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Gary L. Gray, Pennsylvania State University
GARY L. GRAY came to Penn State in 1994 and is an Associate Professor of Engineering Science and Mechanics. He earned a Ph.D. degree in Engineering Mechanics from the University of Wisconsin-Madison in 1993. His research interests include the mechanics of nanostructures, dynamics of mechanical systems, the application of dynamical systems theory, and engineering education.

Francesco Costanzo, Pennsylvania State University
FRANCESCO COSTANZO came to Penn State in 1995 and is an Associate Professor of Engineering Science and Mechanics. He earned a Ph.D. degree in Aerospace Engineering from the Texas A&M University in 1993. His research interests include the mechanics of nanostructures, the dynamic crack propagation in thermoelastic materials, and engineering education.
A Problem Centered Approach to Dynamics

Abstract

When teaching dynamics, one of our goals is to expose future engineers to a variety of real-world problems and modern engineering tools. Historically, we have done this via example problems worked in class and homework problems we assign to the students. On the other hand, the theory associated with new ideas was always presented the way it is done in the most popular textbooks, that is, we would just jump into derivations with minimal motivation as to why these new ideas were needed. Our exposure to the literature on problem-based learning prompted us to experiment with it in a studio environment with small numbers of students. Unfortunately, this required two faculty in every class and, as a result, was very labor intensive. Therefore, we wondered if new material could be introduced in a more contextual fashion (i.e., introducing a problem whose solution is best obtained using ideas that are developed as the problem is solved) to capture the motivational effect of problem-based learning, but in a more standard setting. This paper describes, via a number of examples, this approach to the introduction of new ideas that we call problem-centered. We also relate our experience in teaching dynamics this way, in lectures delivered electronically and in lectures delivered on the chalkboard, to large classes and small, and to honors and non-honors students. Finally, we present anecdotal evidence that the approach, at the very least, captures the interest of the students. While we have no data comparing the performance of students taught the way we used to teach dynamics with the performance of students taught in this problem-centered fashion, we feel it is important to report that problem-centered approach can be used with success in a variety of settings, where success means that it doesn’t get in the way of the amount of material that can be taught and that the students’ interest in the material is enhanced.

Introduction

To maintain and enhance our nation’s ability to be on the forefront of technology development, colleges and universities have been called to adopt the most effective teaching practices of Science, Technology, Engineering, and Mathematics (STEM) courses as well as to provide undergraduates with opportunities to study STEM “as practiced by scientists and engineers as early in their academic careers as possible”. In fact, the practice of engineering today requires that graduates be prepared in a large variety of ways, which are reflected in ABET criteria as well as other recent studies. In addition, as supported by a wide body of literature, educating STEM students to work in a highly diverse environment requires that students acquire knowledge in the same way as it is used in practice.

To begin to address these educational needs, we are developing a framework for teaching freshman and sophomore-level engineering statics and dynamics. In particular, we have altered the way we teach statics and dynamics so that we:

- specifically teach concepts and reinforce that teaching with in-class quizzes of concept questions and with concept questions on exams;
- employ a parametric approach to design by studying motion and loads over intervals of space and time;
emphasize not only the process of creating a model of a real system, but also discuss the limitations of each model;

- use a structured approach to the solution to every problem, which includes an emphasis on the notion that the governing equations in a dynamics problem are always obtained from (i) balance laws, (ii) material relations, and (iii) kinematic relations;

- instill in students the knowledge that mechanics is as relevant today as it was 100 years ago by exposing them to problems that are of interest to today’s mechanicians (this is done through worked examples and assigned homework); and

- introduce each new topic via an interesting and current problem in mechanics — this is the basis of our problem-centered approach.

It is our hope that, with this approach (and the supporting materials), we are exposing engineering students to a variety of real-world problems, modern engineering tools, and engineering design early in their education. Since statics and dynamics courses are required of students in most engineering majors (for example, at Penn State University, of the 16 engineering majors, 11 require statics and dynamics and 2 require both courses for at least some of their students) and because they are the first real engineering courses that most students see, this approach gives engineering programs the opportunity to excite the majority students about their engineering careers.

