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ABSTRACT

This paper looks at the analysis leading to and design of a Web-based "hint system." The hints are designed to help middle-grade teachers participating in a mathematics professional development effort, called InterMath, achieve a high degree of success when working open-ended mathematical investigations. The model upon which InterMath is based assumes that teachers who experience learning in a rich, exploration-based environment will more readily transfer these kinds of experiences to their classrooms. The centerpiece of the InterMath experience and Web site is an extensive set of open-ended mathematical investigations that can be explored using various technologies. These investigations form the central experience of the 15-week workshop as teachers are encouraged to explore a particular set of explorations, choose problems that intrigue them, work those investigations, and write-up the solutions, along with extensive activities. The paper discusses the issues and processes involved with designing this system, paying special attention to the different types of hints and the limitations of the system. It concludes that the use of a Web-based hints system is a potentially valuable tool for supporting teachers in tackling complex math problems, that there are limitations with this plan, but the just-in-time help of a static system can be combined with the asynchronous support of a wider community as a viable option for promoting the development of mathematical thinking. (Contains 19 references.) (Author/AEF)

Developing a Scaffolding System to Support Mathematical Investigations

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Abstract

This paper looks at the analysis leading to and design of a Web-based "hint system." The hints are designed to help middle-grades teachers participating in a mathematics professional development effort called InterMath achieve a high degree of success when working open-ended mathematical investigations. We discuss the issues and processes involved with designing this system, paying special attention to the different types of hints and the limitations of the system.

Background

InterMath (http://www.intermath-uga.gatech.edu) is a web-based, technology-intensive professional development experience for middle school mathematics teachers. The professional development effort is aimed at furthering teachers' mathematics knowledge, providing experience with using a variety of tools to promote learning, and supporting meaningful technology integration for middle school mathematics classrooms. The model upon which InterMath is based assumes that teachers who experience learning in a rich, exploration-based environment will more readily transfer these kinds of experiences to their classrooms. The centerpiece of the InterMath experience and website is an extensive set of open-ended mathematical investigations that can be explored using various technologies (e.g., Excel or Geometer's Sketchpad). These investigations form the central experience of the fifteen-week workshop as teachers are encouraged to explore a particular set of explorations (e.g., triangles or functions), choose problems that intrigue them, work those investigations, and write-up the solutions, along with extension activities.

Unlike the traditional "make and take" professional development experiences, InterMath does not aim to provide teachers with activities they can take back to their classroom and use. Instead, InterMath provides teachers with opportunities to hone their mathematics skills, reinforcing both their understanding of mathematics and their ideas about what it means to learn (and, thus, teach) mathematics.

InterMath is in its third year of development and implementation. During the pilot workshop offerings in Year 2, there were two InterMath workshops conducted by two different faculty members. One workshop was offered near Atlanta as the first course in a cohort-based graduate degree program for middle school teachers. This workshop was taught by a mathematics education professor who is also one of the developers of the InterMath program. The other workshop was offered at the University of Georgia campus by a professor of mathematics. The participants in the UGA workshop received staff development credits for their experience, as well as a stipend.

The Problem

Our initial work with teachers indicated that one of the challenges of InterMath is that the teachers are uncomfortable engaging in problems that they do not feel confident in their ability to finish. The teachers tend to work the easier problems first – and may not ever work the problems they perceive as being the most challenging. However, those challenging problems may be the ones that provide the greatest learning experience. Our interviews with teachers and classroom interactions indicated that there were multiple reasons for these problem selection behaviors. The most troubling reason, however, was an avoidance of mathematics that was viewed as difficult.

To further complicate the situation, teachers in our pilot workshops were considerably more challenged by the variety and uses of technology required for success in the workshop than we had anticipated. We expected teachers to be able, by the end of the workshop, to use Geometer's Sketchpad, NuCalc, and Excel, as well as to be able to create and publish a webpage using a WYSIWYG editor and FTP software. While most of the teachers had already completed a basic technology workshop series, they had little to no experience using technology to support learning in a particular content area. Further, many had little hands-on experience in using the computers with their

students to support mathematics of any kind. In short, InterMath requires teachers to be comfortable with many pieces of technology, as well as to develop a concrete image of what technology can help them accomplish in their content area.

