

NSF Proposal Submitted to Advanced Learning Technologies

*SimEd-Math:
Modeling Differentiated Instruction
in Mathematics*

Principal Investigator

Theodore W. Frick

Principal Co-Investigatgor

Enrique Galindo

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Project Summary: *SimEd-Math*

The design, development and evaluation of a new computer simulation for preservice teachers is proposed: *SimEd-Math: Modeling Differentiated Instruction in Mathematics*. The primary objective of *SimEd-Math* is to give preservice teachers practice in differentiating instruction in mathematics so that they can experience the consequences of their classroom teaching decisions. Each preservice teacher is expected to manage a simulated classroom in which she or he must facilitate individual student engagement and learning achievement by identifying activities and resources most appropriate for each of them. A teacher succeeds in *SimEd-Math* by most efficiently guiding her or his simulated students' mastery of curriculum standards in elementary (P-6) mathematics during a fixed period of time.

During the first 2 years of the *SimEd-Math* project, software engineering is proposed that includes play-testing (formative evaluation) of the simulation with small samples of preservice teachers. This methodology includes iterative, rapid prototyping and frequent user testing as part of the design and development process. In the 3rd year, *SimEd-Math* will be evaluated with preservice teachers in elementary mathematics teaching methods courses.

The principal investigator has previously created successful e-learning products that run via the Web, including the *Diffusion Simulation Game*, using this iterative design process with embedded usability evaluation. The co-principal investigator is a highly experienced teacher educator in mathematics teaching methods and use of technology in teacher education.

Merit. *SimEd-Math* is an innovation that is expected to 1) radically improve preservice teacher learning of how to individualize mathematics instruction for elementary school students, and 2) advance research on effective and efficient development of simulations for preparation of preservice teachers.

The advantage of a simulation for preservice teachers, such as *SimEd-Math*, is that they will get repeated practice and feedback in managing a simulated classroom under various conditions so that their simulated students successfully learn mathematics—or not—and for those preservice teachers to learn from their mistakes without harming real students.

What sets *SimEd-Math* apart from other simulations, such as *simSchool*, is that *SimEd-Math* is grounded in systems theory, as well as in research on academic learning time and first principles of instruction. Consequently, *SimEd-Math* is expected to better prepare preservice teachers for classroom teaching by giving them more mathematics “teaching” experience during their preparation in college that would otherwise not be practical or possible in typical practicum and student teaching placements.

SimEd-Math is expected to include a comprehensive collection of mathematics learning activities for elementary students that involve a wide range of technologies—from relatively inexpensive paper-and-pencil activities, to those which involve physical manipulatives, to hand-held devices, to computers.

A very important merit of *SimEd-Math* software engineering is that it will be designed so that it can be used for modeling differentiated instruction in *other* subjects. Once *SimEd-Math* has been created and its value is demonstrated in teacher preparation, then it will be much easier to develop similar simulations for teaching other subjects in science, technology, engineering and advanced mathematics (STEM areas).

Impact. The initial impact of *SimEd-Math* is expected to be improvement of elementary school mathematics teaching. Preservice teachers who are successful in *SimEd-Math* are expected to become more effective in teaching mathematics in elementary schools. Once *SimEd-Math* is developed, it can be made widely available over the Web for teacher preparation programs in higher education *throughout the U.S.* If elementary school students improve their learning of mathematics as a result of better instruction from teachers who have successfully completed *SimEd-Math*, then those students are expected to be better prepared for mathematics courses such as algebra in secondary schools. Since mathematics serves as a foundation for many STEM-related disciplines, then *SimEd-Math* is expected to indirectly improve the preparation of P-12 students for those disciplines. Furthermore, what is learned from creation of *SimEd-Math* is expected to expedite future development of additional *SimEd-STEM* simulations for preservice teachers. As these additional simulations are implemented in U.S. higher education, preservice teachers are expected to be better prepared to teach P-12 students in STEM areas. Similar to how cockpit simulators have transformed how pilots learn to fly, simulations such as *SimEd-Math* are expected to transform and radically improve how preservice teachers learn to teach.

Project Description: *SimEd-Math: Modeling Differentiated Instruction in Mathematics*

Overview

We propose to design, develop and evaluate a computer simulation, *SimEd-Math: Modeling Differentiated Instruction in Mathematics*, which will run on the Web. *SimEd-Math* will give preservice teachers practice in differentiating instruction in mathematics so that they can experience the consequences of their classroom teaching decisions. Each preservice teacher manages a simulated classroom in which she or he must facilitate individual student engagement and learning achievement by identifying activities and resources most appropriate for them. A teacher succeeds in *SimEd-Math* by most efficiently guiding her or his simulated students' mastery of curriculum standards in mathematics during a fixed period of time.

The advantage of such a simulation for teachers is similar to that of cockpit simulators for pilot training: it gives them repeated practice in flying the simulated plane under various conditions, so that they can learn from their mistakes without harming themselves and their passengers. In the case of preservice teachers, they will get repeated practice and feedback in managing a simulated classroom under various conditions so that their simulated students successfully learn mathematics—or not—and likewise learn from their mistakes without harming students or losing their job.

What sets *SimEd-Math* apart from other simulations is that it is grounded in systems theory, as well as in research on Academic Learning Time and First Principles of Instruction. Consequently, *SimEd-Math* is expected to better prepare preservice teachers for classroom teaching by giving them more mathematics “teaching” experience during their preparation in college than would otherwise be practical or possible in typical practicum and student teaching placements. To succeed in the simulation, teachers will need to give up the notion of “sage on the stage” and adopt a “guide on the side” perspective. Moreover, teacher or student choice of learning activities that integrate information technology will be necessary in order to provide differentiated learning experiences for simulated students to work at their own pace on activities suited to their skill and knowledge levels in mathematics.

We plan for *SimEd-Math* to include a comprehensive collection of mathematics learning activities for elementary students that involve a wide range of technologies—from relatively inexpensive paper-and-pencil activities, to those which involve physical manipulatives, to hand-held devices, to computers with and without Internet connectivity. *SimEd-Math* focuses on what it will take to move towards instruction that is truly individualized—in contrast with the traditional, group-paced model. We expect preservice teachers to learn to be “guides on the side,” by developing technology-, resource-, and classroom-management skills and by selecting appropriate learning activities.

In 2007, we developed an initial board game version of *SimEd-Math*, that we called SimTIE. See Figure 1. We conducted play-tests of SimTIE with a small group of preservice teachers and two instructors who teach education technology courses. The prototype they played contained learning activities that were closely connected with standards for elementary mathematics learning that are recommended by the National Council of Teachers of Mathematics (NCTM). The instructors, who were experienced school teachers before becoming professors, were impressed by the decision making required of the players and the fidelity to real world teaching with technology. The preservice teachers reported a greater appreciation for the complexities and practicalities of managing individualized instruction.

While the board game prototype for *SimEd-Math* shows promise, significant work remains to develop, evaluate, and implement an online version. The computer version will contribute significant improvements that include: 1) easier and quicker play through reduced manual record keeping; 2) more complex and realistic outcomes through rapid data processing and modeling of system state; 3) instant access to game updates; 4) database tracking of game play and results, to provide learning outcome data and an information base which we can use to apply adaptive learning strategies to make the simulation more dynamic and relevant to each preservice teacher.

