Design principles for effective physics instruction: A case from physics and everyday thinking

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Although several successful inquiry-based physics and physical science curricula have been developed, little has been published that describes the development of these curricula in terms of their basic design principles. We describe the research-based design principles used in the development of one such curriculum and how these principles are reflected in its pedagogical structure. A case study drawn from an early pilot implementation illustrates how the design principles play out in a practical classroom setting. Extensive evaluation has shown that this curriculum enhances students' conceptual understanding and improves students' attitudes about science.

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I. INTRODUCTION

There is a national need for physics courses that are designed for nonscience majors, particularly prospective and practicing elementary and middle school teachers.[1,2] Among the issues is the need for undergraduate science courses that not only address fundamental content goals but also explicitly address the nature of scientific knowledge, science as a human endeavor, and the unifying concepts and processes of science. Researchers and curriculum developers have responded by developing inquiry-based physical science curricula especially for the postsecondary, nonscience major population. Such curricula include *Physics By Inquiry*,[3] *Powerful Ideas in Physical Science*,[4] *Workshop Physical Science*,[5] *Operation Primary Physical Science*,[6] *Physics and Everyday Thinking*,[7] and *Physical Science and Everyday Thinking*.[8] Each of these curricula is based on findings from research in physics education, and each has demonstrated large conceptual gains.[6,9,10] Among these courses, only *Physics and Everyday Thinking* and *Physical Science and Everyday Thinking* have demonstrated replicable positive shifts in students' attitudes and beliefs for several different implementations with different instructors in different types of institutions.[11] Although the curricula we have cited are valued by the physics and physics education research community, little has been published that makes clear the design principles on which the curricula were established.

In this paper, we describe the design principles on which *Physics and Everyday Thinking* (PET) is based, how this curriculum was designed around these principles, and how they play out in an actual classroom setting.

In Sec. II, we present the design principles on which the curriculum is based and discuss the overall structure of the PET curriculum in Sec. III. We present a case study in Sec. IV to illustrate how the curriculum and design principles play out in practice. In Sec. V, we provide information about the impact of the curriculum on students' conceptual understanding of physics and their attitudes and beliefs about science and science learning. We end with a brief summary.

II. DESIGN PRINCIPLES

The PET curriculum was developed on the basis of five design principles derived from research in cognitive science and science education. These principles are based on the idea that teachers must create learning environments in which students articulate, defend, and modify their ideas as a means for actively constructing the main concepts that are the goals of instruction. The design principles are listed in Table I and are described in the following.

A. Learning builds on prior knowledge

Cognitive psychologists, cognitive scientists, and educational researchers agree that students' prior knowledge plays a major role in how and what they learn.[12,13] Prior knowledge may be in the form of experiences and intuitions as well as ideas that were learned in formal education settings (both correct and incorrect).[14] Theoretical perspectives from different academic traditions vary on their perceptions of the characteristics, organization, properties, size, and scope of this prior knowledge. However, they all agree that prior knowledge influences learning.[15–17] This prior knowledge is often strongly held and resistant to change,[18] but it also has valuable aspects that can serve as resources for further learning.[19]

In the *PET* curriculum, the *Initial Ideas* section is the first of three main sections within each activity. It is designed to elicit students' prior knowledge about the central issue of the activity. Both in the small-group and in the whole-class discussion that follows, students usually suggest ideas and raise issues that are later explored in the *Collecting and Interpreting Evidence* section. The sequence of questions in the latter section prompts students to compare their experimental observations with their predictions. As often happens, the experimental evidence supports some of their initial ideas but does not support others. The questions in the *Summarizing Questions* section, which address aspects of the key question for the activity, help students recognize what they have learned in the activity and how their final ideas might have built on their initial ideas.

Table I. Design principles of the PET curriculum.

No.	Design principle
1	Learning builds on prior knowledge
2	Learning is a complex process requiring scaffolding
3	Learning is facilitated through interaction with tools
4	Learning is facilitated through interactions with others
5	Learning is facilitated through establishment of certain specific behavioral practices and expectations

B. Learning is a complex process requiring scaffolding

Instruction that builds on students' prior knowledge views learning as a process by which students iteratively modify their understanding.[14] In this way, students move from the ideas they had prior to instruction toward ideas that are consistent with generally accepted principles and concepts with more explanatory power. This view of learning admits that students' knowledge develops gradually and that this process takes time. Throughout the learning process, it should not be surprising that a student's understanding does not become aligned with the target idea immediately and that states of "partial knowledge" can exist. Such a learning process can be facilitated by providing a high degree of guidance and support ("scaffolding") for students as they take their first tentative steps in modifying their initial ideas. As they move toward mastering a certain concept or skill, the degree of related scaffolding provided can be gradually decreased.

The structure of PET incorporates the gradual decrease of scaffolding for student learning at the curriculum, chapter, and activity levels. In terms of curriculum-wide themes,[20] examples introduced in the later chapters are more complex than, but build on, the examples discussed in the earlier chapters. At the chapter level, each complex National Science Education Standard[1] and/or AAAS Project 2061 benchmark[2] idea was broken down into smaller subobjectives that make up the target ideas of individual activities, as illustrated in Sec. III B. In addition, the target ideas addressed in the later activities in each chapter build on the ideas introduced earlier. In the final activity of each chapter, students apply the target ideas to explain real-world phenomena.

C. Learning is facilitated through interaction with tools

One of the most difficult parts of designing instruction that scaffolds the development of students' knowledge is determining how to help students move from where they are in their understanding (prior knowledge) to where the teacher wants them to be (target ideas/learning goals). Within the scientific community, various tools such as laboratory apparatus, simulations, graphical representations, and specialized language are used in the development and communication of scientific ideas. In a classroom, similar tools can be used to facilitate the articulation and development of scientific ideas. For example, computer simulations can serve as visualization tools, and laboratory experiments can provide evidence that can help students test, revise, and elaborate their current ideas. Learning environments that are designed to utilize such tools can promote deep, conceptual understanding.[21]

Major pedagogical tools within the PET curriculum include laboratory experiments, computer simulations, and various types of representations. The simulations include representational tools such as graphs, speed arrows, energy bar charts, and circuit diagrams, requiring students to make sense of these representations and make connections between them and the simulated (as well as the observed) phenomena. For example, in the activity described in Sec. III C, the students make connections between the simulator-generated speed-time graph [see Fig. 1(a)] and their own graph generated by a motion detector and between their predicted force-time graph and the simulator's graph [see Figs. 1(b) and 2]. Students also learn to represent the energy and force descriptions of phenomena by drawing energy diagrams and force diagrams. Questions within the curriculum help students make explicit connections between these two representations of the same interaction, which is a process that helps learning.[21]

D. Learning is facilitated through interactions with others

Interactive engagement refers to settings in which students interact with tools as well as with other learners.[22] Hake[23] demonstrated that courses that use methods of interactive engagement show much higher conceptual learning gains than those that rely exclusively on passive lecture methods. Social interactions in physics learning environments open new opportunities for students to talk, think, and develop their ideas.[24,25] Because the scientific enterprise relies on argumentative practices in the interpretation of empirical data and in the social construction of scientific knowledge, the case has been made for explicitly helping students to learn to engage in argumentation practices in the classroom.[26] As students are put in the position of articulating and defending their ideas in the face of evidence, they are able to move toward more robust explanatory models and deeper understandings of phenomena.

