Learning and Problem-solving Transfer between Physics Problems using Web-based Homework Tutor

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Abstract: We demonstrate learning and problem-solving transfer between related physics problems using the Socratic web-based tutor, MasteringPhysics. Two equally skilled groups of students taking introductory mechanics solve related physics problem pairs in reverse order with respect to each other. We show that for problems containing help ("skill builders" and "self tutoring problems") in the form of requestable hints, descriptive text, and feedback, twice as many students were able to complete problems correctly in real time compared to problems that did not provide any help (end-of-chapter problems). The group that did a problem second (prepared group) in a given related pair was able to solve it in ~15% less time on average compared to the group that did the same problem first (unprepared group). Furthermore, the prepared group requests 7% fewer hints on average than the unprepared group. We conclude that learning and problem-solving transfer is facilitated through skill builders and self tutoring problems, which also are pedagogically superior to end-of-chapter problems.

Introduction

Advances in computer technology are transforming the methods of instruction and their effectiveness for the learners provides a new paradigm of research. Web-based instruction is an emerging such medium which remains largely unexplored in terms of online learning (Mitchell, Dipetta & Kerr 2001). The new technologies also provide data collection on variables that were not possible with the traditional methods of instruction (Sheard, Ceddia & Hurst 2003). The time to solution is an important such variable that can be used for a variety of assessments such as the difficulty of a problem and the amount learned per unit time (unpublished observations; Ketamo & Multisilta 2003; Schnipke & Scrams 1997). In this paper we provide evidence of physics problem-solving transfer using data on time to completion of physics problems for students interacting with the web-based physics homework tutor, MasteringPhysics.

The motivation for the present study is five-fold:

1. To understand how long it takes students to complete online homework problems.

2. To understand the effect of hints and feedback on time to solution.

3. To understand which problems can impart transferable physics knowledge in less time.

4. The data from such a study will be useful in setting the length of assignments.

5. The data will be useful for predicting the reduction in time with repetition.

In this paper we discuss the data relating to the first three of the above motivations. We first provide the pedagogy of the web-based tutoring system, MasteringPhysics (www.masteringphysics.com, powered by myCyberTutor – www.mycybertutor.com) followed by the research design. We then present the major findings of our research, namely:

1. Rate of completion curves isolate three distinct groups of students.

2. Factor of two reductions in real time solvers for problems without help or end-of-chapter problems.

3. Learning and problem-solving transfer from related problems as evidenced from time and hints data.

The particular terms we have used will be defined in the text.

The Pedagogy of MasteringPhysics

A study of time to completion of physics problems is especially apt due to the general pedagogy of MasteringPhysics which is grounded on mastery learning (Bloom 1981). In mastery learning, time to learn is allowed to vary in order to make students achieve mastery (obtain a score of 80-100% on an assessment) of a given topic. This is the reverse of most in-school instruction where the time is fixed and only the most skillful students master the material. In MasteringPhysics mastery learning is implemented within a Socratic dialogue where students are provided with hints and simpler sub-problems upon request, and are given specific criticism (feedback) when incorrect answers are proposed.

It employs skill builder problems where the problem description starts with a learning goal and detailed descriptions or declarative knowledge of the concepts and/or formulae are often included within the problem text. Also, the skill builder problems consists of many parts. The self tutoring problems give detailed guidelines on declarative and procedural knowledge only in terms of requestable hints. The procedural knowledge is imparted through simpler sub-problems within requestable hints. Feedback responses are also available to common student errors on each question for both skill builder and self tutoring problems and in this paper we will refer to them collectively as "problems with help." In addition, follow-up comments are frequently given to highlight important features or implications of an answer that has just been obtained. The follow-ups are designed to foster active engagement of the student (Redish, Saul, & Steinberg 1997; Sokoloff & Thornton 1997). If the students exhaust the available hints they can request the solution to a problem or a sub-problem. Over 93% of the students eventually obtain the solution to a given problem with the help of hints and feedback.

Design and Analysis

The study we report here involves students taking the "Introductory Newtonian Mechanics" course at the Massachusetts Institute of Technology (MIT) in Fall 2003. Our experimental method was to split a class of approximately 400 students into two equally skilled groups – the skill measured by the average scores of the students during the first six weeks of the MasteringPhysics homework assignments. The two groups then solve related physics problems. The problems are related in the sense that they involve the same concepts and methods. The topics for the problems studied include torque, linear momentum conservation, energy conservation, friction, angular kinematics and dynamics, rigid-body motion, and Newtonian gravitation.