At this point, we should emphasize the fact that what we are proposing is not problem-based learning (PBL). It has some of the flavor of PBL, but a full implementation of PBL is best done by adopting a studio setting. At many (most?) universities, this strategy requires systemic changes that is often too expensive from the viewpoint of faculty hours and dollars required to be implemented.

With all of the above in mind, this paper will describe how we have implemented the last item in the bullet list given above in our dynamics classes after our initial experience of teaching dynamics in a studio setting. That is, we will describe how this problem-centered approach can be used with success in a variety of settings and, in doing so, relate our experience regarding how it should be used in each setting. In addition, we will report anecdotal evidence that this approach really captures the interest of students. First though, we will briefly describe problem-based learning and describe how our problem-centered presentation derives from it.

Problem-Based Learning (PBL) vs. Problem-Centered Approach (PCA)

A wide body of literature on STEM course delivery shows that PBL is one of most effective means to deliver instruction. In problem-based learning, an environment is created in which students engage in “meaning-making” as opposed to fact-collecting. In PBL, the students are the principal players in the learning process, and the instructor’s role becomes that of a facilitator rather than the primary deliverer of information. This paradigm shift is realized not by a linear exposition of theory and canned homework problems, but rather by challenging the students with contextualized problem sets and situations that are somewhat ill-structured and that admit more than one meaningful solution.

Unfortunately, changing the teaching modality of a course to PBL may be very complex and time-consuming, especially when computation and visualization are important components of the
course. In our experience, introducing a PBL environment is prohibitive in high enrollment courses such as statics and dynamics. While it is not always possible to offer a PBL course delivery, we feel that the traditional delivery of engineering statics and dynamics courses can still benefit from an infusion of a “PBL culture,” i.e., an approach we call problem-centered, so as to distinguish it from what most people think of when they think of PBL. By a problem-centered approach statics and dynamics, we mean an approach in which:

- each topic begins with an opening problem whose framing and solution require new concepts and skills or the substantial refinement of previously acquired concepts and skills;
- opening, example, and homework problems engage the students in a discussion of what assumptions are needed to make the problem tractable;
- opening, example, and homework problems are interesting, relevant and current and therefore show the students the real-life connections between the course material and applications.

This PCA is guided by the same basic pedagogical principles on which PBL is built. Specifically, it is meant to engage the students by presenting the course subject matter in a motivating context emphasizing real-life applications rather than formulations in the abstract.

We will now describe our problem-centered approach to statics and dynamics and show examples of how we have implemented it in our dynamics lectures (and for both large and small class sizes). In addition, we discuss the good and bad of using it in lecture and relate some of the feedback we have gotten from students who have been exposed to it. As a reminder, our main objective is to show that it is possible to successfully employ a PCA in a variety of settings, including large enrollment sections, without altering significantly the standard setting of the course offering.

**Implementing the PCA in the Dynamics Classroom**

We have used the problem-centered approach in large (> 100 students) classes, small classes (< 20 students), and in non-honors sections as well as honors sections. In the large classes, taught during the spring 2007 semester, the lectures were delivered electronically by computer using slides containing high-quality line art, photos, movies, and animations (e.g., via PDF or PowerPoint). In the small classes, the lectures were delivered via the chalkboard, with interludes in which photos, movies, and animations would be shown that were pertinent to the problem being solved. In both cases, video and animations were used as much as possible during the problem-centered introduction to a subject in order to capture the interest of the students (this revealed one significant advantage of the electronic presentation of material since it allows for a seamless inclusion of video and animations into the lecture — more on this later).

In the examples that follow, we present slides from the electronic lectures we developed for the large classes. When giving problem-centered introduction to a topic via the chalkboard, the content of these slides was all presented, but not everything was necessarily written on the board.

