Students' Reflections on an Introductory Physics Course*

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ABSTRACT FOR AAPT 1994 SUMMER MEETING (NOTRE DAME)

We have created a course format that emphasizes developing students' reasoning skills, structuring students' knowledge, and encouraging students to be self-aware and self-invested learners. An essential ingredient is a set of open-ended projects, which provide specific constraints, but which require students to define the problem and to make decisions about what aspect of the problem they should investigate. We will summarize the format of the course and give examples of materials used during the course. In particular, we will summarize and show examples of reflections of students on their experiences in the course, as expressed in written lectures to a hypothetical high-school physics class.

Introduction: The University of Massachusetts is a state institution with about 22,000 graduate and undergraduate students. Each year about 30 students complete an introductory sequence intended for physics majors, but attended also by math, chemistry, computer science, and even a few engineering majors. In the last two years we have changed the structure of the course considerably. One of the most important changes (we believe) is a set of 13 open-ended "projects", 6 of which are completed each semester. The last project of the year consists of looking back on the course and considering questions such as, "What would you have done differently?" Their reflections are organized into a lecture to a (hypothetical) high school physics class.

Structure and Style of the Course: On the surface, the course structure was traditional. All the typical components were present: three lectures/week, one 2-hour lab session/week, one discussion/week, weekly homework, two in-term exams and a final, and lab reports. However, in each of the components, the style was changed to encourage "concept-based" reasoning and problem-solving. We talked <u>about</u> learning, organizing knowledge, and building self-consistent models of the physical world. We encouraged students to challenge their own thought processes and help re-build their knowledge structure from the inside out. We strongly encouraged students to work in groups, so that they could observe how other people think. Table I summarizes the new style and structure of the course.

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COMPONENT	STYLE
Lecture	**Interactive sessions using a classroom communication system (Classtalk)**. Students work in small groups, struggling with concepts, discussing situations with other students, and usually getting immediate feedback from instructors. There are 3 lectures per week.
Lab	**Professional research teams**. Students work in cooperative groups, performing 3 experiments per semester, with roles modeled after professional research collaborations. Each experiment lasts about 4 weeks, with pre-lab, skill-seeding, data-taking, and data-analysis activities. Students meet for 2 hours each week.
Discussion	**Problem-solving sessions**. Students explore extended contexts and discuss problem-solving and critical-thinking heuristics. Students also talk about thinking, about how they learn, and about how to avoid common obstacles to learning. Discussions meet once per week.
Homework	**Concept-based problem-solving**. Students work on traditional problems with a twist. Emphasis placed on analytic skills, such as interpreting graphs, using variables to express answers, explaining how to solve problems, and sketching graphs. To compensate for Projects (see below), fewer homework problems are given, but assignments are due approximately weekly.
Exams	**Learning experiences for students**. Problems require conceptual analyses, and often students make connections and see relationships between ideas during the exam. Problems are easy if you are good at choosing and applying concepts and principles. There are two exams and one final each semester.
Projects	**Open-ended investigations**. Students must define the problem as well as solve it. They must decide what to focus on, what assumptions to make, and how to approach the problem. Approximately two weeks are given for each project. Six are done each semester.

TABLE I. CHANGES IN THE STYLE OF INTRODUCTORY PHYSICS.

Projects: We believe that the Projects are one of the most important parts of the course. We encourage (but do not require) students to work on the Projects in groups, and to submit a single report for the group. The Projects share some general features.

All Projects...

- *...expose common student difficulties.* For instance, Project #2 (see Appendix A) depends critically on understanding that force is a vector quantity and that the applied force required to accelerate an object is larger than the weight of the object.
- *...are written in the 2nd person.* Students become part of the Project, part of the solution. In one case (Project #9), there are financial incentives on the order of 10's of thousands of dollars. Even though the rewards are fictitious, students are motivated by them anyway.
- *...have extraneous, as well as insufficient, information.* Some (if not most!) of the information given in the write-up is not particularly useful for resolving the inevitable paradox. Students must often comb other sources in order to complete the project.
- *...have more than one "correct" answer.* There is never only one "correct" answer. Depending on the assumptions made, there are usually several valid solutions. We encourage students to be as original or "crazy" as they can be, as long as their reasoning is sound.

Project #12: (See Appendix A.) The last Project of the year is an excellent opportunity for students to evaluate and assess the course, and for the instructors to determine if students have been paying attention to the "big ideas". Examples of students comments have been divided into 6 categories and will be summarized on the following pages. The categories are:

- Value and Purpose of Group Work
- Students' Self-Awareness
- Views of High School Physics
- Awareness of New Approach
- Perceptions of Physics / Attitudes toward Physics
- Advice to Those Who Might Someday Take Physics

Many comments belong in more than one category and have been classified only for convenience. Most speak for themselves. A more extensive sampling of student comments can be found in Appendix B. We now give some examples.

Value and Purpose of Group Work: Although most students had little or no experience working in groups before taking this course, attitudes were generally positive. Here are some typical comments:

> "[Working on Projects] allowed me to work in a group and see how others think and reason."

> "I would have worked in groups from the beginning of the 1st semester — even for homeworks. Your thinking gets sharper and you grasp the concepts better."

> "It is essential to listen to others — both the teacher and your peers! You learn a lot from hearing other ideas and ways to look at problems."

> "Learn to work with others. Working with other students will probably help you more than anything else in school."

Self-Awareness: Students were extremely self-aware, and many were very self-critical. Here are some more of their comments:

> "I have begun to organize my knowledge and begin to give it some structure. I have learned to see the interrelationship of the many seemingly different ideas and how they relate back to certain central ideas."

> "This year… really marks the beginning of teaching myself how to 'think'."

> "Before, I looked at the question first. Now, I look at the situation first."

> "I am learning not to rely on formulas, but use them as mere tools in problem solving which is the final step after recognizing what physical concepts apply and when."

Views of High School Physics: Students were highly critical of their high school curricula. There was not even one positive comment. These are typical:

> "In high school I was taught how to solve specific types of problems that most probably appear on A.P. tests. This method of learning helped me to prepare for the A.P. test and do well, but hurt me if anything in my conceptual learning and understanding when I arrived at college."