Each PET activity is divided into periods of carefully structured and sequenced small-group experimentation and discussion and includes organized and facilitated whole-class sharing of ideas and answers to questions. In the small-group discussions, students are given many opportunities to articulate and defend their ideas. Even as early as the *Initial Ideas* section of an activity, students can engage in discourse regarding their intuitions about the physical world. During the whole-class discussions in *the Summarizing Questions* section, students can compare the ideas they developed within their group with the ideas developed in other groups. This interaction can reinforce their confidence in their ideas and, in cases where they are still struggling with possible ideas, can provide the opportunity to hear ideas or ways of thinking that are helpful to them.

E. Learning is facilitated through the establishment of certain specific behavioral practices and expectations

Classroom behavioral practices and expectations play a large role in science learning, both in what students learn and in how students learn in the classroom setting.[27,28] As students learn physics, they learn not only what is typically referred to as the canonical knowledge of the discipline (such as Newton's second law or the law of conservation of energy) but also how knowledge is developed within the discipline. For example, a student must learn what counts as evidence, that scientific ideas must be revised in the face of evidence, and that particular symbols, language, and representations are commonly used in arguments by experts in the field. Also, in the classroom, teachers and students must agree on their expected roles. These classroom expectations for how students are to develop science knowledge are known in the research literature as *norms*.[27] One such expectation might be that students sit quietly and take notes. An alternative norm might be established such that students are expected (by the teacher and by other students) to talk, to state their current understandings and support their ideas with explanations or evidence, and to challenge the ideas of others.

Regardless of the learning context and the extent to which the instructor attends to classroom norms, obligations and expectations are generated and maintained by the students and the teacher, and these norms greatly impact the type of learning that can take place. Therefore, this last design principle calls for explicit attention to promoting the types of norms that support the view of the learning process that is the basis for the first four design principles.

The PET classroom is a learning environment where the students are expected to take on responsibility for developing and validating ideas. Through both curriculum prompts and interactions with the instructor and their classmates, students come to value the norms that ideas should make sense, that they should personally contribute their ideas to both small-group and whole-class discussions, and that both the curriculum and other students will be helpful to them as they develop their understanding. With respect to the development of scientific ideas, students also expect that their initial ideas will be tested through experimentation and that the ideas they will eventually keep will be those that are supported by experimental evidence and agreed upon by class consensus.

III. DESIGN OF THE PHYSICS AND EVERYDAY THINKING CURRICULUM

We first describe the structure of the PET curriculum and then describe the structure of a typical chapter and of a typical activity. PET was developed over a 6-year period, and we revised the curriculum nine times before it was published.[7] Each draft included changes based on feedback from our pilot and field-testers.

A. Structure and goals of the PET curriculum

PET is a semester-long, guided-inquiry-based curriculum that focuses on interactions, energy, forces, and fields. The learning objectives address many of the benchmarks and standards for physical science enumerated in Refs. 1 and 2. There are two major course goals for PET. The content goal is to help students develop a set of ideas that can explain a wide range of physical phenomena and that are typically included in elementary school science curriculum. The learning goal is to help students become more aware of how their own ideas change and develop and to develop an understanding of how knowledge is developed within a scientific community.

The PET curriculum is divided into six chapters (see Table II), each of which consists of a sequence of five to eight activities and associated homework assignments designed to address one or more of the benchmarks or standards. Because most benchmarks or standards represent comprehensive ideas, each was broken down into a series of subobjectives, which serve as target ideas forming the focus of one or more individual activities. Each subobjective builds on its predecessors toward the development of the broader benchmark idea that serves as the main objective of a sequence of activities.

Table II. Summary of the PET curriculum.

Chapter	Title
1	Interactions and Energy
2	Interactions and Forces
3	Interactions and Systems
4	Model of Magnetism
5	Electric Circuit Interactions
6	Light Interactions

About three quarters of the activities and homework assignments focus on helping students learn the physics target ideas (and help achieve the content goal). The remaining activities and homework assignments focus on *Learning about Learning*, where students are explicitly asked to reflect on their own learning, the learning of younger students, and the learning of scientists. These are embedded throughout the curriculum and are important not only because they help students investigate the nature of science and the nature of learning science but also because they draw the instructor's attention to the design principles that guide the curriculum. These specific activities, as well as students' active engagement in all the content activities, help achieve the learning about learning goal.

As can be seen in Table II, interaction is a unifying theme in PET. Most interactions can be described either in terms of energy or in terms of forces. In an earlier curriculum development project directed by one of us,[29] the energy description of interactions was introduced before the force description because the students' intuitions about energy seemed more aligned with the physicist's ideas than were the students' intuitions about force. Because this approach seemed to work well, the PET project staff decided early on to also start with the energy description. In Chap. 1, students learn to describe interactions in terms of energy transfers and transformations, culminating in the development of the law of conservation of energy. Chapter 2 addresses students' ideas about forces and aims to develop a semiquantitative understanding of Newton's second law. Students then use both energy and force approaches in Chap. 3 (focusing on magnetic, electrostatic, and gravitational interactions) and thereafter use either approach as appropriate throughout the remainder of the curriculum.

B. Structure of a chapter

The conceptual focus of Chap. 2 is on Newton's second law, at a level consistent with the AAAS Project 2061 benchmark:[2] An unbalanced force acting on an object changes its speed or direction of motion or both.[30]

To design a sequence of activities that would help students develop a deep understanding of this benchmark, we first reviewed the research literature on students' understanding of force and motion to determine the common ways that students make sense of their everyday experiences with pushes and pulls. For example, students often think that giving a push to an object transfers force to it that is then carried by the object until it eventually wears out.[31] They also tend

Table III. Target ideas and Chap. 2 activities for Newton's second law benchmark.

Target idea	Activity number
Interactions between objects can be described in terms of the pushes and pulls that objects exert on each other, which scientists call forces. Forces only exist while an interaction is taking place and is not transferred between the interacting objects.	1, 2, 2HW, 3, 4, 5, 8
When a combination of forces is applied to an object, the individual forces can be combined to determine a single "net" force that would have the same effect on the object's motion.	3HW, 7, 8
When a single force (or an unbalanced combination of forces) acts on an object at rest, the object will begin to move in the direction that the (net) force is applied.	1, 2, 3HW, 8
When a single force (or a net force due to an unbalanced combination of forces) acts on a moving object in the same direction as its motion, the object's speed will increase.	1, 2, 3HW, 7, 8
When a single force (or a net force due to an unbalanced combination of forces) acts on a moving object in the opposite direction to its motion, the object's speed will decrease.	3, 3HW, 5, 5HW, 8
When a single force (or a net force due to an unbalanced combination of forces) acts on an object, the rate at which its speed changes depends directly on the strength of the applied force and inversely on the object's mass.	6
If no forces (or a balanced combination of forces) act on an object, its speed and direction will remain constant.	3, 6HW, 7, 8

Note: HW: Target idea is addressed in a homework assignment that follows the indicated activity.

to think that if they observe an object moving, there must be a force in the direction of motion causing it to move and that constant motion requires a constant force.[32] We then teased out these ideas into several smaller subobjectives, which then served as target ideas that became the focus of one or more individual activities. Table III lists the target subobjectives (target ideas) for Chap. 2 and the activities and homework assignments associated with them.