**Some of the Problems Used in the PCA**

In particle dynamics, the problem-centered approach is used in the following contexts:
Position, velocity, and acceleration of a point. We begin by talking about motion tracking and how it is used in GPS systems, broadcasting of professional sports (e.g., FoxTrax in the NHL), and air traffic control. The discussion of what type of information comes from these systems, before talking about the fact that velocity is the time derivative of position and acceleration is the time derivative of velocity, provides us with the opportunity to show how position vectors come from discrete data and how average velocity and average acceleration lead to their continuous counterparts. In this case, we use the motion of a car around a race track to derive the kinematic relations (see Fig. 1).

**A Track and Some Cameras**

- A car moves ccw around a racetrack.
- Cameras record the car’s coords as a function of time.
- The coords are defined by each camera’s frame.
- Position of the car is measured at five locations, corresponding to five different times.
- Only four position vectors are shown, e.g., \( \vec{r}_{B/1} \) is the position of B relative to camera 1.

**Figure 1.** The problem-centered introduction to the description of position, velocity, and acceleration as vectors.

One-dimensional particle kinematics. To motivate the need to derive the usual relations for one-dimensional particle kinematics, we talk about a car moving between two stop signs (see Fig. 2). Given that we have a reasonable model of the velocity as a function of time between the two stop signs, can we find the time it takes to go from one sign to the other, the distance between the two signs, and the acceleration of the car at every point between the signs? The answers to this question motivate the need to derive the integral relations between position, velocity, and acceleration.

Kinematics in normal-tangential components. In studying the representation of the velocity and acceleration vectors in normal-tangential components, we focus on the fact that the velocity is always tangent to the path and that the normal component of acceleration is inversely proportional to the path’s radius of curvature. Because of the geometrical nature of these relationships, we motivate the topic of kinematics in normal-tangential components by trying to establish how the difficulty of a car race depends on the shape of the track on which the race is run. Interestingly, there are publicly available data about the Formula 1 competitions (see the example on the upper right of Fig. 3) with speed and acceleration...
1D Kinematics is Surprisingly Useful

**Motivation** Before we get any deeper into vector kinematics, it is very useful to go over one-dimensional kinematics and see how we can manipulate expressions relating position, velocity, and acceleration. In fact, vector kinematics is often a simple superposition of 1D motions.

Say the velocity of a car moving between two stop signs is empirically described as

\[ v = 9 - 9 \cos \left( \frac{2t}{5} \right) \text{ m/s, } 0 \leq t \leq 5 \pi \text{ s}. \]

We want to know:

- (a) the time between the two stop signs;
- (b) the distance between the two stop signs; and
- (c) the acceleration at every instant along the way.

**How do we find these?**

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**Figure 2.** The problem-centered introduction to one-dimensional kinematics.

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**How Important is the Shape of the Path?**

Here are the Watkins Glen International racing track (left) and the Monaco Grand Prix racing track (right): these tracks have different shapes.

- What is it about a particular track shape that tests the ability of a driver and the engineering of a car?
- To answer this question, we must write velocity and acceleration so that the track’s shape is explicitly accounted for in their expressions.

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**Figure 3.** The problem-centered introduction to the kinematics in normal-tangential components.

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data which can be related to the radius of curvature of the track at various locations. This data allows students to perform quick “back of the envelope” calculations verifying the consistency between the speed and acceleration data and in this way develop an intuition on how to verify the admissibility of some technical data.

*Kinematics in polar coordinates.* To motivate the use of polar coordinates we talk about navigation and how navigation data in the form of polar coordinates can be processed to obtain the velocity and acceleration of an airplane whose flight is being tracked by a radar station.
An Airplane Tracking Problem

An airplane flying at a constant speed along a straight and horizontal path is being tracked by ground-based radar.

- This is a classic problem in tracking: given the distance and angle data to an object as a function of time, how do you calculate how that object is moving?

