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Helping Students Organize and Retrieve Their Understanding of Dynamics

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Abstract

When confronted with the large amount of information presented in an introductory physics course, students often have difficulty assimilating the concepts and seeing the big picture. Thus they may have difficulty transferring their knowledge to new situations. In this paper we present a conceptual framework that we have developed for teaching and applying dynamics at both the secondary school and college levels. In this framework the causes of motion are graphically related to the description of motion using Newton's laws and impulse/momentum relationships. The framework accommodates translation and rotation, multiple dimensions, and time-varying forces. In addition to presenting the framework, we describe how it is used by teachers and students in the classroom as part of a learner-centered curriculum and provide an elevator activity as an example. Finally, we include the response of students to this approach.

Introduction

Most introductory physics texts devote 10 or more chapters to the topics involved in dynamics, including pre-requisite skills such as vector operations, kinematics, Newton's Laws, impulse-momentum relationships and the application of dynamics to a wide variety of situations. Thus it is not surprising that many students do not see how the concepts of dynamics are related to each other. Lacking a solid understanding of how the knowledge is structured, students may concentrate their efforts on learning processes to manipulate equations to solve problems. If this is the case, they will not gain a conceptual understanding of the subject matter, nor will they be able to transfer their knowledge to domains outside the narrow and idealized ones of their experience.

The National Research Council (NRC)[1] summarizes a variety of studies illustrating how experts and novices differ in the way that they solve physics problems. The NRC notes that, "Experts usually mentioned the major principle(s) or law(s) that were applicable to the problem, and how one could apply them." By comparison it is noted that "…competent beginners rarely referred to major principles and laws in physics; instead, they typically described which equations they would use and how those equations would be manipulated…Experts' thinking seems to be organized around big ideas in physics, such as Newton's second law and how it would apply, while novices tend to perceive problem solving in physics as memorizing, recalling , and manipulating equations to get answers." The work of Chi[2] cited by the NRC is particularly relevant to our paper. The NRC writes, "In representing a schema for an incline plane, the novice's schema contains primarily surface features of the incline plane. In contrast the expert's schema immediately connects the motion of an incline plane with the laws of physics and the conditions under which laws are applicable." Further, based upon the work of Larkin[3] and Chi et al.[4], the NRC notes that, "Experts appear to possess an efficient organization of knowledge with meaningful relations among related elements clustered into related units that are governed by underlying concepts and principles…Within this picture of expertise, 'knowing more' means having more conceptual chunks in memory, more relations or features defining each chuck, more interrelations among the chunks, and efficient methods for retrieving related chucks and procedures for applying these informational units in problem-solving context."

Given how important structuring knowledge is to the process of learning physics, the question then is how to most effectively help students with knowledge organization. We will describe a simple conceptual framework to aid the study and application of dynamics and its use in a learner-centered curriculum.

Dynamics Conceptual Framework

The dynamics conceptual framework that we have developed is shown in Figure 1. In this framework, motion is related to its causes by Newton's second law and impulse-momentum relationships. Motion is quantified by position, velocity and acceleration on the right side of the framework. These variables are related by graphical and calculus relationships. We feel that a graphical approach integrated with (or followed at a later time by) a calculus-based approach is most effective for learning kinematics, because graphical analysis allows students to *visualize* motion while working directly with fundamental principles. This approach also takes greater advantage of advances in laboratory technology, including real-time data collection using motion detectors (an ideal tool for measuring, viewing and manipulating motion graphs for motion with constant or time-varying acceleration) and video analysis. Details and example applications of this approach for learning kinematics are given in Ellis and Turner[5].

While the graphical and calculus relationships among variables describing motion are the fundamental feature of the right side of the framework, the left side describes the forces and torques that affect motion. Here we highlight the free-body diagram and how it is used to find the net force and torque on an object. Thus the framework illustrates the need to identify forces, construct a free-body diagram and add these forces. In the middle of the diagram is Newton's second law and impulse-momentum to relate the two sides. It has been our experience that, without proper guidance, students view these relationships as two completely different approaches that apply to entirely different situations. For example, students may feel that impulse-momentum is appropriate for collision problems and Newton's Second Law is appropriate for elevator problems. Seeing both ideas represented visually as relationships between motion and its causes illustrates their similarity. We also show students how Newton's second law and impulse-momentum are related to each other mathematically (as represented by an arrow between the two concepts on the dynamics framework).