The related problems were given in pairs and the two groups solve them in opposite orders relative to each other with no intervening problems. That is, the "first" problem to one group is the "second" to the other and vice versa for any given pair. We will call the group that solves a given problem in a pair first, the unprepared group and the group that solves the same problem second, the prepared group.

The variables we consider in this study are the time to completion, the number of hints requested, and the number of wrong answers submitted. Time to completion in this paper is defined as the time interval between the first opening

of a problem and the submission of the completed problem. No time intervals for interactions in between (even for logins and log-offs) are accounted for. Completion is defined as finishing all the main parts of a given problem correctly (finishing sub-parts when hints are requested is not required).

Time to completion for different students ranges from several seconds to several days for physics problem. Thus, we use a logarithmic time (Ln(t) where t is measured in seconds) as the independent variable, which in this study runs from 2 to 13. This corresponds to a time scale from about 7 seconds to 5 days. We chose to bin the data in time intervals of 0.5 in logarithmic time scale (a factor of 1.6 in real time). We present both the "rate of completion" – i.e. the fraction of students who have completed a given problem during that interval - and the time integral of this curve, the "fraction" complete at the end of that time interval. The fraction of students is relative to all those who have opened it.

We have analyzed 7 related problem pairs or 14 problems that contain help. Surprisingly, we see a consistent three peak pattern for problems containing help in rate of completion plots (see Fig. 1, left). In Fig. 1 three representative problems show the three peak pattern. We essentially identify the peak that occurs before 2.5 minutes as "quick responders." These students typically do not request any help (hints) or submit wrong answers. The peak that occurs after about 2.2 hours, we identify as "delayed solvers." These students request help within MasteringPhysics and submit incorrect answers. Moreover, we believe that the majority of both the quick responders and the late solvers seek assistance outside MasteringPhysics. These may include intellectual dishonesty and/or help from human tutors.
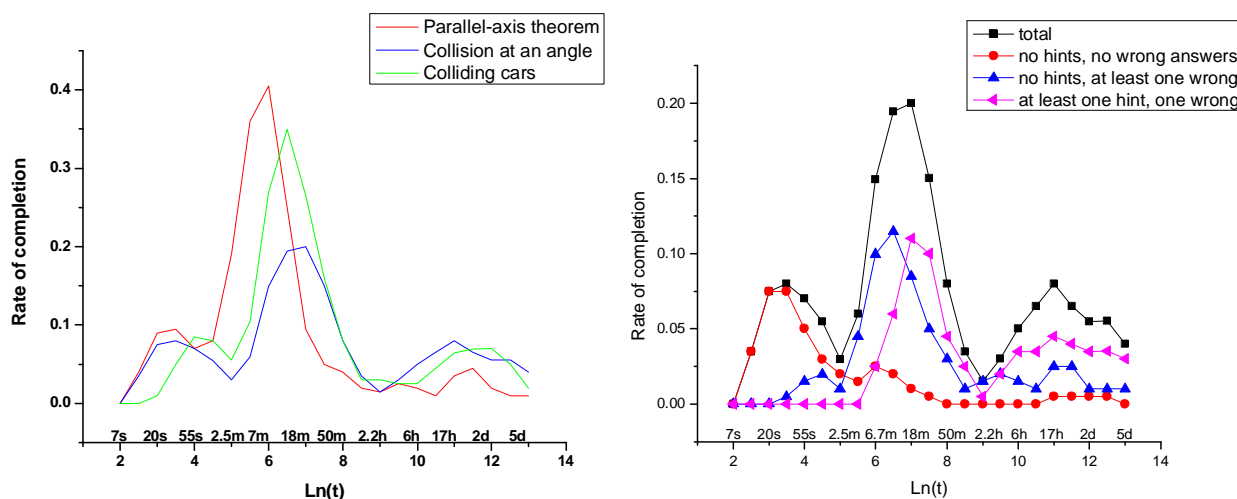

Figure 1: The Rate of completion for three representative problems (left). The plots reveal three distinct groups. The three group structure is preserved although the problems have different median times as measured by the central peak. The detailed composition of a typical rate of completion graph is shown on right. The "quick responders" (typically< 2.5 minutes) are dominated by students who do not ask for hints or give incorrect answers. The "real-time solvers" (typically, 2.5 minutes to 2.2 hours) and "delayed solvers" (typically>2.2 hours) are dominated by those who make mistakes and ask for help (hints).

