

A KNOWLEDGE OBJECT AND MENTAL MODEL APPROACH TO A PHYSICS LESSON

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Merrill (1987) listed as two of the cardinal principles of instruction:

1. The purpose of instruction is to promote the development of that cognitive structure that is most consistent with the desired learned performance.
2. The purpose of instruction is to promote that active cognitive processing that best enables students to use their cognitive structure in a way consistent with the desired learned performance.

In keeping with these principles, therefore, the purpose of this lesson is to assist the student in developing an appropriate mental model (structure plus process) that will enable him/her to solve problems relevant to the process or principle being taught.

The lesson is also based on the following assumptions about learning:

1. Learning is best when a student has a problem to solve.
2. Learning is best when a student can engage a series of successively more complex problems.
3. Learning is best when the presentation and practice provide are consistent with the goal of the instruction (Gagné 1965, 1985).
 - a. The goal is to understand a principle or process (in this case, momentum).
 - b. A consistent presentation for a principle or process is a demonstration (that is, showing how the principle works).

- c. Consistent practice for principle or process involves making predictions (hypotheses) about the consequence of a given event given the conditions for this event.

The learning outcome for this lesson is, "How does it work?" The emphasis is on understanding a process. When the student understands a process, he or she is able to make predictions about the consequence of a given event given the conditions for this event. In our lesson these predictions take the form of hypotheses tested empirically using the visualization provided.

Vincenti (1980) indicates that all design solutions depend on some prior agreement about the operational principle involved and the normal configuration for the product. Ruth Clark (1998) suggests four more-or-less agreed on architectures for instructional approaches: receptive, directive, guided discovery, and exploratory. The architecture of this lesson is guided discovery. Dijkstra (1997) indicates three types of problems that may confront learners in experiential environments: categorization problems, interpretation problems, and design problems. This lesson involves problems of interpretation.

This instruction is not complete. The topics provided to us included *work and power*, *energy*, *the conservation of energy*, and *momentum and interactions*. Because of the space limitations of a journal article, we chose to provide a lesson segment only on the last topic. We hope that this short segment of instruction provides a sufficient illustration of our approach that the reader can extrapolate to a more extensive instructional treatment of all the topics given. Even for the topic of *momentum and interactions* our lesson is incomplete. A complete lesson would involve several more problems for the student to solve. These problems would include additional problems such as one freight car colliding with a second car or set of cars that are also moving in the same or in opposite

directions. In addition, each of these problem types would also include several different situations (other than the railroad) that involve momentum.

Design Philosophy and Instructional Model

This lesson is based on Component Design Theory (CDT₂). CDT₂ is an attempt to describe knowledge objects in a way that is thought to be parallel to a mental model that will enable a student to solve problems of a particular kind, in this case problems of interpretation requiring prediction. CDT₂ describes a knowledge object (parallel to a student's schema) and processes for manipulating this knowledge (parallel to a student's cognitive process). CDT₂ also provides prescriptions for those instructional events thought necessary to enable students to develop an appropriate mental model that will enable them to solve problems of a particular class. In this demonstration lesson we have applied CDT₂ to a physics lesson on momentum.

CDT₂ describes the schema to be attained by the student via a knowledge object (Merrill, 1998). A knowledge object is a container for the information components thought to be required to adequately solve a particular type of problem, in this case problems of interpretation requiring prediction. Table 1 lists those knowledge components thought to be required for a mental model for solving problems of prediction.

INSERT TABLE 1 ABOUT HERE.

An instructional strategy in CDT₂ consists of presenting the components of the knowledge object to the student and requiring the student to manipulate them, thus promoting the acquisition and tuning of a mental model appropriate for solving the problems in the instruction.

In guided discovery we have used an inductive sequence described as follows. The name of the process is told to the student in the introduction to the lesson. The student is also asked a number of questions related to the description, conditions, and consequence

of the process. The student is given a situation and some predictions (hypotheses). The student is directed to do some experiments (show the process) in order to make the necessary predictions. Following the experiments, the student is asked to reflect on the experience by giving the description and identifying the relationships among the conditions (variables) that lead to the consequence. Finally the student is told the description, condition and their relationships to the consequence.