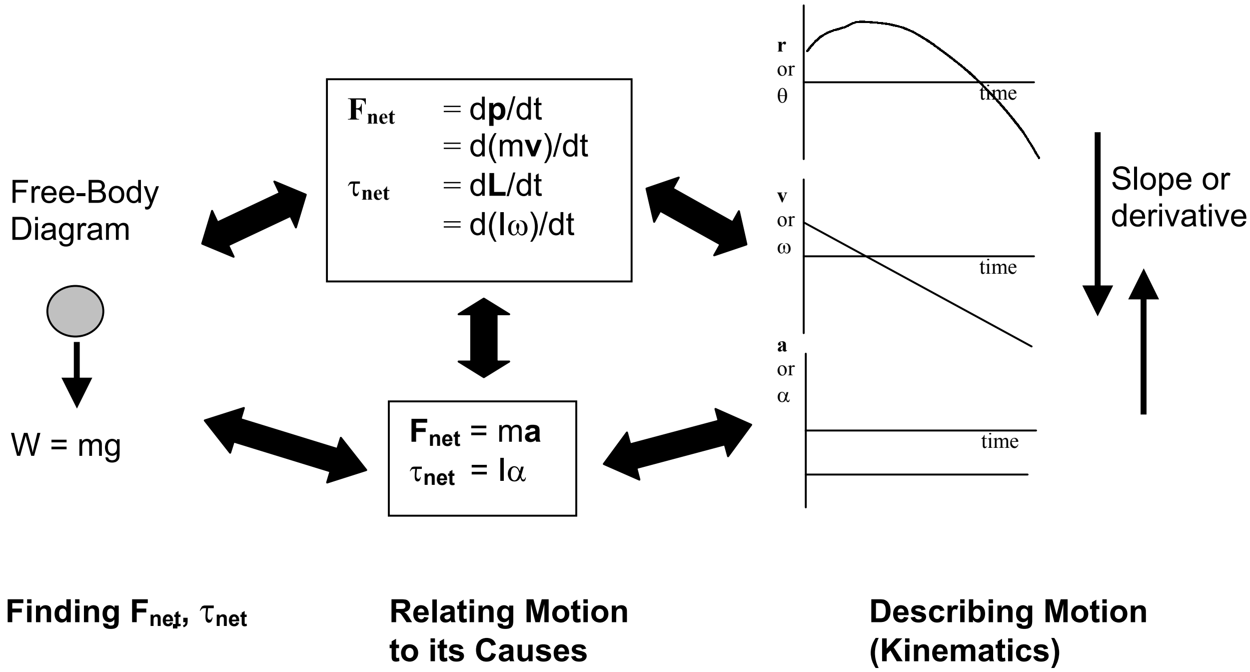

Figure 1. Calculus-based dynamics conceptual framework

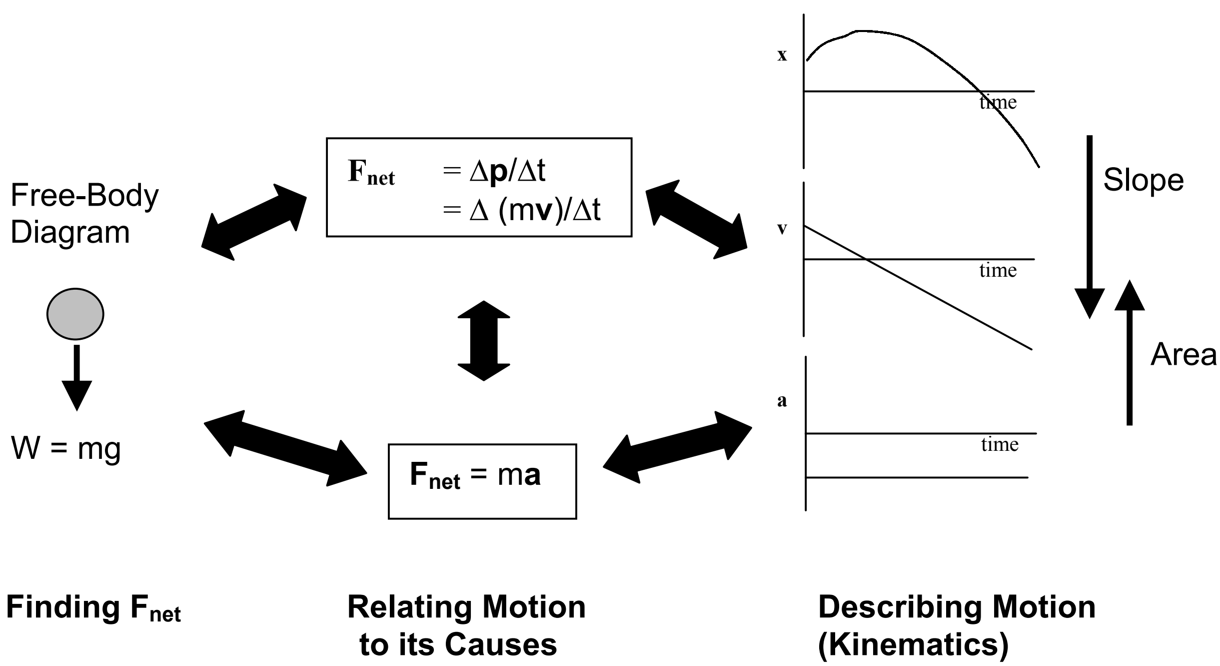

Figure 2. Algebra-based dynamics conceptual framework

We feel that this framework can be a powerful tool for learning dynamics for a wide range of ages. In the form shown in Figure 1, it can be used to help solve linear or rotational dynamics problems in three dimensions with time-varying forces using graphical procedures or calculus. However, it can also be simplified to match the learner's needs. For example, Figure 2 shows the framework simplified for use in an algebra-based physics course. Even though Figure 2 may be a simplification, the fundamental structure of the knowledge remains identical to Figure 1—it is only the details that are simplified. Thus students can begin with an algebra-based approach using Figure 2 and then easily transition to a more sophisticated approach using Figure 1. Ellis and Turner[5] discuss how the transition between an algebra-based approach and a calculus-based approach is made easier through the use of graphical analysis. We also feel that when students work from the beginning with graphs of time-varying forces and time-varying motion, it helps them think beyond the equations of constant acceleration to more generalized motion. Another benefit of the framework in Figure 1 is its use for illustrating that the relationship between linear motion and its causes parallels the relationship between rotational motion and its causes.