C. Structure of an activity

Each activity in PET consists of four sections: *Purpose*, *Initial Ideas*, *Collecting and Interpreting Evidence*, and *Summarizing Questions*. We will describe each section in the context of the first activity in Chap. 2. The two main purposes of Chap. 2, Act. 1, are to help students begin to work out the differences between energy and force (two ideas often confounded by students) and to begin thinking about the relation between force and change in speed, which is the essence of Newton's second law. (Although it would be more accurate to focus on the relation between force and change in velocity, we have chosen to focus on speed rather than velocity because the wording of the Newton's second law benchmark focuses only on changes in speed.[33])

The *Purpose* section of Chap. 2, Act. 1 first reminds students that they described interactions in terms of energy in Chap. 1 and tells them that they will now describe the same interactions in terms of forces. The key question of the activity, "When does a force stop pushing on an object?" is posed after the term "force" is defined as a push or a pull.

In the *Initial Ideas* section of Chap. 2, Act. 1, students' prior knowledge is elicited as they imagine a soccer player giving a ball a quick and powerful kick, projecting the ball straight outward along the ground. They are asked to draw pictures of the ball during the time the player is kicking it and after the ball leaves his foot. On each picture students are asked to draw arrows representing forces they think might be acting on the ball at those times, to label what those forces represent, and then to explain their reasoning. Students first answer this question in small groups and then share ideas in a whole-class discussion, ending up with a variety of plausible ideas about possible forces on the soccer ball both during and after the kick.

Students spend the majority of their time working in small groups on the third section, *Collecting and Interpreting Evidence*. In this section, as the name implies, they conduct experiments and interpret the results. For Chap. 2, Act. 1, this section begins by asking students: Is the motion of a cart after it has been pushed the same as during the push? In this experiment students give a low-friction cart short, impulsive pushes with their fingers (both to start it moving and also while it is in motion) and observe the motion and the speed-time graph[33] generated using a motion sensor and appropriate software. The students are then asked to consider a conversation between three hypothetical students, Samantha, Victor, and Amara, each of whom expresses a different idea about what happens during the times when the hand is not in contact with the cart. Students indicate with whom they agree and explain their reasons.

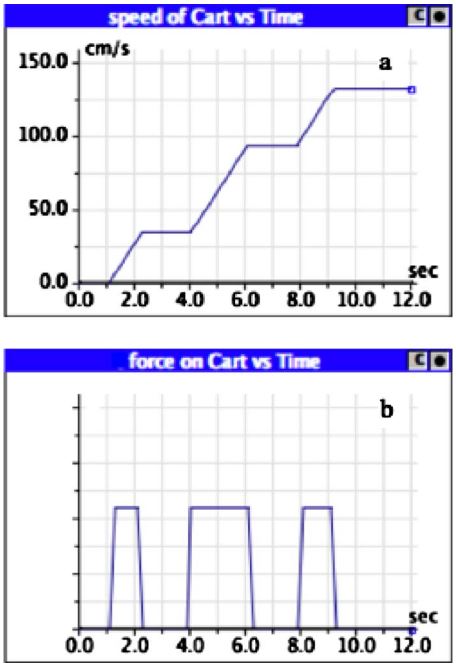


Fig. 1. (a) Computer simulated speed-time graph and (b) force-time graph. Students were first asked to predict the force-time graph from the given speed-time graph. They then compared their prediction with the computer-generated force-time graph.

Samantha: “The force of the hand is transferred to the cart and keeps acting on it. That’s why the cart keeps moving.”
Victor: “The force of the hand stops when contact is lost, but some other force must take over to keep the cart moving.”
Amara: “After contact is lost there are no longer any forces acting on the cart. That’s why the motion is different from when it is being pushed.”

Next, students are shown a computer-generated speed-time graph [see Fig. 1(a)] and are asked to indicate the times on the speed-time graph when the hand was pushing on the cart. Then they are asked to sketch the general shape of a corresponding force-time graph that represents how the force applied by the hand was behaving over the same time. Following their predictions, students run an applet that simulates a cart moving along a track and press the spacebar on the keyboard each time they want to exert a “push” on the cart. The simulator generates the corresponding speed-time and force-time graphs (see Fig. 1). (These graphs represent only the force exerted on the cart by the push and do not include friction or any other forces.) They are then asked a sequence of questions aimed at helping them make sense of the force-time graph and its connection to the speed-time graph.

The final section of the activity, *Summarizing Questions*, is intended to provide opportunities for students to synthesize their evidence to address the key question and to compare their initial ideas with their end-of-activity ideas. Students answer the questions first in their small groups and then share answers in a whole-class discussion. For Chap. 2, Act. 1, the first summarizing question focuses on what happens to the motion of a cart during the time that a hand is pushing it. The second summarizing question asks whether the force of the hand is transferred to the cart during the interaction and continues to act on it (a common initial idea). The last two questions focus on what happens to the cart after the hand loses contact with it and ask students what they think is transferred during the interaction.

Much of what we have described seems straightforward. However, because of the role of students’ prior knowledge in learning and the complexity of the learning process, students’ conversations tend to be quite interesting. We use the case study in Sec. IV to illustrate how students actually construct knowledge with the PET curriculum.

IV. CASE STUDY: STUDENT LEARNING AND THE DESIGN PRINCIPLES

In this section, we describe a case study involving actual students working through the three main sections of Chap. 2, Act. 1.[34] By focusing on a small group of three students (the focus group), as well as on the entire class, we illustrate how the five design principles played out in practice.

A. Context of study

This study was done in a large state university in the southwestern part of the United States. As part of their undergraduate degree, prospective elementary teachers are required to take an inquiry-based physical science course, which in this case was PET. The class met for two 140-min sessions per week. Thirty students were enrolled, mostly females in their senior year, about half of whom had taken a high school physics course. The three students selected to be in the focus group were chosen mainly because of their willingness to verbalize their ideas and to be videotaped. In terms of their final course grades, none of the three focus group students were in the top sixth of the class, but all of them were in the top half of the class (out of 32 students).

We videotaped the selected group throughout the second chapter of the curriculum and collected their workbooks, homework assignments, and exams. Here we focus only on their interactions during the first activity in the chapter. The three students, Deli, Karin, and Ashlie (all pseudonyms), spent about 150 min on the activity, over two class periods.

The following transcript excerpts are intended to show how the students in the focus group were struggling in their attempts to make sense of the phenomena and to emphasize how the curriculum and class structure together provide opportunities for students to make their evolving ideas explicit and subject to critique by fellow students. Although the reader may wonder whether these students ever reached a reasonable understanding of Newton’s second law, we provide evidence in Sec. V that they did.

