Problem solving: Physics modeling-based interactive engagement

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Contents

Abstract

The purpose of this study was to investigate how modeling-based instruction combined with an interactive-engagement teaching approach promotes students' problem solving abilities. I focused on students in a calculus-based introductory physics course, based on the matter and interactions curriculum of Chabay & Sherwood (2002) at a large state engineering and science university in the USA. Characteristic of this course is its emphasis on modeling to foster students' understanding of physics and construction of new physics knowledge and to promote their problem solving ability. In this study, I examined students' problem-solving ability during three physics problem-solving protocols phases.

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Interviews were conducted with students on an individual basis. The results showed that the modeling-based interactive teaching method may have an impact on promoting students' physics problem solving ability and move them towards thinking like experts (physicists). It can be concluded that the modeling-based interactive teaching method may have the potential to promote students' problem-solving ability in an introductory physics course.

Keywords: Modeling, physics, physics modeling, physics problems, problem solving

Introduction

In almost all introductory physics courses problem solving is a main part of the course (Hsu, Brewe, Foster, & Harper, 2004). Physics textbook chapters not only have many drill and practice problems, which are well defined and have all relevant information, but also have many solved examples of problems (Foster, 2000). The traditional lectures are full of standard problems solved by the instructor. Therefore, assessing students' knowledge of physics is based on having students solve standard physics problems. On the other hand, students should know how to apply their physics knowledge and mathematics knowledge both qualitatively and quantitatively. Even physics majors need problem-solving abilities in addition to understanding concepts.

What exactly is a problem? Are they the questions problems at the end of a physics textbook chapter? In order to answer these questions, two types of problems were introduced.

Types of problems

Drill and practice problems: These are also called standard problems (Maloney, 1994). These problems require students to recall, comprehend or apply given rules and principles (Henderson, 2002).

Real problems: These are also called true problems. According to Hayes (1989), "whenever there is a gap between where you are now and where you want to be, and you do not know how to find a way to cross the gap, you have a problem." (p.xii). Some examples given by Hayes explain well what he means by a problem. For example, if you are on one side of a river and you want to get to the other side, but you do not know how to get to the other side, then you have a problem. Another example is that if you are writing a letter and you just cannot find the polite way to say, "No, we do not want you to come and stay for a month," you have a problem (p.xii).

Real problems often require more than one step to solve them, and students usually need to break the problems into parts. After that, students need to combine parts. Also, real physics problems may not contain all of the necessary information or may contain more information than required. The purpose is to make students realize some problems may contain missing or extra information. For missing information, they are required to make estimations and approximations (Henderson, 2002). In physics, these problems are named differently. They are called context-rich problems (Heller, Keith, & Anderson, 1992) or case study problems (Van Heavelen, 1991).

In the following sections, when I talk about problems, I mean *real* (true) problems which can be context-rich problems or case study problems.

Expert-Novice differences on problem solving

Experts vs. novices provide a helpful framework for studying physics problem solving (Foster, 2000). Therefore, we should view how experts and novices approach and solve physics problems.

Experts know more and how to use the knowledge (Foster, 2000): The difference between experts and novices in physics is that experts know more physics. According to Chi, Feltovich, & Glaser (1981), novices used surface features of the problem to solve problems. Surface features are objects, physical terms, and physical configurations in a given problem. Experts did not use these surface characteristics for solving problems. They used physics principles in the solution.

Experts are deliberate and they plan before solving a problem (Foster, 2000): Experts analyze a problem carefully before solving it rather than directly using equations to solve it. This analysis done by experts is a qualitative description based on principles and not mathematical calculation (Larkin, 1979). So, the qualitative analysis is the problem solver's interpretation of the problem. Larkin & Reif (1979) called the qualitative analysis a domain-specific representation. In their study, they gave physics problems to experts and novices to solve by using a think-aloud protocol. They found that experts had qualitative physical explanations. Novices lacked physics knowledge to set up a qualitative physical explanation.

Larkin (1983) showed that experts used their domain-specific representations as a guide to solving problems before they used mathematics. Domain-specific representations include drawing diagrams. Experts in general draw figures to understand the problem before solving, whereas novices do not have this skill (Schultz & Lockhead, 1991). According to Alan Van Heuvelen (1991), students do not draw diagrams because they do not understand concepts and principles. Also, students are not taught how to create their own diagrams, and their alternative conceptions are in conflict with what they know.

An expert's process of solving a problem involves three steps (Reif & Heller, 1982). The first one is the description stage which is a translation of the problem statement into a clear description of the problem. This generates a domain-specific representation. The second one is the search for a solution stage which uses generally applicable procedures. The last one is assessing the solution stage to see if the solution meets the criteria of correct interpretation and completeness.

Larkin (1980) showed that experts used assembling, planning, solving, and checking steps before solving a problem. This means that planning is important for experts. Novices do not use planning (Foster, 2000).

Experts work forward and evaluate often (Foster, 2000): The experts tend to work forward from given values and known quantities to the wanted quantity, whereas novices tend to work backward from the desired quantity to the given variables (Larkin, McDermott, Simon, & Simon, 1980). Experts monitor and control their strategies during problem solving. They ask questions such as. "What am I doing?" "Why am I doing it?" and "How does it help me?" (Schoenfield, 1992). The answers to these questions help them to evaluate their progress and give them ideas of what to do for the next step. In contrast, novices do not tend to ask these kinds of questions during problem solving (Hendersen, 2002). Novices are not likely to evaluate their answers (Maloney, 1994).

In summary, although experts' problem solving frameworks are slightly different based on literature, each one uses the same basic themes (Heller, Keith, & Anderson, 1992).

This study reports an investigation of the impact of modeling-based interactive engagement teaching approach on students' physics problem-solving ability. In other words, do students tend to become experts?

Teaching method: Modeling-based interactive engagement

The modeling-based interactive engagement teaching method was used in the course. "Modeling" used here has a different meaning from "modeling" used in the notation of science education. Modeling is used differently in physics when we say physics modeling; a few specific fundamental principles are used to construct physics models, such as linear momentum principle, energy principle, and angular momentum principle. So it is different than modeling used in science education.

In brief, modeling in physics is defined as "making a simplified, idealized physics model of a messy real-world situation by approximations" (Chabay & Sherwood, 1999). This is also called "physics modeling" in the physics education community. In this course, physics modeling and computer simulations are used to promote conceptual understanding utilizing the interactive engagement method. Hake (1998) defines "interactive engagement (IE) methods as those designed at least in part to promote conceptual understanding through engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and/or instructors..." (Hake, 1998, p.65). It is a method that improves students' conceptual understanding by their interactions with one another encouraging problem-solving and some hands-on activities. This method provides immediate feedback from discussions with their peers, teaching assistants, and/or instructors.

Modeling-based interactive engagement instruction involves physics modeling and computer modeling that focus on the development of building conceptual understanding of physical principles and promoting of problem solving ability of students (Chabay & Sherwood, 2008).

Physics modeling

The physics model in the physics-education community is "a simplified and idealized physical system, phenomenon, or idealization." According to Greca & Moreira (2002), the physics models determine, for instance, the simplifications, the connections, and the necessary constraints. As an example one can think of a point particle model of a system in classical mechanics. Another example is a simple pendulum, which is an idealized system consisting of a mass particle on a massless string of invariant length, moving in the homogenous gravitational field of the Earth without air drag (Czudkovà & Musilovà, 2000).