> "In high school, my idea of a class was to learn material and regenerate it in assignments as well as tests."

> "If you can... erase your memory of any and all of the physics you've learned in high school."

Awareness of New Approach: Some students were able to describe the philosophy behind the course better than we could. They also exhibit the extent of their reflective activity during the year. For example:

> "The course requires you to gain a working knowledge of the underlying concepts and to be able to apply those ideas in different situations instead of simply memorizing equations."

Awareness of New Approach: (continued)

> "One thing I have discovered about the course is that there are not that many concepts you have to understand. The hard part is being able to understand them so well that you can apply them to an unfamiliar situation."
>
> "It took me awhile, but I finally learned that what we were being tested on was our ability to analyze and solve problems that we had not encountered previously in the course. This allowed us to show our ability to apply the newly learned concepts to original problems using nothing more than clear and intelligent thinking."
>
> "The most important word to remember when taking the course is STRUCTURE. With it average students can do well and without it, great students do very poorly."
>
> "And don't forget that someone can know a formula up, down, sideways, and adjacent and not have a clue to what's happening."

Perceptions of Physics /Attitudes toward Physics: Students generally had positive attitudes toward college physics:

> "College physics is about concepts and underlying principles and laws, it is definitely not a memorization class. Don't expect to be regurgitating facts and formulas for the professor. College physics is about problem solving and thinking and thinking about thinking."
>
> "I have realized that physics is more than just equations, and that it takes some good thought."
>
> "I was constantly frustrated, overworked, and forced to withhold from sleep because of this class. [...] It is like hiking up a steep mountain. I hate it when I'm actually doing it, but I love it when I am at the top..."

Advice to Those Who Might Someday Take Physics: Most of the advice (from about half the students) was to keep an open mind. Here are two examples:

> "Other tidbits: keep an open mind, have a willingness to examine one's preconceptions, and be courageous enough to change one's way of thinking."
>
> "One should come to this class with an open mind. A mind that is very accepting of change. There will be numerous times… when you feel you know what's going on, only to find out that you were way off."

Other advice dealt mostly with getting assignments in on time and being overworked. A number also gave advice dealing with frustration and other emotional issues. A typical comment was:

> "In order to be able to think usefully in physics, I would suggest to incoming students that they try to work on their patience. It requires a lot of patience to successfully work on a physics problem."
>
> "Advice I would give students is to not give up easily and to stay calm."

Summary and Conclusions:

(1) Students can learn to be reflective and self-aware. They can learn to be "defensive" learners, participating in the communication process, challenging their own thought processes and those of others, taking an active role in their own learning.

(2) Students like to work in groups and are aware of the benefits of group interaction for their own critical-thinking skills.

(3) Students like working on open-ended projects. Sometimes they complain that the Projects are too interesting, too much fun to work on, and they aren't doing any work in their other courses as a result!

(4) Perhaps it is easier to combat preconceptions from the "inside" by asking students to be partners in the learning process.

APPENDIX A

FULL TEXT OF PROJECTS 1 – 13

What do you tell Joe's parents?

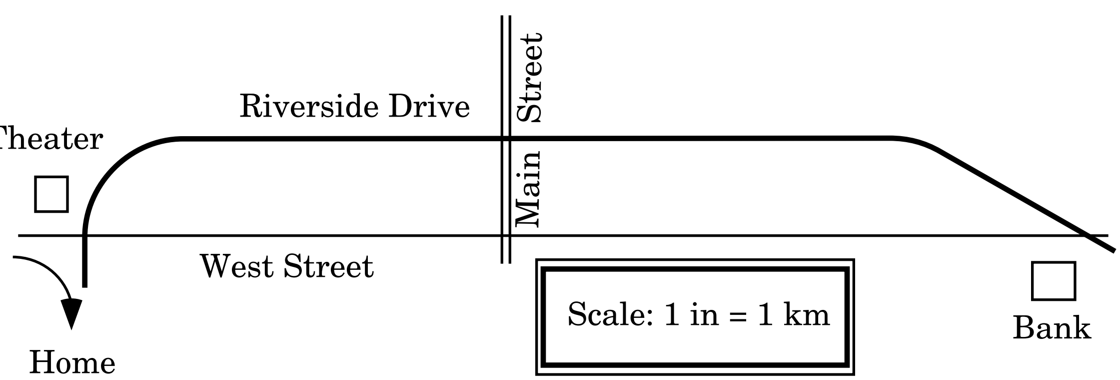
Project #1

Joe is having a fight with his parents. You are Joe's best friend, so he's asked you to talk to his parents. Here's what everyone has to say:

> ***Joe:*** I was driving up Riverside, toward the theater, when I thought I saw Mom's car stopped on West Street. I checked my speedometer to make sure I was going the speed limit—40 mph. (You know, I'm not supposed to speed in Dad's sportscar.) I figured Mom was going home, but I made sure I didn't go over the speed limit anyway. I couldn't believe it when I saw her car again when I was coming down the other end of Riverside. Man, did I get in trouble when I came home! Mom said I must have been speeding, but I wasn't. I made sure of it. But now I can't use the car anyway. I really need a car. Can you talk some sense into them?
>
> ***Joe's mom:*** I was stopped at the stop sign at West Street and Riverside Drive, when I saw Joe drive by. He didn't look like he was speeding, but I thought I'd keep going on West Street just to make sure. I drove at 40 mph the whole time I was on West Street, so I knew I'd get to the intersection first. Of course, I couldn't believe it when he got there before me—by at least 5 seconds!—so I knew he must have been speeding after he passed me the first time. I'm so disappointed.
>
> ***Joe's dad:*** Clearly, he was speeding. Mother went the same speed as the speed limit on Riverside. Since he got to the bank first, he must have been going over 40 mph. Therefore, I can't let him use any of our cars if he's not going to respect our wishes.

What do you tell Joe's parents?

Map of relevant area:



Note: Drivers on West Street have stop signs as they cross Riverside Drive (both times) and Main Street. Drivers on Riverside Drive do not stop as they cross West Street, but must stop before crossing Main Street. All curves are circular arcs.

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What caused the accident?

