

Interactive video tutorials for enhancing problem-solving, reasoning, and meta-cognitive skills of introductory physics students

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We discuss the development of interactive video tutorial-based problems to help introductory physics students learn effective problem solving heuristics. The video tutorials present problem solving strategies using concrete examples in an interactive environment. They force students to follow a systematic approach to problem solving and students are required to solve sub-problems (research-guided multiple choice questions) to show their level of understanding at every stage of problem solving. The tutorials are designed to provide scaffolding support at every stage of problem solving as needed and help students view the problem solving process as an opportunity for knowledge and skill acquisition rather than a “plug and chug” chore. A focus on helping students learn first to analyze a problem qualitatively, and then to plan a solution in terms of the relevant physics principles, can be useful for developing their reasoning skills. The reflection stage of problem solving can help students develop meta-cognitive skills because they must focus on what they have learned by solving the problem and how it helps them extend and organize their knowledge. Preliminary evaluations show that a majority of students who are unable to solve the tutorial problems without help can solve similar problems after working through the video tutorial. Further evaluation to assess the development of useful skills is underway.

Introduction

Problem solving can be defined as any purposeful activity where one is presented with a novel situation and devises and performs a sequence of steps to achieve a set goal.[1] Effective problem solving begins with a qualitative analysis of the problem, followed by planning, implementation, assessment, and reflection. As the complexity of a physics problem increases, it becomes increasingly important to employ a systematic approach. In order to help introductory physics students learn effective problem solving heuristics and develop useful skills, we are developing interactive video tutorial based problems. The tutorials force students to follow a systematic approach to problem-solving and provide appropriate feedback with a focus on helping them develop self-reliance.

Cognitive research indicates that the strategies used for effective acquisition, retention and retrieval of knowledge from memory have implications for helping students develop useful skills.[2] Students do not automatically develop useful skills by spending lots of time solving problems. There is evidence to suggest that the crucial difference between expert and novice problem solving lies in

both the level and complexity of knowledge representation and rules.[1] Experts typically start with an initial plan which provides overall structure. Unlike novices who focus on surface features and jump into the implementation phase of problem solving immediately without thinking if a concept is applicable, experts concentrate on deep features and start with initial qualitative analysis and planning steps before resorting to the implementation issues. Experts are relatively comfortable going between different representations of knowledge (e.g., verbal, visual, algebraic) and employ representations that make problem solving easier.[1] Also, since the typical “chunk-size” for knowledge required for problem solving is larger for experts (they have lots of compiled knowledge), they are able to reflect on the problem solving process while solving problems without experiencing cognitive overload. Because students’ “knowledge chunks” are smaller than that of experts, the limited capacity of short term memory makes the cognitive load high during problem solving tasks, leaving few cognitive resources available for meta-cognition. The abstract nature of the laws of physics and the chain of reasoning required to draw meaningful

inferences makes these issues critical. Appropriate scaffolding during problem solving can reduce cognitive load for students, and provide opportunities for metacognition.

Video tutorials are being designed with these issues in mind so that they can help students learn problem solving, reasoning and meta-cognitive skills using concrete examples in an interactive environment. They are designed to force students to analyze the problem qualitatively and spend time deciding why certain principles of physics are appropriate. Consistent use of qualitative analysis and planning tasks can help students develop reasoning skills. Also, helping students reflect upon the problem solving process at the end of every problem and forcing them to think about what they learned by solving the problem and how it helps them restructure, extend and organize their knowledge can help develop their meta-cognitive skills. Reflection sub-problems are specifically designed for this purpose.

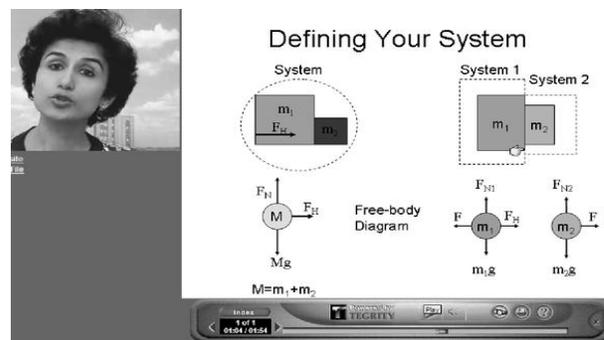
Students working on the tutorials first use a worksheet which divide the problems into five stages involved in problem solving. After attempting the problem on the worksheet to the best of their ability, students access the same problem on the computer. Before inputting their numerical or symbolic solution on-line, students are required to solve several research-guided sub-problems to show their level of understanding at every stage of problem solving. The alternative choices in these multiple-choice questions elicit common difficulties students have with relevant concepts.[3] Incorrect responses direct students to a short video (see the figure) while correct responses give them a choice of either advancing to the next sub-problem or watching videos to learn why the alternative choices are incorrect. While some videos are problem-specific, many focus on more general ideas, such as contact and non-contact forces or conditions for determining when a system is in equilibrium. Students have the option of watching additional videos which demonstrate and exemplify a particular problem solving stage.