In this university's calculus-based introductory physics courses, students do not use pre-defined models. They apply the fundamental principles and create models by making a simplified, idealized physics model of a messy real-world situation by means of approximations. The results or predictions of the model are then compared with the actual system. The final stage is to refine the model to obtain better agreement, if needed. Sometimes it may not be needed to vary the model to get a more exact agreement with real world phenomena. Even though the agreement may be excellent, it will never be exact since there are always some influences in the environment that cannot be considered while building the models. For instance, in an experiment where a rock is falling, while it falls the gravitational pull of the earth and air resistance are the main influences. However, there are also other effects such as humidity, wind and weather, and the rotation of the Earth and other planets (Chabay & Sherwood, 1999).

Based on physics modeling (Chabay & Sherwood, 1999) the procedure is summarized as follows:

(i) start from fundamental principles which are the linear momentum principle, the energy principle, and the angular momentum principle; (ii) estimate quantities; (iii) make assumptions and approximations; (iv) decide how to model the system; (v) explain-predict a real physical phenomenon in the system; and finally, evaluate the explanation or prediction.

In summary, physics modeling is an analysis of complex physical systems by making conscious approximations, simplifications, and idealizations. When students make approximations or simplifications, they should be able to explain why they make them. For instance, in modeling a falling ball, air resistance is generally neglected, thus, there is no force contribution from air resistance. While students do neglect air resistance, they should be able to explain why air resistance is neglected. For instance, one of the reasons is that the effects of air resistance are often very small, so it can be neglected by them for the most part when solving problems by making approximations.

The following example shows how to make use of physics modeling to explain a real-world phenomenon, which can also be considered a physics problem.

An amusement park ride (Chabay & Sherwood, 2002, p.106)**:** There is an amusement park ride that some people love and others hate where a bunch of people stand against the wall of a cylindrical room of radius R, and the room starts to rotate at higher and higher angular speed ω (Figure 1). When a certain critical angular speed is reached, the floor drops away, leaving the people stuck against the whirling wall. Explain why the people stick to the wall without falling down. Include a carefully labeled force diagram of a person, and discuss how the person's momentum changes, and why.

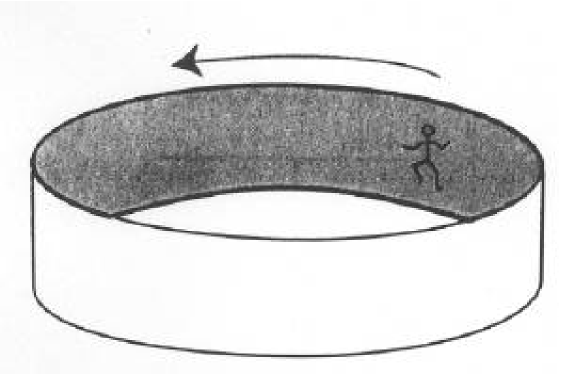

Figure 1.*amusement park ride (Chabay & Sherwood, 2002, p.106)*

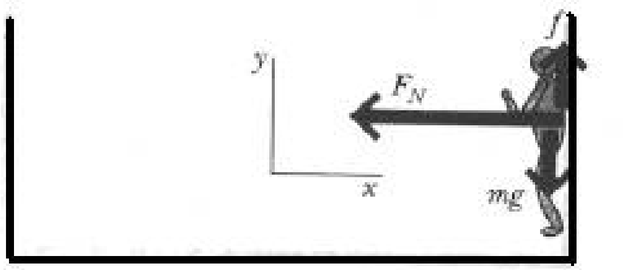

Figure 2. *Physics diagram of the person (Chabay & Sherwood, 2002, p.106)*

Starting from a fundamental physics principle, which is the momentum principle in this situation, we can determine the known forces and draw the force diagram (Figure 2). In the diagram, the person who has a mass m when the person is at the right, moving in the –z direction. The earth exerts a force which is mg downward. The wall exerts a force which has a y component +f because the person is not falling, and x component $-F_N$ normal to the wall because the person's momentum is changing direction. There is momentum change. Since the net force is not zero, the person is not moving in a straight line. From circular motion (no change in y direction), and the momentum principle,

$$\frac{d\vec{p}}{dt} = < -F_N, (f - mg), 0 > \quad p_y = 0 \text{ , so } \frac{dp_y}{dt} = 0$$

$$\left|\frac{d\vec{p}}{dt}\right| = \omega p,\ \mathrm{p} = \left|\vec{\mathrm{p}}\right|$$

$$F_N = \omega p \text{ and } f = mg$$

Combining these two,

$$p = mv = m\frac{d\vec{R}}{dt} = m\omega R,\ F_N = \omega p = m\omega^2 R$$

The vertical component f of wall force is a frictional force. If the wall has friction which is too low, the person will not stick to the wall. So, $f \leqq \mu F_N$ (μ is the coefficient of friction). μ has a value which ranges between 0.1 to 1.0. The angular speed should be enough large. Thus, $\mu(m\omega^2 R) \geq mg \Rightarrow \omega^2 \geq \frac{g}{\mu\omega^2 R}$. The smaller the friction, the higher the angular speed that is needed. When the frictional force is smaller than the gravitational force, people cannot stick to the wall and slide down. For this reason, the angular speed has to be large enough to make the frictional force greater than the gravitational force.

Computer simulations

In this course, students write computer simulation programs to simulate physical systems using the VPython (Scherer, Dubois, & Sherwood, 2000). The VPython computer simulation program is suitable for Chabay & Sherwood's curriculum because students do not need to have a programming background. Chabay & Sherwood (1999) explain why the VPython computer simulation program is suitable for this type of learning environment:

It is desirable that students themselves write the computer programs so that there are no impenetrable "black boxes."…It is also desirable that students produce 3-D animations of physical systems, and electric and magnetic fields, not just graphs, but in standard programming environments this has been very difficult to do, and students in the introductory calculus-based physics course are very knowledgeable about all uses of computers save one: programming…There isn't time to teach programming, much less how to do 3-D graphs, so it is essential to have a suitable programming environment that needs little instruction. VPython provides a suitable environment for the purpose (p.11-12).

David Scherer (Scherer et al., 2000), a student in the Matter & Interactions course at Carnegie Mellon, created VPython in 2000. The VPython program requires that students focus on physics computations to get 3-D visualizations. The VPython supports standard vector estimates, so students can represent calculations in vector form. In other words, students can do true vector estimates, which improves their understanding of the utility of vectors and vector notation. For example, students can study the motion of the earth in orbit around the sun as writing a program by VPython. The printout of the simulation is shown in Figure 1.