It was determined that these problems were serious enough to warrant additional support structures being created to support teachers in successfully expanding their own content knowledge as well as their pedagogical content knowledge. To this end, it was decided that some form of online help or hint system needed to be developed for the InterMath problem set that would allow teachers to be more successful in their interactions with our materials.

This paper describes the design process to date and discusses the implications of our analysis phase on the kind of hint systems we are working on. To date, we have completed the analysis system and have implemented a rapid prototyping (Tripp & Bichelmeyer, 1990) approach to help explore the potential of each option. Further, we have completed an initial paper-based design of the "constructopedia," a separate aspect of the InterMath scaffolding system that will be discussed later in this paper

An Analysis of the Problem

The analysis portion of the hint system project occurred during Winter and Spring 2001. Data were collected in the form of conversations – both live and via email – with a variety of subject-matter experts who are participants in the InterMath project, as well as observations and informal interviews of teachers involved in the pilot workshop. The discussions among team members were a rich source of data for thinking about what we value in the learning process and what matters in how we interact with the learners.

Learner Analysis

Information was collected during each InterMath session through both formal and informal means. InterMath instructors and facilitators informally observed activities and comments while teaching and while circulating to check on participants' progress and to provide them with technological and mathematical assistance when needed. Formally, at least one person was designated as the class observer each session and took detailed notes regarding events that occurred in class, including participants' actions, comments, technical problems, successes, and mathematical difficulties. In addition, many participants were interviewed at the conclusion of the workshops. The informal and formal observations, along with transcripts of the interviews, provided a wealth of information regarding the difficulties the workshop participants had experienced and how the InterMath experience could be changed to better benefit teachers in future InterMath workshops.

As anticipated, an analysis of the data provided much insight into the InterMath experience from the perspective of the teachers enrolled in the class. While every participant said that he or she would recommend or have already recommended InterMath to other teachers, their comments provided valuable information about problems they experienced during the course. Some teachers noted how time-consuming problems can be and how many problems on the InterMath website cannot be used with their classes without modifications. However, two other issues were mentioned repeatedly as the predominate difficulties teachers faced in the workshop – difficulties with the technologies being used and problems with the mathematics itself. This paper addresses the second of these two issues.

A number of the participants expressed frustration over the difficulty of many InterMath problem sets. Some of the participants noted that they do not have strong backgrounds in mathematics, while others described the mathematical rustiness that has occurred while teaching middle grades math.

> *"There's some of the math that, right now, I don't think I have down pat."*
>
> *"I don't have a very strong math background, so I struggle with a lot of the problems.... I mean it's been a long time since I've been in a math class. I know this is a graduate class, but I've only been teaching 7th grade math and there's only so much that we do – so the vocabulary and all is unfamiliar to me."*
>
> *"A few of them it's going to take some brushing up on – because as a 7th grade teacher, there are a few things that we don't hit in 7th grade."*
>
> *"That's the hardest part. Sort of bringing out the true math that's behind it. Because I don't know if I know enough to do it."*

Many participants noted in their interviews how helpful the assistance from course facilitators was when technological or mathematical impasses were experienced.

"Brian and Shannon have been wonderful. They've talked me through so many [problems]."

"I think the very best part is probably the instructors – the people that are helping out.... Because they're so understanding and they don't act like you're stupid when you don't know how to do something."

These comments alone give sufficient cause to consider creating some type of mathematical scaffolding system for the InterMath workshop InterMath workshop, as InterMath personnel are not always on hand when the teachers are working on their problem sets.

In describing how their ideal math classrooms would operate and how they believe students learn, some teachers revealed the importance they place on scaffolding their own students, further prompting InterMath designers to consider the implementation of a hint system.

"I can steer them and give them hints. And it also helps if they're going in a completely wrong direction. I can hear that too and steer them the right way."

"I teach 6th grade – so some are way over their heads and some are more appropriate. So I kind of have to give them a little bit of guidance and they know what they're looking for. If you just let them go blindly, then they're gonna, they're gonna get lost."