The following learner guidance is also included in the lesson: The student is encouraged to conduct experiments so that he or she is shown the process several times. The student is discouraged from guessing at the hypotheses or making predictions from memory, since the system requires the student to do the experiments required to verify each of the hypotheses. The student is encouraged to repeat the experiments since there are different kinds of freight cars. It is not necessary to use different kinds of freight cars but it is hoped that the student will be curious and repeat the experiments. Finally, it is proposed, but not illustrated, that there would be several different situations for the same class of problems as well as a sequence of problems illustrating first momentum, then conservation of momentum, in increasingly more complex situations (with other cars stationary, moving in the same direction, and moving in opposite directions).

Special Equipment

The following program could be implemented using any number of authoring programs that support multimedia courseware development. Similar programs have been implemented at USU using ToolBook™ and Authorware™. At Utah State University the ID₂ Research Group developed a simulation tool IDVisualizer™¹ that is built around the notion of PEAnets and therefore significantly simplifies the implementation of the

¹ The IDVisualizer is available as a commercial product from Mindware Creative Inc. See www.mindware1.com.

program described. Implementation of this program over the Internet presents a greater challenge.

Program Operation

Problem 1

Figure 1 illustrates an experiential environment for momentum.

INSERT FIGURE 1 ABOUT HERE.

The menu structure for the lesson(s), of which this lesson fragment is a part, is not included in this description. The student would link to this experiential environment from the menu page.

When Figure 1 first appears, the following information is displayed in a box below the simulation figure. The other three boxes (*Control Panel*, *Problem*, and *Hypotheses*) appear only after the student clicks the *FIRST PROBLEM* button from the navigation controls. In Figure 1 this button indicates *NEXT PROBLEM* since the first problem has already been selected. When the student clicks the *GOAL* button, this introduction box pops-up over the *Control Panel* and *Problem* boxes for the student to review.

INSERT FIGURE 2 ABOUT HERE.

When the *FIRST PROBLEM* button is clicked, the boxes for *Control Panel*, *Problem* and *Hypotheses* are displayed and the following information is presented via an audio message:

“The situation is a rail yard where a switcher locomotive is sorting freight cars. The switcher pushes the car to a given velocity and then stops. The railroad car continues to roll until its brakes stop it or it collides with other cars. While there is some friction in the wheels and axles, it is very small and for this problem you may consider this a frictionless environment. In this simulation the car will eventually disappear off the screen. Don't

worry; even though you won't see it happen, a brakeman will apply the brakes and stop the car.

Your task is to conduct a series of experiments that will enable you to determine whether the hypotheses that are stated in the hypothesis box (highlight *Hypotheses* box) are either true or false. When you have done an experiment that tests a given hypothesis click either the T or F to indicate if the hypothesis is supported. Your choice will be highlighted in green. The computer will monitor your experiments. It will not allow you to indicate whether a given hypothesis is true or false until you have conducted the experiment that is necessary to test the hypothesis. You may change your mind and change the answer for a given hypothesis at any time.

To run an experiment, select a value for each of the variables listed in the control panel (highlight *Control Panel* box). You select a value by clicking on the down arrow in the variable box and selecting a value from the drop-down menu. When you have selected each of the required variables, click the start button (highlight *START* button) to run the experiment.

The switch engine will push a freight car in from the left of the screen and will release the freight car at the meter post marked 0. The car will continue to roll past the buildings for several seconds before disappearing off the screen. You should observe the momentum of the freight car in the indicator box in the upper right corner of the screen.

Click the *DIRECTIONS* button to replay this message.

When you have tested all of the hypotheses click the *DONE* button."

The animation works as follows: First, the switch engine is animated from the left at the velocity selected. At meter post 0 the switch engine stops but the car continues to roll. As the car reaches the center of the screen, the car stops moving but the buildings in the background and the mileposts begin to scroll to the left giving the appearance that the

freight car is still rolling. The switch engine will also scroll off the screen to the left with the buildings since it is now stationary. After a several seconds the buildings will stop scrolling and the car will scroll off the screen to the right. For the student, the locomotive and car are not shown until the start button is clicked. In Figure 1 the locomotive and car are shown as if the animation was in progress.

The program monitors the student's experiments. For the first problem it is necessary to conduct the following experiments in order to test the hypotheses.

Experiment 1: Select a given mass, select a given velocity.

Experiment 2: Select the same mass as a previous experiment but select a different velocity.

Experiment 3: Select a different mass than a previous experiment but select the same velocity.

If the student has not conducted the experiments required for a given hypothesis then an audio message plays the following message: "You have not conducted the experiments that adequately test this hypothesis. Do some more experiments. Click the *HELP* button if you need a suggestion."

