AC 2007-225: A DESIGN PROCESS FOR CONCEPTUALLY BASED, COUNTERINTUITIVE PROBLEMS

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A Design Process for Conceptual Based, Counter-Intuitive Problems

Abstract

In recent work funded by the National Science Foundation (DUE-0411320), significant improvement in student performance and retention in a sophomore dynamics class was obtained using a series of interventions. These improvements and the interventions have been described elsewhere.[1, 2]

One component of each intervention is the use of a counter-intuitive (CI) problem based classroom activity. The term “counter-intuitive” refers to a problem that appears to have an obvious, simple answer yet displays a behavior opposite to “common sense”. The significance of these counter-intuitive activities was discussed in previous publications and the hypothesis proposed to explain their significance is that they produce learning moments by creating a sense of surprise and excitement in the students.

This paper presents a heuristic that can be used to help create new counter-intuitive learning activities. Although the act of creation can never be automated, it is possible to: (1) establish criteria for a “good” activity, (2) provide resources for identifying underlying concepts, and (3) suggest thought processes to guide in creating the activity.

The process described in this paper was tested in a faculty workshop where faculty worked to prepare learning activities. The workshop included faculty from several Engineering departments and the college of science. Faculty worked in areas they were comfortable teaching. Workshop results suggest that the design process is valid and it is possible to develop counter-intuitive activities for several disciplines.

The processes presented in the paper are based on prior literature that describes what other authors have used successfully. The contributions of the present paper are: (a) to gather these resources together in one location, (b) the establishment of a design procedure for counter-intuitive learning activities, and (c) testing of the design process.

At the present time, only the design process has been tested to demonstrate that it yields new activities. Ultimately, these new activities must be used in a classroom to assess their effect on students. It is possible that the activities are too simple or too complex. If they are too simple, they may not be counter-intuitive to many students. If they are too complex, they may generate high frustration and actually

be detrimental to learning. Testing the activities will be performed in the near future; first at another faculty workshop and second in the classroom.[*]

Introduction

Students come to the classroom with prior knowledge and misconceptions of scientific and mathematical concepts [3]. Their notions allow them to construct understanding and, because too often faculty members deliver instruction in a didactic manner, students with misconceptions are not allowed the opportunity to challenge the misconceptions or to construct understanding of new concepts in engineering. Therefore students will often reinforce misconceptions by incorrectly incorporating new information on an incorrect framework. It is also possible for students to reject new information when it contradicts what they think they know. A simple example of this occurred in Dynamics. Consider the true statement: "when a jet airplane accelerates down the runway, a force pushes an occupant forward". When made in class one student thought to himself,[†] "this guy is crazy, everybody knows the occupant is thrown backward when the plane takes off". The student claims he then started to think about his weekend since this class obviously was just another hurdle and had nothing to do with real engineering.

Three learning theories underpin these claims [4]. First, understanding comes from interactions with the environment (meaning it is physical). Second, cognitive conflict stimulates learning and helps one to organize learning (meaning it is necessary to challenge beliefs). And third, knowledge evolves through social interactions (meaning it is a group behavior). This paper uses these three ideas to lay out a process to develop: (1) reality based, (2) concept oriented, (3) simple cognitive conflict inducing (we do not want to trip them with mathematics), (4) group activities. In particular the paper emphasizes the first three points and leaves it to the reader to design a suitable group activity for the classroom.

Previous NSF-sponsored work (DUE-0411320) at The University of Texas El Paso found that learning was stimulated by creating counter-intuitive (CI) puzzles. The term "counter-intuitive" refers to a problem that appears to have an obvious, simple answer yet displays a behavior opposite to "common sense." Using these puzzles has had demonstrated success in student learning yet two challenges remain. The first challenge is to develop robust puzzles that reveal misconceptions. The second is to find enough colleagues to critically assess the work. The project recently received additional NSF funding (DUE-0618861) and

[*] This material is based on work supported by the National Science Foundation under Grant No. DUE-0618861. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

[†] The student confessed this long after the incident occurred, unfortunately that learning moment was gone.

part of the new project is to develop a methodology for creating these puzzles and for supporting a geographically diverse set of faculty engaged in a "virtual college" for exchanging ideas and assessing effectiveness. The interested reader will find a link to join the virtual college in the summary.