Some other web-based tutorials have been developed, e.g., Cyber Tutor.[4] The novel feature of our tutorials is the incorporation of video, audio, and cursor movement to scaffold student learning. In addition, our sub-problems are typically more

qualitative than Cyber Tutor and our alternative choices for sub-problems are guided by research.

Details of Video Tutorials

The main skeleton of interactive video tutorial based problems is being developed using Macromedia Flash. The videos focus on different topics in introductory physics. Most tutorials are suitable for students in any algebra or calculus-based, introductory physics course. Since the guidance and feedback is customized to students' needs, they can be used as aids to problem solving in homework and as a self-study tool by a diverse group of students. They can be helpful to students with different learning styles and can help them view the problem solving process as an opportunity for knowledge and skill acquisition rather than a "plug and chug" chore or guessing task. Each video tutorial-based problem is matched with other problems (pair problems) that use similar physics principles but for which no tutorial is provided. These pair problems are designed to help students develop self-reliance and determine what they actually learn from the tutorials.



Example of web-based video tutorial.

The development of the video tutorial based problems is guided by research. For the past few years, we have investigated if instruction which is based upon a field-tested cognitive apprenticeship model of learning involving modeling, coaching, and scaffolding can help students learn effective problem solving heuristics and found positive outcome.[5] In this approach, "modeling" means that the instructor demonstrates and exemplifies the skills that students should learn. "Coaching" means providing students opportunity, guidance and practice so that they learn the skills necessary for

good performance. “Scaffolding” means providing students with appropriate support and immediate feedback with a focus on weaning or fading the support so as to help them develop gradual self-reliance. This scaffolding process lies at the heart of Vygotsky’s notion of stretching a student’s “zone of proximal development” and Piaget’s idea of providing “optimal mismatch”.[6] Using a similar instructional model, Schoenfeld has shown that in the context of mathematics, an explicit instruction in problem solving heuristics significantly improves students’ skills.[6]

Preliminary Evaluation

Below, we discuss the insights gained from task analysis and twelve student interviews (from a calculus-based course) for the design of sub-problems and video tutorials in the context of a problem involving the non-equilibrium application of Newton’s second law and Newton’s third law. The problem statement is as follows:

Two adjacent boxes ($m_1 = 5$ kg, $m_2 = 2.5$ kg) are in contact on a horizontal frictionless table. You apply a constant horizontal force $F_H = 10$ N to the larger box. Find the magnitude of the force F exerted on the larger box by the smaller box.

We started with a cognitive task analysis which involves making a fine-grained flow chart of all the concepts that students must know in the appropriate order in which they must be invoked to accomplish the task (solve the problem). A careful task analysis is extremely helpful in identifying and addressing stumbling blocks or subtleties that students are likely to miss. We then interviewed four students using a think-aloud protocol about several problems involving equilibrium and non-equilibrium applications of Newton’s second law and Newton’s third law (including the problem above). Based upon theoretical task analysis and student interviews, we designed the preliminary version of the sub-problems and video tutorials. In eight later interviews using a think aloud protocol, students were first given the worksheet and asked to solve the problem to the best of their ability. Then they were asked to attempt the sub-problems and watch the videos as needed. To evaluate video tutorial’s effectiveness, they were then asked to

solve two other similar problems on the worksheet without any help.

The above problem is apparently so difficult that none of the 12 interviewed students could solve it without help from video tutorials.[3] Many interviewed students, including those with A and B grades in their midterms on related concepts, had great difficulty figuring out whether this was an equilibrium or a non-equilibrium problem. Many believed that unless the problem mentions it, they should take the net horizontal force to be zero on each object. A majority believed that the force exerted by the hand, F_H , should act on both boxes because the box with mass m_2 is in the way of the larger box that is being pushed. Many had difficulty understanding why m_2 will exert a force on m_1 . Some explicitly mentioned that the reason they are confused is that the surface is frictionless here and that is the only force that will push back on m_1 when they exert a force F_H . Newton’s third law is extremely difficult for students [3], and they had great difficulty realizing that the force exerted by m_1 on m_2 is equal in magnitude to the force exerted on m_2 by m_1 . Many felt that the larger object should exert a larger force on the smaller object than vice versa. Some justified their argument by noting that F_H is the force exerted on m_2 by m_1 and F is the force exerted on m_1 by m_2 and it makes sense that the larger box m_1 is exerting a larger force F_H on the smaller box m_2 (some students felt that F and F_H are action-reaction pairs in Newton’s third law).