A highly significant advantage of *SimEd-Math* via the Web is that it could be made widely available to preservice teachers everywhere from a central location (e.g., Web servers at Indiana University). The principle investigator for this proposal has already led development of a Web-based computer simulation

called the *Diffusion Simulation Game (DSG)* (Frick, Kim, Ludwig & Huang, 2003). The *DSG* has been played by over 3,000 students at Indiana University during the past 5 years, and a limited version available to the general public has been played more than 4,000 times in the past 17 months. The principal investigator has also led the design of online learning about plagiarism that has received over 4 million page views in the last 3 years, with over 125,000 students passing the plagiarism test in 2007. We have reason to believe that well-designed and effective Web-based e-learning has great power and reach. We expect *SimEd-Math* to reach a very wide audience of both preservice teachers (our primary target audience) as well as teachers on the job.

Figure 1. Photographs of the initial SimTIE prototype, May 2007, to be adapted for *SimEd-Math*.



How SimEd-Math Meets Criteria for NSF 06-535

The Advanced Learning Technologies RFP calls for research that meets two criteria: “(1) enables radical improvements in learning through innovative computer and information technologies, and (2) advances research in computer science, information technology, learning, and cognitive science through the unique challenges posed by learning environments and learning technology platforms” (RFP, p. 2).

We expect SimEd-Math to meet the first criterion easily. One of the major challenges to teacher education is to provide preservice teachers with enough practice in teaching before they graduate and get their first teaching job. The *SimEd-Math* simulation will provide preservice teachers with repeated opportunities to make planning decisions for selecting student learning activities, and then to experience the consequences of those choices in the simulation.

We know from research on academic learning time that successful student engagement in tasks that are similar to those they are later expected to perform is positively correlated with objective tests of such performance (cf. Kuh, Kinzie, Buckley, & Hayek, 2007; Rangel & Berliner, 2007; Berliner, 1990; Brown & Saks, 1987).

The benefits of flight simulators for training and maintenance of flying skills are well-known and documented. It is routine now for both military and commercial airline pilots to spend numerous hours in flight simulators, before actually flying the real plane. The reasons are clear. Beyond increasing academic learning time (successful practice), the advantage of such simulators is to practice also under conditions that are rarely encountered in the real world. Most importantly, pilot errors that are made in the simulator do not result in human fatalities and loss of expensive airplanes. Pilots can learn from these mistakes, and improve their flying skills. A meta-analysis of flight simulation research (Hays, Jacobs, Prince, & Salas, 1992) found that aircraft training combined with the use of simulators consistently resulted in improved performance compared to aircraft training only.

Similarly, the proposed *SimEd-Math* simulation will give preservice teachers practice in decision making on and planning of learning activities in mathematics. It is difficult in teacher education programs to provide preservice teachers with enough practice. It is costly to place them in real classrooms, and if they make mistakes there are real consequences to students they teach in these practicum and student teaching placements. Thus, *SimEd-Math* would be a radical improvement in preparation of preservice teachers for teaching of elementary mathematics.

With respect to the second criterion, we expect the design and development of *SimEd-Math* to advance research on development of e-learning simulations. In particular, we expect to build a software architecture, inference engine and database schema that will be reusable for other kinds of content, not just teaching of elementary mathematics. In fact, although not proposed here due to limited amounts of funding available in NSF 06-535, we expect to create future simulations such as *SimEd-Technology*, *SimEd-Science*, etc. What we learn from designing, developing and evaluating *SimEd-Math* will be invaluable for designing similar kinds of simulations. The knowledge gained from developing *SimEd-Math* will save considerable time, effort and cost for subsequent development of other *SimEd-STEM* simulations for use in teacher education programs.

A further benefit is that we expect *SimEd-Math* to further our larger aim of modeling educational systems and predicting education system outcomes (cf. Frick & Thompson, 2008; Thompson, 2005a,b). We believe that radical improvements in our current system of education are needed. Such school transformation efforts should not be done by trial and error, as they are largely done now. We need a scientific basis of predicting what happens in an educational system, given the current conditions. This is not unlike what Wal-Mart currently does in anticipating customer needs and sales, based on past patterns that have been observed. For example, when hurricanes approach Florida, Wal-Mart sends extra beer, pop tarts, and children's games that can be played without electricity *before the hurricane actually arrives* (Friedman, 2005). These predictions are based on past sales patterns under these specific conditions. We see the development of *SimEd-Math* as helping to further develop Axiomatic Theories of Intentional Systems (ATIS) (Thompson, 2005a,b), and predicting education system outcomes (PESO) (Frick & Thompson, 2008). What we learn in developing *SimEd-Math* will help us in designing *SimEd-PESO*. We anticipate that *SimEd-PESO* will become an extremely important tool for educators to use at all levels of education. While we plan to patent *SimEd-PESO* technologies that include MAPSAT (Map & Analyze Patterns & Structures Across Time) (Frick, 2005), we view *SimEd-Math* as advancing further theoretical developments of ATIS and potential design of algorithms needed for *SimEd-PESO*.

Benefits of SimEd-Math

The initial impact of *SimEd-Math* is expected to be improvement of elementary school mathematics teaching. Preservice teachers who are successful in *SimEd-Math* are expected to become more effective in teaching mathematics in elementary schools. Once *SimEd-Math* is developed, it can be made widely available over the Web for teacher preparation programs in higher education *throughout the U.S.* If elementary school students improve their learning of mathematics as a result of better instruction from

teachers who have successfully completed *SimEd-Math*, then those students are expected to be better prepared for mathematics courses such as algebra in secondary schools. Since mathematics serves as a foundation for many STEM-related disciplines, *SimEd-Math* is expected to indirectly improve the preparation of P-12 students for those disciplines. Furthermore, what is learned from creation of *SimEd-Math* is expected to expedite future development of additional *SimEd-STEM* simulations for preservice teachers. As these additional simulations are implemented in U.S. higher education, preservice teachers are expected to be better prepared to teach P-12 students in STEM areas. Similar to how cockpit simulators have transformed how pilots learn to fly, simulations such as *SimEd-Math* are expected to transform and radically improve how preservice teachers learn to teach.

Need for SimEd-Math

Traditional and alternative approaches to the preparation of teachers have received increasing attention in the press and in research studies during the last years (Cochran-Smith, & Zeichner, 2005; ECS, 2003a; ECS, 2003b; Kane, Rockoff, & Staiger, 2006; National Mathematics Advisory Panel, 2008). The proposed development and research will contribute to the empirical evidence about the practices required to prepare highly qualified elementary mathematics teachers. We will study the potential of an innovative practice for preparing teachers who are better at paying attention to students' individual differences, and who are knowledgeable in selecting differentiated learning activities.