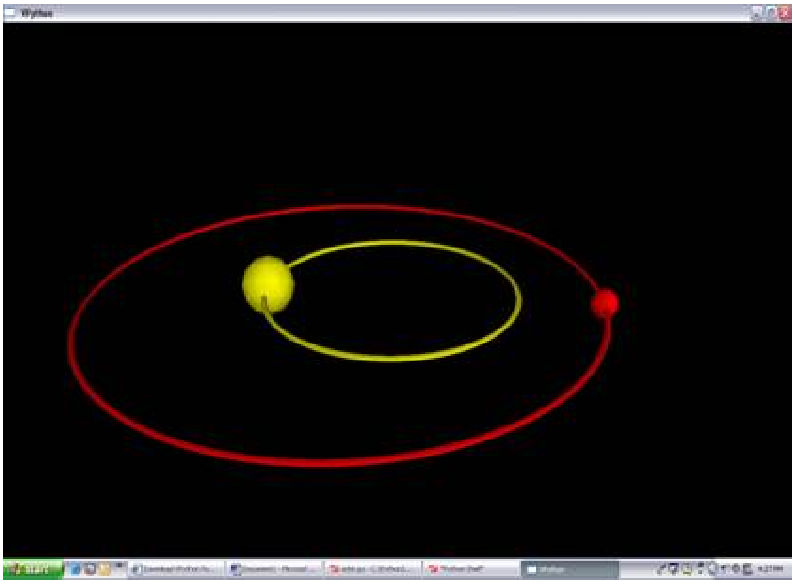

Figure 3. *Visualization for the VPython planetary orbits (Ornek, 2008).*

Figure 3 shows that a planet with a mass of ½ that of the sun is orbiting the sun in a nearly circular orbit while the sun does its orbit. While students write their own computer simulation programs and can vary the mass of the sun and the mass of planet, they need to cope with physics. Thus, Students can understand how the gravitational force law, $F_g = \frac{Gm_1m_2}{d^2}$ works between the Sun and the Earth, and how the momentum principle, $\vec{P}_{new} = \vec{P}_{before} + \vec{F}\,\Delta t$ works (G is the universal gravitation constant, m_1, m_2 represent the masses of two objects—here is the masses of the Earth and the Sun and is the distance separating the objects centers. This is a nice example of complex behavior emerging form simple physics principles, in this case the momentum principle and the gravitational force law. This illustrates the power of fundamental physics principles and gives a graphic example of the time evolution character of the momentum principle (Ornek, 2008). An example is shown in Table 1.

Table 1. *VPython Program for Producing a Real-Time 3-D Animation in Figure 1 of the Earth Going in Orbit around the Sun (Ornek, 2008).*

```
from visual import *
sun = sphere()
sun.pos = vector(-1e11,0,0)
sun.radius = 2e10
sun.color = color.yellow
sun.mass = 2e30
sun.p = vector(0, 0, -1e4) * sun.mass          [initial momentum of the sun]
earth = sphere()
earth.pos = vector(1.5e11,0,0)
earth.radius = 1e10
earth.color = color.red
earth.mass = 1e30
earth.p = -sun.p
for a in [sun, earth]:
a.orbit = curve(color=a.color, radius = 2e9)
dt = 86400
while 1:
rate(100)
dist = earth.pos - sun.pos          [distance between the earth and the sun]
force = 6.7e-11 * sun.mass * earth.mass * dist / mag(dist)**3          [the gravitational force law between the sun and the earth]
```

```
sun.p = sun.p + force*dt              [updating the momentum for the sun]
earth.p = earth.p - force*dt        [updating the momentum for the earth]
for a in [sun, earth]:
a.pos = a.pos + a.p/a.mass * dt
a.orbit.append(pos=a.pos)
print
```

Note: The explanations in [ ] are physics relationships that must be set by students. Setting up these physics relationships is the model-building step.

According to Chabay & Sherwood (2002), the modeling-based interactive engagement method can offer the potential to promote conceptual understanding of physics. Ornek (2007) found that the modeling-based interactive engagement teaching method enhances students to improve their understanding and construction of physics knowledge. In the study of Ornek, Robinson, & Haugan (2008), it was found that students at Purdue University in the US have closer views with most scientists (more favorable views) at the beginning of the course and at the end of the course than students at other universities. That finding suggests that students' expectations, attitudes, and beliefs about a physics course based on modeling and interactive engagement are more sophisticated and professional than those of students in other physics courses at other universities. Hence, we wanted to investigate how this teaching method promotes students' problem-solving ability and whether they act like experts while they are solving physics problems.

Purpose of the study and research questions

The purpose of this study was to investigate students' performance on physics problem solving. The focus of the study was:

1. How does the interactive-engagement modeling-based teaching approach promote students' problem solving ability?
2. Do students act like experts while they solve physics problems?

Methodology

Subjects and settings

We conducted this project by involving students enrolled in Purdue's PHYS 162 and PHYS 163, the two-semester introductory-physics sequence mainly populated by physics majors. We conducted the first interview with 16 volunteer students in PHYS 162 in fall 2004. At the beginning and the end of the spring, 2005, we conducted the second and third interviews with 6 volunteers from the original group of 16. There were several reasons why we lost some of our interview participants. A few of interviewees were majoring in engineering. They were taking PHYS 162 because it counted as an honors course. However, their engineering course and PHYS 163 were at the same time in the spring, 2005. The physics department and engineering department decided that Physics 162 was adequate to count for Physics 152, mechanics for science and engineering majors, instead of having to take both PHYS 162 and 163; thus, there was no need to take Physics 163, and so they dropped the class. One student had not decided about his major, so physics was something he picked up just to have a major to start with.

Structure of the course

The Purdue physics course is a two-semester introductory physics sequence for physics majors. The course, PHYS 162, which covers particles, kinematics, and conservation laws, is taught in the fall semester. PHYS 163, which covers mechanics, heat, and kinetic theory, is taught in the spring semester. The structure of the course is different than many other physics courses. During the fall semester, PHYS 162 consists of two lecture sessions, either small-group work or computer-laboratory sections, and workshops in a computer laboratory. Whether the small-group work or computer laboratory were held was decided by the instructor.

Lectures meet on Mondays, and Wednesdays. During lectures, students are actively involved in their learning. Students interact with each other and with the instructor instead of sitting, listening, watching the instructor, and taking notes. In addition, the instructor performs hands-on experiments.

Small-group work, which is called "recitation" in all traditional physics courses, meets on Tuesdays, and Thursdays. It has three sections which meet on the same day. Each section has about 24 students and is divided into 8 small groups. A traditional recitation is run by a teaching assistant solving problems in front of the class, whereas the small-group work sections in PHYS 162 are run by the instructor, a teaching assistant, and a student helper who has already taken these courses. Each small group has a small white board on which to solve physics problems. After they solve the physics problems, they share their solutions with the class by presenting their solutions. The purpose is to have students be actively involved. Teaching assistants, the instructor, and student helpers are the facilitators.

The computer-laboratory session has three sections as does the small-group work session. All computer sections are scheduled at the same time that the small-group work sections meet. The instructor decides when they will have the computer laboratory or the small-group work. Students always stay in their section of the small-group section. Each student has a computer which he/she can use and write his/her own simulation program. They use a computer program which is called VPython. Again, the instructor, a teaching assistant, and a student helper are present in each computer-laboratory section.

Workshops are held in the same computer laboratory on Fridays to help students with their difficulties understanding the content covered during classes. These workshops are problem-solving and help sessions. Also, they are for students to catch up. There are three sections in a day as well. In each workshop section, the instructor, and a teaching assistant are present. Moreover, not only the instructor, but also the teaching assistants hold office hours for students.

During the spring semester, everything is the same except for an additional lecture per--week and student helpers (they are not available during the Spring semester). Lectures meet on Mondays, Wednesdays, and Fridays at the same time as in the fall semester.