We use the framework throughout the study of dynamics. On the first day of class we present the structure of the framework. Students learn that we can describe aspects of motion by any of a number of inter-related graphs, that changes in motion are caused by forces and torques, and that motion and its causes are related by laws of physics. Thus students learn from the beginning about the big picture and the approach that they will use to solve problems. From then on learning dynamics is a matter of understanding the concepts that make up the framework, adding detail to the framework, and practicing applying the framework to increasingly complex phenomena. During the learning process the framework is used continuously to introduce the context of new topics and organize knowledge.

In addition to helping students structure their understanding, the framework is also used to solve problems. First students locate the variables that are given in the problem statement and those that need to be calculated on the framework. The path between the variables is then identified as the solution procedure. For example, if the forces on a tire with a fixed axis are given and the angular displacement needs to be found, the solution path would be to (1) draw a free-body diagram to calculate τ_{net}, (2) relate τ_{net} to α using $\tau_{net} = I\alpha$, (3) integrate α to find ω, and (4) integrate ω to find θ. One could also choose an alternative solution procedure by taking the impulse-momentum path relating τ_{net} directly to ω. Thus student solutions consist of a free-body diagram and a graphical representation of motion applied through the structure of the dynamics framework. Solutions produced by this procedure not only find the numerical answers, but also illustrate the motion and causes.