The most interesting group of students completes the problems within 2.5 minutes and 2.2 hours. This corresponds to the prominent central peak in rate of completion graphs. Our data lead us to believe that the students that fall within the prominent central peak to be those who make a genuine effort to solve the problems in real time. For this reason we consider them to be real time solvers. These students make mistakes (that is, give incorrect responses) and ask for hints. The detailed composition of a typical rate of completion graph is shown in Fig. 1 (right).

Results

Twice as many Real Time Solvers for Problems with Help

Comparing real time solvers for problems with and without help in fraction complete graphs, we find that twice as many students were able to complete the problems with help in the time interval 2.5 minutes to 2.2 hours compared to problems that did not contain any help (see Fig. 2). The problems without help are the end-of-chapter (EOC) problems of the text (Young & Freedman 2004) assigned for the course, but administered through MasteringPhysics. We find that the fraction of real time solvers (i.e. within 2.5 minutes to 2.2 hours) is $67 \pm 3\%$ for twelve problems with help. In comparison, the fraction of real-time solvers for five EOC problems is $33 \pm 5\%$ which is significantly different ($p = .00001$, one-tailed). This is a result of the fraction complete graphs becoming more linear for problems without help compared to those having help for which we see a sharp rise in fraction within the real time solver interval.
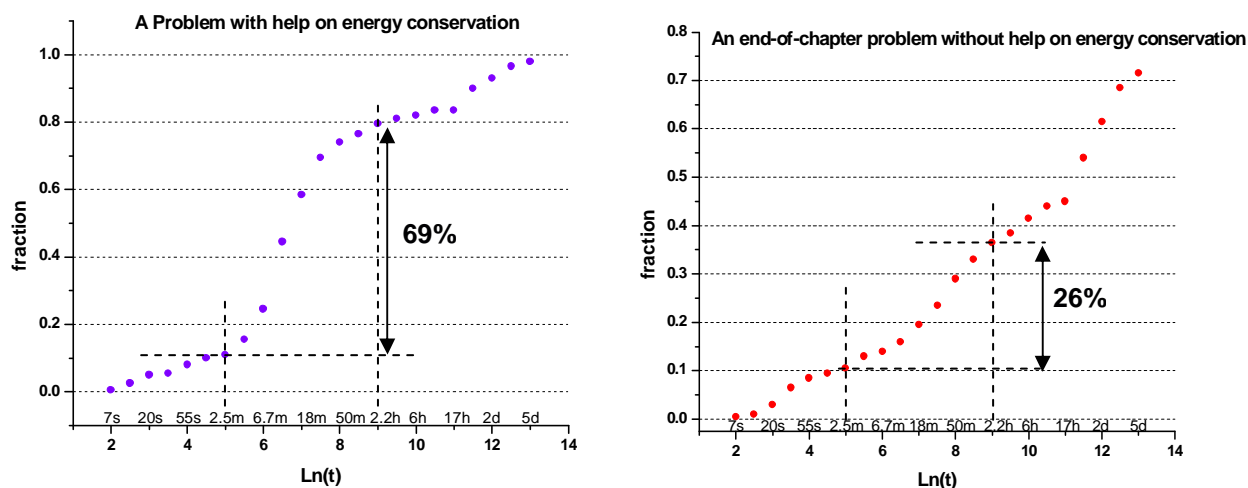