There are three 1-hour exams and a 2-hour final exam for each course. In addition, students are supposed to do homework, computer problems and daily quizzes. Daily quizzes, which happen in all semesters, are given in lecture to identify whether students understand the concepts, and also for attendance, for which credit is given.

Theoretical framework for the study: constructivism

Constructivism is used to describe a large number of different theories which fall under the general thinking that knowledge is constructed (Philips, 1995). Rather than receiving knowledge as a transmission of information that is already complete and ready to use, students construct their knowledge on the foundation of what they have previously learned. Students approach a situation with prior knowledge influencing them (Hoover, 1996). For example, students in a physics class will apply what they already know about how objects react when they are sitting in a car going around a sharp turn (Churukian, 2002). The different theories of constructivism are often delineated by adjectives which describe their primary focus. There are three types of constructivism thoughts which are personal, radical, and social. Personal constructivism (Bodner, Klobuchar, & Geelen., 2001) and social constructivism are appropriate for this study since assistance in the process of problem solving was provided and this situation is directly related to "expert help" framed in Vygotsky's (1978) social constructivismand some students invented their ideas while solving problems.

In Vygotsy's social constructivism, the More Knowledgeable Other (MKO) is a part of constructing knowledge and it happened in this study. MKO is someone who has a better understanding or a higher ability level than the students with respect to a particular task, a physics problem solving in this study. The MOK can be a teacher, or an older adult, but this is not necessarily the case (Galloway, 2001). The researcher was the MKO in this study because she was assisting the students to solve the physics problems.

Personal Constructivism is that learners actually invent their ideas (Stromnen, 1992). That is, "learners assimilate new information to simple, pre-existing notions and modify their understanding in light of new data." He believes that in the process of assimilation the learner's ideas gain in complexity and power, and, with appropriate support, learners can develop critical insight into how they think and what they know about the world.

Data collection and analysis

We began the data collection by recording a think-aloud physics problem-solving protocol, interviewing students to elicit the inner thoughts or cognitive processes that illuminate what is going on in their heads during solution of a physics problem. There was no need to conduct a training session for think-aloud protocol because during small group work, they were solving problems by using think-aloud skills with their peers on the small white board.

The physics problem-solving protocol with the volunteer students was three times throughout fall 2004, and the spring, 2005, semesters. The physics problem-solving protocol provided an opportunity to gain information about how students approached a physics problem (like an expert or not) and how they used physics principles while they were solving physics problems. The duration of a student interview varied depending upon how long a participant took to solve a physics problem. In general, it was between 25 minutes to 45 minutes. Physics problem--solving protocols are listed in Appendix A, B, and C.

The analysis in the following sections has the results of three one-on-one in depth interviews with each of six students and information from the 1st and 2nd interviews with one additional who chose not to participate in the 3rd interview. These students were given a physics problem in each interview. In the first interview, a problem involving the concept of the momentum principle, which leads to Newton's Third Law, was administered. In the second interview, a problem involving the concept of the work-energy principle was given. In the last interview, a problem related to the angular momentum principle was given.

In addition, the rubric was used for the data obtained from the physics problem-solving protocol had four parts. It was adapted it from Foster's study (Foster, 2000), with some modifications, and added some parts were added to it because it was not totally appropriate for the study. According to Foster, the problem-solving ability coding rubric has four dimensions with sub-codes which are listed in Tables 1 through 4 in Appendix D. The first dimension is general approach (GA) which assesses the student's initial qualitative approach. The second dimension is specific application of physics (SAP) which is the assessment of the students domain-specific knowledge. The third one is logical progression (LP) which codes a student's cohesiveness of the solution. The final dimension of the coding rubric is appropriate mathematics (AP) which accounts for a student's level of mathematical ability to transfer the mathematics to the new context of physics.

Results

A very straightforward check of validity of the codes from the rubric was used to analyze data is to see if the codes can be consistently applied by other people. This is called intra-rater reliability (Patton, 2002). For this study, the students' solutions to question 1, 2, and 3 were coded. Later, a graduate student who was in the physics department coded the solutions from three problem-solving sections of six students separately. To establish inter-rater reliability, the Spearman's correlation r_s for each dimension was calculated. Spearman's r_s correlation instead of Pearson's correlation was used because the sample size (N=6) was small and there were lots of ties.

The first problem-solving protocol: The Spearman's correlation r_s for general approach (GP) is 0.98; r_s for specific application of physics (SAP) is 0.95; r_s for logical progression (LP) is 0.83. Since the first question is conceptual, appropriate mathematics (AM) is not included.

The second problem-solving protocol: The Spearman's correlation r_s for general approach (GP) is 0.97; r_s for specific application of physics (SAP) is 1; r_s for logical progression (LP) is 0.89;r_s for appropriate mathematics is 0.99.

The third problem-solving protocol: The Spearman's correlation r_s for general approach (GP) is 1 which is perfect correlation; r_s for specific application of physics (SAP) is 0.73, r_s for logical progression (LP) is 0.82, r_s for appropriate mathematics (AM) is 0.78. Therefore using the codes is reliable and consistent.

The following table shows the scores of students for questions 1, 2, and 3 by using Foster's rubric. Table 2 shows the general approach (GA) scores, specific application of physics (SAP) scores, logical progression (LP) scores, and appropriate mathematics (AM) scores respectively. The numbers in the Table 2 show average scores in the first, second, and third interviews. The average scores were calculated by using the rubric in Appendix D. For each code, the average of 6 students' scores was calculated based on the rubric. For example, each student got 7 points based on the rubric in Appendix D. Six students were involved in think-aloud problem solving. So, the average score= 6x7/6=7. For each dimension, the scores were calculated in the same way.

Table 2. *Students' scores for questions 1, 2, and 3.*

SCORES			
Dimensions	**Q1**	**Q2**	**Q3**
GA	4.83	6.60	4.67

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SAP	6.16	7.50	5.92
LP	5	7	5.66

The only significant differences using Wilcoxon signed ranked tests are those between Q1 and Q2 for GA, SA, and LP.

Appropriate mathematics (AM) scores were obtained from only the second interview since only the second question includes mathematical calculations. The total score is 7.5. The averages of scores of six students are 6, 7, and 7.5. It seems that students used the appropriate math.

In addition to showing how students progress in Table 2, the data obtained from students' interviews were reported to show how students progressed throughout the course. The transcripts contain the following shorthand notation: [   ] represents comments about the interview added after the fact, {…} indicates that unimportant words were omitted from the transcript, and inaudible words or sentences were not included. Names used are pseudonyms.

Due to space constraints, only one student's physics problem solving think-aloud protocols was considered in detail in this paper. From the six students, Clark was randomly chosen by one person who did not have any input in the study and was given information in detail concerning his performance on the physics problem solving.

Clark

1st interview: Clark solves the problem correctly. He drew and identified some forces except for the gravitational forces in a correct free-body diagram for two cars. He solved the first part of the problem by means of Newton's third law instead of the momentum principle containing Newton's third law. Later and for the second part, he used the momentum principle and got Newton's third law from the principle. The excerpt below is taken from the interview.