Researchers have found that effective teaching requires knowing how specific individual students in the classroom think about the content (Carpenter & Fennema, 1992; Carpenter et al., 1988; Carpenter, Fennema, & Franke, 1996; Cobb, 2000; Fennema et al., 1996). Furthermore, there is evidence to show that teachers can improve their content knowledge as they work to understand students' reasoning (Franke & Kazemi, 2001). In the proposed project preservice teachers will work with simulated students and will have to choose learning activities that are appropriate for where their students are in relation to mathematics standards. They will then see the effect of their choices on their simulated students learning and will refine their understanding of their students' knowledge. By providing opportunities for preservice teachers to go through cycles of refining their ability to make instructional choices based on their assessment of students, we are likely to find some of the benefits reported by professional development studies, including: increased efforts to improve student learning (Bloom, 1998), critical reflection on teaching practices (Lord, 1994), and strengthened content knowledge (Nickerson & Moriarty, 2005).

Research on Pedagogical Content Knowledge of Mathematics

Research and recent documents highlight the importance of effective mathematics teachers having well-developed understandings in domains of content and pedagogy (Ball, 1991; Conference Board of the Mathematical Sciences [CBMS], 2000; Duschl, Schweingruber, & Shouse, 2006; Ma, 1999; Mathematical Association of America, 2003; National Mathematics Advisory Panel, 2008; Smith, Desimone, & Ueno, 2005). Recognizing that the intersection of these domains is most critical, researchers have focused on teachers' development of pedagogical content knowledge (Ball, Lubienski, & Mewborn, 2001; Borko & Putnam, 1995; Grossman, 1990; Grouws & Schultz, 1996; Schwartz & Lederman, 2002; Shulman, 1986). Pedagogical content knowledge provides the basis for teachers' decision-making within a discipline; it includes seeing the topics they teach as embedded in rich networks of interrelated concepts, deciding on the use of tasks, selecting useful representations of the ideas involved, teaching mathematics and science as an integrated body of knowledge and practice, and understanding what makes the learning of specific topics easy or difficult for students (CBMS, 2000; Duschl, Schweingruber, & Shouse, 2006; Shulman, 1986; Van Driel, Verloop, & deVos, 1998).

One way for teachers to develop their pedagogical content knowledge is by attending to students' reasoning. The premise is that if teachers listen to children, understand their reasoning, and teach in ways that reflect this understanding, not only will they provide those children with a better mathematics and science education, but this will also have a powerful effect on the way teachers view mathematics learning (Appleton, 2006; Carpenter & Fennema, 1992; Fennema et al., 1996; Franke, Carpenter, Levi, &

Fennema, 2001; Morine-Dersheimer & Kent, 1999; Schifter, 1998; Warfield, 2001). The proposed simulations will help preservice teachers learn to attend to students' reasoning by choosing learning tasks that they think are appropriate for students' knowledge of mathematics concepts and by seeing the effects using those tasks on students' learning.

Building Learning Trajectories

Contemporary research on children's mathematical learning highlights the efficacy of building models of students' knowledge (Carpenter, Fennema, Peterson, & Carey, 1988; Confrey, 1985, 1990; Confrey & Lachance, 2000; Steffe, 2002; Steffe, Cobb, & von Glasersfeld, 1988; Steffe & D'Ambrosio, 1995). Math Recovery, which relies on model building for its highly successful interventions with at-risk students, describes model building as "on-going assessment through careful observation, hypothesizing about the student's current knowledge and strategies, and selecting learning activities closely attuned to the child's current reasoning and strategies" (US Math Recovery Council, 2005, p. 6). Steffe and D'Ambrosio (1995) have suggested that model building should be the central component to teachers' pedagogical knowledge. Our proposed approach follows such research and suggestions by engaging preservice teachers in building learning trajectories of their simulated students and choosing learning activities according to the models they build of their students' knowledge.

Teaching experiments involve a close examination of teacher-student and student-student interactions that support learning. Teaching experiment methodology requires a particular approach to teaching in which the teacher must continually attempt to make sense of the students' language and actions (Steffe & Thompson, 2000). This approach is important on two levels. First, by continually interpreting student behavior, the teacher is developing new hypotheses about students' cognition while remaining open to surprises. Second, by attempting to think as students do, the teacher is in a position to understand the students' ways of operating and compare them to his own in order to design tasks to provoke creative activity in the students (Hackenberg, 2005). On both levels, the teacher experiences constraints in building viable models and meaningful tasks based on the dichotomy of expected (predicted) and observed activities of students. This feedback provides the guiding principle for hypothesis testing, model building, and the design of new tasks within and between protocols.

Although teaching experiments have been used successfully in research on learning and as interventions for at-risk children, they have not been used as part of an undergraduate program for preservice teachers. We propose designing simulations that will allow preservice teachers to learn to develop the skills needed to conduct teaching experiments in order to learn to build models of children's mathematical knowledge and in order to learn to follow the development of children's ideas over time.

Research on Simulations, Games and Learning

A growing number of scholars and researchers are exploring the relationship between simulations/games and learning. Books such as Prensky's (2001) *Digital Game-Based Learning* and Johnson's (2005) *Everything Bad is Good for You* popularized the notion that games can teach, while Gee's (2003) *What Video Games Have to Teach Us About Learning and Literacy* brought academic rigor to the field by examining video games in terms of semiotic domains, situated learning, and identity. Others are exploring how simulations/games motivate and engage (Dickey, 2005; Garris, Ahlers & Driskell, 2002; Paras and Bizzocchi, 2005); how they provide authentic learning experiences (Cannon-Bowers and Bowers, 2008; Galarneau, 2005; Magnussen, 2005; Ruben, 1999); and the relationship between game design and instructional design (Becker, 2005, 2008; Dickey, 2005; Van Eck, 2007).

Research on the use of simulations and games for learning seems to be increasing. Rutter and Bryce (2006) compared the periods of 1995-1999 and 2000-2004 and found nearly twice as many peer-reviewed papers on digital games during the latter period. Bragge and Storgards (2007) used the ISI Web of Science to find 2,100 studies in more than 170 categories related to digital games between 1986 and 2006, with a significant increase beginning in 2003. However, much of the reporting on the use of games for learning is anecdotal, descriptive, or judgmental and not tied to theory or rigorous research (Gredler,

2004; Kirriemuir & McFarlane, 2003; Leemkuil, de Jong & Ootes, 2000; Washbush & Gosen, 2001; Wideman et al., 2007).

Regarding the use of games and simulations with preservice teachers, Kay (2006) reviewed 68 refereed journal articles that focused on incorporating technology into preservice education. He identified ten common strategies, including the use of multimedia (case studies, online courses, and electronic portfolios). He did not report any use of simulations with preservice teachers. Schrader, Zheng, and Young (2006) surveyed 203 preservice teaching students in three different universities regarding their attitudes toward the use of games in education. The majority (76.4%) had played games, and of those, 83.3% played on a weekly basis. Participants recognized the distinction between recreational games and educational games, identifying problem-solving (78.8%), clear rules (63.5%), authenticity (52.2%), and feedback (43.8%) as important characteristics of educational games. The researchers noted that “the data does indicate that preservice teachers are open to new applications of technology and in fact consider games to be important educational tools” (p. 4).