Using the Dynamics Framework in a Learner-Centered Curriculum

The dynamics framework is one element of the learner-centered curriculum that we have developed. A detailed description of the pedagogy used in this curriculum is given in Ellis and Turner[5]. The pedagogical approach to our curriculum is best understood within the context of three principles that the NRC[1] summarizes as being fundamental to learning.

1. *Students come to the classroom with preconceptions about how the world works. If their initial understanding is not engaged, they won't change or they may learn for the test and revert to preconceptions.*

We have designed a sequence of laboratories and activities intended to expose and address student preconceptions—both predictable and unpredictable. Fundamental components of the laboratories are:

- Making individual predictions based upon reason
- Discussing and reconciling differences among group members
- Making measurements for required experimental procedures as well as student-designed laboratory extensions
- Discussing and reconciling the differences between measured and predicted results

2. *To develop competence in an area, students must (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the context of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and applications.*

We address this principle by making the dynamics framework, together with activities that support deep conceptual understanding, central to the learning process.

3. *A metacognitive approach to instruction can help students learn to take control of their own learning by defining learning goals and monitoring their progress in achieving them.*

We feel that helping students to take control of their learning and develop ownership of content is key not only to effective learning, but also to developing an interest in physics. We try to empower students in a number of ways including:

- Making student group discussions a focus of learning,
- Requiring projects that allow increasing freedom for student-directed learning as the course progresses,
- Requiring students to develop laboratory extensions,
- Encouraging extra-credit self-directed laboratory investigations,
- Requiring students to write and share reflections on their learning,
- Providing sample quizzes and tests for self-assessment with guidelines to help students develop their own assessment tools.
- Requiring students to keep portfolios of their learning (beginning Spring 2003)

Example Curriculum Application: Riding an Elevator

To illustrate how we teach dynamics in our curriculum, we will present curriculum elements related to an elevator laboratory used to teach Newton's second law in secondary school. We have also used a similar version of the laboratory in an undergraduate physics course. We feel that several points are critical in this laboratory. First, it is essential for students to understand that the purpose of the elevator laboratory is to better understand all motion; the elevator is just a convenient tool to accomplish this goal. The purpose is not to "learn how to solve elevator problems." Second, although physics texts typically contain problems that look at segments of an elevator's motion with constant acceleration, they seldom look at the entire motion of the elevator from the start to finish. We feel that studying the entire motion of the elevator helps students achieve a more complete understanding. For example, students are surprised to learn that the elevator only accelerates for a short period of time. Also, the meaning of the sign of velocity and acceleration is reinforced as students examine all combinations of positive and negative velocity and acceleration. Third, although we present the elevator laboratory in the context of learning Newton's second law, it could be easily adapted to support learning impulse-momentum or conservation of energy approaches. In fact we apply a variety of approaches to study the same physical phenomena throughout our course to reduce student tendency to compartmentalize their learning. For example, we study the motion of a bouncing ball using conservation of energy (see Turner and Ellis[6]), Newton's second law, and impulse-momentum approaches at different times in the course.

Before starting the elevator laboratory, we begin with simpler activities to develop understanding of the second law and its application. The visual learning and problem-solving support of the dynamics framework play an integral part of this phase. Figure 3 illustrates a homework question that helps students prepare for the elevator activity by requiring them to think carefully about the meaning of mass, weight and net force.

The 100 kg body of a gangster (Franky the Scar) is dropped off of the Brooklyn Bridge. Answer the following questions ignoring air resistance. **Be sure to include units with each answer.**

a. What is the mass of the body while it is being held at rest before it is dropped?
b. What is the mass of the body while it is in freefall?
c. What is the weight of the body while it is being held at rest before dropping?
d. What is the weight of the body while it is in freefall?
e. What is the net force on the body while it is being held at rest?
f. What is the net force on the body while it is in freefall?
g. If air friction is included, which answer(s) above will change?
h. What is the weight of the body in deep space far from any massive bodies?
i. While slowly sinking in the East River, what is the weight of the body?

Figure 3. Example homework question used for practicing dynamics fundamentals.