C: Alright … Uh, diagram..car one..car two..toward the other car. [Sighs] It's got no motion since it is at rest. It's zero. So each car during the collision. Showing all forces. Car one..car two.. [sighs]. The force exerted..on car two by car one is *equal and opposite to the force on car one by car two. That's Newton's Third Law. [Pause] [mumbles something] [pause] [sighs]. Actually-*

Clark stopped talking while he was solving the problem. I asked him what he was doing. After that, he started to talk again. He used the momentum principle to solve the second part of the question. And he got the correct answer. He gave explanations step by step to make everything clear to be understood.

C: Alright. Um, just drew, uh… So I just drew a line at the top that shows the direction of the force- forces acting on the cars. 'Cause I want it to be clear that they are- if they were reading it they'd understand that there's a forces acting this way on this- on this car and forces on this one acting on this car. Um, the car during the collision... [pause] that would be F. Equal magnitude but opposite direction. The forces, uh, rank the magnitude of the horizontal forces. Give your reasoning. Uh, so the momentum principle of p equals f net dt. [Sighs] And..[makes noises] be that one car... Say car two and delta p equals f net times dt. Uh, time for the collision for both of them is equal. So we have...the equations form... [mumbles]. Relate the change in momentum in net force acting on the car. [Sighs] equal to f net..[mumble] change in momentum of one car over the net force on one- on that same car is equal to the change in momentum over the net force, um, of the other car.

C: The delta t is the same for the collision so the force is acting for the same period of time on both cars. D- during the collision. So... [mumbles] This is just the magnitude and this would be direction. Which...[pause] ...The original car is moving in the positive x direction. So the forced applied on car one would be negative. P sub one and p sub two..delta p sub one will be opposite of delta p sub two. So on delta p it can be- since- since they are not relativistic model and the mass- non relativistic model and the masses are not changing you can take mass as a delta p. You have m times negative delta p. Then equals m sub two times p. And since the masses of both cars are equal... v- I mean delta v not delta p on that. And because the mass of the cars are then same get this down to the change in velocity. For car two is equal and opposite in the change of velocity of car one. So..magnitude. Horizontal forces and give you reasoning. I just went through that already, ok. Um, the magnitudes. Magnitudes of all the horizontal forces are equal.

At this point he also used Newton's third law as if he wanted to makes sure he was doing it right.

C: ... Um, the magnitude of the forces are equal and in opposite direc- but in opposite directions. By Newton's Third Law it said that the forces would be equal in that case.

For the second part of the question, Clark uses the linear momentum principle.

C: ...it's because theFord Escort, um, has a change in momentum which by the momentum principle says that there is a force acting over a certain period of time. And there's- the only..other object in this system that it would interact with would be the moving van. So the moving van would s- is applying the force..against the Ford Escort. I mean which the Ford Escort is experiencing. Uh, (b). Does the Ford Escort exert a force on the moving van? Uh, yes it does. Same thing as the last case. There's a change in momentum of the moving van. And other objects being acted- only other object being considered in this diagram would be the Ford Escort. And the force is a, uh, is proof of an interaction. So any other way it could interact with the Ford Escort is through physical contact. Which it would be during the collision. And (c). If the answers to (a) and (b) are yes which force is larger? Explain your answers to (a), (b), and (c). Alright here's the fun part. Which force is larger? So now delta v and delta p equals f net delta t that would be our Ford escort here. And delta p of the moving van f knot and then delta t. So, same way the collision happens over the same period of time. So delta p of the Ford Escort over f net Ford Escort equals delta t. And same thing for the moving van, delta t. Delta p of van over f net. Moving van equals delta t. And since those two equations are equal to each other you can pull them together. And delta p over f net escort. Equals delta p moving van over f net. Moving van. Alright. Um... [pause] [mumbles] The force- I forgot which one I'm thinking of. So... [mumbles] [sighs] The net force- the force that the...I think that that's right. Newton's third law- by Newton's Third Law ... [sighs] the force f e. Escort- the Ford Escort on the moving van equal- would be equal and opposite to the force of the van on the Ford Escort.

C: Ok, delta- delta p of the Ford Escort... net Escort equals p over net- net van. Ok. Since this is a non-relativistic you can move the mass of each. So it will be mass of Ford Escort..delta v Ford Escort. M v. Mass of Escort equals *mass of moving van delta v. F from that. Moving van would be..initially moving at the same speed. So..um...(mumble) Um..where I'm going with this but... V is..moving van that. Let me give one equals one which proves the equation is equal. 'Cause the delta- delta p f e is equal to the delta p of the moving van. But the forces are not equal because by the equals f equals m a...this takes place because of the Ford Escort. Acceler- acceleration is..it being experience is going to be equal and opposite to. I know this problem as I'm sure most people do. So by Newton's Third Law force is equal and opposite to each other. And-*

Clark is really confused about Newton's third law and in what situations it can be applied. He started to think he cannot apply Newton's third law because of the different masses of cars. Then he does correct himself soon after.

C: ... So Newton's Third Law doesn't really apply because, um, actually yeah it does apply. But the amount of de- the amount of deceleration that the Ford Escort and the moving van experiences is equal, but the masses are different. And since the mass of the moving van is a lot larger than the Ford Escort the amount of force applied to the moving van is greater than the amount of the force applied to the Ford Escort. But…[mumbles] By that, um, the force of the moving van would be a lot larger because they would- the basic assumption right here is that acceleration- is their velocity would drop down to zero in collision. They would- they wouldn't just keep going through each other. Or they wouldn't keep going a certain direction at a certain speed. But that the accelerations would drop down to zero and because the truck was more massive than the Ford Escort the amount of force that would be required would be larger than the Ford Escort. No no that's not right… The amount of force required on the Ford Escort is equal to the amount of force required on the van.

In last part, Clark tried to explain Newton's third law in his own words. Although it is not very clear, it can be understood that this explanation says Newton's third law.

C: [pause] [sighs] one f equals f two and one two. Much that pushes back. The answer now is, um, the basic equation is used is f one on two is equal and opposite to f two on one.

Clark solved the problem correctly, but he was always in a dilemma. He was therefore exhibiting some profound conceptual difficulties with Newton's Law because he thought he could just use Newton's third law when the masses are equal.

He has the p-prim which states that since the truck is more massive, it requires larger force. He could not make links between the pieces pf knowledge. He cannot make some connection between the momentum principle and Newton's third law correctly. Finally, after a long process he got the correct answer by struggling back and forth between Newton's third law and the momentum principle. The idea of momentum principle concept and Newton's third law concept is not clear in his mind.

2nd Interview: Clark solved the problem concerning the energy principle in a short amount of time. As in his first problem solving attempt, he was aware of what principle he needed to apply. Clark answered correctly without hesitating by applying the integrated knowledge regarding choosing a system which makes the problem easy to solve, making approximations, and then applying the energy principle. He was really good at explaining each step that he followed while he was solving the problem. For example, he explained why he chose a system which is reasonable for solving the problem. The researcher did not have to talk or prompt him by asking any questions. The excerpt below is taken from the interview.

C: … Umm, objects in the system would be block, spring, and earth. Umm, well since the block is falling there's interaction between the block and the earth, and it would just be like, to contain that system. And the spring is also involved even though, because the spring is resting on the earth, and at one point the block interacts with the spring. So once you start using, once you start going in to the computations and everything, the change in energy equations will be very simple because there are no outside interactions with the system I've chosen…

At this point, he started to apply the energy principle and explain. Also, he mentioned that the speed is not relativistic, which is one of approximations. He wrote formulas correctly and did calculations. He did not make any calculation errors.