Project #2

The consulting firm at which you are employed has been asked to investigate an accident and provide expert advice to the owner of a stevedore company. The accident occurred while unloading cargo from a ship's hold. Cargo was damaged and a worker was injured, so it will likely be a large lawsuit. The worker (Al) and the owner of the cargo have both filed suit against the company. The owner of the company (Mrs. Sheldon) wants to know if there is any basis for suing equipment providers. Your firm has sent an investigator (Janice) who has gathered information and taken the testimony of the principals involved. Her report contains the following information:

Testimony of the crane operator, Ernie: The loaded palette was over the dock and I was just about to set it down when I heard this squealing noise from the windlass behind me. The palette couldn't have been more than a foot or so off the ground. The next thing I know the load tipped and the crates crashed to the dock. It wasn't my fault.

Testimony of the worker, Al: I don't know whose fault it was, but, in my opinion, they never should have had four crates on that palette. They each weigh 1500 kilos and three's plenty heavy. Any more than four would have obstructed the cables. I clearly saw one of the four palette cables, which are rated at 20,000 N, snap just before the load reached the dock.

Testimony of the foreman, Mikel: Al is nuts. We could have put a fifth crate on; they are only a meter cube, but I don't like to stack them. I run a safe shift. I make sure the palette is well-balanced, and I make sure the crates are as far from the edge of the palette as possible; at least a foot. Besides, the crates had to be centered or they would interfere with the cables. I think it's Ernie's fault. He's always been a cowboy. He drops the load at maximum speed and then tries to stop it in the last meter.

Testimony of the owner, Mrs. Sheldon: I pride myself on a safe operation. I always keep the equipment in good repair. That main cable is rated at 80,000 N, well over the requirement. I don't think it is Ernie's fault. He's a very safe worker. Hasn't had an accident in 10 years on the job. Ernie says it was the windlass and I believe him. That was a brand new windlass. If it was the windlass I want to know so I can sue the manufacturer. Here are its specs: Max. power rating 150 kN-m/s; Max. force 75 kN; Max. speed 2 m/s.

Comments by the investigator, Janice: Typical operation consisted of loading a 3-meter square metallic palette with cargo. The palette itself weighs 500 kg. Attached to each corner of the palette is a cable, the other end of which is attached to the main crane cable. The palette cables consist of twelve twisted strands of steel, each rated at 2000 N. Inspection of the unsnapped cables revealed that two had a broken strand. This damage may have been caused at the time of the accident. In any case the remaining eleven strands would still provide the required 10% safety margin for the rating. The windlass shows no permanent damage and can not be made to malfunction.

Your report should analyze the accident and assess the likelihood that the accident was due to the windlass, faulty cables, or human judgment.

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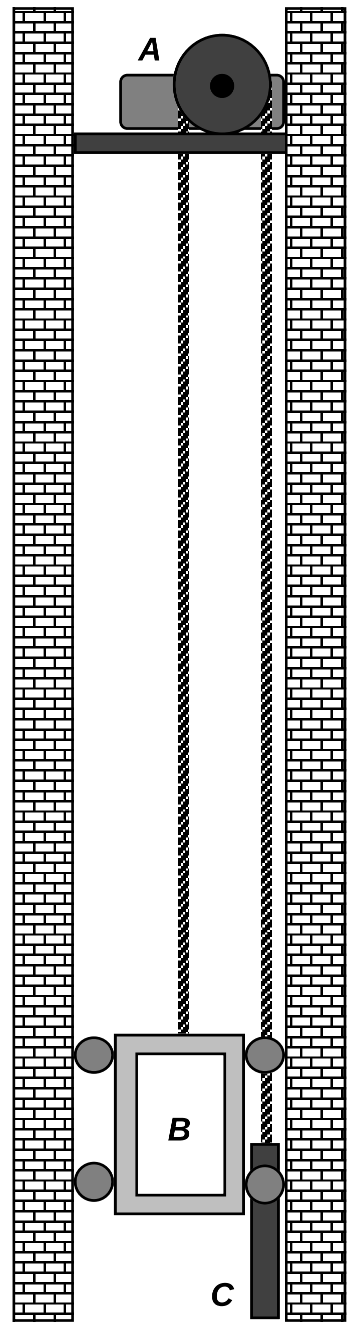
How would you design the elevator system?

Project #3

As part of your job for a construction firm, you are asked to provide some specifications for an elevator system. In particular you are to specify the force required by the drive motor and some features of the safety system. The building has eight stories above ground and one basement level. Each floor has a height of 3 meters. The elevator cage has a mass of 1000 kg. The elevator is to have a maximum load capacity equal to its own mass. The balancing weight is equal to that of the cage plus half the maximum load capacity.



The Drive

A diagram of the elevator system is shown at right. It is desired that the elevator (*B*) should be able to accelerate (up or down, loaded or unloaded) with an acceleration of $0.2g$, and be able to maintain a maximum constant speed of 3 m/s.

What maximum force should the motor (*A*) be capable of delivering? What maximum power?

Comment on whether you think that the choice of balancing weight (*C*) is optimal. What considerations do you think should be involved in the selection of the balancing weight?

The Safety System

Should the motor slip or disengage, or if the cable breaks, the elevator is equipped with 4 brakes which grab the four beams that guide the elevator (not shown in the diagram). Each brake grabs its beam with a normal contact force of 10,000 N. The coefficient of kinetic friction between the brake shoes and the beam is 0.35, and the coefficient of static friction is 0.5. In the event that the friction brakes are insufficient to prevent motion, a set of springs is installed just below the lowest point of the elevator's motion. Each of these springs has a spring constant of $k = 20{,}000$ N/m, and it is desired that the elevator stop descending within 2 m after making contact with the springs.

For what range of loads are the friction brakes sufficient to prevent motion? Does your answer depend on the state of motion of the elevator when the failure occurs? How?

What is a practical minimum for the number of such springs that should be installed to prevent the elevator from crashing when it does slip? Describe the subsequent motion of the elevator after it stops for the first time.

