however, requires highly structured instructional strategies and as Cozzens [1] remarks, demands teachers who are knowledgeable about both scientific content and pedagogy. Findings reported by Bransford et al. [2] and Jensen [3] about effective teaching and learning strategies highlight the importance of

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

Learning, defined by Simon [4] as changes that allow systems to *adapt and improve performance*, is influenced by both motivational and cognitive processes. Like Fischer et al. [5], 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, hands-on problem-solving inquiry-activities presents perennial challenges for several reasons. The lead author, during his 16-years of teaching science and technology in middle and secondary schools, 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 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 [6] observed that fully implementing findings from research and coping with classroom reality has often been overwhelming for teachers and students.

This paper describes an attempt to address these challenges using a design experiment to inform both theory and practice. The conceptual framework (section 3.1) describes the theory. Concurrently, we are developing a prototype and necessary instruction for teaching science, technology, engineering, and mathematics (STEM) to middle-school students.

2. STRUCTURED-SCENARIO ONLINE GAMES

2.1 Why STRONG?

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 [7] observe that this is due to students' preconception of experimentation as a way of trying things out instead of *testing* their *ideas*.

STRuctured-scenario ONline Games (STRONG, in short) are modular, self-contained, easily accessible, multi-player, online *interactive learning environments*, to direct, facilitate, and assess students' conceptual STEM learning and understanding through deliberate reflection.

STRONG scenarios and challenges will promote a deliberate *STOP --> REFLECT --> THINK --> ACT* approach to rekindle players' intentionality and inherent preference for goal-oriented actions. Besides, as Balasubramanian [8] discussed, such deliberate thinking fosters self-organized learning. Schön [9] remarked that such "reflection-in-action" situations also fosters new ways of thinking and coping with surprises.

The engaging scenarios in STRONG unfold as cliff-hanger chain of events to captivate students attention, rekindle their motivation, and provide meaningful contexts for learning. For instance, the 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 ya! 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.

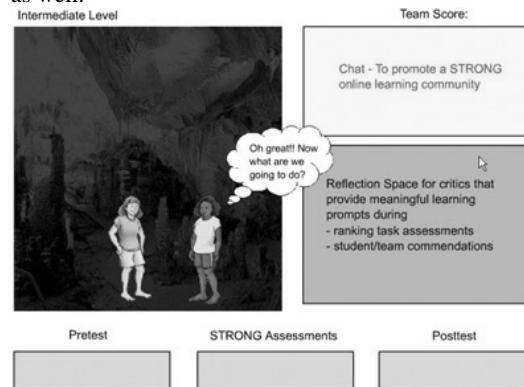*Cassandra*: We could scream for help, someone might hear us as well.

Fig. 1 The STRONG Interface

Then a circuit construction [10] Java simulation pops up on the screen for students to experiment and build circuits for a warning device using wires, light bulbs, batteries, and switches in a safe and non-threatening environment.

STRONG scenarios are designed to enable more students to view surprise and failure as potential opportunities that help them develop good problem-solving, reasoning, and critical thinking skills as outlined in the *Benchmarks for Science Literacy* [11].

2.2 Curriculum-centered design

From their review of educational gaming literature over a period of 28 years, Randel [12] 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, players learn, use and understand *one* concept from the *National Science Education Standards* [13], "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* [14]: 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* [11]. 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* [11] 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 [11] 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 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 [15] 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 a 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).

The pedagogical strategy underlying this conceptual framework is adapted from Vygotsky's model of developmental teaching. Giest and Lompscher [16] 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.
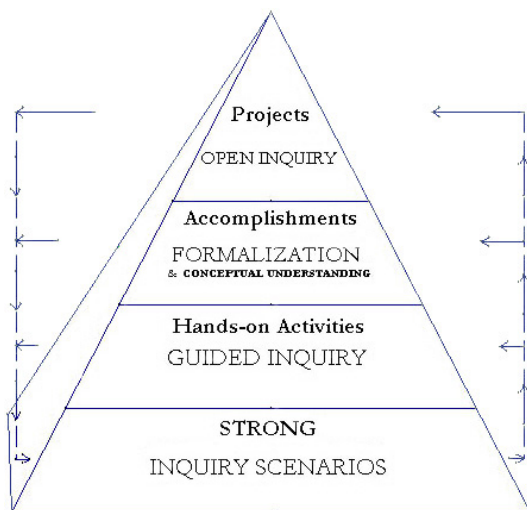

Fig. 2 The STRONG Model, illustrating our conceptual framework.

Although designed to be pre-reflective of the formal subject matter, first, STRONG elicits students' rudimentary and incomplete conceptual understanding
and prior knowledge in their ZAP. Students work in teams (of two, recommended) 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 peers, and helps elicit their preconceptions and fragile conceptual understanding during their social interactions and peer mentoring.

McDonald and Hannafin [17] 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 [7] 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, as Roth [18] remarked, empowers students with new ways to talk, think, and act in middle schools.

