# Leveraging Handhelds to Increase Student Learning: Engaging Middle School Students with the Mathematics of Change

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**Abstract:** Handheld computers are poised to build upon the success of graphing calculators in mathematics classrooms, as they share important characteristics such as small size and low cost, while increasing representational richness. However, few studies provide evidence that these devices can help students learn complex mathematics. In this paper we provide such evidence. We show that the communication capabilities and representational infrastructure of handheld computers can support a variety of effective learning activities, ranging from activities that are collaborative to activities that are practice-oriented. Furthermore, we show that eighth grade students who participated in a month-long curriculum using our handheld technologies outperformed high school students on AP Calculus Exam items.

## Introduction

Graphing calculators have had a profound influence on mathematics education (Burrill et al., 2002; Doerr & Zangor, 2000), as evidenced by the NCTM's principle that technology (typically in the form of graphing calculators) is "essential" to teaching and learning mathematics (NCTM, 2000). Handheld computers are poised to build upon the success of graphing calculators, as they share many important characteristics—both are small, inexpensive, portable, boot-up immediately, and enable rich interactive representations. These characteristics allow frequent, integral use of technology in the math classroom, which can lead to increased student learning (Burrill et al., 2002; Norris & Soloway, 2003; Tatar et al. 2003; Tinker & Krajcik, 2001; Vahey & Crawford, 2002). However, much existing use of handhelds in math is for supporting calculations, and few studies provide evidence that handheld computers can be used to help students learn complex and conceptually difficult mathematics.

To investigate the potential of handhelds in education we built upon an already proven educational intervention, SimCalc (Roschelle, et al., 2000), in the creation of *NetCalc*. In this paper we discuss (1) how we leveraged affordances of handheld computers in the creation of NetCalc learning activities, (2) aspects of these activities we found to be most productive, and (3) evidence that student use of NetCalc led to students learning complex mathematics. Among other things, we set out to investigate the following: Are dynamic mathematical representations still powerful when translated to a small screen and stylus-based interaction? Are there collaborative mathematical activities that addresses NCTM standards and can be supported with peer-to-peer beaming?

## Related Research: Collaboration and Representations

There is a significant research base on designing external representations to support side-by-side student collaboration in the areas of mathematics and science learning (e.g. White, 1993; Roschelle, 1992; Vahey, et al., 2000). White, in particular, compared the achievement of middle school students to norm-referenced measures of high school achievement as a way to show proof of concept of effectiveness. We will build on this precedent.

The paradigm for much prior CSCL research is students sharing a relatively large display, jointly manipulating the available representations, and engaging in collaborative sense making. This research shows that the primary value of representations is not to embody experts' knowledge so that students absorb the experts' mental models, but instead to provide a resource for discussion and sense making as students come to understand the conceptual meaning underlying the representations (Roschelle, 1996). Effective learning activities leverage resources such as the shared screen, gestures, and conversational norms to help students jointly construct meaning, become more proficient in participating in representation-based discourse, and build an understanding of the subject matter (Roschelle, 1992). In this paradigm students are provided little opportunity to privately interact with the educational environment.

Related research investigates representation use with traditional graphing calculators. This research shows that calculator-based whole-class activities are more productive than small group activities (Doerr & Zangor, 2000). While engaged in whole class discussions the teacher's calculator is typically projected to the front of the room, and students can either watch the projection, or follow the teacher's instructions for pressing keys. In more recent efforts, the whole-class display is tied to a central server that networks all the students' calculators, displaying either an individual student's work, or an aggregation of student work (Kaput & Hegedus 2002; Wilensky & Stroup, 2000). While this research combines private work and whole-class activities, the small, low-resolution screen and the lack of peer-to-peer communication of graphing calculators can be a challenge for small group collaboration.

In our investigation we sought to exploit the unique capabilities of handheld computers while leveraging findings from prior research. For instance, to leverage the small, private displays and the beaming capabilities of handhelds, while also allowing students to take advantage of aspects of face-to-face communication (such as talk and gestures) we created a set of "information hiding" activities. We also created a set of "practice" activities that allowed students to privately work on difficult problems, with the ability to send their responses to a partner for face-to-face grading and feedback. This flexibility in creating activity structures that combine private work with face-to-face collaboration was a key aspect of our innovation, and is a key differentiator between handheld computers and previous technologies. We sought to determine if leveraging this flexibility could provide students the opportunity to learn complex and conceptual difficult mathematics.