C: … You must do the analysis in terms of the system chosen in part A. All right. So…first there's no outside work done on the system. So delta E on the system is zero. So… that means that E total initial and E total final are equal, since there's no change. What you have to worry about, with the E total, is the potential gravitational energy of the block, kinetic energy of the block, energy of the spring. There is the energy of the block, but that is ignored since we're not dealing with relativistic speeds, other than change. Umm, so, plug everything in…(calculation *mumbling). Potential energy of spring initial is zero since it's at its relaxed length, there is no energy stored in each spring. (…More calculation mumbling…). So it ends up being that gravitational potential energy initial plus kinetic energy initial equals gravitational potential energy final plus kinetic energy final plus spring potential energy final. At this point, just plug in all the earlier equations. (…Calculation mumbling and writing…). So at this point you plug everything in.*

C: So…I take what is on the right side of the equation, which is 8.82 + 10 joules plus 1.5 times velocity squared final, add like terms together, and the on the left side, which is initial energy…so I just take the out energy now on the right side, and subtract it from the energy on the left side, so its 29.52 minus 18.82 which equals 10.7 joules equals 1.5 times velocity final squared. 10.7 divided by 1.5, which equals 7.13 repeating. Take that and square root of it. And the answer would equal 2.67, basically one sig fig, so it would be about 3 m/s at that point in time, and because it's in the downward direction it would be, the velocity would equal the speed.

In the last part, Clark talked about the approximations which he made. He made all approximations correctly.

C: Umm, I assumed there was no air resistance, because I am given no information on that. I assumed there were no outside interactions with the system that might have been causing work to be done, to change the energy. I assumed the spring was mass less because it would change the, how much force is on it throughout the spring. Umm, there's no energy lost to sound or any of that fun stuff. Umm, let me think. Earth is stationary.

There is no more to say about Clark's performance because he was very good at solving this problem. He used the energy principle correctly, made correct approximations, and chose the correct system. It was not possible to tell if Clark changed his problem solving skills because he also did very well in the first interview concerning the linear momentum principle.

3rd interview: Clark solved the problem correctly. Moreover, he used vector and matrices notions to solve it. He knew the concepts well and integrated them with the mathematics very well. He chose the matrices to do the cross product. Actually, it was a long way to complete the problem, but a more sophisticated way to solve it.

In other words, the way in which he used shows how to do cross product. On the other hand, it is not required to solve the problem.

C: ... Uh, object and disk system so, uh, energy... angular momentum, and momentum are conserved. So the immediately after the collision was the angular momentum of the combined-

C: Alright. Immediately after the collision what is the angular momentum of the disk plus mass m. This should be the same of the sys- same angular momentum of the system before, um, they collided. So... sighs.. Angular momentum initial equals angular momentum final so m initial. Uh...[some noise]... mass m. That's angular momentum disk. Angular momentum ball. So that would be the disk is stationary so that means there is no spin and there is no translational motion which the center of the disk is taken to be the point at which we are taking angular momentum from. So that momentum initial is zero for the disk. And angular momentum ball- or object- we'll call it ball right now- um, [mumble] Anyway initial. So and that's all translational because there's no, uh, there's no speed on it- the ball. I mean there's no spin on the ball because there is no rotational. But there is one to the- there's- there's angular momentum relative to the point relative to the center of the disk. So, and so just before the collision which would be..when is was at distance R from the center- from that point. So... uh that equals R- uh distance from that point crossed with..momentum of the object. And ok, I'm going to assume that the object is a point mass so there is no radius. So the distance at which right before it collides is the radius of the object. So [sighs].. Um, theta R... that would be v o it can have any direction. So the momentum of the ball- the momentum of the points would be the mass times the x component times the y component and the z component of the velocity vector. Put the m in it's m x , m v y, m v z is the momentum. So it would be m v x, v y, v z. For R. Distance from the- the direction I forgot how to do that one. Um...it's theta- trying to remember how to so the vector of the angle…

Clark now finds initial momentum using matrix. The following excerpt shows how he used matrix and found the initial momentum.

C: Yeah. Um, times x component of the radius zero plus one phi dx prime. Um, the other two parts.. Um... [mumbles] Ok… So the y component is, um, according to this would be R cosine theta. Yeah. And the x component would be R sine theta. Ok. [Laughs] [Mumbles] So we get zero for this matrix. This is the fun part. R *sine theta R cosine theta, zero, zero. Going to be.. first one he's out since there's a zero R. Next one is another zero. Last one would be r sine theta time m v- uh, v knot…*

C: Z component of the angular momentum. So, um, immediately after the collision the uh, angular momentum would be R sine theta time m v knot.

At this point he answered the second part of the question which asks to estimate the angular velocity of the disk. Since it is not required to know the rotational inertia for different objects, I told him the rotational inertia of a disk. On the other hand, he was supposed to know how to find the rotational inertia of combined systems. He did not know how to do that. After some assistance, he got the right answer.

C: In the z direction. Uh, two. Immediately after the collision estimate the angular velocity of the disk. Um, let's see. Angular velocity of the disk… Alright so angular velocity can be shown like this: angular velocity final. So angular of the disk would be.. Um, this would be the initial…

I: For the disk is one half, uh, m R squared.

C: One half m R squared is the moment of inertia for the disk. Um, so that means that is an initial for that last one. So it would be fi- angular momentum final would be angular momentum ball plus angular momentum disk. Its uh, angular momentum disk…

C: … With angular momentum there would be no translational because it would be all rotating at a point. So, um, momentum of the disk would equal moment of inertia times angular velocity…

I: Yeah, m R squared.

C: Be m R squared?

I: Umhm, m R squared.

C: Alright. (Sighs) Alright, so angular momentum ball equals m R squared…

C: Ok, ok. Um.. So that total momentum for the disk is one half m R squared equals angular velocity. And then angular velocity is the same moving at the same *rate, so the ball and disk [mumbles]... Plug everything back in. So R sine theta time m v y initial. So that's angular momentum final. Equals, um, m, uh, times R squared, angular velocity of system plus one half m disk R squared.*

Finally, he found the angular velocity of the disk. Also, he answered the last part of the question correctly.

C: The kinetic energy of combined system should be less because it is an inelastic collision. Some internal energy will be lost. The lost energy can be transferred to sound, vibration, or thermal energy.

Clark's performance for this interview was very good even though he had one difficulty concerning the rotational inertia for combined system. He did not have any conceptual difficulties and he made connection between energy principle, momentum principle, or approximations correctly. He did a good job in all three interview questions. He grasped the ideas of making approximations and using principles which are the linear momentum, energy, and angular momentum principles. Also, he could make links between the different concepts easily.

Conclusions and discussion

In the interviews, students were expected to use the linear momentum principle, the energy principle, and the angular momentum principle even though students were not instructed to use these principles just before the physics problem-solving protocol. At the beginning of the study, most of the students were not using expert way of solving problems especially we were looking for whether they were using the fundamental physics principles such as the linear momentum principle to solve the problems instead of starting with equations.