Why Use Simulations/Games to Teach? Two main reasons for using instructional simulations/games are their power to engage and motivate and their ability to facilitate learning through doing (Kirriemuir & McFarlane, 2004). According to Garris et al. (2002), there are several reasons why educators should be interested in using simulations and games in instruction, including the shift to a learner-centered model and the intensity of involvement and engagement in games. The memorization of facts and concepts that is easily measured on a standardized test has led to the presentation of abstract, decontextualized knowledge that is divorced from purpose and instrumentality. In contrast, simulations require players constantly to use what they have learned to solve situated problems (Shaffer, Squire, Halverson & Gee, 2005; Wideman et al., 2007). Findings demonstrate that the kinds of experiential learning available in simulations and games improve learners’ problem-solving skills and judgment. In part this is because the active learning required in games facilitates integration of knowledge with existing cognitive structures (Feinstein & Cannon, 2002; Randel, Morris, Wetzels, & Whitehill, 1992).

In their review of the literature, Mitchell and Savill-Smith (2004) found several frequently cited benefits of games in education. These include increases in perseverance, confidence, and self-esteem among learners; the ability to visualize, manipulate, and explore concepts; and greater academic, social, and computer literacy skills. Some studies cited improved metacognition, strategic thinking, problem recognition, and problem solving. In the health sciences, simulations enable students to diagnose and manage virtual patients’ problems. In business education, teams manage virtual companies. In both areas, simulations are used to identify students’ problem solving abilities and to bridge the gap between classroom instruction and real-world practice (Gredler, 2004).

Many of the attributes of games are also attributes of good instructional design. Games often involve problem solving, provide rapid feedback, and can adjust to optimal level of difficulty (Oblinger, 2003). Gee (2003; 2005) identified dozens of learning principles that are found in good games, including manipulation and control by the learner, scaffolding and elaboration, well-ordered problems, optimal challenge, skills as strategies and cycles of expertise, information as needed (just in time), systems thinking, and learning by doing.

Many studies of the benefits of playing games to learn have emphasized the motivational or social aspects rather than knowledge acquisition (Kafai, 2001). However, intrinsic motivation is generally considered a prerequisite for learning. Garris et al. (2002) describe the motivated learner as enthusiastic, engaged, focused, and persistent. The factors that make an activity intrinsically motivating are challenge, curiosity, and fantasy (Malone, 1981). Not surprisingly, these are all common elements of games. Garris et al. (2002) propose an input-process-output game model that facilitates intrinsic motivation. The input is a combination of instructional content and game features. The features promote a game cycle of user judgments, user behavior, and system feedback in an iterative loop which, when successful, results in increased engagement, greater persistence of effort, and greater likelihood of achieving intended learning outcomes.

How Games Are Used for Instruction. Gredler (2004) states that the purposes of games and simulations in education are to practice or refine existing knowledge and skills, to identify gaps or

weaknesses in knowledge or skills, to develop new relationships among known concepts and principles, and to serve as a summation or review. These are consistent with reviews of the reported use of games, in which games were most frequently used to learn new skills and practice existing skills, generally after the learners had received some introductory instruction to prepare them for the game (Dempsey et al., 1993-1994; Dempsey et al., 1996). Options for integrating games into a curriculum include use as a pre-instructional strategy, a co-instructional strategy, and a post-instructional strategy (for assessment and synthesis) (Oblinger, 2006).

A review of the literature led Leemkuil et al. (2000) to conclude that there is some consensus that games and simulations will not be effective unless accompanied by instructional support, such as model progression, prompting, feedback (from the game/simulation or the instructor or peers), debriefing, and reflection. Gredler (2004) concurs that open-ended, discovery learning in a simulation is problematic. She recommends that students acquire required knowledge and capabilities (including metacognitive skills) prior to using a simulation. Research consistently concludes that students need some structure in order to learn in discovery-oriented simulations (Kirschner, Sweller, & Clark, 2006). Rieber (2005) recommends short explanations offered at the appropriate times within the simulation. He also suggests model progression in which the simulation becomes increasingly difficult based on the learner's mastery of required skills.

Research on Differentiated Instruction

The current "assembly-line" curriculum approach used by the American school system since the beginning of the industrial revolution was intended for preparing all students in much the same way; however, with the advent of the information revolution, this approach is just not working any longer (Reigeluth, 1994; Schrenko, 1994; Senge et al., 2000; Toffler, 1980). In response to the alarming decline of US students' achievement (National Commission on Excellence and Education, 1983), the American Psychological Association published 14 principles of effective learning, based on a synthesis of research on learning (APA, 1997).

Differentiated instruction is an approach to teaching and learning that focuses on learner individual differences. Hall et al. (2003) define differentiated instruction as "a process to teaching and learning for students of differing abilities in the same class. The intent of differentiating instruction is to maximize each student's growth and individual success by meeting each student where he or she is, and assisting in the learning process" (p. 2). Tomlinson (1999) suggests that teachers using differentiated instruction should take into consideration students' individual levels of readiness (entry point to a particular topic or skill), interest (student's curiosity or passion for the topic or skill) and learning profile (learning style, culture, gender, and intelligence preference as described by Gardner's (1999) multiple intelligences theory).

The problem is that, while differentiated instruction appears to be a good idea, it is impossible to make it work in practice—at least given the way current educational systems are organized. If a teacher is faced with 30 students, she or he cannot individualize instruction for each student. There is simply not enough time. For instruction to be truly individualized, there must be many more "teachers." To accomplish this requires a change of conception of what and who a teacher is. The possibilities are to bring in a lot more instructors, e.g., retired persons and student parents to help out, or to utilize the people we currently have in schools and to add better learning resources that serve as effective "teachers."

The main source of human capital we already do have are students in school, who themselves can become teachers—if the conditions are right to support this. This will not work if students are grouped homogeneously, as they largely are in today's lock-step grade-level system. Students will need to be grouped heterogeneously—otherwise they would be equally ignorant and could not help each other. Moreover, students would need to be supervised by the same adult teacher for multiple years, which means that classrooms would also have age heterogeneity as well as knowledge and skill heterogeneity. This also allows the adult teacher to get to know his or her students very well if she or he has them for several years in the classroom.

In addition to more knowledgeable peers who are accessible, the other source of instruction must be scientifically-validated, effective and proven curriculum resources that do the “teaching” by virtue of their design. These resources must embody First Principles of Instruction described below. This means, among other things, that control of error is built in to the activities themselves. If students are grouped heterogeneously, and stay with the same teacher for several years (e.g., ages 9-12) before moving on, then at any given time there are likely to be students in that classroom who have learned more advanced knowledge and skills, and who are in a position to help less advanced students when they need it—if given the opportunity and supervised by the adult teacher. What this means is that the adult teacher does less direct instruction herself or himself, only when necessary when nobody or nothing else can do it in the classroom. The adult teacher’s job shifts to become one of managing classroom learning resources for students to engage in, and to spend most of her or his time observing and monitoring student learning in order to decide what learning resources to add and take away from the classroom learning environment. In other words, teachers will need to do less instruction themselves in order to accomplish differentiated instruction. This means that much more instruction must come from the curriculum resources and from more advanced students (cf. Frick & Thompson, 2008). This also means much less group-paced instruction to the whole class; rather, students engage with such proven curriculum resources, learning from and through them—with few students actually doing the same thing at the same time. If heterogeneous groups are used, then if one student needs help and the adult teacher is not available, then that student can ask a more advanced peer to help. That activity of helping someone else learn what one has already learned himself is an example of integration (First Principle #5, described below).