## Prior SimCalc Research

As detailed elsewhere (Kaput, 1994; Kaput & Roschelle, 1998; Roschelle et al., 2000), the goal of SimCalc is to provide access to the mathematics of change and variation (MCV) to all students. Although understanding change is of critical importance for a variety of economic, social, scientific, and technological issues, only a small percentage of students are introduced to MCV. This introduction typically is in calculus class, where students tend to master symbol manipulation without coming to a deep understanding of the topic (Tucker, 1990).

To achieve its goal, SimCalc builds on three lines of innovation: restructuring the subject matter; grounding mathematical experience in students' existing understandings; and providing dynamic representations. In this study we built upon the following SimCalc principles within the constraints and affordances provided by handheld computers, to help eighth grade students learn the fundamentals of MCV in the context of a unit on algebra:

Student definition and direct manipulation of *graphically defined* functions, especially piecewise-defined functions. Students can manipulate these functions without ever seeing the algebraic description, which might be quite complex.

Links between the graphically defined and editable functions and their derivatives or integrals. For example, as students manipulate a velocity graph, they can see the impact on the corresponding position graph (or vice-versa).

Links between graphical representations and motion simulations. This relationship aids student in interpreting the graphs, as the mathematics is *about something*.

## The Design of NetCalc

We undertook a multi-year design experiment to create NetCalc. NetCalc was not intended to be a stripped-down version of desktop SimCalc—instead we designed a new set of applications and activities based on the principles (and lessons) of SimCalc. This work took place in parallel with the creation of a graphing-calculator version of SimCalc for other classrooms (Kaput & Hegedus, 2002). This paper does not discuss the iterative design issues surrounding the creation of NetCalc (interested readers should see Tatar et al, in submission). During this design research we found that the interactive representational forms of SimCalc, which were designed for large displays and included rich, detailed graphics, could be modified to be instructionally effective on small, personal learning devices. We then focused on the most appropriate way to leverage the communicative and representational flexibility of handheld computers in creating the NetCalc activities.

The NetCalc curriculum and technology was co-developed by the research team, the software development team, a retired teacher, and the classroom teacher. We focused on the following content:

Reinforcing existing understandings of position graphs, and especially the notion that the slope of a position graph represents the velocity of the motion

Understanding characteristics of velocity graphs with constant velocities, including forward, backward and stopped motions

Translating between position and velocity graphs (the essence of the concept of derivative)

Computing the area under a velocity graph to get displacement (the essence of integration)

Understanding characteristics of non-constant linear velocity graphs and the resulting parabolic position graphs

Table 1 provides an overview of a subset of our technology-based activities. Each activity lets students participate in specific mathematical processes while learning particular content. We chose to create a variety of activities to allow students to participate in a range of important mathematical practices. The activities in Table 1 represent our decision to provide enough variety to shed insight into the range of activities that could be supported by handheld computers, while not overwhelming the students.