Students begin the elevator laboratory shown in Figures 4a by riding in an elevator and observing the forces that they feel. Following their ride, each student must make reasoned predictions of the six graphs in Figure 4b. Once they have made individual predictions, they must then discuss and reconcile the differences among their group's members. We have found that group discussions among students (and sometimes involving the instructor) are an ideal opportunity for addressing student misconceptions. The instructor is also provided with an excellent opportunity to assess student understanding. While some students predict the shapes of the graphs in Figure 4b correctly at this point, it is more common that their predictions illustrate areas of incomplete understanding or misconceptions such as:

- The force of gravity changes during the motion.
- The net force is not equal to the sum of the gravitational and normal force.
- There is confusion between acceleration and velocity or with the signs of velocity and acceleration. For example, students might predict that an upward moving elevator will have positive acceleration when it slows down or that any elevator that slows down must have negative acceleration.
- Approximate values predicted by students are not reasonable.
- The net force graph has a different shape than the acceleration graph.
- The elevator is accelerating throughout its motion.

Once the prediction phase is completed, students then ride the elevator again to collect data on the normal force on their feet and the time of the ride. We have used bathroom scales and Vernier force plates[7] for collecting data and have found both to be effective. Once the data is collected, students must calculate each graph in Figure 4b from the values that they recorded on the elevator. A key learning moment occurs at the beginning of the calculations when students decide what the bathroom scale (or force plate) is measuring. Eventually they come to the understanding that it measures normal forces on their feet at all times, and the force of gravity when the elevator is not accelerating. Once the gravitational and normal forces are correctly plotted, it then becomes an exercise in working through the dynamics framework. Students find the net force graph by adding force components, the acceleration graph by using Newton's second law, and the velocity and position graphs by graphical analysis or calculus. (Later these graphs can be revisited using the impulse-momentum solution path to find an equivalent solution.) We have found that the calculations involved in this laboratory help students synthesize many concepts learned in the course. The conversations that take place as groups work together to find their graphs are often lively and students feel a sense of accomplishment when they have successfully completed the activity and compare their final results to their predictions. Some students also choose to conduct laboratory extensions such as comparing the motions of different elevators.

Once the laboratory is completed, we focus on expanding their understanding of dynamics by applying the concepts learned in the laboratory to a variety of new phenomena. An example of a homework problem that applies the concepts learned in the elevator laboratory is illustrated in Figure 5. In this problem students investigate the forces and motion involved in jumping. At this time we also investigate a variety of other phenomena with a time-varying net force. One example is a laboratory in which students design an experiment using motion detectors and Logger*Pro*[8] to measure the changing air force on coffee filters falling to the earth. We have found that in loosely defined activities such as the coffee filter laboratory, the dynamics framework becomes a particularly important tool for helping students to develop a plan of action. Similar results were found when the dynamics framework was used for project work[9]. Finally, a typical test question used to assess student learning in this curriculum unit is given in Figure 6.

1. Take an elevator ride up and down. Record any forces that you feel acting on your body and describe what you think causes them.

2. On the following graph axes, use a dashed line to show your predictions for position, velocity, and acceleration as a function of time as you ride the elevator up and down. Also predict what the **NET** force acting on you, the gravitational force acting on you, and the force of the floor on your feet will look like as a function of time and plot them on the following force versus time axes. **Do this carefully and neatly. Each graph should be consistent with the others.**

3. Ride the elevator again while one member of your group stands on a bathroom scale. Record the values of the scale reading throughout the ride and convert the force into Newtons. (Note: the scale readings change rapidly and only approximate readings are possible.)

4. Based on the scale readings and what you know about Newton's Second Law, use a solid line to plot the force and motion graphs.

Make sure that your plots are neat, consistent with each other, and show approximate numerical values whenever possible.

Question 3-1: Draw a free-body diagram showing all the forces acting on you when you are standing on the scale in the elevator.

Question 3-2: Does the elevator ever travel at a nearly constant velocity? If so, when?

Question 3-3: Does the changing value of the scale indicate that your weight or mass changes during the ride? Explain any changes.