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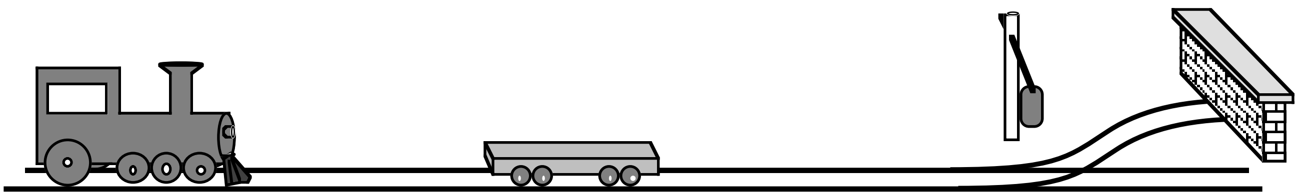
Can you help Indy... survive?

Project #4

Your firm has been hired as technical consultants for a Hollywood filmmaker to advise them on the safety of a stunt scenario they are considering for an action film. There are several variants of the stunt and you are to assess the possibility and safety of each variant. The basic scenario is that our hero, m_{hero} = 80 kg, is on a flat railroad car, m_{car} = 800 kg, which is moving with a speed of 15 m/s. The villain is chasing him with a locomotive, $m_{locomotive}$ = 3000 kg, traveling with speed 28 m/s. The hero must take some action or be killed when the locomotive strikes the flatcar. The director is considering four possible actions for the hero as described below. The initial situation is depicted below. (Note: this diagram is *not* to scale.)



The flatcar has a length of 10 meters and the locomotive has length 15 meters. The flatcar and locomotive are initially positioned so that the collision (assuming the hero remains stationary at the center of the flatcar) would occur just after the switching tracks (used in variant C) and mail-transfer arm (used in variant D).

Variant A. The hero goes to the back of the flatcar, runs forward until his velocity relative to the flatcar is 5 m/s. He then jumps into the air just before the locomotive collides and couples to the flatcar. The hero then lands on the flatcar, which has an increased speed as the result of the collision.

Variant B. Same as variant A, but the locomotive does not couple to the flatcar. The collision is, therefore, not perfectly inelastic, but may not be elastic either.

Variant C. A fraction of a second before the collision the hero diverts the flatcar to a siding, which (naturally!) terminates in a brick wall after 50 m. The hero can lock on the flatcar's brakes, which provide a stopping force of 1000 N. The hero then proceeds to the front of the car and, just before the car hits the wall, runs towards the back of the car and jumps off.

Variant D. Looking ahead, the hero sees a mail sack, m_{sack} = 40 kg, suspended from a rotating steel rod of length 3.2 meters. (Assume for these purposes that the rod is massless.) The hero walks to the back of the flatcar, then runs forward until his speed relative to the flatcar is 5 m/s. Timed to occur just before the collision, the hero then jumps up, grabs the mail sack, and rotates about the pivot of the rod. The hero makes one revolution just in time to jump on the back of the locomotive (the collision being over) and is able to subdue the villain.

Your firm's task: You should examine each of the variants for their practicality and safety. Typically, a stunt person can safely tolerate an impact equivalent to jumping off a one-story building (3 meters). They can jump between two surfaces so long as the relative speed between the surfaces is less than 4 or 5 m/s. If you conclude that a variant is possible with slight changes in the parameters, you should describe the changes.

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Which rod hits the ground first?

Project #5

Four students from one of your classes approach you and ask that you resolve a disagreement that they are having about a Physics problem that they have been trying to answer. The problem is this:

> A thin rod having mass *m*, length *L*, is initially at rest in a vertical position and falls to a horizontal position under the influence of gravity. Consider the time that it takes the rod to achieve a horizontal position in each of the following cases:
>
> (*a*) The rod is standing on a perfectly frictionless surface.
> (*b*) The bottom of the rod is held fixed by a frictionless pivot.
> (*c*) The rod is free but standing against a wall on a frictionless surface.
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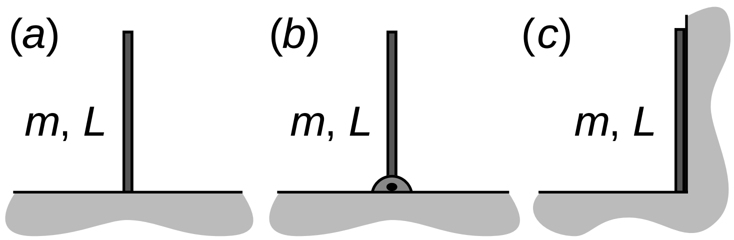
> 
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>
> In which of the three cases is the time between release and the time that the rod hits the horizontal surface the shortest? Which case takes the greatest time?

Alissa says: I think that they all hit at the same time. After all, the only force around that can do work is gravity, and that's conservative. They all have to have the same kinetic energy when they hit.

Bob argues: I'm not sure about the other two cases, but I think that the pivoted stick hits first. Clearly the top of the stick is always moving fastest in that case.

Cathy responds: Look, case (*a*) must be fastest because the center of mass of the rod moves the shortest distance—straight down.

Dan asserts: What we've got to do is be methodical about this. Now there are other forces around besides gravity. They might not be able to do any work, but… er… it seems to me that they might still be able to provide impulse. All of the rods have to rotate… Hmmm… Consider case (*c*) for example. Although they all have the same kinetic energy when they hit the surface, in case (*c*) the rod continues to move in the *x*-direction. That ought to mean something. Since gravity acts down, it can't be the source of the horizontal momentum. Some other force had to provide that velocity. Probably the wall. But then why wouldn't the same be true for the pivoted case. Still, if some of the kinetic energy is for horizontal motion, that should leave less for vertical motion. Unless, of course, it is compensated by the rotational kinetic energy. But that is just a rephrase of the problem, isn't it. All of the rods make a quarter turn in the time it takes them to reach the horizontal position. If we knew that time, we could find out the speed of rotation and the kinetic energy associated with rotation. The rest of the kinetic energy would be available for the downward motion. On the other hand… Well, anyway… I am sure that case (*b*) can't be the fastest. I mean, like, how could it be? Right?

Your Task

What would you tell these students to help them resolve their confusion? Which statements are correct? Which are incorrect? How would you clearly explain to them the way to determine the time it takes each of the rods to hit the surface? Which hits first? Which hits last?

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How would you change orbits?