It would seem that Cartesian coordinates would be the way to go to find \( \vec{v} \) and \( \vec{a} \) since the plane is flying in a nice straight line.

- But it is the radar station that is tracking the airplane, and all it knows about from its fixed location is the distance \( r \) to the plane and the direction to the plane as defined by the angle \( \theta \).

Let’s see how we translate \( r(t) \) and \( \theta(t) \) into \( \vec{v}(t) \) and \( \vec{a}(t) \) for the airplane.

Figure 4. The problem-centered introduction to kinematics in polar coordinates.

applications and because it brings out an important but often hard to convey idea, namely that the values of the time rates of change of the polar coordinates \( r \) and \( \theta \), i.e., \( \dot{r} \) and \( \dot{\theta} \), contribute to the velocity vector in a way that is dependent on the values of \( r \) and \( \theta \) themselves.

Relative Kinematics. The subject of relative kinematics is motivated by analyzing a moving target problem. This problem is contextualized by asking the students to help design a movie scene, described in Fig. 5. While the “real life” aspect of this problem might be questioned by some, this particular problem takes advantage of the fact that the vast majority of students, through their movie viewing experience, relate very directly to the idea of “camera angle”, which, using a more technical language, translates into the idea of “moving reference frame”. In the examples, students are asked to describe a scene both from the viewpoint of the shooter (Mr. Bond) and from the viewpoint of the target (a robot controlled by Dr. Nasty).

Particle kinetics and Newton’s 2nd law. To motivate the study of particle kinetics and applications of Newton’s second law of motion, the students are asked to estimate the cohesive force that the tongue of a chameleon must exert in order to capture an insect (see Fig. 6). The “real life” aspect of this problem lies in the fact that there are studies in biology that concern the mechanical behavior and physiology of some animals, studies that can have relevance in the understanding of human physiology. For example there are studies on the mechanical response of the brain of a woodpecker under the extreme loading to which they are subjected during pecking that have relevance in the understanding of human brain response during collisions. This is a “real life” problem and is intended to make the students think “out of the box” and realize that there are applications of the principles of dynamics outside the study of machines. The purpose of this example is to invite the students to consider
A Typical Scenario: Moving Targets

- In a movie scene James Bond needs to stop a deadly threat.
- Bond is traveling on car $A$, $v_A = 18 \text{ m/s} = \text{constant}$.
- An explosive loaded car $B$ has $v_B = 40 \text{ m/s} = \text{constant}$.
- $A$ and $B$ will collide at $C$ in 4 s unless Bond is able to destroy $B$.
- If Bond fires 4 s before the collision, and if the shell $P$ travels at 300 m/s relative to the gun at $A$, how should Bond aim his gun?

**Figure 5.** The problem-centered introduction to relative motion kinematics.

How Much "Stickiness" Does a Chameleon Need?

A chameleon propels its long tongue out to snatch an insect to retrieve back into its mouth for a meal.
- This process occurs very quickly as you can see.
- Since it is the "stickiness" of the chameleon’s tongue that allows it to latch onto the insect and since it happens so fast, the question is, how much stickiness is required to get that small insect where the chameleon would like it to be?

Let’s find out . . .

**Figure 6.** The problem-centered introduction to one-dimensional kinetics.

a complex problem and make enough simplifying assumptions to obtain an approximate, but sensible answer. The central element of the problem is Newton’s second law, which is the key to relating the acceleration of an insect that is captured by a chameleon and the insect’s mass. The acceleration of the insect is estimated by briefly analyzing a video of a chameleon capturing the insect in question (shown in the lower right corner in Fig. 6).

In Figs. 7–12, which can be found in the Appendix to this paper, we report some of the other examples used in class for problem-centered introductions to motivate the study of the various
topics in dynamics. A short description of each of the problems illustrated in the figures can be found in the corresponding figure captions.