Some students did not use the momentum principle in the first interview. They preferred to use the Newton's third law instead. The reason can be that students learned to solve this kind of problems using Newton's 3rd law in high school. On the other hand, after I asked them to use it they were able to use it. Before the interview, I did not ask or instruct them to use it since the course is based on using these principles. On the other hand, this does not show they were not able to solve the problem. They used an alternative approach, which is the Newton's 3rd law, to solve it. In general, students may use particular aspect knowledge to answer a question or solve a problem. The following sections explain how students' performance altered throughout the course.

The First Problem-Solving Protocol: Application of the linear momentum principle and obtaining Newton's 3rd Law from the linear momentum principle

Only one student used the linear momentum principle to solve the problem and made the connection with Newton's 3rd law. One student used Newton's 3rd law and solved the question correctly. After the researcher asked him to use the linear momentum principle, he was able to use it and got the correct answer as well. Therefore, this indicates that students can use the linear momentum principle too. In other words, students who have sufficient understanding or experience acted like experts. Four students acted like experts and two students acted like novices. The other students solved the problem after some assistance. Unfortunately, three of them had conceptual difficulties and used only pieces of knowledge. Their content knowledge was fragmented. They have p-prims (diSessa, 1993). For example, their p-prim is "the bigger mass exerts the bigger force." They also were not able to make connections between the linear momentum principle and Newton's 3rd law. There might be a number of possibilities that account for some of the difficulties being observed in how students answered the question. These possibilities include the fact that the first interview was at the beginning of the semester, so students might not be familiar with the linear momentum. If they were, they would not have p-prims (diSessa, 1993) because they would get Newton's 3rd law from the linear momentum principle and saw that it does not matter having different masses. Since they used directly F=ma, they thought that the bigger mass had the bigger force.

The Second Problem-Solving Protocol: Application of the Energy Principle

All students solved the problem correctly by using the energy principle except one. Three students especially really did a good job on this problem. They used the energy principle, made the approximations correctly, and solved the problem while explaining each step well. Also, Thomas did a very good job on the conceptual part of the problem; however, he made a calculation error. Later, he realized his mistake and corrected it. The one who was struggling was Jennifer. She knew that she needed to use the energy principle, but she did not know what kind of energies would be involved. After some assistance, she did correctly. Consequently, the results appeared that students seemed to improve their problem solving ability since the first interview. In the first interview, while only two students solved the problem without prompting, four students solved the problem without prompting in the second interview.

The Third Problem-Solving Protocol: Application of the Angular Momentum and Energy Principle

Jennifer did not join in this interview. So, there were five students. Two of them were good. They used the angular momentum and energy principle correctly and made correct approximations. They did not have any problem with finding the rotational inertia of a combined system, although Clark had a problem with it even though he used the angular momentum and energy principle. Elizabeth and Thomas had some conceptual difficulties. Elizabeth had pieces of knowledge, and she tried to use them. She used the angular momentum and energy principle after some assistance. Thomas had a mathematical problem too, because he had a problem with cross product. He did not have any problems using the angular momentum, but he did with the energy principle. He used the energy principle after some assistance. From the results of the third interview, even though it may not show that there is an improvement in students physics problem-solving ability, they were aware of using the angular momentum and energy principle. There might be some reasons for not showing improvement. One can be that the third interview was at the end of the semester and students did not care much about solving the problem. The second one can be that this topic in physics is a hard topic to grasp easily, so, they were struggling solving this problem, with the exception of John and Mark. The performances of John and Mark were really good from the first interview. So, it is difficult to tell whether their problem-solving ability improved. As for Jennifer, my guess from her previous performance is that she would have some difficulties too if she joined the third interview.

Does the modeling-based instruction and interactive engagement promote students' problem solving ability and have students act like experts or not?

Protocol analysis of six students' problem solving process revealed that some students had the potential to improve their problem solving ability even though students' performance on the third problem solving protocol was lower. Students analyzed problems qualitatively before they attempted quantitative manipulation or using equations to analyze problems. Students increased their reliance on the use of principles in writing qualitative explanations of physical situations. Students' shift toward the expert-like competencies was observed. In other words, students had the potential to improve in their problem-solving performance. It was concluded that the modeling-based interactive engagement teaching approach demonstrated a success in improving students' problem-solving ability under the constraints of the study such as last interview was conducted during finals week that could affect their performance on problem solving because their minds were occupied by their exams. The research can provide evidence in favor of this instruction in terms of its success in using qualitative analyzing of the physics problems by using the fundamental physics principles.

The implications of this research in terms of instructional strategies to promote physics problem-solving ability:

The research has shown that the modeling-based interactive-engagement teaching approach can promote students' problem solving ability, so this approach can be used to teach an introductory physics course. The approach using a modeling-based interactive engagement can facilitate opportunities for students to make their problem solving processes explicit to promote their problem solving ability. In other words, students' thinking can change towards expert thinking and positive attitudes even if they cannot completely value the 3rd problem.

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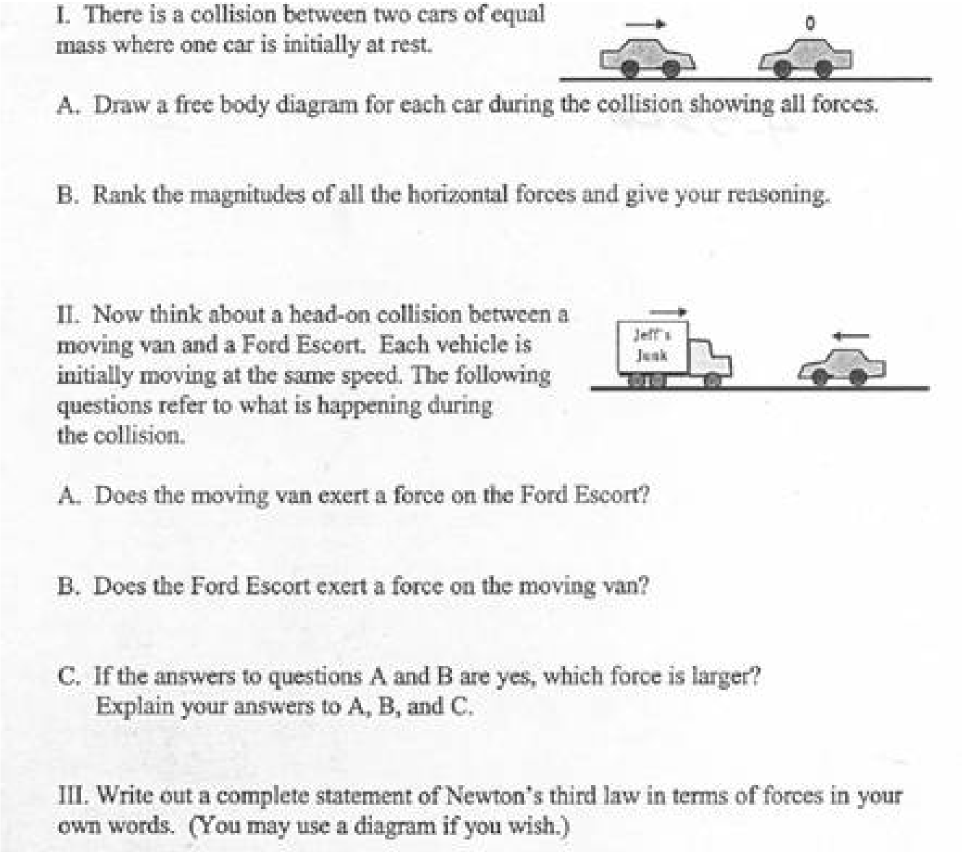
Appendix A

1st interview question for fall semester



I. There is a collision between two cars of equal mass where one car is initially at rest.

A. Draw a free body diagram for each car during the collision showing all forces.

B. Rank the magnitudes of all the horizontal forces and give your reasoning.

II. Now think about a head-on collision between a moving van and a Ford Escort. Each vehicle is initially moving at the same speed. The following questions refer to what is happening during the collision.