Project #6

As a member of the orbit simulations group at NASA, you have been consulted by the launch division to help remedy a problem they have. They have just launched a 3000-kg satellite. Unfortunately, due to a booster malfunction, the satellite is in a circular orbit at six times the radius of the Earth when it should be in a geosynchronous orbit (one having the same angular velocity as the Earth). Your group's task is to advise them how to correct the orbit using as little fuel as possible.

Having worked on problems of this sort before, you are aware that the total energy of the satellite and its angular momentum completely determine the orbit parameters—*i.e.*, apogee, perigee, eccentricity, *etc.* Therefore, you set about determining the radius, speed, energy, and angular momentum of the initial and final orbits. Once these are known, your group can determine how to make the transition from one orbit to the other most efficiently.

A hint on how to proceed.

Starting from the original orbit, consider giving the satellite an instantaneous linear impulse equal to some fraction (*e.g.*, 5%) of its momentum. The new orbit will depend upon the direction of the impulse. (Obviously, the rocket engines can not provide instantaneous impulses, but close enough for our purposes.)

If the impulse is directed radially, for example, the energy of the satellite will be changed, but its angular momentum will remain the same. What are the apogee and perigee of this modified orbit?

If the impulse is delivered in any other direction, both the energy and the angular momentum will change. Consider the cases when the impulse is directed in the forward and backward directions. The new energy and angular momentum are easily found in these two cases. Again, what are the new orbit parameters?

To help you get started, consider the expression for the total energy of the satellite given below in polar coordinates.

$$E = \tfrac{1}{2}mv^2 - \frac{GM_{\mathrm{earth}}m}{r}$$

where:

$$\mathbf{v} = \frac{\mathrm{d}r}{\mathrm{d}t}\,\hat{\mathrm{r}} + r\frac{\mathrm{d}\theta}{\mathrm{d}t}\,\hat{\theta} = v_r\,\hat{\mathrm{r}} + v_\theta\,\hat{\theta}$$

So the total energy can be written:

$$E = \tfrac{1}{2}m\left(v_r^2 + v_\theta^2\right) - \frac{GM_{\mathrm{earth}}m}{r}$$

This expression can be rewritten to show the explicit dependence of the energy upon the angular momentum. Note that the apogee and perigee—the largest and smallest distance to the center of the Earth—are given by the values of *r* for which the radial component of the velocity is zero.

$$E = \tfrac{1}{2}m\left(v_r^2 + \left(\frac{\ell}{mr}\right)^2\right) - \frac{GM_{\mathrm{earth}}m}{r}$$

since $\ell = mv_\theta r$, or simply:

$$E = \tfrac{1}{2}mv_r^2 + \frac{\ell^2}{2mr^2} - \frac{GM_{\mathrm{earth}}m}{r}$$

For many problems, this is the most convenient form for the total energy of a satellite of mass *m* orbiting the Earth.

The problem of fuel efficiency can be rephrased as follows: How can the satellite be made to assume the desired orbit by delivering the least amount of impulse? It will take at least two impulses to accomplish this.

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How would you design the dam?

Project #7

The consulting firm for which you work has been hired to do a rough feasibility study of the practicality of constructing a hydroelectric dam at a certain location. Your group has just received a copy of the field report which contains the following information:

The river flow rate ranges from 1600 m^3/sec during Spring to 1200 m^3/sec in the Fall.

The region behind the dam is a canyon with relatively sheer walls of height 250 meters with an average separation of 400 meters, closed at one end by a rock wall roughly half-cylindrical in shape. The river drops from the height of 250 meters at the closed end and runs between the canyon walls for about 5000 meters.

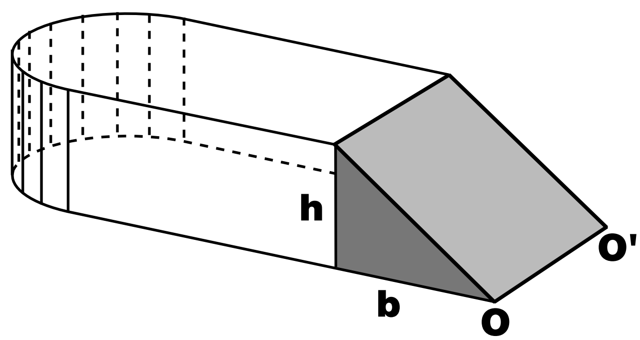
Other relevant facts:

It is usually uneconomical to construct a hydroelectric dam unless the average power production is at least 2 GW.

Generally, a good conversion factor for converting mechanical energy to electrical energy using a water driven turbine is about 0.6.

Dams are constructed to be thicker at the base than at the top to be able to withstand the greater force per unit area near the base and have a base of sufficient length to have no net torque about the forward edge (line OO' in the drawing).

Take a simple model of the dam as an object of length sufficient to close off the canyon, having a wedge-shaped cross section with base b and height h. Assume that the dam is constructed from reinforced poured concrete. Take the density of concrete to be 4 times that of water.



Your report should discuss the practicality of such a model dam and specifically address the following questions:

(*a*) What is the minimum height of a practical dam?

(*b*) If the full depth of the canyon is used, what is the maximum power-generation capability?

(*c*) Assuming that the dam is constructed so that the torque about the line OO' due to the water behind the dam equals the torque due to the weight of the dam itself, what is the base of the dam?

(*d*) Estimate how long it would take to fill the canyon.

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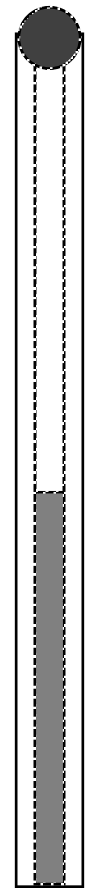
How would you design the pendulum of a clock?

Project #8



Your group is exploring the possibility of applying for a patent for a pendulum clock that is very accurate over a wide range of temperatures. The basic design of the clock is very simple and consists of a pendulum made from a glass tube partially filled with mercury, as shown to the right.