Figure 2: Typical time to completion curves are shown here for a problem with and without help on energy conservation. End-of-chapter problems (right) that do not have help reduces the real-time solvers (within 2.5 minutes to 2.2 hours) by a factor of two compared to problems that have help (left).
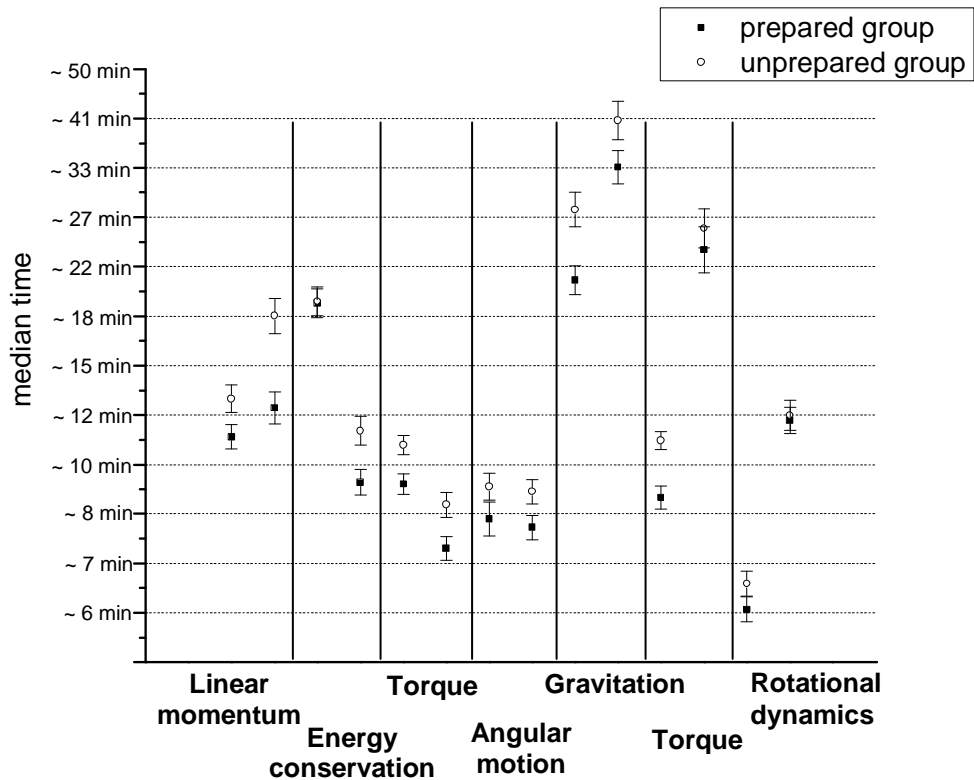
Prepared Group Solves in less Time

Our major finding here is that the prepared group (that is the group that solves a problem second) is able to solve a given problem in a shorter time compared to that of the unprepared group (see Fig. 3 for two representative curves). This is true for all fourteen problems (see Fig. 4). This result is arrived at by fitting the best-fit differentials of three sigmoidal functions (Logistic, Boltzmann, and Gompertz) to the rate of completion data for the real time solvers.

It must be noted in Fig. 3 that the unprepared group for "colliding cars" is the same as the prepared group for "collision at an angle" and vice versa. Having solved "colliding cars" first, the unprepared group was better prepared for "collision at an angle" and were able to solve it in less time (31% advantage) compared to the unprepared group for that problem. Similarly, having solved "collision at an angle" first, the unprepared group for that problem was better prepared for "colliding cars" and were able to solve it in less time (14% advantage) compared to its unprepared group. The advantage (reduction) in time averages to $14.6 \pm 2.2\%$ for fourteen problems.
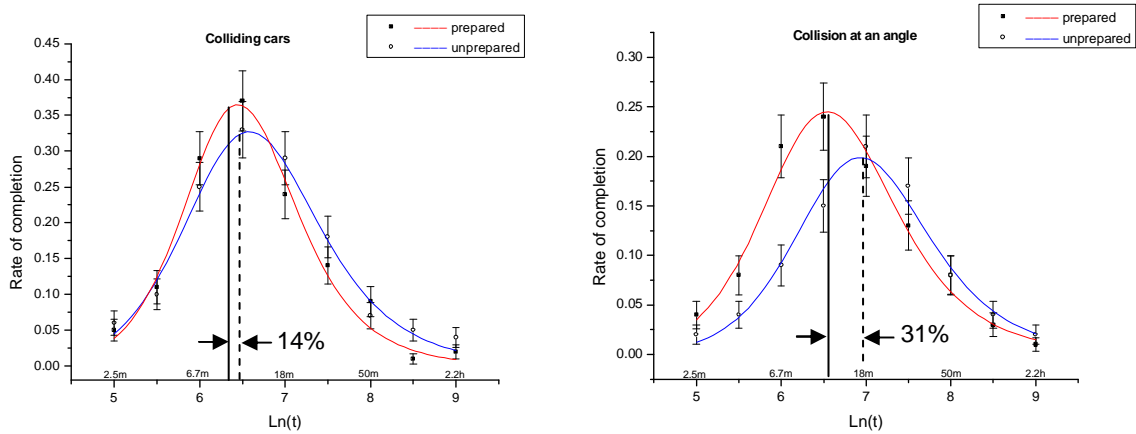
Figure 3: Evidence of learning from prior problems (linear momentum conservation). The unprepared group for "colliding cars" is the same as the prepared group for "collision at an angle" and vice versa. Having solved "colliding cars" first, the unprepared group for that problem was better prepared for "collision at an angle" and were able to solve it in less time (31% advantage) compared to its unprepared group.