After engaging all students using the game, teachers could use the student performance data to provide formal explanations, promote further reflection, and guided-inquiry hands-on activities to develop students' knowledge and formal conceptual understanding in their ZPD, before formally assessing student accomplishments.

According to Perkins [19], students' flexibility in thinking and performing hands-on activities, beyond the rote and the routine, is one measure of their understanding. Observing students creative and imaginative solutions to problems, and their attitude towards challenges encountered while engaging with hands-on activities is another.

Finally, students learn by developmental teaching through projects and problem solving. In 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.

The recommended sequence of engaging all students with the game first, then providing formal explanations and opportunities for hands-on investigations, before formal assessment and projects in the STRONG model will be used for evaluating the design experiment.

3.2 Collaborative Problem Solving and Reflection

Collaborative problem solving and deliberate reflection are two cornerstones in STRONG. By stimulating thoughtful conversations in non-threatening low-stress, high- challenge small-group settings, the game increases the domain knowledge and motivation of all students.

Horizon Research Inc.'s [20] report *Looking Inside the Classroom*, showed that the weakest elements observed in science and mathematics classrooms were the limited time, opportunity, and structure for students to engage, ask questions, make sense, and understand all the material. We need better tools, like STRONG, to foster more reflection and metacognition in middle-school students.

The game requires 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. [21], the dynamic feedback students receive, based on the embedded fuzzy logic and machine learning techniques in the STRONG system architecture, promotes students' active learning.

Bransford and Donovan [7] describe how, using physics inquiry curriculum called *ThinkerTools*, low-achieving students from inner-city schools demonstrated deeper conceptual understanding of physics because of a metacognitive component in the reflective assessment.

Likewise, with rekindled intentionality and better domain knowledge afforded to the players through deliberate reflection during play, students are launched into active inquiry 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 [22], an outcomes-oriented process requiring identification of desired learning goals and then working backwards to develop meaningful learning opportunities and assessments, to promote learning through reflection-in-action. The STRONG model described in section three described how the dilemma of "informing" through direct instruction and "doing" in inquiry-based learning might be reconciled.

Design experiments afford researchers opportunities to theorize and address complexities observed in the real-world. Cobb et al. [23] underscored the connections between developing theories and increased learning afforded through better instructional design – the primary goal being improving initial designs by testing and revising conjectures.

Besides, teacher observations and feedback, tools like STRONG will help researchers gather real-time data on student learning and performance. Student performance on the online pre-tests, six assessment questions, and the post-tests are used to test and improve the design of the prototype.

Our research agenda has a two-fold purpose. The STRONG model depicts our early efforts at developing a theory. Developing a prototype while developing assessment and support instructional materials support instructional practice.

4.2 Contextual and Experiential Learning

The case study by Yeo et al. [24] and our personal experiences show that interactivity and animated graphics in 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 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' correct, partially correct, and wrong answers have pre-assigned fuzzy logic scores from +1 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 – 10, for "I am guessing" and "I am 100% confident," respectively, multiplies the raw score (with fuzzy values between -1 and +1), before displaying scaled team scores.

Although the word "game" has various connotations, following Glazier [25], Prensky [26], and Rasmusen [27], in our design, games refer to interactive learning environments designed to include the basic components in Table 1:

Table 1: STRONG 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 -1 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 reflection on the critiques and feedback in the STRONG prototype.

As students play the game, real-time data on their performance will be collected into a database supporting *Microsoft Access*. 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 of the

STRONG home page www.GamesToLearn.us include relevant *Benchmarks* [11], sample worked examples, STRONG assessment, and links to the Java simulations of a STRONG prototype.

5. NEXT STEPS

Mitchell and Savill-Smith [28] 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 of the game design.

We are currently using our STRONG model to develop a prototype that will help students understand electrical circuits. While the existing prototype can be played on www.GamesToLearn.us, we are testing and improving our design. We look forward to sharing preliminary findings from our tests during our presentation.

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 hands-on inquiry learning. A solid foundation in STEM during students' critical developmental years will help students enhance their lifelong learning goals.

6. REFERENCES

[1] M. B. Cozzens, **Foundations: The Challenge and Promise of K-8 Science Education Reform**. Arlington, VA: Division of Elementary, Secondary, and Informal Education. National Science Foundation, 1997.

[2] J. D. Bransford, A. L. Brown, R. R. Cocking, M. S. Donovan, J. D. Bransford, & J. W. Pellegrino, **How People Learn: Brain, Mind, Experience, and School** (Expanded ed.). Washington, D.C.: National Academy Press, 2000.

[3] E. Jensen, **Teaching with the Brain in Mind**. Alexandria, VA: Association for Supervision and Curriculum Development, 1998.

[4] N. Balasubramanian, & R. Muth, (in press). Simon, Herbert Alexander (1916-2001). In J. M. Blount. (Ed.), **Sage Encyclopedia of Educational Leadership and Administration**, Thousand Oaks, CA: Sage.