Based on the information gathered throughout the course of the InterMath workshop and post-workshop interviews with the participants, it seemed obvious that a hint system would be a beneficial addition to this professional development endeavor. The goals of this system would be to encourage teachers to select problems that are more difficult than those hey might otherwise attempt, assist them in furthering their mathematical thinking and understanding, and decrease the frustration that can occur when they come to a point where no more progress can be made without some type of assistance.

Hint System

Because the teachers needed more support than could be offered in the workshop and because our team could not be available all the time, we decided that an online system to support teacher learning anytime, anywhere was a critical element of the support system. To this end, we determined that developing some form of scaffolding system would be appropriate. By adding a "hint" to the more complicated problems, we may be able to aid teachers in persevering to become more successful problem-solvers. These hints may focus on the mathematics or on the use of technology to support the mathematics. We are striving to balance between providing too little and too much support to the teachers.

One of our primary concerns in considering this support system has been that it may inadvertently limit the cognitive growth potential for users of InterMath. Based on our initial field test of the hints, this concern is well-founded. Teachers in our test group clicked on the hint before they attempted to solve the problem on their own. The static hint system cannot provide the cooperative problem-solving effort between the learner and a more knowledgeable other that defines scaffolding (Collins, Brown, & Newman, 1989), nor can it anticipate exactly when the learner may require assistance. Learning in this environment comes from engagement in the problem-solving process, therefore the learners need to be actively involved in the process in order to benefit. If they click on the hint before struggling on their own, the potential of the learning experience may be significantly weakened. Further, the hint system needed to push thinking forward and promote metacognitive engagement rather than provide a crutch that eases the cognitive involvement of the learners and results in over-reliance in the system over time (Kao & Lehman, 1997).

Another issue that arose in the analysis phase was the purpose of the hints. We identified three distinctly different purposes hints might serve. The team also explored some of the arguments against developing an online scaffolding system. Because of these concerns, we were working toward developing a system that attempted to use only questions or tools that the learners will be able to use on other problems and in other ways (Polya, 1981). In this way, we aimed to develop a tool that, while static, might support the development of transferable knowledge for the learner.

No Hints

The arguments against the hint system arose from our beliefs about learning and our previous work with teachers supporting students in computer-based environments (e.g., Hawley & Duffy, 1998). In addition to the concern that the hint system might become a crutch, we were further concerned about the ability of an online scaffolding system to provide the kind of help the learner needed at the time he needed it – his zone of proximal development (ZPD) (Vygotsky, 1978). After all, the online system cannot sense where the learner is within a problem, what the learner's mathematical knowledge is, or whether the problem is a technical one (e.g., not knowing how to construct a shape or write a formula) or a mathematical one (e.g., not knowing how to approach a problem). It was the "inside help" that we felt the system could not provide (Polya, 1981). That is, the computer is not sensitive or "intelligent" enough to provide the learner with the kinds of questions or suggestions that may have occurred to the student – and those are the questions that move the student to new levels. This kind of help assumes that there are some general ideas that can guide the learner from one problem to another. This is in sharp contrast to "outside help" which should be treated as a last resort (Polya, 1981).

Additionally, the use of a static hints system in an online setting requires the student to be responsible for "fading" the scaffolding. It is unclear that learners can effectively self-monitor to determine where they are in their own ZPD. It is clear, however, that fading is a critical part of the scaffolding process (Kao & Lehman, 1997; Oliver & Hannafin, 2000). Therefore, finding ways to provide support without over-supporting became a theme in our development process.

Finally, the static hints system is problematic in that scaffolding is often considered an interactional approach (Driscoll, 1994). It, ideally, provides for an interaction between two people that can evolve and/or fade over time. The reciprocal teaching research (e.g., Palincsar & Brown, 1984; Brown & Palincsar, 1982) provides a compelling description of a scaffolding system that exemplifies this approach. Our design team considered how or if the hint system could serve as a scaffolding device without this kind of teacher-learner interaction.