There are other activity design methodologies that differ from the approach taken here. An excellent example is [5] that begins with identifying stake holders and takes into consideration many factors in activity design. That work is a superset of what is reported here. It is assumed you know your constituent, and you are aware of good pedagogical practices so this paper focuses on how to find or design the CI problems.

Components of a Good Counter-Intuitive Activity

Before listing the characteristics of a good CI activity, a short presentation of other activities will be given to contrast CI activities from other forms. A number of researchers have proposed components of a good learning environment. In [4] for example, eight principles are used. These principles are interpreted here to be: (1) make activities part of something larger, (2) the learner should own the problem, (3) it should be real, (4) make the problem emulate the complexity of real engineering practice, (5) the student should own the solution process, (6) make the environment supportive and challenging, (7) encourage testing of ideas and (8) allow the student to reflect on the content and learning process.

The work reported here develops a methodology to do all these components except (4) and (8). The problems being developed herein are intended to be simple enough to allow the student to understand the concept without the complex number crunching present in so many "real" engineering problems. The point is to not confuse understanding with complexity. Point (8) is important and it is one component in the new NSF project however it is not discussed in this paper. The point of the current paper is to show a method for finding the problem, not in the classroom pedagogy that provides the other essential support.

In [6] four elements of a good problem are listed: (1) students should be able to make a testable prediction, (2) it should use inexpensive equipment, (3) it is complex enough for students to develop multiple solution strategies and (4) it is assisted by group effort. The work here contrasts point (3); it intends to help students understand basic concepts not develop a problem solving strategy therefore the activities are not very complex. CI problems are not intended to develop problem solving skills but to force students to confront and resolve cognitive conflict.

This work differs from the six principles presented in [7] in the level of complexity. The six principles in a Model Eliciting Activity are: (1) the activity requires students to construct a "mathematically significant" model; (2) pose the activity in reality; (3) allow the students to self assess; (4) require students to document their thinking; (5) require sharable solutions and (6) that the model be as simple as possible yet remain mathematically significant. Again the main difference here is in the level of complexity of the activities.

Most of the characteristics of counter-intuitive activities agree with previous work and the most significant difference is in the level of complexity. The activities here are intended to be performed predominately in a single class period. Additional work, homework and reflections may extend the activity but the CI is a “modular” activity that can be injected at key points in a traditional course.

CI problems should be based in reality; they should lead toward practical applications. They should pass the “so what” test. A puzzle may be interesting but if it does not make a better engineer, so what? It is imperative that CI activities force students to make a commitment to what they think they know, before showing them a misconception. The CI’s challenge must confront the student with a dilemma to resolve or else a student may label it a magic trick; something of passing interest. The author also believes that the CI should not humiliate the student. There should be follow-up problems and questions that allow the student, in a group setting, to apply intuition and make accurate predictions. Reliable intuition is valuable to an engineer. CI problems also need to be simple enough that the student does not drown in mathematics attempting to predict an answer.

To summarize, the characteristics of CI activities should be:

1. Prediction based – Students must make a prediction and their most common prediction should be incorrect.

2. Conceptually based – They can be reasoned out using simple diagrams and arguments. Students should not bog down in mathematics, they should be thinking not computing.

3. Not solved by balancing one concept against another – The solution should not depend on how much of one thing exists. For example it is not a function of whether rotational kinetic energy happens to be greater than translational energy. A CI could be based on the student forgetting about rotational kinetic energy but not from a problem where rotational is greater or less than translational. Follow up activities can balance concepts against each other but multiple ideas can be confusing to students.

4. Be physical – Solutions should be demonstrated using an experiment, a video tape or visual simulation. It helps if follow up activities relate the principle to a “real design” problem; they must pass the “so what” test.