[5] G. Fischer, E. Giaccardi, H. Eden, M. Sugimoto, & Y. Ye, (in press). "Beyond Binary Choices: Integrating Individual and Social Creativity," **International Journal of Human-Computer Studies**, Special Issue on Creativity (Eds: L. Candy and E. Edmond), 2005. Retrieved April 11, 2005 from http://l3d.cs.colorado.edu/~gerhard/papers/ind-social-creativity-05.pdf

[6] S. Etheredge, & A. Rudnitsky, **Introducing Students to Scientific Inquiry: How do we Know What we Know**. Boston: Allyn and Bacon, 2003.

[7] J. D. Bransford, & M. S. Donovan, Scientific Inquiry and How People Learn, M. S. Donovan, & J. D. Bransford (Eds.), **How Students Learn: History, Mathemtaics, and Science in the Classroom**, Washington, D.C. : National Academy Press, 2005.

[8] N. Balasubramanian, Smart education: Blending subject expertise with the concept of career development for effective classroom management, 2003, University of Georgia, **Instructional Technology Forum** Web site: Retrieved April 11, 2005 from
http://it.coe.uga.edu/itforum/paper73/paper73.html

[9] D. A. Schön, **The Reflective Practitioner : How Professionals Think in Action**, New York : Basic Books, 1983.

[10] Circuit Construction Kit, . **The Physics Education Technology Project** (**PhET**). Retrieved April 11, 2005 from http://www.colorado.edu/physics/phet/simulations-base.html

[11] American Association for the Advancement of Science, **Benchmarks for Science Literacy**, New York: Oxford University Press, 1993.

[12] J. M. Randel, B. A. Morris, C. D. Wetzel, & B. V. Whitehill, The effectiveness of games for educational purposes: A review of recent research. **Simulation & Gaming**, Vol. 23, No. 3, 1992, pp. 261-276.

[13] National Research Council, **National Science Education Standards**, Washington, D.C.: National Academy Press, 1996.

[14] American Association for the Advancement of Science, **Atlas for Science Literacy**. Washington, DC: AAAS and the National Science Teachers Association, 2001.

[15] B. G. Wilson, The postmodern paradigm. In C. R. Dills & A. J. Romiszowski (Eds.), **Instructional Development Paradigms**. Englewood Cliffs, NJ: Educational Technology Publications, 1997, pp. 297-309.

[16] H. Giest, & J. Lompscher Formation of Learning Activity and Theoretical Thinking in Science Teaching. In A. Kozulin, B. Gindis, V. S. Ageyev, & S. M. Miller (Eds.), **Vygotsky's Educational Theory in Cultural Contexts**, New York: Cambridge University Press, 2003, pp. 267-288.

[17] K. K. McDonald, & R. D. Hannafin, Using web-based computer games to meet the demands of today's high-stakes testing: A mixed-methods inquiry. **Journal of Research on Technology in Education**, Vol. 35, No. 4, 2003, pp. 459-472.

[18] K. J. Roth, Talking to understand science. In J. Brophy (Ed.), **Social Constructivist Teaching: Affordances and Constraints**. Oxford, UK: Elsevier Science, 2002, pp. 197-262.

[19] D. Perkins, What is understanding? In M. S. Wiske (Ed.), **Teaching for Understanding: Linking Research with Practice**. San Francisco: Jossey-Bass, 1998, pp. 39-57.

[20] I. R. Weiss, J. D. Pasley, P. S. Smith, E. R. Banilower, & D. J. Heck, **Looking Inside the Classroom,** Chapel Hill, NC: Horizon Research Inc., 2003.

[21] K. J. Cios, W. Pedrycz, & R. W. Swiniarski, **Data Mining Methods for Knowledge Discovery**. Boston: Kluwer Academic Publishers, 1998.

[22] G. Wiggins and J. McTighe, **Understanding by Design**, Alexandria, VA: Association for Supervision and Curriculum Development, 1998.

[23] P. Cobb, J. Confrey, A. diSessa, R. Lehrer, & L. Schauble, Design Experiments in Educational Research. **Educational Researcher**, Vol. 32, No. 1, 2003, pp. 9-13.

[24] S. Yeo, R. Loss, M. Zadnik, A. Harrison, & D. Treagust, What do students really learn from interactive multimedia? A physics case study. **American Journal of Physics**, Vol 72, No. 10, 2004, pp. 1351-1358.

[25] R. Glazier, **How to Design Educational Games** (4th ed.), Cambridge, MA: ABT Associates.

[26] M. Prensky, **Digital Game-Based Learning**. New York: McGraw-Hill, 2001.

[27] E. Rasmusen, **Games and Information: An Introduction to Game Theory** (3rd ed.). Malden, MA: Blackwell, 2001.

[28] A. Mitchell, & C. Savill-Smith, **The Use of Computer and Video Games for Learning: A Review of Literature**, London: Learning and Skills Development Agency, 2004.