This kind of organization is only possible when there is a sufficient pool of learning resources with proven effectiveness with the levels of students in that classroom. Such resources are *not* likely to be textbooks as they are now conceived, since they are not designed for differentiated instruction, but rather for instruction in largely homogeneous groups. In fact, each student often gets the same textbook in a classroom. To be effective, these learning resources will need to incorporate First Principles of Instruction, described below (cf. Frick, 2007).

Moreover, there must be sufficient room for storage of those curriculum resources which are physically removed from the classroom, since only a relatively small subset should be present in the classroom at any given time which are within those students’ current zones of proximal development (cf. Vygotsky, 1978). Such a system of learning may seem to be impossible, but it can and has been done successfully (cf. Lillard, 2005).

In summary, differentiated instruction is only possible if we change the current way instruction is conceived and carried out. The system must be designed differently in order for differentiated instruction to actually work. *SimEd-Math* should be able to model different systems and predict what happens under specific conditions. This is the real power of *SimEd-Math* and the value of the underlying Axiomatic Theories of Intentional Systems (Frick & Thompson, 2008; Thompson, 2005a,b). An important part of systemic change is the adoption of new mental models. Teachers who engage in *SimEd-Math* will develop a vision of what is possible and be better prepared to participate in the transformation of education systems from teacher-centered, time-based paradigm to a student-centered, achievement-based paradigm (Watson, Reigeluth, & Watson, 2008).

Research on First Principles of Instruction

First Principles of Instruction were synthesized from extant theories of instruction (Merrill, 2002; 2007; Merrill, Barclay, & Schaak 2008). One or more of these principles were observed to occur in all of these theories, although the names of these principles may differ. Merrill (2002) claimed that “there will be a decrement in learning and performance when a given instructional program or practice violates or fails to implement one or more of these first principles” (p. 44):

- 1) A series of simple-to-complex *real-world problems* (authentic whole tasks) in which students engage;
- 2) *Activation* of student learning so that students connect what is to be newly learned with what they already know or can do;

- 3) *Demonstration* of knowledge and/or skills that students are expected to learn;
- 4) *Application* of what students have newly learned, so they are able to try it out with instructor guidance and feedback as needed; and
- 5) *Integration* of what is newly learned for use in students' personal lives.

In a MAPSAT APT pattern analysis, Frick et al. (2007, in press) found that when students in 89 different college courses agreed that First Principles occurred *and* they also agreed that they experienced ALT, they were 9 times more likely to report mastery of course objectives, in contrast to when both were reported to be absent. Chadha, Frick, Watson, Zlatskovsky and Green (2008) are currently conducting an empirical study of college student ratings of use of First Principles in their classes, their perceived ALT, and their instructors' independent ratings of student mastery of course objectives. Preliminary results ($n=190$ students) indicate that when students agreed that their instructors used First Principles, those students were nearly 3 times as likely to agree that they experienced ALT in the course. Moreover, students who agreed that they experienced ALT were nearly 4 times as likely to be rated as *high masters* of course objectives by their instructors, compared with students who did *not* agree that they experienced ALT. Conversely, students who did *not* agree that they experienced ALT were about 8 times as likely to be rated as *low masters* of course objectives by their instructors, compared with students who did agree that they experienced ALT.

We believe that First Principles of Instruction hold considerable promise for measures of quality of learning activities in mathematics. We propose that each learning activity that goes into the *SimEd-Math* database will be rated according to its incorporation of First Principles. We plan to incorporate these ratings into the prediction algorithm described below.

How SimEd-Math is Expected to Work

Figure 2 below illustrates what the *SimEd-Math* user interface might look like. This is only a mock-up of an initial prototype interface—it does not work and is simply a graphic created with an image editor. Eventually, the working interface would need to be developed in order to interact with users and send information to the *SimEd-Math* inference engine and database. Nonetheless, Figure 2 shows the major components of *SimEd-Math*. Note also that we do *not* plan to develop an immersive, 3-D simulation (e.g., *Second Life*, many popular video games). Rather, what we plan to model are elements that teachers need to consider when selecting and planning instructional activities for students, not a virtual classroom that is 3-D interface typical of quests and adventure games that the user explores and navigates.

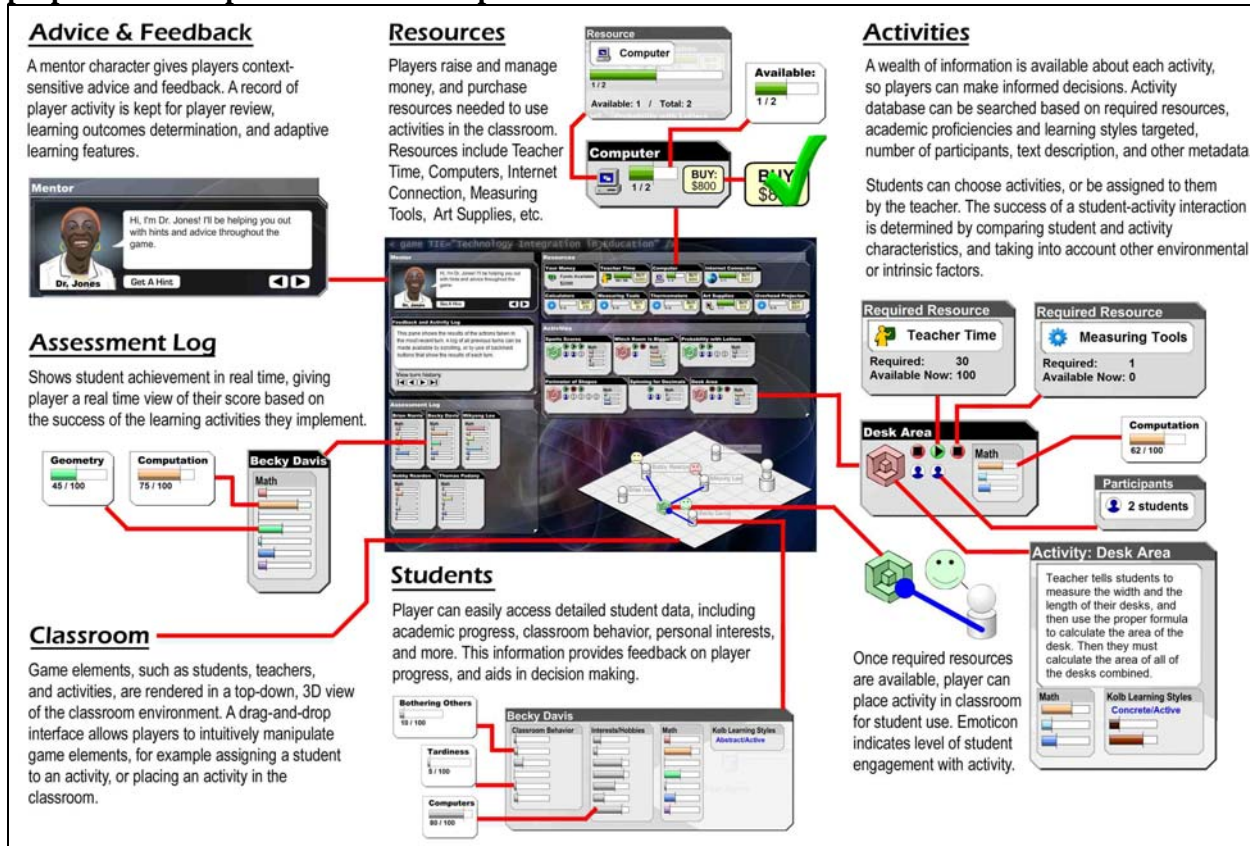
In the beginning of the simulation, the teacher will get 3-5 students that are selected at random (and in more advanced levels, the number of students increases). The goal of *SimEd-Math* is to advance each student as far as possible towards each mathematics standard during the allotted time for playing that round (a school “year”). Information will be available about each student, including his or her name, picture, background, hobbies and interests, learning style, etc. Each student also has an assessment log which shows where he or she is with respect to attainment of each area of mathematics (e.g., computation, geometry, etc.). There is a large pool of learning activities that a teacher can choose from. Each of these learning activities is color-coded as to which area(s) of mathematics is or are addressed. Additional requirements are also listed, such as whether it requires the teacher to lead the activity or not, how long it is likely to take, what additional resources or equipment is needed, etc.