Clicking the *HELP* button causes the program to check which experiments the student has done and to suggest the next experiment that the student has not done. For example, if the student had conducted experiment 1, but not experiment 2, then clicking *HELP* would provide the following audio message: "Select the same mass as a previous experiment but select a different velocity."

After the student has conducted his or her experiments and presses the *DONE* button on the navigation panel, he or she will be given the following questions for reflection. The *Control Panel* and *Problem* boxes are hidden and the following questions appear in a box in the lower left quadrant of the screen

INSERT FIGURE 3 ABOUT HERE.

After the student finishes his or her reflection and has clicked the *DONE* button, he or she is presented this audio message: "The answers to hypotheses you may have missed are indicated in red." The following summary is shown to the student in the same area of the screen.

INSERT FIGURE 4 ABOUT HERE.

Problem 2

Problem 2, illustrated in Figure 5, is designed to illustrate conservation of momentum. The illustration is similar to Figure 1 except that there is one or more freight cars already sitting on the siding. The car being switched collides with and couples to the stationary cars and causes them to roll also.

INSERT FIGURE 5 ABOUT HERE.

When the student clicks *NEXT PROBLEM*, he or she is shown the simulation graphic in Figure 5 and the following information is displayed below the picture. The *Control Panel*, *Problem* and *Hypotheses* boxes are hidden.

INSERT FIGURE 6 ABOUT HERE.

When the *DIRECTIONS* button is clicked the above box is hidden and the *Control Panel*, *Problem* and *Hypotheses* boxes are shown and an audio message tells the student the following additional explanation.

"In this problem the switch engine will push a freight car in from the left of the screen and will release the freight car at the meter post marked 0. The car will continue to roll past the buildings until it collides and couples with the freight cars already sitting stationary on the siding. These cars do not have their brakes set, so they may also roll when the freight car collides with them. In the real world there is some friction in the wheels and axles of

the cars but for the purpose of this problem you should consider this a frictionless environment. You should observe the momentum of the freight car in the indicator box in the upper right corner of the screen. You should also observe the velocity shown in the box in the upper right hand corner of the screen. After the car collides with the stationary cars, the indicator boxes will give the momentum and velocity of all of the cars combined. After a few seconds the cars will roll off the screen. Don't worry; even though you won't see it happen, a brakeman will set the brakes and stop the cars."

At this point, the audio instructions about the task and procedures to use in responding are identical to those presented for problem 1. As with the first problem, if the student has not performed the experiments necessary to test a given hypothesis, the system provides a message indicating that the student needs to conduct more experiments. The *HELP* button provides a suggestion about what kind of experiment to conduct.

When the student clicks the *DONE* button he or she is given the following suggestions/questions for reflection. The *Control Panel* and *Problem* boxes are hidden and this box appears in the lower left quadrant of the screen.

INSERT FIGURE 7 ABOUT HERE.

After the student finishes her or her reflection and has clicked the *DONE* button, he or she is presented this audio message: "The correct answers to hypotheses you may have missed are indicated in red." The following summary is shown to the student in the lower left quadrant of the screen.

INSERT FIGURE 8 ABOUT HERE.

Specifics of Design

A PEAnet (**p**rocess, **e**ntity, **a**ctivity network) represents the process necessary for manipulating the knowledge component of a knowledge object. This PEAnet relationship

enables an instructional visualization (simulation) in which the student can manipulate the components of the knowledge object in a way thought to enable the student to acquire the required cognitive processes to make predictions.

Figure 9 illustrates the PEAnet relationships among the components of a knowledge object.

INSERT FIGURE 9 ABOUT HERE.

The specific knowledge entities (parts) required for implementing the PEAnet for the momentum visualization are indicated in Tables 2 and 3. The PEAnet for the momentum visualization is indicated in Tables 4 and 5.

INSERT TABLE 2 ABOUT HERE.

Students select items with asterisks (*) from a drop-down menu of “legal” values.

Mass is computed by the system and displayed to the student. These values depend on the type of the freight car and whether it is loaded or empty. Table 3 gives the values assigned to the different freight cars.

INSERT TABLE 3 ABOUT HERE.