B. Initial ideas

On the first day of Chap. 2, Act. 1, the group began their discussion of the *Initial Ideas* questions. Delia and Karin expressed many useful prior ideas and intuitions. For example, both students agreed that in a soccer ball kick, the foot exerts a force on the ball during the kick and friction is the force that slows the ball down. They also tried to make direct connections with what they had learned about interactions and energy from Chap. 1. The following excerpt illustrates how the students used prior knowledge in the discussion. At first they tried to apply energy ideas from the previous chapter to the soccer ball question, replacing chemical (potential) energy with chemical force and motion energy with motion force. (Ashlie was absent during the first discussion in the following, and another student in the class, Barb, replaced her.)

We use ellipses to indicate where we have left out a segment of the transcript for brevity. Descriptive comments are shown in brackets [ ], and a slash represents moments when two students are talking at the same time. The numbers in the first column are included for easy reference to specific statements made by the students.

1 Karin The foot exerted a force on the /ball.… Now, what kind of force do you think?…
2 Barb Yeah, it would be the same [like with energy], but we're just calling it a force now.…
3 Karin Do you think it means like a chemical force or a motion force? Is that what it's meaning?
4 Delia I think it's motion force, which is causing the ball to move, to go somewhere.…
5 Karin Remember before [in Chap. 1], like if our hand pushed the cart it was a stored… [potential], uh, energy.… Cause what I was thinking, if we were going back to what we learned before, you know with the energy, I was thinking like, okay, the foot was exerting a chemical force on the ball, which in turn, you know, increases the motion in, er, force of the ball.

The group eventually abandoned energy terminology, and in the ensuing whole-class discussion, they spoke only in terms of force. Three main ideas emerged from the subsequent whole-class discussion: The foot exerts a force on the ball during the kick; this force continues to act on the ball after the kick, keeping the ball moving forward; and other forces such as gravity and friction act on the ball as it moves forward. No judgments were made by the teacher or students regarding the correctness of these ideas. Instead, the variety of ideas provided motivation for the class to carry out experiments in the next section of the activity.

C. Collecting and interpreting evidence

This section begins with an experiment designed to help students answer the question: Is the motion of the cart after it has been pushed the same as during the push? At the beginning of the experiment, students give a low-friction cart a series of impulsive pushes and observe its motion along the track and the speed-time graph generated on the computer display using the motion detector. The graph made by the three students was similar to the idealized one in Fig. 1(a), and they were able to interpret the graph by making explicit connections between the features of the graph (the upward-sloped parts and the nearly horizontal parts) and what they had done to the cart. All three students wrote in their workbooks that when the hand was in contact with the cart, the cart sped up quickly, and when the hand was not in contact with the cart, the cart moved at a constant speed. At this point, the first day ended.

For the second day of the activity, the students began considering the hypothetical discussion among Samantha, Victor, and Amara about what happened after the hand lost contact with the cart (see Sec. III C). Delia and Karin tried to clarify what Victor and Amara were saying, in particular, whether motion after the push implied that there was a force acting on the cart. Ashlie initially supported Samantha because she thought that energy was transferred. However, Karin pointed out that they were talking about force, not energy. At the end of the following transcript, Karin reminds the group that they don't have to reach a consensus at this time and that they will soon perform an experiment to help them figure it out.

6 Karin I think Victor's right. Who do you think?
7 Ashlie I was going to say that Samantha was right.
8 Delia …Amara's saying that she's not saying there's no motion. She's just saying it's different.
9 Karin No, no, so you're saying that just because there's motion, that doesn't mean there's any force.…
10 Delia [To A] Why do you think Samantha's right?
11 Ashlie Um, because I'm thinking of, as far as energy transfers, the energy that's being transferred is still with the cart.
12 Karin It's force. We're not doing energy. Its force transfers. We're not talking about energy.
13 Ashlie Okay, force transfers. Well, I'm saying the transfer is still with the cart, so, yeah, that's why I thought she was right, but I could be totally wrong.
14 Delia I mean, what you're saying makes sense to me too.
15 Karin I don't think we have to answer it as a consensus of the group, do we? … It doesn't have to be right. We're going to be doing an experiment to figure it out anyway. I'd say, just go with your initial thought, and whatever your initial thought is, we'll figure it out.

This discussion illustrates how all five of the design principles in Table I come into play. Ashlie's initial interpretation of Samantha's idea about force transfer was in terms of energy (line 11) that she had learned about in Chap. 1 (design principle 1). Karin's reminder that they were talking about force, not energy (line 12), helped Ashlie distinguish between the two (line 13). Karin's comment at the end of line 15 suggests the students recognized that learning will take some time (design principle 2) and that it was okay to not fully understand something in the midst of the learning process because they would eventually perform experiments (design principle 3) to help them figure it out for themselves (design principle 5). Finally, the transcript shows students engaging in collaborative discussion and respecting (line 14) and clarifying one another's ideas (line 9, design principle 4).

At the end of their discussion, the students wrote their ideas in their notebook. Karin agreed with Victor because she believed there was another force that kept the cart moving besides the initial push of the hand. Although Delia initially was inclined to agree with Amara, she ended in agreement with Victor for reasons similar to Karin's. Ashlie justified agreeing with Amara by claiming that the cart remained at a constant speed after the push because there was no longer any force changing its motion, an idea aligned with the physicist's view.[35]

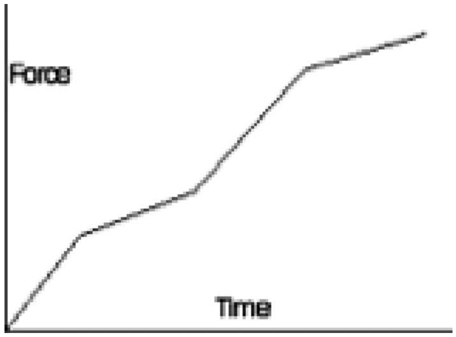


Fig. 2. Karin's predicted force-time graph corresponding to the speed-time graph shown in Fig. 1(a).

Immediately before producing the simulated force-time graph, students considered the simulator speed-time graph that represented the motion of the cart with three successive pushes [see Fig. 1(a)]. After a brief discussion in which the students correctly identified the intervals on the speed-time graph corresponding to the hand pushing on the cart, they spent over 6 min considering what they thought the corresponding force-time graph would look like. For brevity, we comment just on Karin's ideas. She struggled with trying to understand how to represent friction and/or gravity on the force-time graph—forces that she believed were acting on the cart after each push and that would be consistent with Victor's idea. The force-time graph she sketched in her workbook is shown in Fig. 2. She apparently assumed that the slope of the graph, rather than its ordinate value, corresponds to the amount of force acting on the cart, and thus she represented more force acting on the cart during the push and less force acting on it between pushes by drawing steeper slopes during the pushes and less-steep slopes between the pushes. She expressed uncertainty but thought that eventually she would be able to figure it out.