While compelling, the arguments against the hints system did not provide alternatives for supporting teachers in attempting or completing the problems that offered the most promise for their mathematical development – the "hard" math problems. Using Bruner's view of scaffolding, we wanted to protect our learners from frustration (Bruner, 1981). Therefore, three different approaches and views of the content-oriented hints were considered: hints that aimed to keep the teachers motivated, hints that aimed to provide generalizable strategies for the learners, and hints that modeled expert thinking for the teachers. The first kind of hint sought to provide scaffolding that supported the teachers through the rough spots and helped them feel successful. The second and third kinds of hints served the purpose of trying to help the teachers become more expert-like in their approaches to mathematical problem solving.

Motivational Hints

Occasionally teachers in the InterMath course became frustrated after working on a problem for an extended period of time without making any headway. Sometimes the teachers would give up on problems such as these and move on to less challenging ones. As InterMath is a professional development environment, one in which teachers are encouraged and expected to develop and expand their mathematical understanding, this "avoidance behavior" played a large role in our decision to develop the hint system. We believed that such a system would motivate the teachers to choose and persevere with more challenging problem sets.

In describing general principles for motivating people, Ford (1992) describes the importance of providing indirect facilitation for goal attainment, rather than controlling learners' actions. In our case, the hint system would be that facilitation, which, for some teachers, would be the determining factor for whether they would choose a more challenging problem over a simpler one. This is particularly relevant because problems are not *assigned* to teachers in the InterMath course; teachers *choose* which problems they wish to explore, giving them more ownership of the process.

Along with the notion of learner control comes the idea of self-efficacy, or learners' judgments about whether or not they can succeed at specified tasks (e.g., Bandura, 1989; Pajares, 1996). It was our hope that providing a hint system as scaffolding would increase learner's feelings of self-efficacy, increasing their likelihood of choosing more complex problems and expanding their mathematical horizons.

Self-efficacy is closely tied to the concept of personal agency beliefs (Ford, 1992). Ford describes these beliefs as the evaluative thoughts comparing a desired outcome (successful completion of a problem) to an anticipated outcome (successfully and easily completing a simple problem, or possibly failing to correctly complete

a more difficult one). Ford believes that in addition to *being able to* achieve goals, learners need to *believe* in their abilities to achieve them.

> *Personal agency beliefs are often more fundamental than the actual skills and circumstances they represent in the sense that they can motivate people to create opportunities and acquire capabilities they do not yet possess.* (page 251)

We hoped that providing the hint system as scaffolding would increase learners' estimations of their own abilities to solve difficult mathematics problems, improve their success rate when they do choose these problems, and provide a "safety net" in case they do become stuck on the problems. We believe that a motivation-guided scaffolding system will ultimately help teachers to achieve the ultimate goal of InterMath – improving their understanding of mathematics.

Table 1: Motivational Hints for "Penning for Pony" Problem

Problem: To make a pen for his new pony, Ted will use an existing fence as one side of the pen. If he has ninety-six meters of fencing, what are the dimensions of the largest rectangular pen he can make? (Source: Mathematics Teaching in the Middle School, Nov-Dec1994).
Hint 1: Is it possible to relate the amount of fencing in terms of the side length of one side of fence? **Hint 2:** What equations can be written to relate the side lengths created by the fencing?

Generalizable Hints

Because of our team discussions, we decided to explore multiple forms of hints for this system. To this end, Polya (1957) provided the basis for our thinking in the development of the second kind of hints – those that support the development of transferable, generalizable problem-solving strategies. Polya identified a four-step problem-solving process that includes a number of substeps. The four key steps are: (1) Understand the problem; (2) Devise a plan; (3) Carry out the plan; and (4) Look back. In reviewing the process and reflecting on the kinds of challenges the teachers we had worked with thus far faced, we determined that providing hints that helped the learners work in phases one and two of Polya's work would be most beneficial. To this end, a set of hints that provided both the strategy (e.g., "Can you restate the problem?") and a specific hint for the problem of interest (e.g., "Before you answer the given problem, think about the definitions and formulas of circumference and area. On what part of each circle do you really need to focus? How do these parts relate to each other?"). The goal was to support the learner through a combination of macro- and micro-level scaffolding (Guzdial, 1994).