Tables 4 and 5 indicate the PEAnet process for Problems 1 and 2. The first column indicates actions by the student, the third column indicates conditions and the 4th column indicates the consequence. Column 2 lists a name for the process, when the process is not obvious from the conditions and consequence. In Table 4 for Problem 1, Row 1 indicates that when the student selects a type of car that the system looks up the car in table 4 (the condition) and sets a value for the type of car in the variables of the system. Row 4 is where the visualization executes. When the student clicks *START*, the mass is set from table 4 depending on the type of car and load (conditions). The momentum is then calculated and the portrayal of the car is shown as required by the animation. The

velocity previously set determines the speed of the animation, and the value for the momentum is shown. The process for Problem 2 shown in Table 5 is similar.

INSERT TABLES 4 AND 5 ABOUT HERE.

Why knowledge objects and PEAnets? What is the advantage of components of knowledge in designing instruction?

First, having an agreed-on vocabulary enables designers to be more precise and efficient in their communication about the instructional design process. Note that in this paper we have been able to describe rather complex interactions via a rather concise table.

Second, if knowledge is represented in known slots (components), then it is possible to write a computer program (instructional strategy shell) that knows how to manipulate these knowledge slots. Thus an instructional strategy shell can be written once and then used over and over with different content with very little additional programming effort. The ID₂ Research Group has built such an authoring shell, the IDVisualizer. (See Merrill, 1999, for a more complete description of this tool.) This tool implements components of instruction. The author/developer must first specify the entities (parts) involved, their properties, the legal values of these properties, and the portrayal of each property value (see Tables 2 and 3). The author/developer then specifies the processes that act on these properties and the actions taken by the student that triggers these processes. The tool has a built-in simulation engine that can then run the visualization. It also has a built-in explanation system that can explain what happened (the consequence) and why it happened (the conditions). SimQuest, developed by Ton de Jong, University of Twente, is another simulation tool that can implement visualizations and simulations using the equivalent of knowledge objects and PEAnet processes (www.simquest.to.utwente.nl).

Third, a knowledge object emulates a schema and a PEAnet emulates the processes composing a mental model, which, if acquired by the student, will enable he or she to solve interpretation problems involving prediction.

Lessons Learned/Conclusions Drawn/Summary

Perhaps Questions to ask is better than lessons learned as the heading for this section. The above lesson has not been empirically tested. Does the model presented by this visualization facilitate the development of an appropriate mental model of momentum? Does this visualization facilitate the student's ability to solve other momentum problems? Does the hypothesis testing experiments help guide the student's interaction with the visualization? How many problems are necessary for an adequate sequence of problems to facilitate the student's development of an appropriate mental model? These are only a few of the questions surrounding the proposed lesson.

This lesson attempts to implement recommendations from cognitive psychology (See Mayer, 1992) and recent prescriptions for instructional design for solving complex cognitive problems (van Merriënboer, 1997). It attempts to implement current thinking in instructional design. The adequacy of the implementation is a judgement call for the reader. Whether or not the lesson is instructionally effective is an empirical question.

150+ word bio.

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Dr. Merrill is listed among the most productive Educational Psychologists (*Educational Researcher*, 1984), the most frequently cited authors in the computer-based instruction literature (*Journal of Computer-Based Instruction*, 1987), and the most influential people in the field of Instructional Technology (*Performance & Instruction*, 1988.)

Selected as Person of the Year in Educational Technology for 1989 by Educational Technology Magazine. Al Avner Award for Scholarship and Research by the Association for the Development of Computer-based Instructional Systems, 1992. Instructional Technology Ronald H. Anderson Memorial Award by the American Society for Training and Development 1992. Utah State University College of Education Outstanding College Scholar/Researcher of the Year 1992-1993. Special Award for contributions to the literature of the field, DID, AECT, 1995.

Principle contributions: TICCIT Authoring System 1970's, Component Display Theory and Elaboration Theory 1980's, Instructional Transaction Theory and ID based on Knowledge Objects 1990's.

Reaction to the assignment

When asked by Ward Cates to undertake the design of a physics lesson, using our approach to instructional design, I was delighted for the opportunity. Component Display Theory (CDT) is widely used as a guide for instructional development efforts. I was anxious to provide a new example of our extensions to CDT which involve an orientation toward problem solving, an attempt to promote the development of mental models, and the use of simulation for instruction. We had already developed a simulation-oriented authoring tool, IDVisualizer, that I thought would be an ideal vehicle for teaching physics principles. The reader can judge as to whether our approach represented by this brief lesson fragment significantly extends CDT.

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Figure 1 Display for Problem 1 Experiential Environment for Momentum.