The group then ran the simulator to generate the speed-time and force-time graphs for the three successive quick pushes. They spent about 30 min trying to make explicit connections between their pressing and releasing the keyboard spacebar (which generated "pushes" on the simulated cart), the resulting speed-time graph and the resulting force-time graph (see Fig. 1). At the end, they all wrote in their workbooks that the force was not acting on the cart during the time that the speed was constant. Delia wrote: "No, the simulator force-time graph did not agree with my prediction. Once the cart is being pushed there is force acting on it and once it is released there is no force anymore, and I agreed with Victor [who] believed that there was another force that acted on the cart which kept it moving." Karin wrote: "The simulator did not agree with my prediction. It showed that there was no force on the cart after it was pushed. I had agreed with Victor in saying there was another force on the cart at that time. New ideas: There may be another force acting on the cart but it is not significant when discussing the pushes. I have switched to Amara's ideas." Ashlie wrote: "Yes. In the beginning I was going to agree with Samantha but then I was reminded by my teammate that we are now talking about forces not energy; after that I agreed with Amara."

The discussion further illustrates how the five design principles come into play. Karin's belief that there was another force present after the ball left the kicker's foot influenced both her predicted force-time graph (Fig. 2) and her interpretation of the simulator force-time graph shown in Fig. 1(b) (design principle 1). The significant time the group spent on predicting and then making sense of the computer-generated force-time graph for the three pushes suggests the complexity of the situation and how the activity guides them through the process (design principle 2) by focusing their attention on the simultaneous comparison between the kinesthetic experience of pressing the spacebar and the speed-time and force-time graphs that are generated (design principle 3). Much of the discussion within the group was to clarify how they were interpreting the graphs and connecting those interpretations to the previous discussion between the three hypothetical students (design principle 4). Finally, the effort put forth by the group in trying to understand the graphs suggests that they understood their role was to make personal sense of the phenomena and to take the reasoning of their peers seriously even when it was different from their own reasoning, sensing that the curriculum would eventually help them if they could not resolve the issues themselves (design principle 5).

D. Summarizing questions

The final section of an activity is *Summarizing Questions*. In our case study, it included the following questions: "Do you think the force of the hand was transferred from the hand to the cart during the interaction and then continued to act on it after contact was lost? What evidence supports your idea?" We expected these questions to generate much discussion within the group and the class because they explicitly address the difficult issues involving the relations between force and motion and between force and energy that are at the heart of the activity. The focus group did struggle with their answer to these questions, and the same issues also emerged during the subsequent whole-class discussion.

A student (S1) from another group began this discussion by describing how she and her group were confused. She initially thought that the force was transferred and stayed with the cart, although the simulator graph suggested otherwise. She then thought there was not any transfer of the push from the hand to the cart and that perhaps the transfer had something to do with energy not force, but she was very uncertain. She later sought help from the class.

16 S1 But as I got to thinking about it, I got more confused.... I thought it had something to do with some type of energy or something and not a force, and we didn't really know and we were hoping that someone might have some other way to explain it to us.

Rather than respond directly to her confusion, the teacher asked the class for further comment, and Karin and then Delia shared their own confusions. Karin still believed there was another force acting on the cart after it was let go, but was troubled because she found no supporting evidence from the activity. Delia didn't understand how there could be motion without a force pushing on the object, and was confused because the simulator-generated force-time graph didn't show any force even though the cart was still moving.

17 Karin I don't understand. 'Cause, like I am not completely convinced through this experiment that there's not another force on the cart after…the hand has let go of the cart. I understand on the graph like she was saying, after you let go, there's, on the graph, there's nothing in that point in time when the cart is moving at a constant speed, you know you're not touching it anymore, that shows no net force. Um, but I'm not completely convinced there's not something else acting on it. So, I don't know how to, I don't know how to back that up with evidence, except that this hasn't convinced me of that, so I don't know. That's why I'm confused.

18 Delia I'm confused also.… When they're saying that the force of the hand was transferred from the hand to the cart during the interaction and then continued to act on it, I think it does. But then I have to write "no" because the graph is telling me otherwise. But I think there's still because if it was no more force, then why the cart keeps moving?…I don't know if there's a relationship between speed and force. I don't know. I'm confused.

Again the teacher asks the class if anyone can offer a suggestion for how to resolve this confusion. Student S2 then offers a distinction between force and energy, drawing on what she had learned in Chap. 1 about energy transfer. She suggests that the force actually pushes the cart, but that the cart's energy stays with it.

19 S2 Maybe since like we were doing energy before, when you give force to an object, I mean I don't know, maybe force creates energy and the energy continues but the force stops. So it would be like the force is actually pushing it but the energy stays with it.

The teacher does not validate this comment but merely queries the students about their thinking. It is apparent that not all are convinced, and so the teacher points out that it is okay for this issue to remain unresolved at this early point in the chapter.

The discussion of this summarizing question, coupled with those earlier in the activity, provides another illustration of how the five design principles play out in the PET classroom. Delia's labeling of "motion force" (line 4) in the *Initial Ideas* discussion, her support of Victor's idea in the *Collecting and Interpreting Evidence* section, and her admission of her confusion in line 18 suggest that her prior belief that motion requires force strongly influenced her thinking and learning during the entire activity (design principle 1). The fact that Karin (line 17) and Delia (line 18), as well as other students in the class (represented in line 16), continued to be confused about the distinction between force and energy and the relation between force and motion suggests that these issues are complex and require multiple opportunities to revisit them in various contexts before we expect students to make sense of them in a way consistent with the physicist's ideas (design principle 2). Moreover, even though Karin and Delia both understood the substance of the computer simulated force-time graph [Fig. 2(b)], their comments in lines 17 and 18 suggest they still had difficulty accepting its implication that there was no (forward) force on the cart after the initial push (design principle 3).

The *Summarizing Questions* section provided the opportunity for several students to articulate their ideas and confusions so that other students could address them or at least hear them (design principle 4). The whole-class discussion also provided evidence that norms related to responsibility for learning and for the development of scientific ideas had been established (design principle 5), at least in part. S1 in line 16 asked the class to help her resolve her confusion about whether force is transferred. Both Karin and Delia added their own confusions (lines 17 and 18). Finally, student S2 (line 19) responded with a plausible resolution. These student comments suggest that they expected ideas to make sense and they expected other students to help them resolve their confusions rather than depending only on the instructor. The teacher, in turn, promoted this class responsibility norm by deflecting questions to the class rather than answering them himself. Furthermore, Karin's concern about the lack of evidence to support her idea (line 17) suggests she expected that for ideas to be accepted, they needed to be supported by evidence.

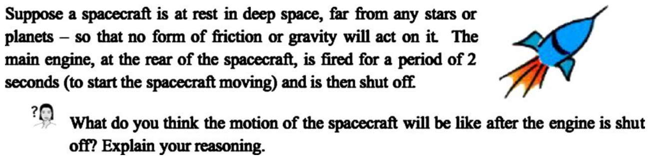
These classroom norms did not happen serendipitously. Instead, they were partially established by the structure of the curriculum and partially established and maintained by the teacher and the students. If the teacher had intervened as soon as students showed signs of confusion, the students might not have felt the need to grapple with the issues or make sense of the phenomenon. Instead, they might have waited for the teacher to tell them the answer, resulting in less personal investment in their interactions with the tools and with one another.