The preservice teacher's challenge for each step of *SimEd-Math* is to try to identify the best learning activities for the simulated students she has in the classroom. The preservice teacher will need to determine the difficulty of the learning activity based on the students' profiles and assessment logs. An activity that is too easy or too hard for a given student is not likely to be successful; rather one in the student's zone of proximal development (ZPD, Vygotsky, 1978) will be needed.

Furthermore, the teacher must judge the quality of the learning activity with respect to its incorporation of First Principles of Instruction, and the extent to which it is a good match for the students' learning style. When the teacher has selected one or more activities for the students, then she “starts” the classroom by clicking a button, and the simulated students begin to do them (or not). A period of time elapses on the timeline, until one or more students are finished. When the classroom “pauses,” the

preservice teacher will learn the outcome of that activity with those students, to see whether there is any change in the students' assessment logs (i.e., has the level of attainment in math areas changed).

Figure 2. What the computer version of the *SimEd-Math* user interface might look like. The call-outs identify various interface components and functions. The software to run this game is what we propose to develop and evaluate with preservice teachers.



Whether a student successfully learns from the activity will be affected by a number of factors: whether or not the resources required are available (e.g., teacher time, technology needed, other supplies), the degree to which First Principles are incorporated in the activity, whether or not the activity is in the student's ZPD (i.e., fits appropriately in that student's learning trajectory), and how well the activity matches the student's learning style and interests. Fuzzy set theory is likely to be used as part of the *SimEd-Math* inference engine. In the *SimEd-Math* database, each activity will have been previously coded by experts according to its qualities, i.e., which of the First Principles are present or absent, level of difficulty with respect to where it fits in the curriculum map of attainments, learning styles it is compatible with, etc.). This information is hidden from the preservice teacher but does affect the outcome of the activity with respect to student engagement and degree of success. In addition, the activity will not work if teacher time is not available when required (because she or he is tied up with other students at that time, resources needed for the activity are not available at that time). A chance factor is also thrown into the mix that can affect the outcome, such as the student becomes ill or tired, technology needed is broken, students misbehave, fire drill, etc.). The preservice teacher will learn of the outcome in a feedback window, where a mentor describes what has happened. The mentor may give some hints or clues as to why the activity worked or did not work, and might also provide suggestions for the next activity (e.g., pick one that is a little easier, try to find an activity that is a good match to the students learning style and background, find one that will be more motivating, etc.). As the preservice teacher becomes more

proficient, this mentoring will be reduced to sustain the level of challenge and avoid the expertise reversal effect (Sweller, 2008).

In order to do well in *SimEd-Math*, a preservice teacher will need to figure out each student's learning style, qualities of each learning activity with respect to First Principles of Instruction, and that student's learning trajectory. These qualities will not be explicit but must be inferred from the activity descriptions, student profiles, assessment logs (of math skills and knowledge attained in each standards area), and results of activities (feedback from the mentor, hints and clues). Furthermore, a preservice teacher will be more successful in *SimEd-Math* to the extent to which instruction is differentiated (i.e., not all the students doing the same activity but different ones at the same time which are good matches to those students).

At some point in *SimEd-Math*, especially as the number of students increases, the preservice teacher will "hit the wall," where she cannot improve the learning outcomes, if she tries to make all the decisions for what each student will be learning at each moment, and if she continues to try to be the "sage on the stage." The only way to get past the "wall," will be to develop strategies similar to those described above on differentiating instruction—i.e., becoming less of a "sage on the stage" and more of a "guide on the side." Even then, if the learning activities available to students in her classroom are not well-chosen with respect to their qualities (lack First Principles, poor match to student's learning style and ZPD), the simulated students will not be successful.

The simulation is over after the end of the school "year." At that time, the preservice teacher finds out her overall assessment during an interview with the principal. Positive outcomes of that interview could include getting a raise in salary, hearing praise from student parents, satisfied students, etc. The preservice teacher will be able to repeat *SimEd-Math* as many times as desired, in order to get a higher score—i.e., by increasing student learning of mathematics in her simulated classroom.

We have not worked out all the details of *SimEd-Math* at this time, but the above description is generally what we have in mind. The details will be adjusted as we develop and test *SimEd-Math* prototypes and test them with preservice teachers, described below.

How is SimEd-Math Different from other Existing Simulations for Preservice Teachers?

We have identified a small number of simulations for pre-service teachers that are currently in use or under development. In general these simulations differ from *SimEd-Math* in their models and underlying theories, their focus and goals, and their interfaces.

aha! Classroom SIM. This simulation was developed as a companion to Dr. Ruby K. Payne's (2006) book *Working with Students: Discipline Strategies for the Classroom*. A free demo is available on the Web but must be downloaded and run locally. Its purpose is to provide pre-service and novice teachers with practice in applying Payne's discipline strategies (Oskorus, 2007). Students have interests and parents with various parenting styles. The user must identify disruptive events in the classroom and respond appropriately based on school and classroom rules. Feedback is provided through visits from the principal and in the form of graphs of the class's happiness, learning, and behavior.

Cook School District Simulation. Cook School District is a Web-based, text-based simulation designed to give pre-service teachers practice in "connecting teaching and learning" (Girod, Girod, & Denton, 2007, p. 208) by designing and implementing teacher work samples. The user designs the instruction by selecting elements for specific independent variables, which include test sequence, item type, curriculum area, instructional strategy, and domain and level. These choices affect the student's academic achievement and on-task behavior. The effectiveness of these choices is moderated by contextual variables which may be public (e.g. student's parent information, academic records, school activities, etc.) or private (a student's prescribed range of scores for each independent variable which are hidden from the user) (Girod, Girod, Hockett, & Gibson, n.d.). Algorithms are used to calculate results based on the weights for the independent variables and values for the contextual variables.

simClass. *SimClass* is a Web-based simulation developed at Korea National University of Education. The purpose is to provide practice in motivating students in the classroom (Cheong, Baek, & Kim, 2007). Students' motivational variables are based on Keller's ARCS model (Keller, 1987) and are represented by

their eyes, posture, facial expression, and text bubbles. The simulation is intended to be used as an exercise after traditional instruction and followed by review and discussion (Cheong, Baek, & Kim, 2007).

simSchool. SimSchool is a Web-based simulation that was developed with funding from the U.S. Department of Education's Preparing Tomorrow's Teachers to Use Technology (PT3) program. The primary purpose is to provide a safe environment for experimenting with teaching techniques that address different learning styles and for practicing managing student behavior (Gibson, 2007). The user assigns generic tasks to students and selects behavioral assertions that include "Get back to work now," "You're setting a good example for others," and "Go to the office" (simSchool, n.d.). The user monitors the student's graphs for Power, Happiness, and Academic Status and in the end views graphed results of the student's academic success and "mental state" factors, which are calculated based on the user's decisions and the student's personality, sensory preferences, and cognitive background. The student model is based on the Five Factor (or OCEAN) model with additional visual, auditory, and kinesthetic dimensions (Gibson, n.d.). The main difference between simSchool and *SimEd-Math* from a user's perspective is that the former has more of a focus on classroom management skills.