A. Does the moving van exert a force on the Ford Escort?

B. Does the Ford Escort exert a force on the moving van?

C. If the answers to questions A and B are yes, which force is larger? Explain your answers to A, B, and C.

III. Write out a complete statement of Newton's third law in terms of forces in your own words. (You may use a diagram if you wish.)

Appendix B

2nd interview question for spring semester

The work-energy principle

A rebounding block

A metal block of mass 3 kg is moving downward with speed 2m/s when the bottom of the block is 0.8 m above the floor (Figure B1). When the bottom of the block is 0.4 m above the floor, it strikes the top of a relaxed vertical spring 0.4 m in length. The stiffness of the spring is 2000 N/m.

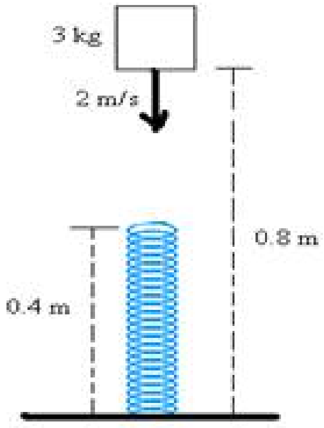


Figure B1. *A block Rebounds from a Vertical Spring (Chabay & Sherwood, 2002, p.199).*

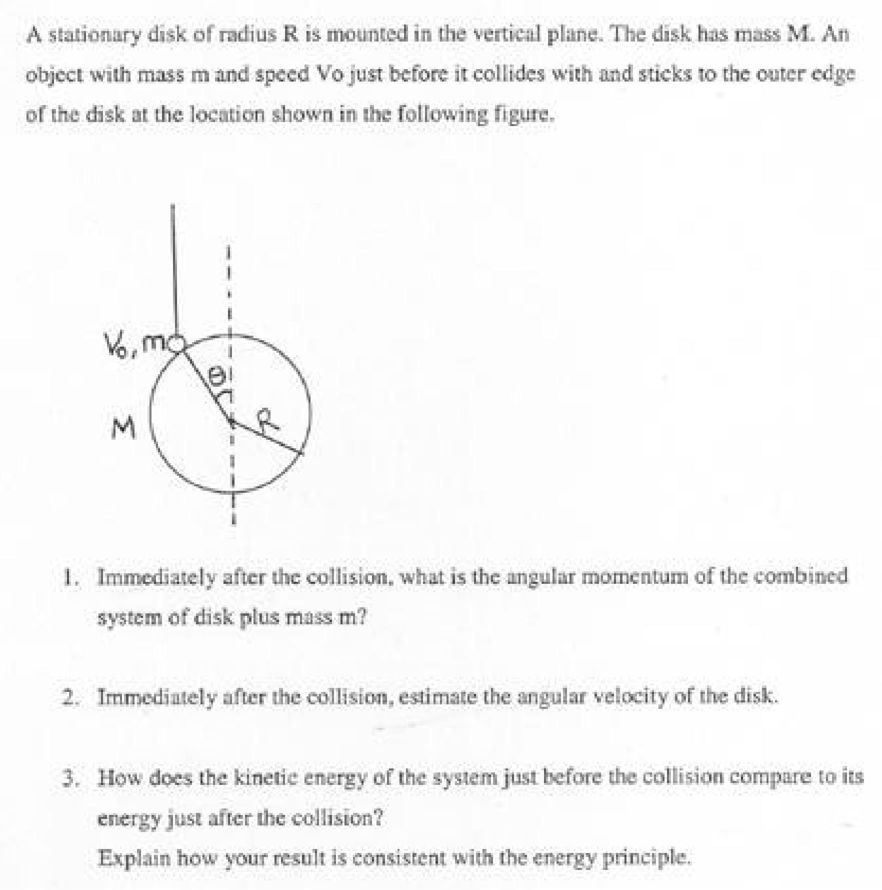
a) Choose your system and answer (b) and (c) according to your system.

b) The block continues downward. When the bottom of the block is 0.3 m above the floor, what is its speed?

c) What approximation did you make?

Appendix C

3rd interview question for spring semester



A stationary disk of radius R is mounted in the vertical plane. The disk has mass M. An object with mass m and speed Vo just before it collides with and sticks to the outer edge of the disk at the location shown in the following figure.

1. Immediately after the collision, what is the angular momentum of the combined system of disk plus mass m?
2. Immediately after the collision, estimate the angular velocity of the disk.
3. How does the kinetic energy of the system just before the collision compare to its energy just after the collision?
   Explain how your result is consistent with the energy principle.

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Appendix D

Table D1. *General Approach*

1. Nothing written.
2. Physics approach is inappropriate. Successful solution is not possible.
3. Physics approach is appropriate, but the manner of its application indicates a fundamental misunderstanding.
4. Physics approach is appropriate, but a wrong assertion is made as a serious misinterpretation of given information.
5. Physics approach is appropriate, but neglects one or more other principles necessary for the solution.
6. Physics approach is appropriate and all necessary principles included, but errors are evident.
7. Physics approach is appropriate and all necessary principles included without any conceptual errors.

Table D2. *Specific Application of Physics*

1. Nothing written.
2. Difficult to assess- Physics approach is appropriate, but the manner of its application indicates a fundamental misunderstanding.
3. Solution does not proceed past basic statement of concepts.
4. Vector/scalar confusion, or specific equations are incomplete, or confusion resolving vectors into components.
5. Wrong variable substitution: Poor variable definition. Wrong variable substitution: Difficulty in translating to a mathematical representation.
6. Careless use of coordinate system without a coordinate system defined. Careless use of coordinate system with a coordinate system defined.
7. Careless substitution of given information.
8. Specific equations do not exhibit clear inconsistencies with the general approach, but hard to tell due to poor communication.

9. Specific equations do not exhibit clear inconsistencies with the general approach and the solution is clear.

Table D3. *Logical Progression*

1. Nothing written.
2. Not applicable-one step problem.
3. The use of equations appears haphazard and the solution unsuccessful. Student may not know how to combine equations.
4. Solution is somewhat logical, but frequent unnecessary steps are made. Student may abandon earlier physics claims to reach answer.
5. Solution is logical, but unfinished. Student may stop to avoid abandoning earlier physics claims.
6. Solution meanders successfully toward answer.
7. Solution progresses from goal to answer.
8. Solution progresses from general principles to answer.

Table D4. *Appropriate Mathematics*

1. Nothing written.
2. Solution terminates for no apparent reason.
3. When an obstacle happens, “math magic” or other unjustified relationships occurs.
4. When an obstacle happens, solution stops.
5. Solution violates rules of algebra, arithmetic, or calculus.
6. Serious math errors.
7. Mathematics is correct, but numbers substituted at each step.
8. Mathematics is correct, but numbers substitute at last step.

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