Finding the Concepts

Concepts are the big ideas used in engineering such as energy, momentum, force, strain, continuity and current. Big ideas are found in nearly all disciplines of engineering and are the transcendent ideas from which other solutions derive. The activities developed by the process described in this work deal with these concepts without requiring mathematical sophistication.

The first step in the model development process is to identify a concept for the activity. An experienced teacher probably has a good idea of concepts that cause student problems and can pull ideas from memory. This paper will also list a number of sources for the big ideas that cause problems.

One excellent source for engineering concepts is a test developed to measure conceptual learning. Some of these tests for engineering can be found in [8]. An example of a conceptual question from the dynamics concept inventory is:

> "A large truck collides head-on with a small compact car. During the collision:
>
> (a) the truck exerts a greater amount of force on the car than the car exerts on the truck;
>
> (b) the car exerts a greater amount of force on the truck than the truck exerts on the car;
>
> (c) neither exerts a force on the other, the car gets smashed simply because it gets in the way of the truck;
>
> (d) the truck exerts a force on the car but the car does not exert a force on the truck;
>
> (e) the truck exerts the same amount of force on the car as the car exerts on the truck."

Here the big idea is that forces are always equal and opposite; a simple, non-mathematical idea.

If the concept inventories are unexciting, there are many other idea generators/lists throughout the literature. In [9] a Delphi study (a means for prioritizing) was performed on concepts in thermal sciences. Their study gives a chart and graphics ranking 28 concepts in terms of difficulty and importance. Spinning off that study is [10] that discusses the concept of rate versus accumulation (amount) and student misconceptions regarding the difference between the two are described. In their work, they describe how students must face their misconception; something CI activities are intended to do. Rate processes are typically studied in thermodynamics but the ideas of rate and accumulation span many engineering disciplines and would be an excellent place to look for misconceptions. Similar work in [11] show rate and accumulations as having clear student misconceptions again applied in thermodynamics. They also describe some mechanisms (a substance based conception of energy) that can lead to these misconceptions.

As a continuation of the Delphi study in thermodynamics, [12] worked on prioritizing concepts in mechanics and electrical circuits. Also in electrical engineering materials work in [13] used student interviews to identify difficult concepts in logic design.

In the area of solid mechanics (stress) work in [14] describes student difficulties with the concept of shear stress.

There should be no doubt that there are a number of sources of misconceptions available in the literature. The objective is to select one of these misconceptions for the class you are working on. Select or devise a problem that:

- Can be demonstrated (or visually simulated) for the class.
- Has a clear discrete objective (yes/no, a, b, or c) answer.
- Can be embedded in something bigger than the demonstration; it passes the so what test.
- Can be "reasoned out" without significant mathematics. Undergraduate students may think your solution is a mathematical "trick" or they may never "get it" if they get lost in the mathematics.
- Has a single answer independent of amounts and initial conditions. For example, pushing on a refrigerator and asking if it will tip over is a poor problem because the answer depends on where you push it and the mass distribution of the refrigerator.

Admittedly, you may need to think hard about your problem to find one but that is the price of creativity. This paper is intended to focus you on what to think about but cannot make you creative.

For the remainder of this paper, a problem inspired by work in [15] will be used. In the cited work, the following problem (which will be hereafter called the terminal velocity problem) is posed, "Ignore the retarding effects of air resistance. A rigid wheel is spinning with an angular speed ω_o about a frictionless axis. The wheel drops on a horizontal floor, slips for some time, and then rolls without slipping. After the wheel starts rolling without slipping, the center of mass speed is v_f. How does v_f depend upon the kinetic coefficient of friction μ_k between the floor and the wheel?"[‡]

The concept that governs the terminal velocity problem is that rolling is a kinematic phenomenon, not a kinetic one. Once rolling ensues, the dry friction μN (as students understand it) disappears. There is an energy loss term in a rolling wheel called rolling friction but rolling friction is not the μN term with which students are familiar; it is caused by deformation between the surfaces in

[‡] Do not think me nasty, but I plan to leave it up to the reader to figure out the answer. Or you can look up the source reference. Keep in mind that many faculty get the incorrect answer.

contact during the motion. There are some basic problems with the problem statement as presented so it will be recast to make it more suitable as a CI problem.