Table 1. NetCalc learning activities

| **Activity Name** | **Type** | **Student Exposure** | **Primary Process Goal** | **Content Goals** |
|---|---|---|---|---|
| *Exciting Sack Race* | Expressive | 2 class periods:<br>30 minutes<br>15 minutes | Reasoning | *Class 1*: Characteristics of position graphs.<br>*Class 2*: Characteristics of velocity graphs, including backward and stopped motions. |
| *Summary:* Students make a two-car race that ends in a tie and is as exciting as possible, with a corresponding narrative (See Hegedus & Kaput, 2002). | | | | |
| Match My Graph | Hidden information | 3 class periods, of 30 minutes each. | Communication | *Class 1*: Characteristics of position graphs.<br>*Class 2*: Characteristics of velocity graphs.<br>*Class 3*:Translating between position and velocity graphs |
| *Summary:* Working in pairs, one student (the grapher) creates a function that is hidden from the other (the matcher). The matcher makes and beams an initial guess of the function, and receives a verbal clue from the grapher. The matcher makes more refined guesses based on the clues. In this activity students struggle to create and interpret clues such as “Mine is steeper” and “Yours is not as fast.” In the first instance of this activity the grapher and matcher both had position graphs, and the grapher received the matcher’s position graph and motion (see Figure 1). In the second instance the grapher and matcher both had velocity graphs, and the grapher only received the motion (not the graph). In the third instance, the grapher had a position graph and the matcher had a velocity graph, and the grapher received both the motion and the graph. | | | | |
| **Slot Machine** | Incentivized practice | 3 class periods:<br>40 minutes<br>30 minutes<br>20 minutes | Representation | *Class 1*: Relationship between simple position and velocity graphs.<br>*Class 2*: Relationship between complex position and velocity graphs.<br>*Class 3*: Relationship between position graphs and non-constant linear velocity graphs. |
| *Summary:* Students working individually are presented with a position graph, a velocity graph, and an animation. They determine which, if any, of these representations describe the same motion, and click the corresponding set of checkboxes (the representations and checkboxes are color coded, and a white checkbox indicates no match). Students can have the computer check their answers and provide feedback, or can exchange problems with a partner, who “grades” the other’s work. Students receive points for getting their individual problem correct, for grading the partner’s work correctly, and receive bonus points for correctly answering and grading five problems in a row. Students can complete many problems in rapid succession, allowing for significant practice in building their representational competency. See Figure 1. | | | | |
| **Aggregation** | Aggregation | 2 class periods, 15 minutes each | Reasoning | *Class 1*: Understanding characteristics of velocity graphs<br>*Class 2*: Understanding characteristics of non-constant linear velocity graphs. |
| *Summary:* Each student is responsible for creating one part of a function family, and the students investigate the resulting pattern. (See Kaput & Hegedus, 2002). | | | | |

The “Exciting Sack Race” and Aggregation have already been reported on (Hegedus & Kaput, 2002; Kaput & Hegedus, 2002; Roschelle et al. 2003) and will not be discussed here. In this paper we will analyze the two activities that NetCalc students had the most exposure to: Match-My-Graph and Slot Machine. Example screen shots of these activities are found in Figure 1.

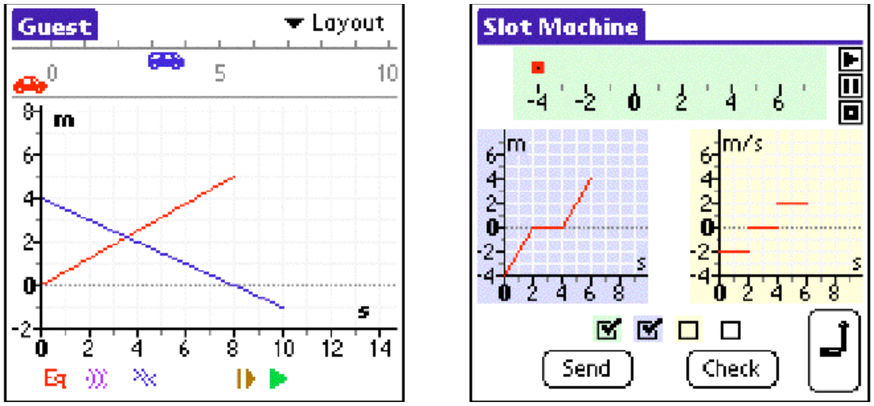


Figure 1. Screen shots of Match My Graph (left) and Slot Machine (right)

Although the focus of this paper is a set of technology-based activities, we stress that paper-based activities played an important role in our classroom. The classroom teacher wanted students to be able to apply what they learned with technology to paper-based situations (such as high-stakes assessments) and often assigned paper-based homework that reinforced the technology-based activities. She also preferred that student work be handed in on paper, because she considered that easier to grade and hand back. Fortunately, we found that this did not interfere with our activities. In fact, we found that the use of handheld technology allowed a natural shift between technology- and paper-based activities, and students could easily move between different tasks and technologies.