After completing Chap. 2, Act. 1, the students went through the next activity, focusing on what happens when an object is subject to a continuous and constant force. Then they went through the rest of the activities and homework assignments in Chap. 2, where they considered forces applied in a direction opposite to the motion, friction, the effects of force strength and mass, and combinations of forces (see Table III). Despite the students' difficulties that emerged during Chap. 2, Act. 1, on the relation between force and motion, in the next section we provide evidence that the focus group students did eventually develop a good understanding of this relation. We also discuss the extent to which the PET curriculum achieved both its content and learning about learning goals (see Sec. III A).

V. COURSE EVALUATION

The case study we have described suggests there was considerable uncertainty within the focus group about the relation between force and motion following the first activity in Chap. 2. How did the students' understanding of this relation evolve during the chapter and the entire course? To help address this question, we look at the focus group students' performance on a relevant homework they did shortly after finishing the first few activities in Chap. 2, on the test following Chapters 1–3, and on a conceptual assessment administered at the beginning and at the end of the course.

Following Chap. 2, Act. 4, students were given a home-



Suppose a spacecraft is at rest in deep space, far from any stars or planets – so that no form of friction or gravity will act on it. The main engine, at the rear of the spacecraft, is fired for a period of 2 seconds (to start the spacecraft moving) and is then shut off.

What do you think the motion of the spacecraft will be like after the engine is shut off? Explain your reasoning.

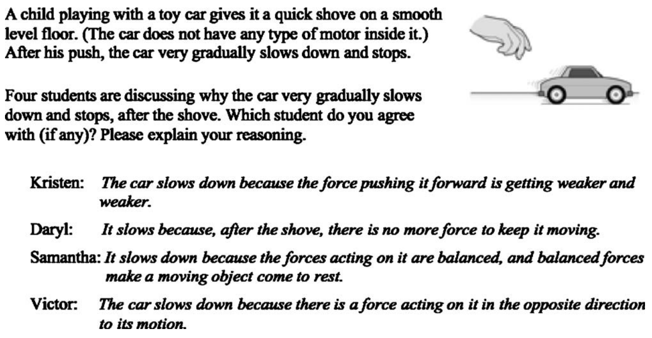
Fig. 3. Homework question following Chap. 2, Act. 4.

work assignment that focused on what the motion of a object would be like if it were subject to a short duration force and then the force was removed (see Fig. 3).

The responses of the three students in the case study suggested a reasonable understanding of what would happen in this situation. Karin wrote: “The spacecraft will continue to move forever without ever slowing down or stopping. Because if there is no gravity and no other forces acting on the ball, it has no reason to slow down. It can travel forever without any interactions from anything.” Ashlie wrote: “The spacecraft would continue moving because there would be no forces acting on it to cause any change in its motion.” Delia wrote: “The spacecraft will continue moving in the direction it was heading. If it has no interaction, or there are no forces acting on it, I believe it will continue to move at a constant speed.”

The class test following Chap. 3 included questions from the first three chapters of the curriculum and was administered two weeks following the completion of Chap. 2. The question most relevant to the issues raised in the case study described a conversation between four hypothetical students about why a toy car (without a motor) slows down and comes to a stop after being given a quick push on a floor. The statements of one of the four hypothetical students reflected the scientific reason, and statements of the three others represented incorrect ideas that students commonly articulate. The students were asked to state which of the four hypothetical students they agreed with and to write a justification for their choice (see Fig. 4).[36]

The three case study students all chose the correct choice (Victor) and provided adequate justifications for their choices. Karin wrote: “I agree with Victor because when an object is moving, in this case, a car, there is an opposing force constantly acting on the object. Friction is present and is a constant, single unbalanced force acting in the opposite direction of the motion. This constant force causes the car to gradually decrease its speed and come to a stop. If there were no friction to oppose the car’s motion, then the car would continue to travel at a reasonably constant speed.” Ashlie wrote: “I agree with Victor because the force of friction is acting on the car in the opposite direction of its motion. The force of friction would be a single unbalanced force which causes the car to slow down.” Delia wrote: “I agree with Victor because the car slows down due to the force of friction that acts in the opposite direction of the car’s motion which causes the car to slow down and stop.”



A child playing with a toy car gives it a quick shove on a smooth level floor. (The car does not have any type of motor inside it.) After his push, the car very gradually slows down and stops.

Four students are discussing why the car very gradually slows down and stops, after the shove. Which student do you agree with (if any)? Please explain your reasoning.

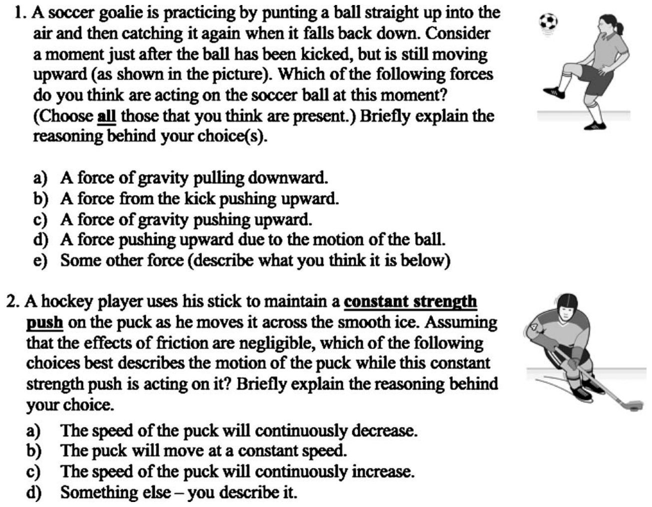
Kristen: *The car slows down because the force pushing it forward is getting weaker and weaker.*

Daryl: *It slows because, after the shove, there is no more force to keep it moving.*

Samantha: *It slows down because the forces acting on it are balanced, and balanced forces make a moving object come to rest.*

Victor: *The car slows down because there is a force acting on it in the opposite direction to its motion.*

Fig. 4. One of the questions on the exam following Chaps. 1, 2, and 3.



1. A soccer goalie is practicing by punting a ball straight up into the air and then catching it again when it falls back down. Consider a moment just after the ball has been kicked, but is still moving upward (as shown in the picture). Which of the following forces do you think are acting on the soccer ball at this moment? (Choose all those that you think are present.) Briefly explain the reasoning behind your choice(s).

a) A force of gravity pulling downward.
b) A force from the kick pushing upward.
c) A force of gravity pushing upward.
d) A force pushing upward due to the motion of the ball.
e) Some other force (describe what you think it is below)

2. A hockey player uses his stick to maintain a constant strength push on the puck as he moves it across the smooth ice. Assuming that the effects of friction are negligible, which of the following choices best describes the motion of the puck while this constant strength push is acting on it? Briefly explain the reasoning behind your choice.

a) The speed of the puck will continuously decrease.
b) The puck will move at a constant speed.
c) The speed of the puck will continuously increase.
d) Something else – you describe it.

Fig. 5. The first two questions on the PET pretest and post-test.