Figure 4: Median times for unprepared and prepared groups for seven related problems pairs (fourteen problems). The prepared group solves a given problem in a related pair in less time compared to the unprepared group. This effect holds for all fourteen cases.

Prepared Group Request Fewer Hints

We find that generally about 48% of the students request hints for a given problem. And 88% of the students do so only after submitting at least one incorrect response. For related problems, the prepared group requests 7% fewer hints compared to the unprepared group. The maximum reduction in hint requests (19%) occurs having solved a skill builder problem (see Fig. 5) first. Part-by-part analyses of the fraction of students who request hints also reveal similar conclusions (see Fig. 6); that the prepared group requests fewer hints. Further evidence is seen by the rate of completion curves where we find that more real time solvers of the prepared group being able to complete a given problem per 0.5 of logarithmic time without requesting hints (see Fig. 7)
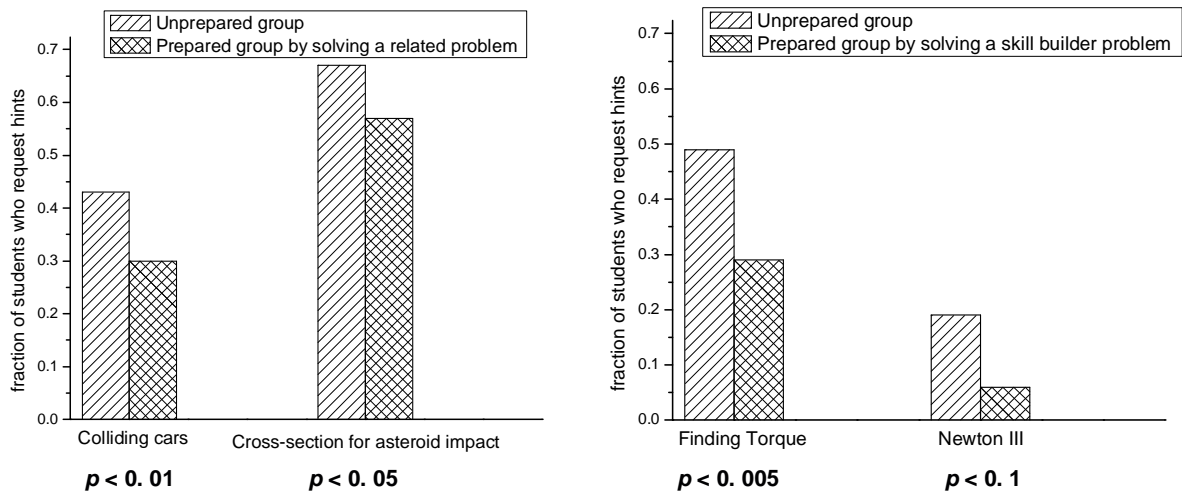
Figure 5: Prepared group requests 7% less hints on average compared to the unprepared group (left). The maximum reduction (19%) occurs after solving skill builders (right).
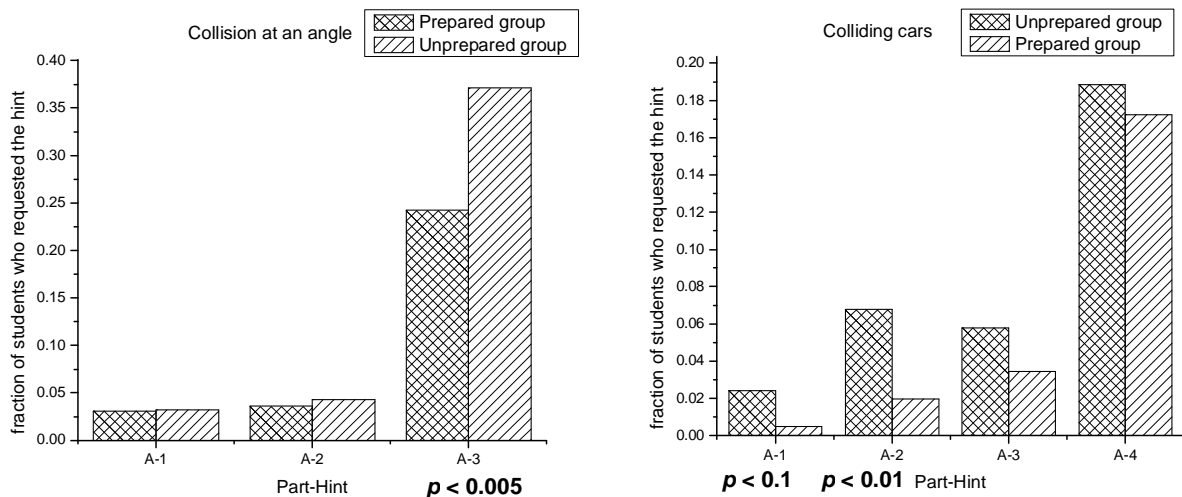
Figure 6: Hint requests by main parts of a problem before giving the correct solution to that part (A-2, for example, stands for hint number two of part A). The prepared group requests fewer hints for a given part. It should be noted that the prepared group for "collision at an angle" is the unprepared group for its related problem "colliding cars" and vice versa.
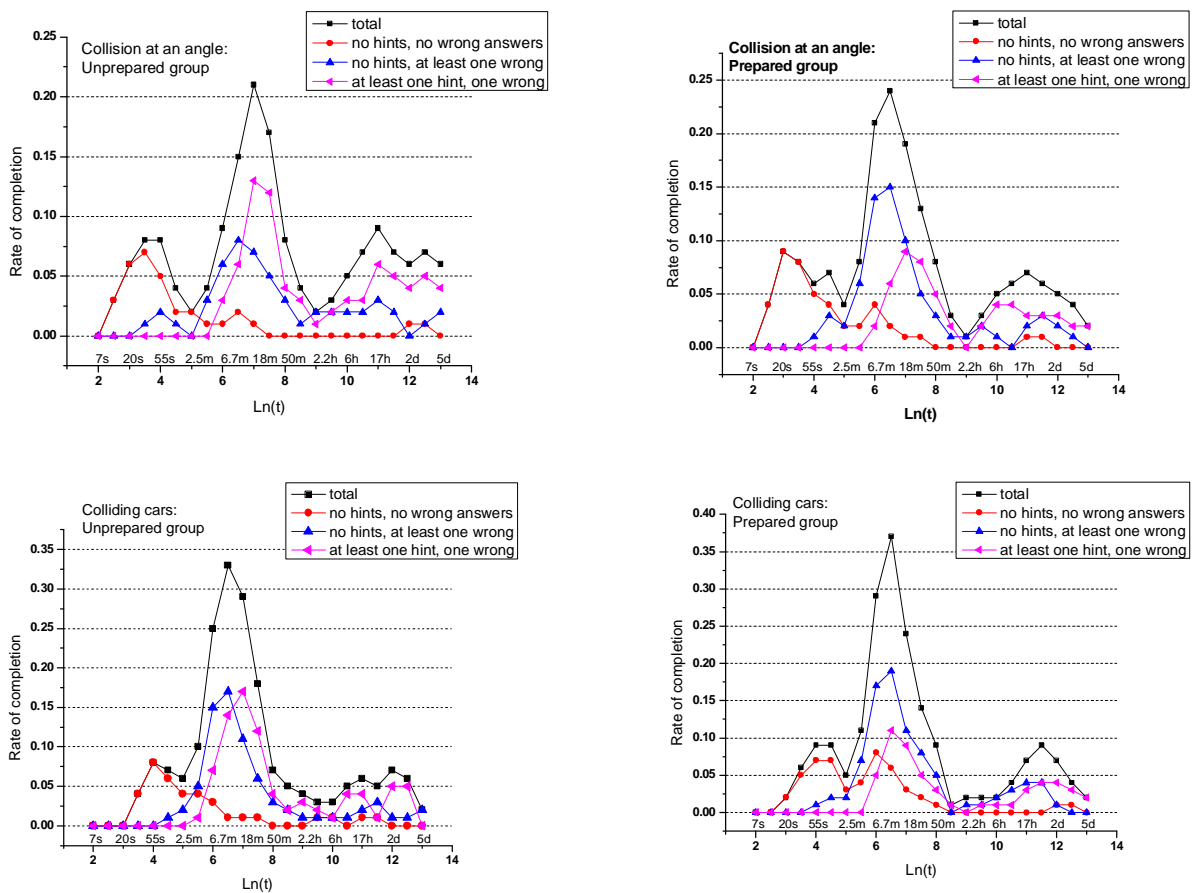
Figure 7: More students in the prepared group were able to complete "collision at an angle" per 0.5 of logarithmic time without hints compared to the unprepared group for the same problem. The same is true for "colliding cars."