Momentum = 100

START

0

10

20

30

40

Control Panel:

Freight Car type = Box Car	▼
Empty or Load = Load	▼
Mass of car = 50,000 kg	
Velocity of car = 1 m/sec	▼

Problem:

Select type of freight car.
 Select empty or load and observe weight.
 Select velocity at time of release.
 Observe momentum.
 Repeat experiment with different values.
 Select hypotheses that are supported.

Hypotheses:

When velocity increases momentum increases for a car with a given mass. **T F**

A car with the same mass always has the same momentum. **T F**

A car with more momentum travels further than a car with less momentum. **T F**

Momentum is equal to mass times velocity. **T F**

Momentum is equal to mass times distance traveled. **T F**

A car moving at a given velocity always has the same momentum. **T F**

GOAL	DIRECTION	DONE	HELP
MENU	PREVIOUS	NEXT	QUIT

In this instruction
you will do some experiments
to learn about **momentum**.

You should ask yourself these questions:

- What is momentum?
- How is momentum related to velocity?
- How is momentum related to mass?

Click the **First-Problem** button to continue.

Figure 2. Pop-up Introduction Box.

Please type an answer to the following questions:

1. What is momentum? Please describe in your own words.
2. How is momentum related to velocity? To mass? To distance?

Type your answer here. Click DONE when you are finished.

[]

Figure 3. Questions/Answer Box for Problem 1.

What is momentum?

It is a characteristic of a moving object. It requires a force equal to its momentum, applied in opposition to its direction of movement, to stop a moving object.

How is momentum related to velocity?

Momentum (p) = mass (m) times velocity (v).

How is momentum related to mass?

$p=mv$

How is momentum related to distance?

It is not.

Click NEXT PROBLEM to continue.

Figure 4. Summary Box for Problem 1.

Figure 5 Display for Problem 2 Experiential Environment for Momentum.

START

Velocity = 1 m/s

Momentum = 100

Control Panel

Freight Car type = Box Car	▼
Empty or Load = Load	▼
Mass of car = 50,000 kg	
Velocity of car = 1 m/sec	▼
Number other cars = 2	▼
Combined mass of other cars = 40,000 kg	

Problem

Select type of first freight car.
 Select load or empty and observe weight.
 Select velocity of first car at time of release.
 Select number of cars sitting on siding.
 Observe combined weight of cars sitting on siding.
 Observe momentum of first freight car.
 Observe momentum of combined cars after collision.
 Observe velocity of combined cars after collision.
 Repeat experiment with different values.
 Select hypotheses that are supported.

Hypotheses

The freight car will stop when it collides with the stationary cars. T F

The combined momentum is the same as the momentum of the first car. T F

The velocity of all cars after the collision is the same as the velocity of the first car. T F

The momentum of all cars after the collision depends on how far the first car travels before the collision. T F

GOAL	DIRECTION	DONE	HELP
MENU	PREVIOUS	NEXT	QUIT

In this lesson you will learn about the conservation of momentum. The total momentum after a collision will be the same as the total momentum just before the collision.

You should ask yourself this question:

What happens to the momentum of an object when it collides with another object?

Click DIRECTIONS button to continue.

Figure 6 Pop-up Introduction Box for Problem 2.

Explain in your own words the conservation of momentum.
How is velocity related to conservation of momentum?
How is mass related to conservation of momentum?

Type your response here. Click DONE when your are finished.
]

Figure 7. Suggestions/Questions Box for Problem 2.

This problem should have helped you answer the questions posed earlier.

What is conservation of momentum? Conservation of momentum means that the total momentum is the same after a collision as just before the collision.

How is conservation of momentum related to velocity? Momentum is the product of mass times velocity ($p=mv$). The momentum of the single car in motion is its mass x its velocity. The momentum of all of the cars after the collision is their combined mass x their combined velocity. Since the mass of the combined cars is larger than the mass of the single car, and since the total momentum must remain the same, then the velocity of the combined cars must be less than the velocity of the single car before the collision.

How is conservation of momentum related to mass? The mass of the objects involved in the collision is added to the mass of the original object in motion. The total mass has increased but the momentum remains the same because of the decrease in the velocity of the combined objects.

Click on NEXT PROBLEM to continue.

Figure 8. Summary Box for Problem 2.