Our Experience Using PCAs

As mentioned earlier, we have used problem-center introductions to new material in a variety of settings. What we have discovered in all cases is that the PCA provided the following advantages:

- it gives an opportunity, right from the beginning of a topic, to discuss modeling and how it relates to that topic;

- it presents an interesting, relevant, and timely example that is introduced before any theory is presented or discussed—this almost always captured the students’ interest in way that simply diving head-first into the theory never did;

- it allows for the solution of an additional example problem via the presentation a new topic; and

- perhaps most importantly, it provides an opportunity for the instructor to show students that by thinking “outside of the box” one can find all sorts of interesting mechanics problems that necessarily lead to new methods of solving problems (the chameleon example and the associated discussion in class is a beautiful example of this).

In the semesters we have used the PCA, it has become clear that the only way to seamlessly integrate quality figures, photos, videos, and animations into the lecture is to present the entire lecture electronically. With that said, the PCA can be very effectively used with “chalk and talk” style lectures, but the classes need to be very small (i.e., less than approximately 20 students). We have observed that with small classes, the short break that occurs when moving from the blackboard to a computer (in classrooms at Penn State this involves lowering a screen, dimming the lights, and turning on a projector) is patiently tolerated by a small class. With larger “chalk and talk” classes, dozens of students immediately start chatting and the din the room rises quickly. Once this happens, it takes a little additional time to regain the students’ attention.

We should also note that the PCA is not without its disadvantages. For one, it takes longer to introduce a new topic using the PCA than it does when theory is simply presented without a problem-centered introduction. Although, in our experience, this is positively offset by the opportunity it provides to do an additional example problem on a topic. Another disadvantage is that the electronic lectures take a tremendous amount of time to develop. Laying out slides, inputting equations, finding good relevant photos, and creating quality line art all take time. While the “chalk and talk” version of the PCA more efficient, it still takes time to pull together and/or create good videos and animations to show the students.

Student Response to the PCA

The feedback we received from students was overwhelmingly in favor of the PCA and the associated problem-centered introduction to new topics. They liked the additional examples, the opportunity to see applications of mechanics they hadn’t thought of, and they really liked the videos and
animations we frequently used. We did discover that the opportunity to spend more time talking about modeling that the PCA afforded did lead to some confusion on the part of the students. For example, in student focus groups held near the end of the semester we discovered that many students found problems involving springs to be rather abstract and they didn’t understand how this component we used in so many models could be applied to the real world. This seemed especially perplexing to them since springs were so ubiquitous in the course! This is the sort of misunderstanding and confusion that is easily prevented by making sure that when the spring model is first introduced, a proper presentation of the model is done by the instructor (we were originally guilty of not demonstrating to the students that “springs” are everywhere in the real world).

Summary and Conclusion

Our experience using a problem-centered approach in teaching dynamics to a variety of students in a variety of settings has been very positive. While we have not acquired data comparing the performance of students taught using the PCA with the performance of students taught without the PCA, we have demonstrated that problem-centered approach can be successfully used in a variety of settings. It allowed us, the instructors, to do spend additional time discussing modeling and it made the course even more fun to teach. For the students, it made the class more fun because it provided the perfect vehicle to bring more video and animations into the course than we had previously been able to do.

Bibliography


Appendix: Additional Examples of Problem-Centered Introductions Used in Class

Nanotechnology and Molecular Dynamics

- **Nanotechnology** is a new and exciting field of engineering and science.
- A basic objective in nanotechnology is to engineer, i.e., control, the structure of materials at the nanoscale.
- Since 1 nanometer = $1 \times 10^{-9}$ m, to work at the “nanoscale” is to work with “few atoms at a time” — roughly speaking, a one-nanometer long chain of atoms consists of just 3 atoms.
- **Molecular Dynamics** is one the more popular computational tools used to understand the properties of materials at the nanoscale.
- At its core, molecular dynamics is simply “E MCH 12” dynamics applied to systems of many atoms (sometimes millions of atoms).
- The key idea is that we can use Newton’s laws of motion, along with a model of the interaction between atoms, to understand the behavior of the material as a whole . . . let’s see how.