How to determine if a problem is CI

When you are looking for potential CI problems look for problems described by one concept that is similar to another. For the terminal velocity example, the familiar concept of coulomb (dry) friction is similar to but totally different from rolling friction. The expectation is that the students will incorrectly attempt to apply coulomb friction to the problem. Knowing this the problem should be reworded to "encourage" students to use the incorrect principle of dry friction.

Another method to find CI problems is to look for one that uses part of a concept commonly forgotten. For example, suppose the grey sphere shown in Figure 1 is rolling on the stationary track as shown. The question is from how high must the sphere be released to not leave the track when it gets to the position shown?

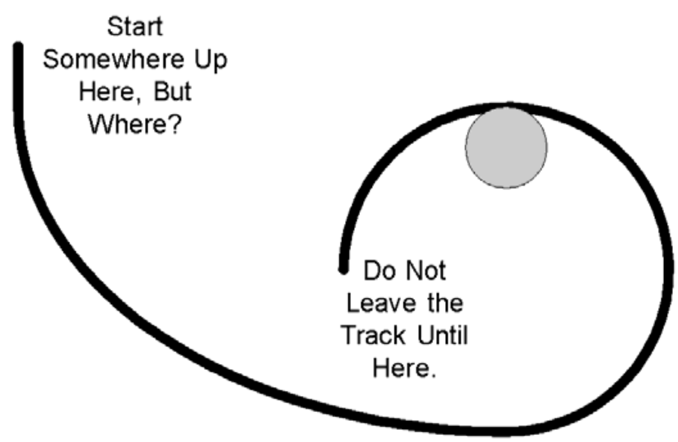

Figure 1 - Sphere Rolling on a Roller-Coaster Track.

In this problem, the concept to use is conservation of energy combined with momentum. Many students will get this problem wrong because they forget that the sphere must have some kinetic energy at the top of the circle so it has an acceleration that balances gravity. Once they get that however they again get the incorrect answer because they forget that the sphere's energy is made up of both translation and rotation. To achieve the required momentum at the top of the circle, there needs to be a given amount of translational speed. Since the ball is rolling however the translational speed requires a given amount of rotational speed. Hence to have the total amount of energy required at the top of the circle, one must release from a higher level than expected.

This particular problem is a bit complex but the point is that even though the student may apply the conservation of energy concept, they often forget about the energy in rotation. Hence it is an example of a CI problem in which students forget part of the concept; kinetic energy of rotation.

The next step in choosing a problem is to make sure it is counter-intuitive. If it is not CI, then return to the previous step and identify a new problem. The only way to know if a problem is CI is to test it. Test it first on experts from a different area. For example test a thermodynamics problem with dynamics faculty and vice versa. Pick an expert group that should have sufficient understanding of the basic principles but have a small chance of having memorized the solution. When you test the problem, make sure you identify what the solver is thinking by asking for an explanation of the answer; this will help you understand if there is a common misconception.

Second, test the problem with experts in the area of the problem. If they are able to solve it quickly it probably means it is an "intuitive" problem. Keep in mind that not all "simple" problems (the terminal velocity problem for example) are solved correctly by experts.

Finally, you should test the problem with students. Try to determine any misconceptions they have in common so you can prepare questions that address these during the presentation.