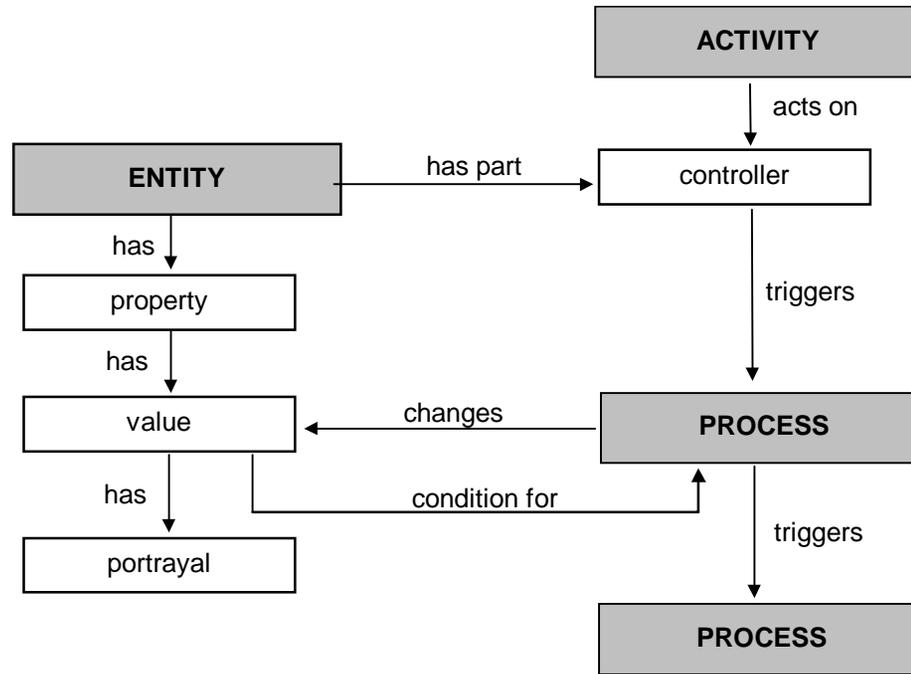


Figure 9. PEAnet Relationships among Components of a Knowledge Object

<p>Entity or Part</p> <p>Name Description Portrayal</p>	<p>Property</p> <p>Name Description Value Value portrayal</p>
<p>Activity</p> <p>Name Description Process trigger</p>	<p>Process</p> <p>Name Description Condition (Value of Property) Consequence (Property value changed) Process trigger</p>

Table 1. Components of a Knowledge Object for Problems of Prediction

Entity (Part)	Property	Legal Values
Freight Car	Velocity (v) *	1,2,3,4,5 m/sec
	Mass (m)	20,000 30,000 40,000 50,000 60,000
	Kind of car *	kg
	Load *	box(B), flat(F), hopper(H), gondola(G) empty (E), loaded (L)
Standing freight cars	Number cars*	1, 2, 3
	Combined mass	20,000 30,000 ... 180,000 kg

Table 2 Active Entities (Parts) for Momentum Visualization

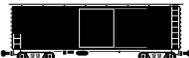
Type	Load	Assigned Mass	Portrayal ²
Flat Car (F)	Empty	20,000 kg	
	Loaded	30,000 kg	
Box Car (B)	Empty	20,000 kg	
	Loaded	40,000 kg	
Gondola (G)	Empty	30,000 kg	
	Loaded	50,000 kg	
Hopper (H)	Empty	30,000 kg	
	Loaded	60,000 kg	

Table 3 Types of Freight Cars and Assigned Mass.

² Freight car fonts © 1994 Ben Coifman zepher@cory.eeis.berkeley.edu

Action	Process	Condition	Consequence
Select type of car		Table 4	Set type = fc
Select load		Table 4	Set load = ld
Select velocity			Set velocity = v
Click START	Compute momentum	Type = fc Load =ld Velocity = v	Set mass = m P = mv Show portrayal fc Start animation Show momentum p

Table 4. PEAnet for Problem 1 Experiential Visualization for Momentum

Action	Process	Condition	Consequence
Select car type		Table 4	Set type = fc
Select load		Table 4	Set load = ld
Select velocity			Set velocity = v_1
Select # cars	Randomly select n cars	Table 4	Set # cars = n Set type = fc_1, fc_2, fc_3
	Compute combined mass	Table 4	Set c-mass = m_2
Click START	Compute momentum	Type = fc Load = ld	Set mass = m_1 Show portrayal fc Show portrayal fc_1, fc_2, fc_3
	Determine collision Compute new velocity	Velocity = v_1	Start animation Show momentum Show v_1 $v_2 = v_1 * m_1 / m_1 + m_2$ Show v_2

Table 5. PEAnet for Problem 2, Conservation of Momentum