Question 3-4: How would the diagram and graphs differ if the elevator cable suddenly broke

Figure 4a. Elevator activity

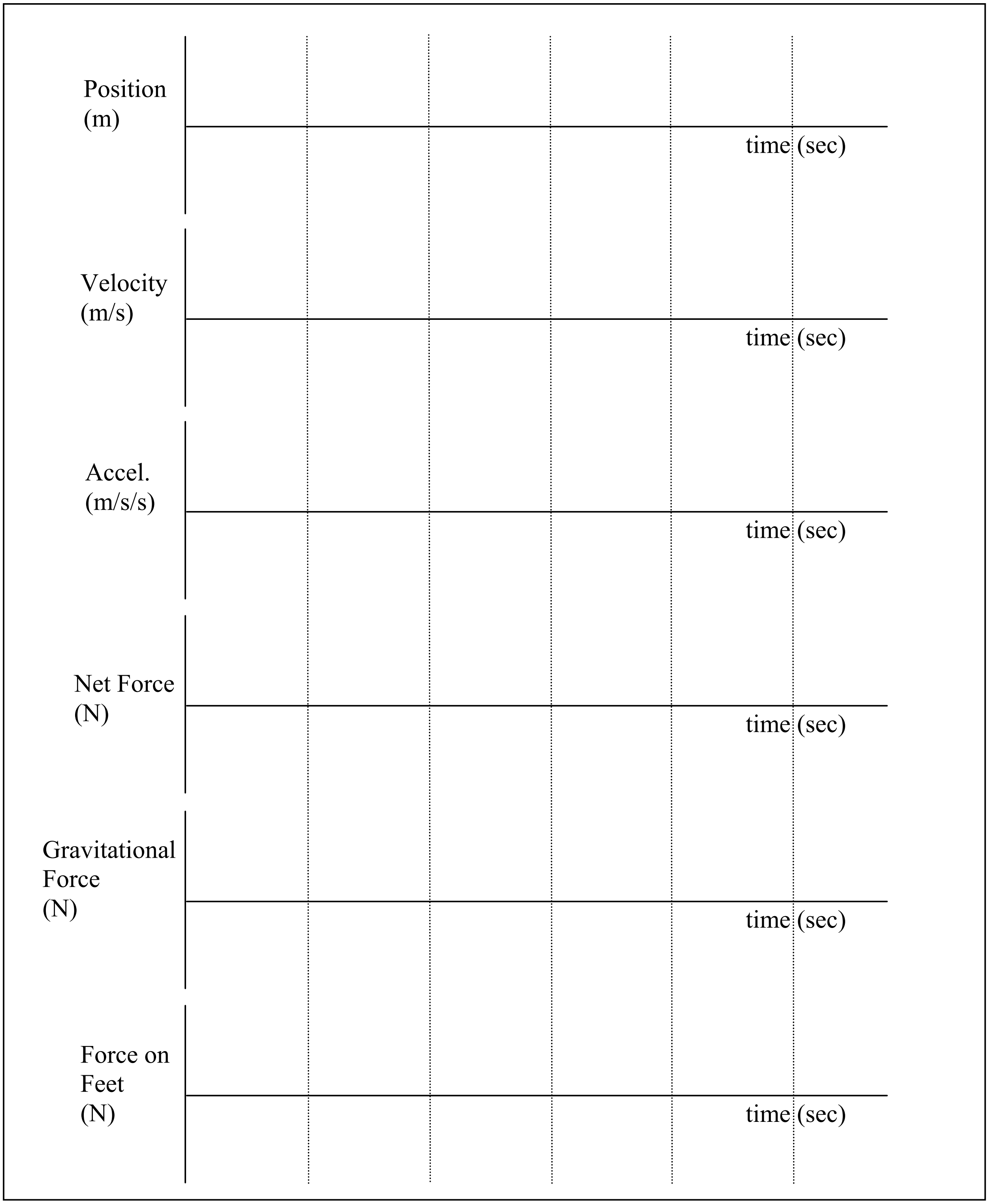

Figure 4b. Elevator activity graph axes

Stand on a chair or any other stable object. Jump off several times and concentrate on the forces acting on you (and in particular your feet) before, during, and after your flight.

a. Draw a free-body diagram of yourself while
   (1) Standing on the chair,
   (2) Pushing off of the chair,
   (3) Soaring through the air,
   (4) Landing on the floor, and
   (5) Standing on the floor.
b. Carefully fill in the following graphs to illustrate the motion in your jump. Label each section of the graphs to indicate your motion at the time.