## Participants and Context

This study took place in an affluent suburb in the San Francisco Bay Area. We developed a one-month curriculum for an advanced eighth grade mathematics class with 25 students (16 male, 9 female; 1 African-American, 4 Asian-American, 20 Caucasian). We report on our last instantiation of this curriculum, which took place in March 2003. The school used block scheduling, and math class met every other day. The NetCalc curriculum consisted of nine 90-minute periods over the course of a month, with two additional days for testing.

The classroom teacher in this study preferred small group work over other activity structures, occasionally punctuating the small group work with short teacher-led discussions (typically of less than 10 minutes). During group work, the teacher typically walked around the class and answer individual students’ questions. Although this teacher was technologically advanced (for example, she taught digital video as an after-school activity), had six computers in her classroom, and had access to the school’s computer lab, she rarely used graphing calculators or computers in her mathematics classes. When given the choice of collecting student work electronically (via either a handheld computer or laptop) or on paper, she chose paper for ease of grading and redistribution. In short, while a technology proponent in many ways, she has found that traditional technology does not meet her needs as a mathematics teacher.

This site, with advanced students and a reform-oriented teacher, was chosen for three reasons. The first was to address a criticism of prior SimCalc work. While SimCalc has demonstrated impressive gains while working with some of the most disadvantaged students in Massachusetts and New Jersey, these gains need not be attributed to SimCalc, but to the fact that students are getting more attention than is normal in their school, thus boosting performance. This study strengthens prior SimCalc work by investigating the effectiveness of SimCalc’s representational affordances for high-performing students learning conceptually difficult topics. The second was to provide a sister site with a significantly different population of students than the graphing calculator study that was occurring in parallel with disadvantaged students in Massachusetts (Hegedus and Kaput, 2003), which also reported strong learning gains. The third was to provide a testbed that allowed us to easily introduce new collaborative structures. To investigate the potential of handheld computers in supporting a wide range of collaborative activity structures, we chose to enlist students and a teacher who were already accustomed to collaboration. This allowed us to focus on how well handheld computers fit into the range of activities used in a collaborative classroom, instead of focusing on how to transform classroom practice to be more collaborative.

## Methodology

Three or more members of the research team observed all class sessions. Research team members did not participate in the instruction, although they were available to help with technical glitches. Two members of the research team each videotaped a *focus* table during small group work, and each of the two focus tables consisted of four students, typically working in pairs. During whole class discussions each of the two cameras captured half of the class. Extensive classroom field notes, transcriptions of select portions of the videotapes, debriefing interviews with the teacher after each class, pre- and post-test results, log files generated by NetCalc, and planning sessions with the teacher and research team constitute the data used for this study.

In this study we set out to ask: can the representational and communicative capabilities of handheld computers provide students with an opportunity to master complex and conceptual difficult mathematics? Three related analysis will provide insight into this question:

*Students' content learning*, as measured by our pre- post-test results. Pre- and post-test items consist of a set of previously administered SimCalc items and a set of slightly modified Calculus AP exam items. The AP exam items were modified to use language familiar to the students (e.g., when necessary "velocity" was substituted for "f'", and graphs that crossed the y-axis were translated so as to not invoke negative time).

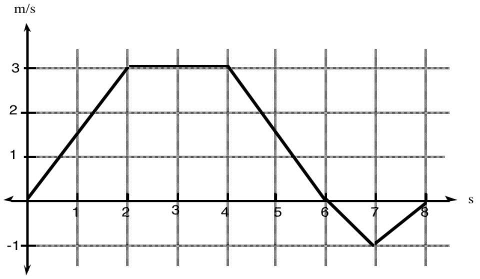
*Students' mathematical communication*, as measured by the quantity and content of hints provided in Match-My-Graph. To determine the quantity and content of hints, the videotapes from the two focus tables were transcribed for all three "Match" activities. All hints (defined as statements by the grapher that had the apparent intent of providing information to the matcher for the next hint) were excerpted from the transcripts and entered sequentially into a file. The hints were then coded for content, as described in Table 2. The first author coded all hints, and another member of the research team coded a subset of hints from all "Match" activities, achieving an inter-rater reliability of 86%.