Relating problems to the real world

The final step in problem definition is to construct the question as simply as possible while avoiding obvious unrealistic statements and assumptions. For example consider the original terminal velocity problem as posed but with problematic words underlined; "<u>Ignore the retarding effects of air resistance</u>. A <u>rigid</u> wheel is spinning with an angular speed ω_o about a <u>frictionless axis</u>. The wheel drops on a horizontal floor, slips for some time, and <u>then rolls without slipping</u>. After the wheel starts rolling without slipping, the center of mass speed is v_f. How does v_f depend upon the kinetic coefficient of friction μ_k between the floor and the wheel?" This is an excellent problem statement if you are dealing with faculty because it tells you what assumptions to make so you will arrive at a precise answer. But do these assumptions really matter in the case of a CI? Remember, the CI purpose is to confront the student with an unexplainable problem. If you provide simplifications to the problem in the form of assumptions, students may excuse their ignorance by blaming it on the "unrealistic" assumptions, not their incorrect knowledge. For example, students may think an unusual behavior is the result of ignoring air resistance, or be confused by the notion of a frictionless axis.

For example consider the following as a rewritten terminal velocity problem to make it a CI problem statement. You plan to bowl competitively and you want your ball to have the maximum speed when it hits the pins 60 feet away. You have the option of bowling on a dry floor where the coefficient of friction is relatively large, or on a "lubricated" floor with a small coefficient of friction. Which floor would you prefer and why? (a) The smooth floor because the ball will have a much larger speed when it hits the pins. (b) No preference, because the speeds will be nearly the same regardless of the friction coefficient. Most students will select (a).

Compare the problem statements. The first says ignore air resistance, the second leaves that to the student. Most students would ignore air resistance, possibly because they are naïve, but why bring up the issue. In the first, you have a wheel spinning on a frictionless axle; the second requires no such language. Now it is true the axle has nothing to do with the problem so why mention it? Again the first mentions a rigid wheel; the second does not mention it. Again most students will consider the bowling ball rigid so why bring it up? Remember the point is to force the student to face the reality that their explanation is insufficient to describe real world behavior and the less said about simplifications the better.

Implementing the Problem

This paper's scope does not cover how to design an activity once a problem has been designed, but it is helpful to describe the kind of activity that is desired in the classroom. Essentially an activity should be used that allows the student to find the solution to the question while working with others. Three methods to allow the student to solve the problem will be described here. When designing your activity it may be helpful to use a combination of the three depending on the resources present.

The least sophisticated of the three (and least visual) is to relate the terminal velocity of the ball to its energy. After relating speed to energy have the students compute the energy lost in a rolling bowling ball that weighs 6 lbs and rolls 60 feet on a floor having a coefficient of friction of 0.3.[§] Most students will compute the energy loss as 6*60*0.3 = 108 foot-pounds. Next show a video of a very small child rolling a bowling ball so slowly it takes a long time to travel the 60 foot lane. Ask <u>if</u> the ball is losing energy, <u>why</u> does it appear to move at such a small speed for such a long distance? How could the ball lose 108 foot-pounds of energy and not stop? How could such a small child put 108 foot-pounds of energy into the ball to begin with? The conclusion is the energy loss is far less than 108. Have the students estimate the change in ball speed versus time. They should conclude that the ball speed does not change significantly. Ask the students why. You want the students to deal with the fact that there is a minimal energy loss.

A second method to help students discover an answer is to roll a bowling ball and measure its speed versus time. There are a number of ways to accomplish this task. It will require some hardware, but the required equipment may be on campus already, especially in the physics department. The students will discover that the ball speed achieves a terminal value which means energy loss drops to near zero. The next question is why?

[§] According to English[16] the threshold friction coefficient required to avoid slipping is between 0.2 and 0.4. Since people walk on bowling alleys, assume the friction coefficient is approximately 0.3.

A third method is to simulate the bowling ball. Using a simulation you can show the effect of friction and initial speeds/spins. A video of a simulation performed with MSC.Adams can be downloaded from http://2020engineer.iss.utep.edu/World1/Forms/AllItems.aspx and a plot of speed and spin for two values of friction coefficient (0.1 and 0.9) is shown in Figure 2. Note that the figure shows that the terminal speed of the ball is the same for each value of friction which is typically unexpected (and the answer to the terminal velocity question). The simulation shows a terminal velocity and this indicates that the energy loss drops to near zero. Again the question is why?