A final piece of data that provided information on the focus group’s understanding of the relation between force and motion was a conceptual test developed by the course authors and administered to the class at the beginning and end of the Spring 2003 semester. The pretest and post-test included five questions, the first two focusing on force and motion, the third dealing with multiple forces, the fourth on light and seeing, and the fifth on energy conservation. Each question presented a scenario and a question, several possible answer choices, and space for students to explain their reasoning. The first two questions are shown in Fig. 5.

During the Spring 2003 semester, the first author and another member of the project staff, a doctoral student, scored the pretests and post-tests of the students in the class. Responses to each question were scored on the basis of 0, 1, 2, or 3 points, according to a rubric designed by the project team. To receive a score of 3, a response needed to indicate the correct answer and include a full and appropriate justification. A correct answer, with an incomplete (but not incorrect) justification, received 2 points. A response including the correct answer, with either very little justification or with one that was partially incorrect, received 1 point. (A response that included both the correct answer and one or more incorrect answers, with justification for questions for which more than one answer was allowed, would have received 1 point.) To receive 0 points, the student could have chosen a wrong answer with justification or provided any answer (correct or incorrect) with no justification.

To give a sense of how the ideas of the three focus group students changed from the beginning to the end of the semester, we provide both their pretest and post-test responses to each of the two questions in Fig. 5 along with their scores. All three students had preinstruction ideas that were consistent with the belief that a force (from the foot) continues to act on the ball even after the ball leaves the foot (from question 1) and that an object experiencing a constant force moves with constant speed (from question 2). On the post-test, both Karin's and Ashlie's answers to the two questions were consistent with an understanding of Newton's second law. The results for Delia were mixed. For the first question, her answer on the post-test suggested she still believed the force from the kick remains with the ball after it leaves the foot. On the second question, her response is consistent with the idea that an object acted on by a constant strength force will continuously increase in speed.

For question 1 on the pretest, Karin circled answers (a) and (b) and wrote: "My reasoning for my choices is there is a force when a ball is kicked upward and gravity is always present so there is also a force pulling the boy downward." On the post-test she circled (a) only and wrote: Gravity is the only force acting on the ball pushing (pulling) it downward because gravity is a constant force. Also the force of the kick ends when the foot leaves contact with the ball. The only force is gravity." She received 1 out of 3 points on the pretest, and 3 out of 3 points on the post-test.

For question 2, on the pretest Karin chose answer (b) and wrote: "If the strength push is constant so is the speed to the puck." On the post-test she chose answer (c) and wrote: "The speed of the puck will continuously increase if there is a constant strength push on it because the push get [sic] the puck to move and then it is like the speed keeps adding on top of itself creating more speed even though the push is the same." She received 0 out of 3 points on the pretest and 3 out of 3 points on the post-test.

For question 1, on the pretest Ashlie circled answers (a) and (b) and wrote: "Gravity is a constant force. The force of the kick is acting against gravity." On the post-test she circled (a) and (e) and wrote: "The force of gravity is constantly acting on the ball. That is why the speed of the ball decreases and eventually moves in the opposite direction (down). Otherwise the ball would continue to rise. Under choice (e) she wrote: Force of friction of the air against the ball (but not very significant)." She received 1 out of 3 points on the pretest, and 3 out of 3 points on the post-test.

For question 2, on the pretest Ashlie chose answer (b) and wrote: "The puck will continue to move for a short time of [sic] the stick stops pushing it." On the post-test she chose answer (c) and wrote: "If an object receives a constant push (force) then its speed will continually increase as long as friction is negligible. Eventually the puck will move faster than the stick and the player will have to adjust it in order to maintain contact with the puck." She received 0 out of 3 points on the pretest and 3 out of 3 points on the post-test.

For question 1, on the pretest Delia circled answer (b) and wrote: "The force from the kick pushing upward is the force acting on the soccer ball because as the girl puts the force on the ball then it will go up and it depends how much force she puts on the ball that will determine how far upward the ball will go." On the post-test she again circled (b) and wrote: "As the ball moves upward just after it was kicked, the only force that are acting on the soccer at this moment is the force from the kick pushing upward because the ball continues to move upward. Therefore there is no other force at this time acting on it." She received 0 out of 3 points on the pretest and 0 out of 3 points on the post-test.

For question 2, on the pretest Delia chose answer (b) and wrote: "I believe that the puck will move at a constant speed because if the hockey player maintains a constant strength push than is logic that the puck will also move at a constant speed unless the hockey player chooses to change the strength." On the post-test she chose answer (c) and wrote: "As a constant strength push keeps being applied to the puck, then it will continuously increase. The puck will continuously increase when a constant force is applied as long as no other force is applied in the opposite direction." She received 0 out of 3 points on the pretest and 3 out of 3 points on the post-test.

The results from the homework assignment, the unit test, and the pre-post test suggested that the activities in Cycle 2 provided the opportunity for both Karin and Ashlie to develop an understanding of the correct relation between the force and motion. Although Delia displayed a good understanding of the relation between force and motion on the homework and unit test, she reverted to her initial non-Newtonian thinking on at least one of the postassessment force and motion questions. Even though the case study in Sec. IV C emphasized that all three of the students were struggling to make sense of the relation between force and motion during Chap. 2, Act. 1, in later assessments two of the students consistently applied Newton's second law appropriately and the third student did so on most of the assessments.

How representative were these three students with respect to the whole class? To help answer this question, we compared their average pre-to-post score changes on the two questions described in Fig. 5 to the average changes for the other 28 students in the class. For question 1, the average pretest to post-test score changes for the three focus group students were 0.7–2.0, compared to the other students for which the average pretest to post-test score changes were 0.8–1.4. For question 2, the average pretest to post-test score changes for the three focus group students were 0.0–3.0 compared to 0.8–2.3 for the other students. The pre-post data suggest that for the two questions, the average pre-to-post changes for the three focus group students were higher than the average pre-to-post changes of the remaining students. These results are consistent with their final course grades, which were also somewhat above average (see Sec. IV A).

Our data suggest how some of the force and motion ideas of the three students in the focus group evolved during the semester. In Sec. III A, we mentioned that the content goal for PET was to help students develop a set of ideas that can be applied to explain a wide range of physical phenomena. In the following, we provide some data about the impact of PET on students' conceptual understanding.