*Students' translating between representations*, as measured by their performance in Slot Machine. Slot Machine log files were used to generate a summary of student activity, including the number of attempted problems and the number of correct responses.

## Results

### Students' Content Learning: Pre- and Post-test Results

All twenty-five students took the pre-test and post-test. Out of a total of 33 points, students on the pre-test averaged a score of 9.3 (SD = 4.0), and on the post-test averaged a score of 22.7 (SD = 2.8). This improvement is statistically significant ($t(24) = 16.11$; $p < .0001$), and shows that students did increase their proficiency in MCV during the NetCalc curriculum. Furthermore, the NetCalc students performed well on AP Calculus items when compared to published figures on high school students taking the AP exam: Figure 2 shows two slightly modified AP exam items administered to NetCalc students. We expected these items to be especially challenging for NetCalc students, as they were worded in a more formal manner than most NetCalc materials, and addressed non-constant velocity, a difficult topic covered only late in the NetCalc curriculum. Figure 3 shows those NetCalc students made large gains from pre- to post-test, and outperformed high school students taking the AP exam (The College Board, 1999). We note that students who take the AP Calculus exam are self-selected high mathematics achievers; to have even high-achieving eighth grade students outperform this elite group is no small feat. We next look at two activities that may have led to these gains.



A bug begins to crawl up a vertical wire at time *s* = 0. The velocity *v* of the bug at time *s*, $0 \le s \le 8$, is given by the function whose graph is shown above.

**1.** At what value of *s* does the bug change direction?

(A) 2 (B) 4 (C) 6 (D) 7 (E) 8

**2.** What is the total distance the bug traveled from *s* = 0 to s = 8?

(A) 14 (B) 13 (C) 11 (D) 8 (E) 6

Figure 2. Modified AP Exam Question (the only modifications were to maintain consistency with NetCalc terminology: time is denoted by *s* instead of *t*, and the y-axis label is *m/s* instead of *v*).

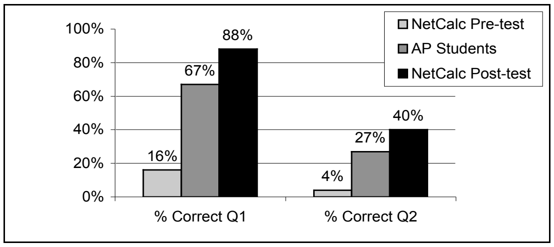


Figure 3. NetCalc student performance compared to AP High School student performance on items in Figure 1 (AP Results from The College Board, 1999).

### Students' Mathematical Communication: Hints in Match My Graph (Information Hiding Activity)

Classroom observations suggest that students in "Match" were engaged, on topic, and provided mathematically appropriate hints. An indicator of this engagement was the rate at which students provided hints. Averaging over all three "Match" activities for all videotaped pairs, hints were delivered at a rate of 1 per minute. Previously reported results confirm that students were actively engaged in this activity, as over 90% of student utterances were on topic (Tatar et al., 2003). While student engagement is important, the content of hints (defined in Table 2) is important to our argument that this activity addressed the NCTM "Communication" standard. Table 3 shows that in the first Match activity, in which the matcher and grapher both had access to position graphs, the hints were predominantly related to the graphical representation. In the second and third match activities, where the grapher and matcher had access to different representations, the hints were predominantly related to the simulation. That is, the student's mathematical communication reflected the mathematical content of their displays.

Table 2. Codes used for hints in Match My Graph

| Code | Description | Examples |
|---|---|---|
| Graph | Refers to aspects of the graph, such as slope or steepness on a position graph, height on a velocity graph, or a point on the graph | "Your graph is too steep"<br>"Your line stops above mine" |
| Simulation | Refers to aspects of the simulation, such as the speed or direction of the motion or the distance traveled. | "You're going too fast"<br>"I go farther than you" |
| Graph/Sim | Ambiguous in referring to the graph or simulation, typically referring to distance in a shorthand manner | "Yours is less meters" |
| No Math | A statement without any explicit mathematical content, typically used when a student is closing in on the solution | "You are close"<br>"Still wrong" |