Consider a specific example of a clock that uses a pendulum made from a hollow tube of Pyrex glass of length 1 meter. The Pyrex tube has a mass per unit length of 4 grams per centimeter, and the cross-sectional area of the hollow portion of the tube is 1 square millimeter. (The coefficient of linear expansion for Pyrex glass is $3.2 \times 10^{-6}/C°$.) At room temperature (25° C) the tube is half-filled with mercury.

Your report should contain:

(*a*) A derivation of the expression for the period of a physical pendulum.

(*b*) The value of the period of a clock that uses the particular pendulum described above.

(*c*) The range of temperatures over which the clock is accurate to within 1 second per day. (You may use any procedure you wish to find this range.)

(*d*) Suggestions for design modifications that would produce a clock having this accuracy over a range of ±20° C from room temperature.

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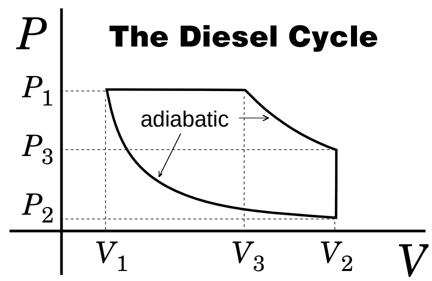
How would you design a more efficient engine?

Project #9

The company for which you work has just announced a new cost-cutting program. The essence of the program is that employees submitting suggestions on how the company can be run more efficiently and economically will be paid a one-time bonus equal to 20% of the annual savings realized if the suggestion is adopted. Each suggestion must be accompanied by a reasonably detailed and convincing presentation of the effectiveness of the modification.

Over lunch, you and your colleagues have come up with a great idea that could lead to a significant bonus for all of you. Basically, the idea is that the company should replace its existing power generating equipment, which consists of internal-combustion Otto-cycle engines, with more efficient Diesel engines. In both cases assume that the air and fuel mixture can be approximated by a perfect diatomic gas having $\gamma = c_p / c_v = 1.4$.

The Otto engine is a thermodynamic cycle consisting of two adiabats and two constant volume portions. The Otto reversible cycle is an idealized version of a typical automobile internal combustion engine. The Diesel cycle is shown at right.



Your group has found out from accounting that last year the company spent $140,000 on gasoline used to power a number of Otto-cycle engines. Your friends from maintenance have informed you that the engines used are 2.4-liter engines with a compression ratio of 6.

Under what circumstances would a Diesel engine operating between the same volumes be more efficient? Need you modify any of the other operating parameters?

Now Diesel fuel can be purchased at 70% of the cost of higher grade fuels but only have about 85% of the energy content. The cost of replacing the engines would run about $50,000, but that expense could be amortized over a 5-year recovery time.

Assuming that all other efficiencies in the manufacturing process remain the same, and that maintenance costs are the same for both types of engines, estimate what bonus you and your colleagues might be able to get.

Your report should contain:

(*a*) a drawing of the Otto cycle, and a determination of the efficiency of the present Otto engines;

(*b*) a design and specifications of a Diesel engine, together with its efficiency and compared to a Carnot engine operating between the same temperature extremes; and

(*c*) the estimated annual fuel savings for the company.

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Could you track something using sound waves?

Project #10

The company for which you work is studying the feasibility of an ultrasonic tracking device for use in surveillance. The device transmits a signal with a frequency of 100 kilohertz.

The task of your analysis team is to develop tracking algorithms that enable an observer to track the movements of the device using the Doppler-shift phenomenon and the fact that the power per unit area in a spherical wave front falls off as the reciprocal square of the distance to the source. Your team has been provided with a set of data containing the observed intensity, the observed frequency, and the direction of the observed signal as an angle measured to the direction of the original observation, all as a function of time at one-second intervals. The data is collected by a receiver located at a fixed point while the transmitter is moved along a closed regular geometric shape.

Your report should contain the coordinates of the transmitter as a function of time as it traverses the regular geometric shape and a plot of this shape. A complete explanation of the algorithm used to construct the path of the transmitter should also be in the report. Further, a plot of v_r, the (polar) radial component of the transmitter's velocity, vs. t should be obtained.

Additional issues you should consider in your report:

- What are the primary sources of error in your reconstruction? Can you think of ways to reduce this error?
- How would you have to modify your algorithm to reconstruct 3-dimensional motion? Would it work if the transmitter were on a device submerged in water? How well?
- How does your algorithm take account of the retardation effect, *i.e.* that the signal received was sent at an earlier time?

Hints: You will probably find it helpful to review the transformation from Cartesian to polar coordinates. You should also note that position and velocity can be decomposed into a radial component (component along the line of sight) and one perpendicular to this direction. How can you determine the radial component of the velocity of the transmitter from the data given? How can you determine the *change* in distance to the receiver (origin) from a plot of the radial velocity? How can you best estimate the initial distance between transmitter and receiver, *without* knowing the power output of the transmitter?

Note: You have been provided data at one-second intervals. You may not need all of this data to generate an idea of the motion of the transmitter. Obviously the more data used the more accurate your result will be. If you desire you may obtain a copy of the data on disk as a text or numerical data file. You should use 340 m/s as the speed of sound in air.

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time (s)	angle (°)	intensity ($\times10^{-6}$ W/m^2)	frequency ($\times10^5$ Hz)	time (s)	angle (°)	intensity ($\times10^{-6}$ W/m^2)	frequency ($\times10^5$ Hz)
0	0.0	0.796	1.000				
1	1.1	0.795	0.999	26	26.2	0.972	1.086
2	2.3	0.411	0.998	27	27.2	1.038	1.086
3	3.4	0.793	0.996	28	28.2	1.111	1.084
4	4.6	0.791	0.995	29	29.6	1.199	1.092
5	5.7	0.788	0.994	30	28.8	1.219	1.019
6	6.8	0.785	0.993	31	27.1	1.206	0.988
7	7.9	0.781	0.992	32	25.3	1.196	0.984
8	9.1	0.776	0.991	33	23.7	0.644	0.983
9	10.2	0.771	0.990	34	21.9	1.160	0.980
10	11.2	0.765	0.989	35	20.3	1.141	0.978
11	12.3	0.251	0.988	36	18.8	1.122	0.977
12	13.4	0.203	0.986	37	17.1	1.101	0.977
13	14.5	0.142	0.986	38	15.6	1.079	0.974
14	15.5	0.138	0.984	39	14.0	1.059	0.972
15	16.6	0.135	0.984	40	12.8	1.034	0.970
16	17.6	0.131	0.983	41	11.5	1.009	0.971
17	18.6	0.128	0.982	42	9.7	0.985	0.968
18	19.6	0.124	0.981	43	8.5	0.962	0.968
19	20.6	0.120	0.980	44	7.2	0.539	0.966
20	21.6	0.115	0.968	45	6.0	0.913	0.965
21	22.3	0.187	1.079	46	4.6	0.893	0.962
22	23.0	0.246	1.088	47	3.8	0.865	0.960
23	23.7	0.257	1.088	48	2.5	0.838	0.960
24	24.5	0.271	1.088	49	1.3	0.816	0.957
25	25.4	0.324	1.086	50	0.0	0.796	0.958

How would you explain these illusions?