Teaching Literacy in a Virtual Kindergarten Classroom. A team of educators and researchers in Australia are developing a simulated kindergarten classroom intended to give pre-service teachers practice in teaching literacy and classroom management (Ferry et al., 2005). They cite the limited access to real classrooms and the inability of pre-service teachers to make links between theory and practice as reasons for developing the simulation. The simulation is currently more of a "walk-through" of scripted episodes based on the educators' experiences with some interactivity at key decision points (Ferry & Kervin, 2007; Kervin et al., 2005). A key goal of the simulation is to foster reflection about decisions through the use of a built-in tool that scaffolds the articulation of the user's understandings (Ferry and Kervin, 2007). Formative evaluation has so far consisted of several trials with education students. Results suggest that a classroom-based simulation is a feasible supplement to classroom-based experience and helps pre-service teachers develop awareness of the challenges they will encounter and to think in more detail about the decisions they will have to make as teachers (Ferry et al., 2005).

Research Questions

As a result of repeatedly playing *SimEd-Math*:

1. Do preservice teachers improve their ability to predict how well a given learning activity will work with a particular student, given knowledge of that student's prior mathematics knowledge, skill and learning style?
2. Are preservice teachers better able to select mathematics learning activities such that instruction is differentiated according to student individual differences?
3. Are preservice teachers better able to judge mathematics learning activities according to presence and absence of First Principles of Instruction?

Project Design, Development and Formative Evaluation Plan: Years 1 and 2

The first year will be focused on *SimEd-Math* simulation design, testing of paper prototypes, and initial software development. As a general design and development strategy, we will use an iterative rapid prototyping, user testing, and revision cycle. This is an efficient and effective development method (Frick, Su & An, 2005; Dumas & Redish, 1999; Nielsen, 2000; Snyder, 2003; Tripp & Bichelmeyer, 1990). This process consists of the following phases: a) needs assessment of stakeholders; b) rapid prototyping on paper and usability evaluation with target users to identify design problems and fix them; c) rapid prototyping on computer and further usability testing with target users to identify design problems and fix them; d) building the production version of the software system; e) maintenance and refinements of the system (Frick, Su & An, 2005, p. 21).

SimEd-Math simulation will rely on the Internet connectivity and Web browsers for users to access the simulation and its functions. This means that each user will have a username and password to login. Then users will interact with *SimEd-Math* through Web browser interfaces that we design and provide.

We plan to develop these interfaces in Flash ActionScript, Flex Builder, PHP, JavaScript, HTML and CSS. This will allow the Web interface to seem like an interactive application (e.g., e-mail, word processing) rather than a sequence of Web pages.

We have found it very useful to initially create paper prototypes and to conduct usability tests with the target audience (cf. Frick, Su & An, 2005). This actually speeds up the development process, by creating a rapid paper prototype initially. Although we have developed an early board version of SimTIE that shows promise with preservice teachers, that was focused on technology integration as a learning goal for the preservice teachers. In *SimEd-Math* the goal is to create a simulation of a classroom and the goal is mathematics instruction. Thus, we will need to create a new board version for the *SimEd-Math* simulation. We want to do this as rapidly as possible and get members of the target audience to do the simulation. What is critical in these play tests is to have users do authentic tasks in the simulation, listen to them think-aloud, and observe them without helping. Problems the users experience serve to identify parts of the simulation design that need to be fixed or completely redesigned. After several rounds of usability testing with individual preservice teachers (each round with 5 users typical of the target audience), we normally will resolve most problems and can then move on to developing computer prototypes. We also plan to have a small number of elementary school teachers to do the board version of the *SimEd-Math* simulation in order to get a sense of its fidelity with respect to actual elementary students they know and their experience in teaching mathematics to those students.

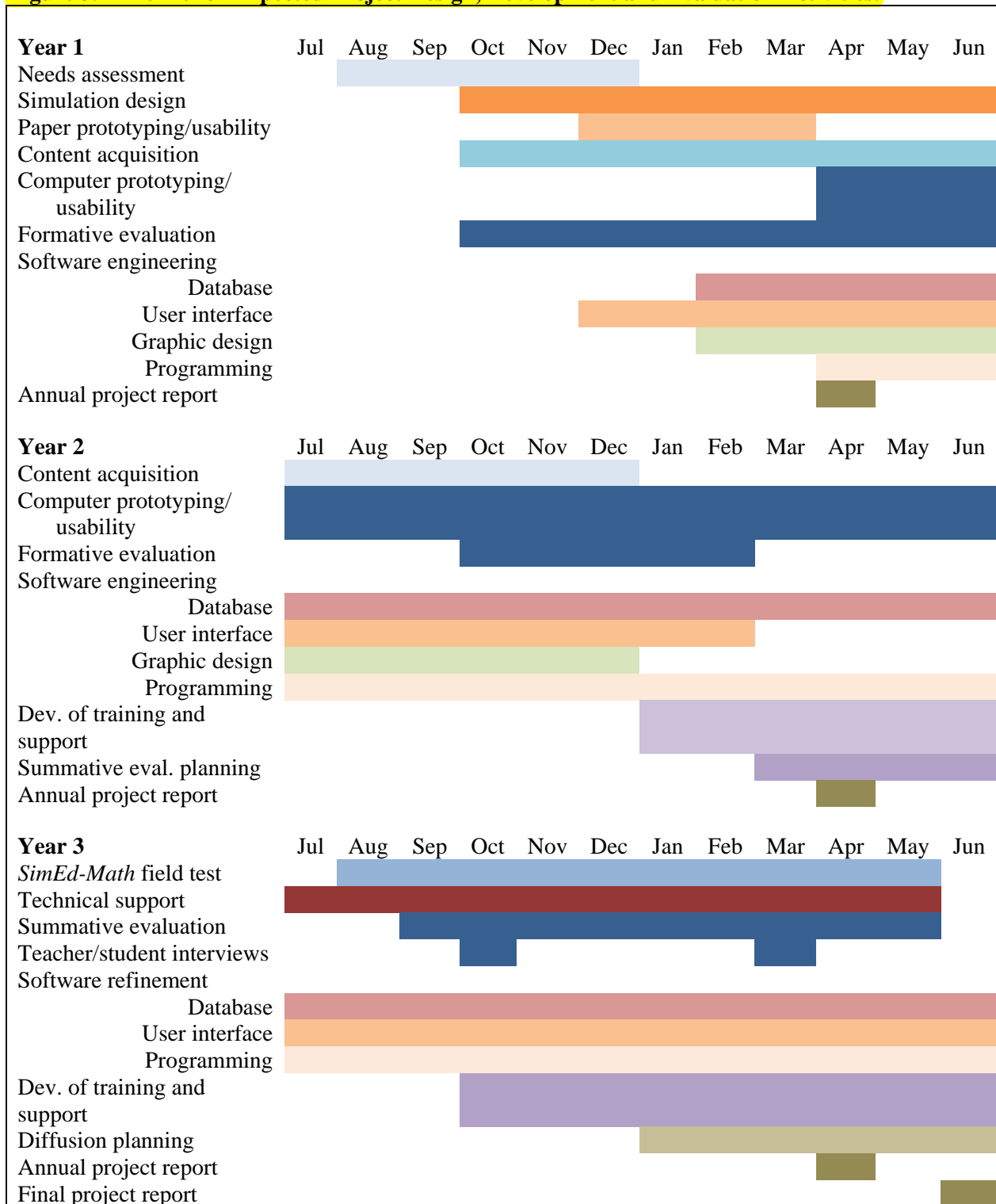
During the second year we plan to complete software development for the computer prototype and then to conduct several rounds of usability and play testing with preservice teachers. This will allow us to make improvements in the simulation design and the way in which the preservice teachers use the computer interfaces. We also will conduct usability and play tests with several elementary school teachers in the area to evaluate fidelity to real classrooms. Furthermore, we expect to have the simulation reviewed by several experts in mathematics education and preservice teacher preparation. These usability and play tests will occur in the VX Lab (Virtual eXperience Laboratory) in the School of Education at Indiana University. This lab is specially equipped with computers, video cameras, recorders, etc. for observing and evaluating games and simulations. We will not need to purchase any equipment for this project, since we will have access to the VX Lab. The Lab allows us to record video of user faces, audio of what they say, and their moves on the computer screen, which are automatically mixed into a master recording. The recorded session can then be played repeatedly for purpose of evaluation of how users perform and react to the simulation or game.