A majority could not make up their minds about what should be the system for which they should draw a free body diagram (FBD). Most did not understand that you can choose either m_1 , m_2 or both of them together as a system and based upon the choice of the system, the forces exerted by m_1 on m_2 and vice versa become internal forces that cancel in pairs or external forces that should be taken into account. Several started drawing FBDs but had difficulty committing to the system that the diagram was for. Several were not clear about the fact that FBDs should only include forces exerted on the system of choice by objects in the environment and not the forces exerted by the system on objects in the environment. This kind of confusion often led students who noted they were drawing FBD of $m_1 + m_2$ to include the force exerted by m_2 on m_1 ; an internal force for this

system. Although the students were recruited from different sections with different instructors, almost all of them had great difficulty with non-equilibrium applications of Newton's second law and Newton's third law. Some students could only recall $F_{\text{net}} = 0$ while others did not know what to do about "a" after writing down $F_{\text{net}} = ma$. A majority of students by themselves could not translate their FDBs into algebraic representation.[3] While some explicitly noted that the two boxes will have different accelerations since they have different masses, others said that the net on them should be the same since they move together. Some students who drew the force F exerted by m_2 on m_1 in the FBD in addition to F_H wrote $F_H = m_1 a$. When asked why they did not include F in the equation, some were perplexed while others wrote a separate equation with $-F = m_1 a$.

After solving the sub-problems and watching the videos as needed, all eight students opted to watch the video related to the implementation phase of problem solving in detail (students knew that they would have to solve other problems involving similar concepts without any help from videos). All students correctly solved the reflection subproblem that dealt with the hand applying a force $F_H = 10 \text{ N}$ in the opposite direction on the smaller box. The first problem that they had to solve without any help (after the tutorial) related to three boxes in contact on a frictionless surface and one pushed by a horizontal force. Students had to find the magnitude of the mutual force between the boxes. All students were able to draw the correct free body diagrams for the three boxes and write down Newton's second law equations for the non-equilibrium situation. Due to the time constraints during the interviews, once students drew the free body diagrams and wrote down Newton's second law equations correctly, they only had to explain verbally how they would solve them to find the required quantities. The only difficulty some students (typically those with lower course grade) had was whether the force exerted by box 1 on 2 is equal in magnitude to the force exerted by box 2 on 1. This finding motivated us to include additional sub-problems that specifically deal with Newton's third law. Think-aloud protocol shows that while students were doing the reflection sub-problem and pair-problems, they were explicitly trying to make connection with the tutorial problem and

articulating, for example, how Newton's second law or third should apply to that problem or how contact force of hand should not act on the object that the hand is not touching.

Summary and Future Plans

Teaching students to plan, reflect and draw qualitative inferences from quantitative problem solving is important for developing their skills. The need-based and self-paced nature of the research-guided video tutorials along with rewinding and stopping ability makes them suited for all students in introductory algebra- and calculus-based courses. Preliminary evaluations show that a majority of students who could not solve the tutorial problem on their own were able to solve similar problems on their own after working through video tutorials. Future evaluations will compare the development of skills in video tutorial learners with a control group that learned the same material for the same period of time using other means. Eventually, we also plan to pursue questions such as whether students still do original or similar problems after a couple of weeks.

References

1. J. Larkin and F. Reif, *Problem solving in Physics*, Eur. J. Sci. Ed. 1, 191, (1979); D. Maloney, *Research in Problem Solving: Physics*, in Handbook of Research on the Teaching and Learning of Science, D. Gabel (Ed.) MacMillan (1994); J. Mestre, R. Dufresne, W. Gerace, P. Hardiman, J. Touger, (1993), *Skilled Problem Solving*, J. Res. Sci. Teach., 30, 303-317 (1993); A. Van Heuvelen, *Overview Case Study Physics*, Am. J. Phys. 59, 898-907 (1991); P. Heller, R. Keith and S. Anderson, *Teaching Problem Solving: Part I*, Am. J. Phys. 60, 627, 1992.
2. H. Simon, C. Kaplan, *Foundations of Cognitive Science*, Posner (ed.), MIT press, 1989.
3. See for example, A. Arons, *A Guide to Introductory Physics Teaching*, Wiley, 1990; L. C. McDermott, P. S. Shaffer, and the Physics Education Group, University of Washington, *Tutorials in Introductory physics*, Prentice Hall, NJ, 2002.
4. <http://www.masteringphysics.com> (Pritchard et. al.)
5. A. Collins, J. Brown, and S. Newman, *Cognitive Apprenticeship*, in Resnick (Ed.), *Knowing, Learning, and Instruction*, Hillsdale, NJ: L. Erlb., 453, 1989.
6. Vygotsky, *Mind in Society*, Harvard University Press, 1978; H. Ginsberg, and S. Opper, *Piaget's Theory of Intellectual Development*, Englewood cliffs, Prentice Hall, N.J., 1969; A. H. Schoenfeld, *Mathematical Problem Solving*, New York: Academic press, 1985.