Figure 5. Example homework question following elevator activity

A crane with an electromagnet lifts up a 1000 kg car as follows:

Time	**Car Motion**
0 to 5 sec	not moving
5 to 6 sec	accelerating upward at 0.5 m/s/s
6 to 10 sec	moving at constant velocity

At 10 seconds the electromagnet releases the car.

a. Neatly draw a free body diagram of the car during each time period: 0-5 sec, 5-6 sec, 6-10 sec, 10 sec until the car reaches the ground. **Include the source and value of each force.**

b. Neatly draw the position, velocity and acceleration versus time graphs for the motion of the car from t = 0 sec until it hits the ground. Label all critical values. Be sure to show all calculations to receive full credit.

Figure 6. Example test question used to assess dynamics understanding.

Student Response

We have used the approach described in this paper to teach dynamics at both the high school and college levels. We have also used the dynamics framework in a sophomore level engineering mechanics course. In all cases we have found the approach to be successful and popular with students. We are currently planning a formal assessment of its effectiveness in an undergraduate introductory mechanics course for Spring 2003. In this assessment we will be able to compare the effectiveness of this approach to a control group by comparing student achievement on the force concept inventory[10-12], TUG-K[13] and through common test questions. We will also use surveys to assess attitudes and focus groups to better understand the student experience.

In addition to our experiences in teaching the course, we currently have one assessment tool that supports use of the framework. In an introductory course in continuum mechanics that included engineering dynamics applications, students learned to use the dynamics framework as part of a physics review during the first week of class (see Ellis et al.[9] for a more detailed description). Even though they had not seen the framework in their physics courses, students immediately saw its usefulness in synthesizing concepts and as problem-solving tool and used it throughout the course. Their responses to a mid-semester survey on its helpfulness are shown in Table 1. No student expressed a negative opinion regarding the helpfulness of the framework, while many students found it to be very or extremely helpful.

Conclusions

We have developed a curriculum of laboratories, activities, discussions and homework assignments that use a learner-centered approach to teach dynamics. Essential to this approach is the dynamics framework, an organizational and problem-solving tool presented in this paper. This framework addresses a number of key issues.

- It places mechanics into a single context and seeks to identify connections between seemingly disparate situations rather than presenting them as a series of fragmented and fractured pieces.
- It promotes active learning and provides a platform that allows students to extend their knowledge to new situations, particularly non-idealized ones.
- When combined thoughtfully with preliminary activities and follow-up questions and exercises it provides the backbone from which to address the key issues in learning identified by the NRC and detailed above.

We have provided an in depth, detailed description of a series of activities exploring the motion of an elevator. Through these activities tudents come to understand that this is an example of a broad group of vertical motion problems. This activity series is useful in a wide range of educational settings, from an algebra-based high school class to a calculus-based undergraduate physics course. It is useful for both conceptual concerns and in doing rigorous computations. Anecdotal evidence and a student survey support the effectiveness of the approach. A formal assessment is planned for Spring 2003.

Acknowledgement

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Student	Response
1	extremely helpful! Helps show how all those formulas and concepts are related which helps me to understand new ones based on old ones I'm already comfortable with
2	extremely
3	?
4	very helpful
5	Puts the class and semester into an easy to understand form. We always know where we're going
6	helped to synthesize imformation
7	really great? One method of looking at all that type of problem
8	helpful but I wish I had a review of integrals first
9	what is this?
10	I think it's really important
11	extremely helpful
12	very helpful
13	very to see how everything fits together
14	very! It's great to be able to fall back on the basic F=ma when I'm struggling with a problem. The graphs are very helpful also
15	this was very helpful for me to understand how to set up every problem. I think it's a very good approach for this class
16	very helpful in clarifying the concepts
17	
18	good reference
19	necessary

Table 1 Student response to the question, "How helpful is it?" for the Dynamics Framework (Based upon the responses of 19 of the 27 students enrolled in the course EGR 270: Continuum Mechanics I, Smith College, Fall 2002.)

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