Table 3. Types of hint used in each activity

| Match Activity | Graph | Simulation | Graph/Sim | No Math |
|---|---|---|---|---|
| Both Position | 59 | 0 | 3 | 4 |
| Velocity/motion only | 3 | 78 | 0 | 7 |
| Velocity/Position | 3 | 45 | 5 | 4 |

### Students' Translating Between Representations: Problems Solved in Slot Machine (Practice Activity)

Slot Machine was created as a reaction to our teacher's observation that in the first years of the study NetCalc students seemed to make simple mistakes that could be attributed to a lack of practice with the representations. Slot Machine was designed to provide students with practice in translating between position graphs, velocity graphs, and motion. Classroom observations suggest that participation in Slot Machine resulted in significantly less discussion than during Match My Graph, and students were engaged privately during much of this time. On average each student solved more than 20 problems in a session, with 72% of problems answered correctly (each problem had five possible answers). These results indicate that Slot Machine problems were at a level of difficulty that was appropriate for these students, without reaching a ceiling or floor effect. A closer look at student performance, found in Table 4, indicates that the third activity was harder than the previous slot machine activities. We believe this is due to the more complex content in the third activity. While in the first two activities students practiced with motions described by constant velocities, the third activity mixed constant and non-constant velocities, which our prior research suggests presents a significant challenge. This practice may have prepared students for the AP items discussed earlier (but we do not have a research design that allows us to infer causality). Based on this evidence, we conclude that students were engaged in the Slot Machine activity, and were given significant opportunity to practice the challenging and assessment-relevant skill.

Table 4. Problems attempted and solved in Slot Machine

| Slot Machine Activity | Attempted | Correct | Percent correct |
|---|---|---|---|
| Activity 1: Simple Position and Velocity* | 120 | 87 | 73% |
| Activity 2: Complex Position and Velocity | 502 | 400 | 79% |
| Activity 3: Linear Velocity | 545 | 356 | 65% |
| **Overall Performance** | **1167** | **843** | **72%** |

*Due to technical difficulties, over half the entries were not logged for Activity 1

## Conclusions and Discussion

This study provides evidence that handheld computers can be used to increase student learning of complex and conceptual difficult mathematics, allowing eighth grade students to become proficient in concepts typically only found in a high school Calculus class. Thus we showed that the learning gains due to dynamic representation can be retained despite a move from expensive, large devices to inexpensive small ones. Furthermore, we have identified a form of small group collaboration that can productively leverage the capabilities of these devices. Through Match My Graph we demonstrated that the small screen and built in peer-to-peer beaming allowed the creation of “information hiding” activities that engaged students in addressing the “Communication” standard. While information hiding is common in everyday games (such as Battleship, MasterMind, and card games), it is surprisingly rare with traditional classroom technologies (but see “Monsters, Mondrian, and Me”, NRC, 1999). Possible reasons are that the large screen of traditional desktop computers makes this interaction cumbersome (for instance, it is easy for someone to see the “private” screen), and neither the at-a-distance nature of web collaborations nor the stand-alone nature of traditional graphing calculators are amenable to face-to-face classroom conversation. We also demonstrated that handheld computers could be used to create variations across the same basic activity structure, shown with Match-My-Graph. Reusing an activity structure with increasingly difficult content is one technique to focus cognitive load on the content learning and not the activity structure. Finally, we demonstrated that handheld computers can support a wide range of activity structures, from the communication intensive “Match” to the practice-oriented Slot Machine.

While our research suggests that handheld computers and beaming are promising innovations for the mathematics classroom, much work still needs to be done before we can expect handhelds to have a widespread impact. A variety of requirements must be fulfilled before an innovation scales up, including providing full curricular materials (see Curtis, et al., 2003), designing for local adaptability (Fishman, 2002), and aligning curricular goals with assessments (Shephard, 2000). We also emphasize that we do not consider our preliminary work to be the only approach that can lead to successful student learning of more complex and conceptually challenging mathematics. Other approaches to employing this new generation of low-cost, portable, networked technologies also have great potential (e.g. Colella et al, 1998; Hegedus & Kaput, 2003; Wilensky & Stroup, 2000), and research is required to determine the relative merits of each approach.

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