Project #11

You and a friend have just attended a show by the famous illusionist, David Copperfield. Your friend, who does not know much physics, asks you how some of these apparently impossible feats can be performed.

(*a*) Using only simple optics, explain to your friend how mirrors can be used to make it appear that you see the entire interior of a box when in fact you are only seeing a portion of the interior. Your response to this question should be accompanied by convincing drawings and diagrams.

(*b*) Can you think of a method to make it appear that you are looking completely <u>through</u> a box when you are not? If you can't think of a way to do this in general, can you design a system having a particular geometry or arrangement?

(*c*) You have been shown several of his famous illusions: Being sawed in half; removing someone's head; collapsing someone's body into nothing; *etc*. Explain how you think one of these illusions might have been done. Again your explanation can not simply be an opinion. You must back up your statements with a credible explanation of the details of the illusion.

What would you say to a high-school physics class?

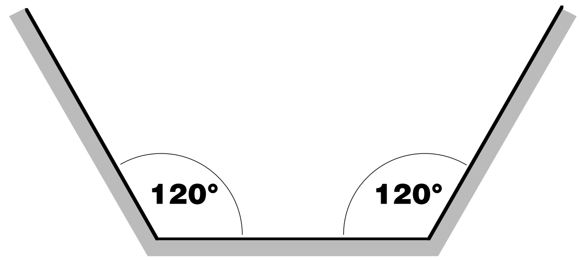
Project #12

A local teacher has asked you to address a high-school physics class. What new physics have you learned? How has your perception of physics changed? Has your interest in physics increased or decreased? Why? Would you recommend that they take physics in college? Under what circumstances? What advice do you have for those students who will take physics in college? In particular: What skills should they have or should they develop before taking physics? What attitude(s) should they have? How should they approach the course? Knowing what you do now, would you have done anything differently? What would you have done differently?

How many “images” do you see?

Project #13

Consider an arrangement of three plane mirrors as shown. (Such devices are typically seen in clothing stores.) There are locations in the region between the mirrors where someone would see only a single image of themselves. There are other regions where two images could be seen, and still other regions where more than two images could be seen.



(*a*) Indicate on the grid below (or a suitable copy) each of these regions and ***explain*** your method for defining each region.

(*b*) What is the maximum number of images that can be seen?

Remember that you are the observer as well as the object. For simplicity, assume you are a point object. (*I.e.*, close one eye; how many images of your open eye would you see?)

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Appendix B

Written Comments by Students (from Project #12: "What would you say to a high-school physics class?")

I feel that I could have done better in group interactions. I have always been a quiet person, but in the past year I have changed a lot in that respect. If I had changed earlier, I may have gotten even more from the course.

I would have worked in groups from the beginning of the 1st semester — even for homeworks. Your thinking gets sharper and you grasp the concepts better.

In the context of group projects, I discovered that talking about physics concepts is a wonderful supplement to individual studying.

It is essential to listen to others — both the teacher and your peers! You learn a lot from hearing other ideas and ways to look at problems.

Learn to work with others. Working with other students will probably help you more than anything else in school.

Many times throughout the course we were presented with complex problems in the form of projects to be worked on in groups. At first, some of these projects seemed overwhelming and unsolvable. But be working in small groups we were able to use what every individual knew or was good at and then the projects became a little less threatening. As the course went on I became very comfortable working with others and I really believe this is a skill that is very important for those who wish to study any of the sciences.

My interest in Physics has increased greatly. There have been many different factors that have contributed to this: a good working group in which ideas flowed and we forced each other to think more thoroughly; the 'fun' of the subject; all the thinking.

[Working on Projects] allowed me to work in a group and see how others think and reason.

FIGURE B1. VALUE AND PURPOSE OF GROUP WORK.

Another area of learning I have experiences is in the general thought process involved in scientific thinking—If there is a problem I don't understand, I break it into parts that I can understand.

Before, I looked at the question first. Now, I look at the situation first.

I am learning not to rely on formulas, but use them as mere tools in problem solving which is the final step after recognizing what physical concepts apply and when.

I had a lot of concepts ... in my head from High School Physics class, but it was mostly unstructured knowledge. At the most, it was structured according to whatever order the book followed. Right now I am more able to make up my own order and relate the concepts in a way that I can recall easily.

I have begun to organize my knowledge and begin to give it some structure. I have learned to see the interrelationship of the many seemingly different ideas and how they relate back to certain central ideas.

I need to not get so uptight, paralyzed, when first doing a problem.

If I could go back and do anything differently, I would change the way I did homeworks. I would have liked to be able to read through the problems and then go away and think about them for a while before I actually sat down to do them. I have discovered that my mind functions better when it has plenty of time to let things sink in.

It was amazing how all of these problem solving skills I learned influenced my day to day life. I jump to less quick conclusions. I seek realistic and conclusive information from others. I am able to take on task and leadership responsibilities.

My perception of physics has changed a lot in the sense that I have recognized that it is all a Big idea (it is not surprising that Physicists try to find the "one law" that will explain everything).

Sure, I've learned equations and concepts, but better yet, I've learned how to approach problems and decide on how to solve it before I've even started writing.

The amount of work is also important because it gives students a chance to demonstrate their strengths and learn what their weaknesses are. It is important to know what you need to work on, otherwise you will never improve.