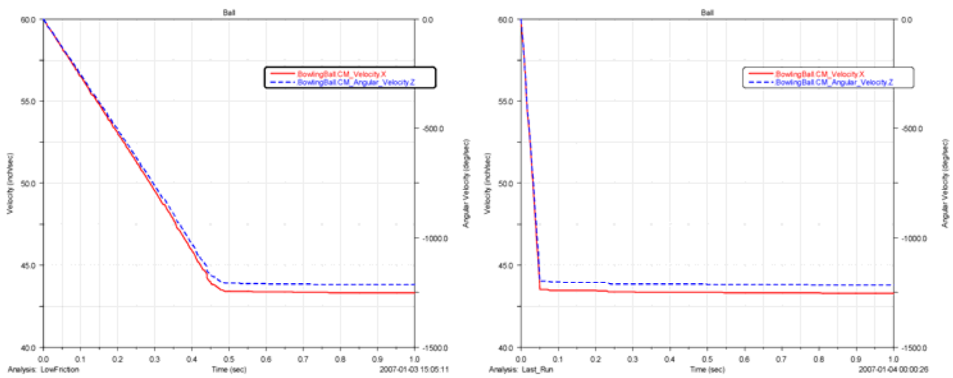

Figure 2 - Terminal Speeds Versus Friction Coefficient.

It is imperative that the students develop their own understanding of why the energy loss becomes negligible. One of the successful ways of guiding the students through this thought process is to ask them about the direction of friction if the ball starts with a translation and no rotation. Most students when working in a group can draw a correct freebody diagram showing friction opposing the speed. Ask them to determine the sign of the linear and angular acceleration and they will typically realize the ball slows and begins to spin faster toward roll.

Ask the students again to describe what happens if the ball begins with too much spin and after some discussion they realize the friction causes the ball to speed up and slow in spin. Finally the students need to put the two together to realize that when the ball actually begins to roll, the friction cannot be forward nor backward hence it must be zero. This is counter intuitive to them and that is why they must come to the conclusion themselves in their group. Once they do, you have created a learning opportunity to teach a number of important points that include: (a) dry friction does not remove a significant amount of energy during rolling, (b) rolling is the special kinematic condition when there is no slip between the rolling objects, it is the no slip condition that prevents friction from removing energy (c) when there is no slip (when there is rolling), dry friction is less than the coefficient times normal. All of these statements are consistent with what is taught in class but until the students face the issue they seldom listen.

Once the students have faced and resolved the conflict you designed, begin to ask them related questions. For example, if friction coefficient does not impact the terminal speed of the ball, why is it that an adult can roll a bowling ball faster than a child? The answer is that the terminal velocity does depend on the initial speed/spin but not on the friction. An adult can throw the ball with a much larger initial speed so its terminal speed is also much larger. The point is friction is just one parameter in the problem. Another follow up question is: does the friction force always disappear and if not, is there a terminal velocity then? To answer this, consider a bowling ball placed on an incline. In this case, depending on the parameters of the problem, the ball may achieve roll but even if it does, the friction force will not disappear. The reason is because gravity will continue to drive the ball to higher speeds and the friction will be required to increase the spin to keep it rolling. Although the ball never hits a terminal speed, friction still does not remove any kinetic energy from the ball because when it is rolling there is zero velocity at the point of application of the friction.

Next ask the students if a rolling ball will ever stop rolling? Some may be tempted to say theoretically no due to the conclusion that a rolling rigid body has no energy loss due to dry friction. Rolling a ball of putty on the floor will quickly convince them it will stop. The point is to encourage the students to use observations and resolve their model of the process to match the data. The resolution here is that the putty ball stops rolling because of rolling friction not coulomb friction. Figure 3 shows a diagram of a deformed putty ball moving to the right. Note that due to the deformation, there is a flat bottom of the putty. The flat bottom causes a force distribution. The actual force distribution depends on the parameters of the putty and floor but causes a moment that slows the spin. Once the spin slows the speed slows and eventually the putty stops moving. The same thing occurs if the floor deforms rather than the putty. A bowling ball will eventually stop moving but it takes longer than a putty ball because the bowling ball is massive and because there is little deformation. Rolling friction is the effect whereby deformation causes motion to stop; it is not the dry friction.