The goal of transfer in this static environment is a difficult one to achieve. Research has indicated that the greatest opportunity for transfer involves an active system in which the hints become more specific as needed (e.g., Bransford, Brown, & Cocking, 1999; Campione & Brown, 1987). This graduated prompting provides a way to more actively engage the learner as a partner in the scaffolding system. Due to the limitations of a static hints system, we could not offer the progressive drilling into an area that a teacher could, though we did explore that option. Instead, we chose to provide a set of hints rather than one that provided the learner with both the general hint and the specific. Our intention would be for the learner to be self-regulating in choosing to use both the hints system itself and the specific hint.

Table 2: Generalizable Hints for "Penning for Pony" Problem

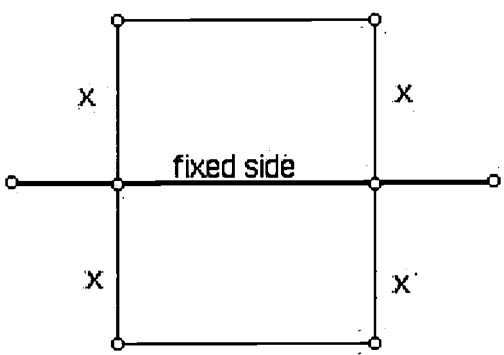
Problem: To make a pen for his new pony, Ted will use an existing fence as one side of the pen. If he has ninety-six meters of fencing, what are the dimensions of the largest rectangular pen he can make? (Source: Mathematics Teaching in the Middle School, Nov-Dec1994).
Strategy 1: What are the data? What is the condition? **Hint 1:** What does the ninety-six meters of fence tell you about the rectangular pen? **Strategy 2:** Go back to the definitions. **Hint 2:** How do you find the area of a rectangle? How do you find the perimeter of a rectangle? How are the area and perimeter of a given rectangle related to each other?

Model Hints

Wood, Bruner, and Ross (1976) define the expert's role in scaffolding as directing and maintaining the learner's attention, while also modeling the task and highlighting the critical features of that task. Our third approach to hints builds from that notion. It is well-documented that there are fundamental differences in the way experts organize knowledge and the way novices organize that same knowledge (e.g., Bransford, Brown & Cocking, 1999). Experts tend to organize thinking and strategies around core concepts whereas, more novice thinkers tend to exhibit signs of more linear and procedural understandings. Further, experts are better able to identify appropriate instances for applying theories and procedures to problem-solving instances. Therefore, if the scaffolding system were to promote the development of more expert thinking about mathematics, one possible approach might be to provide a rich set of problems for the learners to solve and provide models of expert approaches to solving those problems.

Modeling has been shown to be an effective means for supporting learning (e.g., Palincsar & Brown, 1984; Schoenfeld, 1991). It provides an example for learners to take and adapt for their own purposes. The limitation of the modeling method is that it, too, relies on learner self-regulation. If the learner does not engage in reflective adoption and adaptation of the modeled example, that learner has learned only a prescriptive task rather than a generalizable approach. With a hint system of this kind, our goal would be to support the learner to reflect on what was important in a situation. The instructor may need to spend time engaging learners in reflective activities to gain the skill necessary to do this. However, this may be a powerful way to help move middle grades teachers, notoriously underprepared in their content areas (e.g., SREB, 1998), toward developing more expert levels of content understanding.

Table 3: Model Hints for "Penning for Pony" Problem

Problem: To make a pen for his new pony, Ted will use an existing fence as one side of the pen. If he has ninety-six meters of fencing, what are the dimensions of the largest rectangular pen he can make? (Source: Mathematics Teaching in the Middle School, Nov-Dec1994).
Hint 1: What if we built a similar figure on each side of the fixed wall? 
Hint 2: Use the algebraic mean – geometric mean inequality to find the greatest possible area, then use that information to determine the length of each side. (Hint 2 also includes working of the mathematical equations.)

The Design Process

Our design process ran parallel to our evaluation process. We began by looking at existing systems to see how they provided support for learners. These systems included the support system in the Knowledge Integration Environment (KIE) (Slotta & Linn, 2000), as well as EMILE (Guzdial, 1994) and CSILE (Scardamalia et al., 1992). These tools provided very different approaches to scaffolding learning, ranging from static to very dynamic and including various levels of teacher/knowledgeable other support within the system.