This year… really marks the beginning of teaching myself how to "think".

FIGURE B2. STUDENTS' SELF-AWARENESS.

I myself have taken two years of high school physics. Unfortunately, such beginner's courses seem only to stick to equations and simple physical problems.

If you can... erase your memory of any and all of the physics you've learned in high school.

In high school I was taught how to solve specific types of problems that most probably appear on A.P. tests. This method of learning helped me to prepare for the A.P. test and do well, but hurt me if anything in my conceptual learning and understanding when I arrived at college.

In high school physics you are told the Newtonian Laws, and various other derived "laws", which you are expected to accept and to apply without fully understanding the underlying principle behind them.

In high school we learned formulas and learned how to "plug them in" and "crank out an answer", but no one ever taught anyone how to set up a problem logically.

In high school … I remember having to learn a lot of seemingly meaningless formulas and then using them correctly in order to pass the exams.

In high school, my idea of a class was to learn material and regenerate it in assignments as well as tests.

No longer will formulas be handed down like the Ten Commandments.

Physics is high school was pretty much a breeze. We were given formulas and were taught how to solve for certain situations.

Sure, I had two years of high school physics, but I could never see what I learned in action as my knowledge was minuscule.

The difference between college and high school is like the difference between major league baseball and little league. There's no comparison.

The way the educational system for high school is currently set up, regurgitation is the mainstay of education.

FIGURE B3. VIEWS OF HIGH SCHOOL PHYSICS COURSES.

And don't forget that someone can know a formula up, down, sideways, and adjacent and not have a clue to what's happening.

The most important word to remember when taking the course is STRUCTURE. With it average students can do well and without it, great students do very poorly.

It took me awhile, but I finally learned that what we were being tested on was our ability to analyze and solve problems that we had not encountered previously in the course. This allowed us to show our ability to apply the newly learned concepts to original problems using nothing more than clear and intelligent thinking.

One thing I have discovered about the course is that there are not that many concepts you have to understand. The hard part is being able to understand them so well that you can apply them to an unfamiliar situation.

The course requires you to gain a working knowledge of the underlying concepts and to be able to apply those ideas in different situations instead of simply memorizing equations.

The first thing I'd tell a high school physics class is that the most important skill they can acquire in preparing for college, is how to learn. I'd say that most high school students are only taught how to use rote memory... [High school students have] been taught that it is considered sufficient for them to pass a class (and do well in it, as well) if they can recite back to the teacher what was said in a lecture or read in a textbook... Once you learn how to learn, you can learn anything you want to.

The lectures of my physics class were devoted to analyzing those impulses that led us to prefer a certain solution to a problem, exposing and evaluating the underlying thought processes. We actually improved our thinking skills.

The more material you understand, the greater the sense of accomplishment. That's one of the things I loved about the Projects. When you first pick it up you're like, how can I ever do this, but when you sit down and work at it and things begin to fall into place, you look back (with pride) and say, "I did that."

FIGURE B4. AWARENESS OF NEW APPROACH.

College physics is about concepts and underlying principles and laws, it is definitely not a memorization class. Don't expect to be regurgitating facts and formulas for the professor. College physics is about problem solving and thinking and thinking about thinking.

College physics is about learning how to think.

I have realized that physics is more than just equations, and that it takes some good thought.

I was constantly frustrated, overworked, and forced to withhold from sleep because of this class... It is like hiking up a steep mountain. I hate it when I'm actually doing it, but I love it when I am at the top...

I would suggest to any non-science majors to take physics above any other physical science... You'll probably forget most of the equations afterwards, but the principles behind facing a problem and solving it will never leave you.

My perception of physics has changed in the sense that I no longer see it as a body of knowledge describing the physical world, but rather as a process of thinking, reasoning, and refining.

Physics is more than memorization and regurgitation. Physics is a way to think. It's the way to approach a problem and not whether an answer is correct to the third decimal point.

FIGURE B5. PERCEPTIONS OF PHYSICS / ATTITUDES TOWARD PHYSICS.

Advice I would give to students is to not give up easily and to stay calm.

Another part of physics is to have confidence. Never think that only people with high "IQ's" can handle this course.

As far as an attitude that should be taken it is important to keep an open mind and to not rely on what you already know or think you know.

Be like a sponge and try to absorb everything the professor tells you. Don't let your preconceived intuitive ideas block you — keep an open mind.

Discuss questions and figure problems out with an instructor or fellow students.

Don't stop thinking and don't stop asking questions. Whatever you do, don't take anything for granted.

Go in open minded. Someone who goes in with a complete knowledge of all of the formulas and is pushy with what he or she knows will not get very far. You are going to have to learn relationships, the formulas will come along on the side.

I would also recommend to keep an open mind; watch those preconceived intuitive ideas! They are usually WRONG!!! — or their explanations have the wrong basis.

In order to be able to think usefully in physics, I would suggest to incoming students that they try to work on their patience. It requires a lot of patience to successfully work on a physics problem.

My advice to those who are going to take physics is, "Keep an open mind." You should come to the course with the intent of learning and understanding, not trying to get an "A". Misunderstanding now will hurt you a lot later.

Never let physics intimidate or frustrate you.

One should come to this class with an open mind. A mind that is very accepting of change. There will be numerous times… when you feel you know what's going on, only to find out that you were way off.

Other tidbits: keep an open mind, have a willingness to examine one's preconceptions, and be courageous enough to change one's way of thinking.

Showing up to class does not help if you just sit there and count on osmosis to get the knowledge into your head.

The attitude you should carry with you into such a course is one of seriousness and pliancy of thought... when I say that your mind should be pliant, I mean that you should always be open to the explanations behind the current physics topics and how they relate to earlier ones. Making these connections can boost one's level of physics consciousness.

The attitude/approach you should have when you come in is to forget THAT you've had experience in physics.

The only advice I would give you is that you need to have an open mind. Be prepared to change your method of going about doing something, whether it is a physics problem or a history essay.

You will be faced with totally unfamiliar problems in which formula memorization will be of no help. You must develop a new style of thinking.

FIGURE B6. ADVICE TO THOSE WHO MIGHT SOMEDAY TAKE PHYSICS.