Conclusions

As reported above we see consistent results from time to completion and hints data. The prepared group benefits from prior skill builder or self tutoring problems, which contain help in the form of requestable hints, descriptive text, and immediate feedback in terms of spontaneous wrong answer responses. We have demonstrated the reproducibility of the results through fourteen problems across a wide range of topics in physics. The results are not biased since the effects we see are reciprocal; that is the prepared group for a given problem in a pair is the unprepared group for its related problem and vice versa. Pedagogically we see that the end-of-chapter problems are less helpful to students. We believe that skill builders and self tutoring problems are much more effective when students reach an impasse (VanLehn et al. 2003). Among skill builders and self tutoring problems our data (unpublished observations) suggest that skill builders impart twice as much learning per unit time spent on them compared to self tutoring problems and reduces the difficulty of a subsequent skill builder problem by about 25%. We also see that the maximum reduction in hint requests follow having solved a skill builder problem.

Our results show robust evidence of learning from a prior related problem and problem-solving transfer (Mayer 2003). Our use of the term problem-solving transfer in the present context refer to the ability to solve a problem in less time with less hints having solved a prior related problem. We consider time and hints as measures of difficulty. Thus, in short, our use of the term problem-solving transfer refers to students being able to solve a problem with less

difficulty after some training. The problem-solving transfer may have been also facilitated by the presence of similar types of quantities in the two related problems in a given pair since they belong to the same conceptual domain (Bassok 1990).

The various comparisons we have made in this study are general in nature in the sense that the problems are related only by content and the relevant conceptual domain. Also, the problems with and without help are not isomorphic to each other although in some cases their contents and the conceptual domains agree. A study designed to look at isomorphic problems with and without help has been carried out. Experiments have been also carried out to identify the reasons for the apparent effectiveness of the skill builder problems over self tutoring problems. In this context our larger goal is to investigate and establish best pedagogical practices in web-based tutoring (Hannafin & Kim, 2003). The findings from these studies will be reported in a future publication.

While we have shown that time to completion curves divide the student population into three distinct groups, it will be interesting to see whether we can use their detailed shape as a tool to categorize physics problems beyond the simple help versus no help difference discovered here. These issues are currently under investigation.

References

Bassok, M. (1990). Transfer of domain-specific problem-solving procedures. *Journal of Experimental Psychology,* 16, 522-533.

Bloom, B. S. (1981). *All Our Children Learning*. NY: McGraw-Hill.

Hannafin, M. J., & Kim, M. C. (2003). In search of a future: A critical analysis of research on web-based teaching and learning. *Instructional Science,* 31, 347-351.

Ketamo, H., & Multisilta, J. (2003). Towards adaptive learning materials: Speed of interaction and relative number of mistakes as indicators of learning results. *Education and Information Technologies,* 8, 55-66.

Mayer, R. E. (2003). Learning and Instruction. NJ: Pearson.

Mitchell, C., Dipetta, T. & Kerr, J. (2001). The frontier of web-based instruction. *Education and Information Technologies,* 6, 105-121.

Redish, E. F., Saul, J. M. & Steinberg, R. N. (1997). On the effectiveness of active- engagement microcomputer-based laboratories. *American Journal of Physics*, 65, 45-54.

Schnipke, D. L. & Scrams, D. J. (1997). Modeling item response times with a two-state mixture model: A new method of measuring speededness. *Journal of Educational Measurement*, 34, 213-232.

Sheard, J., Ceddia, J. & Hurst, J. (2003). Inferring student learning behaviour from website interactions: A usage analysis. *Education and Information Technologies,* 8, 245-266.

Sokoloff, D. R. & Thornton, R. K. (1997). Using interactive lecture demonstrations to create an active learning environment. *Physics Teacher*, 35, 340-347.

VanLehn, K., Siler, S., Murray, C., Yamauchi, T. & Baggett, W. B. (2003). Why do only some events cause learning during human tutoring? *Cognition and Instruction*, 21, 209-249.

Young, H. D. & Freedman, R. A. (2004). *University Physics*. San Francisco, CA: Pearson.