The tools that we reviewed ranged, also, from technologically complex to those that were relatively simple. In the end, the decision to follow a simpler path was tied to two issues: budget and time. The enormous undertaking of developing a dynamic support system was outside the scope of our efforts and was not included in the budget. Further, InterMath is a multifaceted system that includes communication tools, a dictionary, materials for instructors, and, of course, the investigations. Because each of these pieces requires support, the need to keep the scaffolding system to a manageable size was considerable. Further, the InterMath team recognized that teachers in need of more specialized support could contact an InterMath team member or could use the communications tools to pose questions to other members of the community. The trade-off with this was the loss of momentum caused by the delayed communication in an asynchronous environment. However, if we paired a just-in-time scaffolding system with these other tools, we felt we could offer support for the learners that would be meaningful.

The most critical decision made as a result of our process was the decision to split the hints system into two distinct pieces. One piece would be the hints as discussed in the analysis section. The other part would be the "constructopedia," which is a system to support teachers in completing mathematical constructions using Geometer's Sketchpad. While making constructions in this program is still a mathematical process, it is the point where mathematical concepts intertwine with technology. The support that teachers struggling with the technology needed was not the same kind of support they needed to conceptually understand the problem. The constructopedia borrows heavily from the Lego approach to instruction – teachers are provided with pictures that show the construction being put together. They are provided with minimal text as well because our rapid prototyping process indicated that the images alone were too confusing. The goal of the constructopedia is to provide teachers with the support they need, while forcing them to remain engaged in the mathematics of the construction.

A final portion of the design phase has been the identification of which investigations need hints and what kinds of hints they might need. This process was begun by having a new graduate student whose mathematical background was similar to our target audience's work several of the investigations to identify places where they became difficult as well as ways she was able to overcome those difficulties. This provided a beginning guide for the hints system. However, her activity on the project team and in graduate-level mathematics education courses quickly moved her beyond the mathematical content knowledge of our target audience. Therefore, further work to identify investigations in need of support will need to be done a different way.

The Development Process & Future Work

The analysis and design phases employed three instructional design strategies: 1) having a person similar to our target audience work through investigations to identify potential problems and discuss how those complications affect the successful completion of the problem; 2) reviewing existing computer-based scaffolding systems to explore the characteristics and possibilities of effective systems; and 3) working with SMEs on our team to determine how to translate face-to-face questioning strategies to static online strategies. The development phase introduces a fourth key strategy – rapid prototyping.

Both the constructopedia and the hints system itself have gone through multiple iterations. During the pilot courses, we were able to bring in different kinds of hints and test them out with members of our target audience. This provided extremely valuable feedback as we were able to put the hints system to work, watch the users interact with it, and talk to them about their reactions to it. Interestingly, in the audition of the hints strategies, the participants claimed that the hints were not useful, despite having relied on them to complete their problems.

We are currently involved with the development stages. There are still obstacles to overcome, including making the final decisions about which approach to the hints system to adopt. There are very practical considerations that must be weighed in this decision. For example, we must choose a hints system that members of our team can create and refine with little SME intervention. From this perspective, the generalizable hints are a strong contender. We must also choose the system that offers the greatest level of promise and that is most consistent with our overall approach. From this perspective, the model hints are more appropriate. At this point, the motivational hints have been left behind because our initial evaluation showed that participants found them less helpful than the others.

Another critical obstacle is determining which investigations need hints and what kinds of problems teachers might have with them. This is problematic because all of our team members have either extremely high mathematical ability, or mathematical ability that is too limited. To address this problem, we have considered a number of approaches including conducting more teacher observations during our next workshop offering and using our best guesses to find problematic investigations.

Conclusion

In short, we see the use of a web-based hints system as being a potentially valuable tool for supporting teachers in tackling complex math problems. We recognize that there are limitations with this plan, but see combining the just-in-time help of a static system with the asynchronous support of a wider community as a viable option for promoting the development of mathematical thinking. We are currently involved in a rapid-protoyping approach to find appropriate ways for supporting teacher development.

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