Figure 7. (a) The problem-centered introduction to the kinetics of particle systems. The problem is meant to illustrate the relevance in modern engineering and material science of molecular dynamics studies.

**Velocity Changes vs. Time Intervals**

To determine the change in velocity of an object between two different times, we must have a detailed knowledge of the forces acting on the object as a function of time.

- In a collision, a car’s speed can be reduced by 45 mph in < 0.2 s.
- As collisions go, 0.2 s is a long time. Many impacts (e.g., a bat and baseball, golf club and golf ball) typically last about a millisecond.
- As it can be seen above, the impact of a racquetball against a wall takes about $0.004 s$ (4 milliseconds).
- The message is that forces, be they large (as in the examples given above) or small, change how fast and in what direction objects move. That is, forces change the velocity of objects. Let’s explore this . . . .

Figure 8. The problem-centered introduction to the impulse-momentum principle. The problem is intended to describe a situation in which it is crucial to relate changes of velocity to the time interval over which the change in velocity occurs.
Two Cars Crashing

Impacts are everywhere and they are the subject of a great deal of research. *Let’s take a look at one* . . .

Two cars $A$ and $B$ of mass $m_A$ and $m_B$ travel with constant velocity $\vec{v}_A$ and $\vec{v}_B$ in the same lane along a horizontal stretch of road.

$A$ catches up with $B$ and, because the driver of $A$ is talking on a cell phone, a collision occurs.

- The classical impact problem is to *predict the post-impact velocities of the cars knowing their pre-impact velocities*.
- The problem of finding the pre-impact velocities given the post-impact velocities is solved very similarly and is, essentially, the problem one finds in *accident reconstruction*.

**Figure 9.** The problem-centered introduction to the theory of impacts. The problem constitutes a simple introduction to the field of accident reconstruction.

A Skater’s Forward Spin

Let’s consider *forward spin*, a common maneuver in ice skating.

- The skater rotates about a vertical axis through the body.
- The skater controls the spin rate by extending/retracting arms and/or legs.

- *How is it possible to control the spin rate without applying an external moment to the skater?*

- To answer this question notice that:
  - the spin rate increases when arms and/or legs are brought closer to the spin axis, and that
  - the spin rate decreases when extending arms and/or legs outward.

- Let’s explore the following: *the spin rate can be controlled by adjusting the mass distribution relative to the spin axis*.

**Figure 10.** The problem-centered introduction to the angular impulse-momentum principle. The students are asked to construct a single-particle model of the forward spin of a skater.
What is Rigid Body Kinematics?

In studying rigid body motion:
- We begin with planar kinematics of a rigid body (motion of an object without any concern for what causes the motion).
- We will assume that (i) the body is no longer a particle, but a rigid body whose mass is distributed over a region of space and that (ii) the velocity of each of the body's points is parallel to a common plane.

Let's start learning a little about rigid body kinematics by looking at slider-crank mechanisms.
- These can be found in IC engines and many other places.

Figure 11. The problem-centered introduction to rigid body kinematics. The problem asks the students to characterize the motion of slider-crank mechanisms found in common automobile combustion engines.

Maximum Horizontal Acceleration of a Motorcycle

The Kawasaki Ninja ZX-14 sport bike is one of the most powerful and fastest production motorcycles in history:
- from a standstill to 60 mi/h in under 2.5 s;
- its top speed (electronically restricted by the manufacturer) is 186 mi/h (300 km/h).

With that much power, it is easy to cause the front tire to come off the ground when accelerating. Hence, a basic question is: how much acceleration is too much? That is, what is the maximum acceleration that the bike and rider can experience and still keep the front wheel on the ground?

Figure 12. The problem-centered introduction to rigid body kinetics. The problem asks the students to create the simplest possible model capable of accounting for the rotational motion of a motorcycle.