Summative Evaluation Plan: Year 3

During the third year, we plan to do a summative evaluation with preservice teachers in elementary education at Indiana University in the School of Education. We expect to do this in the context of E343, which is a methods class on teaching elementary school mathematics. This course will provide a good setting for conducting an evaluation study. There are typically 6-8 sections of E343 each semester, each with 20-30 students. This will allow us to randomly assign sections of E343 to those who play *SimEd-Math*, and to sections which serve as the control group. The control group is expected to spend similar amounts of time engaged in other simulations and games intended for learning, but not *SimEd-Math*. For all preservice teachers who play *SimEd-Math*, all their moves and outcomes of their moves will be recorded in the *SimEd-Math* database. We will administer a knowledge test of mathematics teaching which will be done via Web forms and data storage of student answers. This test will be given to both the *SimEd-Math* sections as well as the control group sections, near the beginning of the semester and again near the end.

Questions on this test will be used to answer Research Questions #1 and #3 stated above. For Research Question #1, test questions will present cases to the preservice teacher that describe a particular student and 4 different learning activities, and the teacher will be asked to predict what is likely to happen if each of those activities is used with that student. These kinds of cases will provide evidence of preservice teacher ability to make decisions about learning activities appropriate to students in elementary

Figure 3. Timeline for Expected Project Design, Development and Evaluation Activities.



mathematics. To address Research Question #3, preservice teachers will be presented with descriptions of learning activities in elementary mathematics. Each of those activities is rated on a 5-star scale, which corresponds to First Principles of Instruction. The task on the test will be to rate the activity with 0-5 stars, based on the presence and absence of First Principles. On the test they will not be told what First

Principles of Instruction are. We can then compare *SimEd-Math* preservice teachers with those in the control group with respect to their scores on these different item types. We would expect to find significant differences in favor of the *SimEd-Math* group and the control group on the posttest for Research Questions 1 and 3. Preservice teachers in the control group can do *SimEd-Math* at a later time.

Research Question 2 will be addressed by examining records of repeated plays of the *SimEd-Math* simulation. If the simulation is effective, the preservice teachers should improve their decision making with respect to differentiating instruction. In other words, they should do better in the simulation each time. By doing better, they will successfully *move more students further along towards achievement of mathematics learning objectives* in the same fixed period of time in the simulation (the “school year”). We will be able to answer this question by retrieving and replaying the simulation moves made by each preservice teacher during each play.

A longer term longitudinal evaluation of the *SimEd-Math* simulation is not possible in Year 3. We believe that it is realistically possible to develop, pilot test, and conduct a small field test of *SimEd-Math* in the 3-year time frame proposed here and the amount of funding available. See Figure 3 for a timeline of major project tasks and evaluation activities.

Qualifications of Key Personnel

Principal Investigator and Project Director: Theodore Frick. Dr. Frick most recently served as long-time Web Director for the Indiana University (IU) School of Education, where he designed, developed, evaluated and managed a complex, highly successful Website for the School of Education, supervising a staff of 28 content providers. He also provided leadership for the IU Bloomington campus in development of its Website. He has extensive experience in successful design and development of software for educators, most recently with online, interactive Web technologies (e.g., the *Diffusion Simulation Game* and *How to Recognize Plagiarism*). He has done seminal work on inventing algorithms for computerized classification tests (Frick, 1992). He is the creator of MAPSAT Analysis of Patterns in Time (APT: Frick, 1990), and has written computer algorithms for Analysis of Patterns in Configurations (APC: Thompson, 2008). He has been principal or co-principal investigator on numerous technology-related projects since 1976 with total funding of over \$3M.

Co-Principal Investigator: Enrique Galindo. Dr. Galindo is an experienced educator in elementary mathematics teacher education. He designed and developed the initial NCTM Website, and he has been co-principal investigator in a number of funded projects related to teacher education in the past 9 years.

Software Development. Rodney Myers, Ph.D. student at IU, has over 20 years of experience as a software engineer. He most recently worked at Santa Clara University in developing and implementing Web applications, database applications and information management systems to facilitate administrative decision making.

Special Facilities: VX Lab for Research and Evaluation of Computer Simulations and Games

The Virtual eXperience Lab is located in the Wright Education Building on the Bloomington campus of Indiana University. This state-of-the-art lab contains computers, video recorders, mixers, etc. for capturing user moves, voice and facial expressions during play-testing of e-learning computer simulations and games. This allows researchers to view a recording that shows the computer displays and user interactions with it, with a superimposed video image of the user’s face and audio recording of what the user said during the play-test session. In addition to the VX Lab for formative evaluation of computer prototypes during Years 1 and 2, the *SimEd-Math* software itself will capture and store all user computer moves and simulation states in its MySQL database for each user. This will allow further analysis of interaction patterns with MAPSAT software developed by the principal investigator (Map & Analysis Patterns & Structures Across Time) as part of the evaluation. During Year 3, preservice teachers will use the *SimEd-Math* simulations on any convenient computers that are connected to the Internet, which will also allow capture of their computer moves that will be stored for analysis of usage patterns.

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