One objective of your follow up questions is to allow the students to use the CI concept to explain something that is intuitive. This will encourage them to use concepts to make predictions. For example, ask students to describe the difference when you push a wheel-barrow with a highly inflated tire and one that is low on air pressure. The high pressure configuration is easier to push because it avoids deformation and reduces rolling friction. Note that the difference has nothing to do with friction on the axle. When you get your car stuck in sand, ask what you can do to get the car out. One answer is you can deflate the tires slightly to increase the deformation, increase the contact area between rubber and soft sand thereby avoiding the entire car from sinking. You will however pay the price in reduced gas mileage.[**]

[**] Of course if you are stuck in sand, you are not getting great gas mileage either.

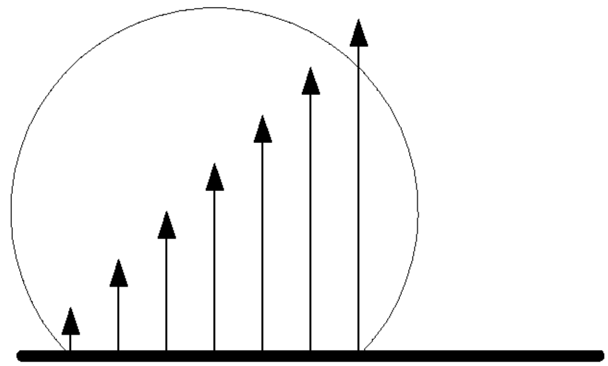

Figure 3 - A Deforming Ball on a Floor With Exaggerated Forces Shown.

The So-What Test

Your CI problem should also pass the so what test which means you should be able to answer the student who asks “so what”? You should have a response (or better yet, an activity) that explains how the concept described in your problem is useful to an engineer designing real world products.

For example in the bowling ball problem, as the ball begins to roll on the floor, the energy loss due to coulomb friction shrinks to a negligible value. What this means for a bearing designer is that you can reduce friction losses by designing bearing surfaces to “roll” on each other. An investigation of journal bearings versus roller bearings could form a sideline activity. Also an investigation of ball bearings versus needle bearings can be useful in understanding the difficulty of supporting thrust loads. For a gear designer, you should shape gear teeth so they “roll” on each other therefore an activity that finds gear surfaces that can roll could be used.

Conclusions

This paper described the purpose of a CI problem and gave characteristics of CI problems. The paper then described a design process for developing CI problems and gave an example of a problem having the desired characteristics. The paper also described the types of questions that can be asked in a classroom to help students face their faulty logic and help them resolve their misunderstandings.

When using CI problems care should be taken to avoid humiliating students. The objective is to encourage students to face what they think they know and test it against experiment and logic without humiliating them. This can be done if students believe they are learning to be discerning in the application of principles. You can accomplish this by asking follow up questions related to the CI problem in which application of the principle leads students to the correct decision. The author believes that intuition and the simple application of principles when reasoning is a desirable engineering skill. It is imperative to use follow up questions to encourage students to develop this skill. Be careful not to use CI problems so frequently and exclusively that students become discouraged.

Currently the author is a member of a "virtual college" that meets regularly via the internet with like minded faculty to discuss CI problems, the design of classroom activities and student assessment. To become a member and get help designing, using and assessing CI activities, you need only have a computer with high speed internet connection, a microphone and speaker and download some free software. You may then, free of charge[††], connect to the college during the meetings. For more information on how to configure your hardware and to find the meeting times visit
http://2020engineer.iss.utep.edu/World1/Forms/AllItems.aspx

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[††] At the time of writing, there is no charge for the software or to connect to the meetings.

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