The students in the Spring 2003 class used an early draft of the PET curriculum. Based on feedback from pilot and field test implementations, the PET curriculum was revised several times over the following years prior to the publication of the first edition in 2007. To gather student impact information over this development period, an external evaluator administered two versions of a pre/post physics conceptual test to 45 different field-test sites between Fall 2003 and Spring 2005. The first version of the conceptual test, administered in Fall 2003 and Spring 2004, included the same five questions mentioned in Sec. IV, including the two force and motion questions shown in Fig. 5. Each question required students to choose an answer from several choices and justify their choice. One member of the external evaluation team graded all the questions on both the pre- and post-tests using the scoring rubric developed by the project staff and discussed with the external evaluator. Eleven different instructors were involved in administering the tests in 16 classrooms, and a total of 349 students completed both pre- and post-tests. Most of those instructors had previously taught courses with a pedagogical approach similar to PET, which is why they were selected to field-test the initial drafts of the curriculum. The mean pretest score across all sites was 21.2%, and the mean post-test score was 65.2%. The average normalized gain[37] for all sites was 0.56 with a standard deviation of 0.12. Values for the average normalized gain across sites ranged from 0.37 to 0.72. To determine the significance of changes from pretest to post-test, a paired *t*-test was done on total scores. For all sites, the change in scores from pre to post was significant at $\alpha \leq 0.01$.[10]

The second version of the pre-post test included the same five questions as the first version plus two additional questions involving electric circuits (because later field-test versions of the PET curriculum included additional activities on this topic). This version was administered during Fall 2004 and Spring 2005. Twenty-one different instructors were involved in administering the tests in 27 classrooms, and a total of 719 students completed both pre- and post-tests. Two of these instructors had also administered the first version of the pre-post test. Most of the rest had not previously taught a course with a similar pedagogical approach. These field testers also administered the pre-post assessment during their first semester of teaching PET. The mean pretest score for all sites was 24.1%, and the mean post-test score was 54.2%. The average normalized gain for all sites was 0.40, with a standard deviation of 0.13. Values for the average normalized gain across sites ranged from 0.14 to 0.62. As with the results from the first version, a paired t-test showed that for all sites the change in scores from pre to post was significant at $\alpha \leq 0.01$.[10]

In summary, the overall student responses to test questions were significantly higher (based on the scoring rubric criteria) from pre to post for both versions of the test and suggest that the PET curriculum helped students at diverse sites enhance their conceptual understanding of important target ideas in the curriculum, including Newton's second law, light, energy and electric circuits, thus achieving our content goal. As the field-test data suggests, classrooms taught by instructors who had previous experience teaching with a pedagogy similar to PET showed much higher average normalized learning gains (0.56 compared to 0.40) than classrooms with teachers who did not have that previous experience. Hence, we expect that the average normalized learning gains in the classrooms of the instructors in the 2004–2005 study would improve as the instructors gained more experience teaching the PET course. However, we could not test this conjecture because our evaluation study did not follow these teachers beyond their first implementation. Furthermore, there was considerable variation across sites in the average normalized gains in both the 2003–2004 and 2004–2005 studies, especially in the latter. Hence, although our evaluation data show that students made learning gains that were statistically significant, future instructors who might consider using PET in their classrooms need to be cautious in drawing conclusions from the data about what specific student learning gains they might expect to achieve.

We now discuss the extent to which the PET curriculum helped students become more aware of how their own physics ideas changed and developed and to develop an understanding of how knowledge is developed within a scientific community. Because the PET classroom pedagogy and curriculum were designed to promote more student responsibility for developing physics ideas and because there were many activities embedded in the curriculum to engage students in thinking about the nature of science and their own learning, one might expect that the PET course would have a positive impact on students' attitudes and beliefs about physics and physics learning. To gather information on this possible impact, the Colorado Learning Attitudes About Science Survey (CLASS) (Ref. 38) was administered in Spring 2007 in a separate study.[33] This survey consists of 42 statements about physics and physics learning. Students respond to each on a five-point Likert scale (from strongly disagree to strongly agree). The survey designers interviewed university physics professors with extensive experience teaching the introductory course about the questions and thus determined the "expert" responses. The students' responses are compared to the expert responses to determine the average percentage of responses that are "expertlike." Of particular interest is how these average percentages change from the beginning to the end of a course. A positive shift suggests that the course helped students develop more expertlike views about physics and physics learning. A negative shift suggests students became more novicelike (less expertlike) in their views over the course of the semester.

The CLASS was given to 395 PET and PSET (*Physical Science and Everyday Thinking*, a related curriculum) students from ten colleges and universities with 12 different instructors, in classes of 13–100 students.[11] Results show an average of 9% shift (+4%–+18%) in PET and PSET courses compared to average shifts of −6.1–+1.8 in other physical science courses (of 14–22 students) designed especially for elementary teachers.[6] Results for larger sections of introductory physics typically show shifts in traditional courses of −8.2–+1.5 in calculus-based physics (40–300 students in each course section) and −9.8–+1.4 in algebra-based physics for nonscience majors and premed students.[39] The nationwide PET/PSET study concluded that CLASS presurveys suggested that the students thought about physics problem solving as a process of arriving at a predetermined answer through memory recall and formulaic manipulation. Their answers on the CLASS postsurveys suggest that after experiencing PET/PSET, students were more inclined to think about physics problem solving as the process of making sense of physical phenomena. The curriculum focus on eliciting initial ideas, collecting and interpreting evidence, and using that evidence to support conclusions in the summarizing questions section was different from what they have experienced in other lecture-based college-level or high school physics courses. Otero and Gray[11] concluded that the rich experience of engaging in the scientific experiments and discussions allowed them to obtain a more personal connection to the physics content of the course.

VI. CONCLUSIONS

We have described how a set of research-based design principles was used as the basis for the development of the *Physics and Everyday Thinking* curriculum. These principles dictated the pedagogical structure of the curriculum, resulting in a guided-inquiry format that has been shown to produce enhanced conceptual understanding and to improve attitudes and beliefs about science and science learning. We also used the same design principles to develop *Physical Science and Everyday Thinking* (PSET).[8]

The curriculum development and associated research we have described are intended to assist other faculty in considering alternative methodologies not only for courses for nonphysics majors but also for all physics courses that frequently fail to include opportunities for students to connect their own sense-making about the central principles covered in the course with the physical phenomena from which these principles were derived. We presented some data to support claims about the efficacy of curricula, and we continue to study the impacts of the PET and PSET curricula in both small- and large-enrollment settings.[40]

ACKNOWLEDGMENTS

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[20] We have not discussed the role of explanations in this paper, but throughout the curriculum, the students practiced constructing their own explanations of phenomena and evaluating the explanations written by "hypothetical" students. To guide this process, the curriculum provided a set of evaluation criteria. In the early chapters, students were given significant help in applying the criteria. In later chapters, they were expected to write and evaluate explanations with little or no assistance.

[21] P. Kohl and N. D. Finkelstein, "Patterns of multiple representation use by experts and novices during physics problem solving," Phys. Rev. ST Phys. Educ. Res. **4**, 010111 (2008).

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[23] R. Hake, "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," Am. J. Phys. **66**, 64–74 (1998).

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[25] P. Heller, R. Keith, and S. Anderson, "Teaching problem solving through cooperative grouping. Part 1: Group versus individual problem solving," Am. J. Phys. **60** (7), 627–636 (1992).

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[27] P. Cobb and E. Yackel, "Constructivist, emergent, and sociocultural perspectives in the context of developmental research," Educ. Psychol. **31** (3), 175–190 (1996).

[28] J. Tuminaro and E. F. Redish, "Elements of a cognitive model of physics problem solving: Epistemic games," Phys. Rev. ST Phys. Educ. Res. **3**, 020101 (2007).

[29] F. Goldberg, S. Bendall, P. Heller, and R. Poel, *Interactions in Physical Science* (It's About Time, Herff Jones Education Division, Armonk, NY, 2006).

[30] The benchmark also includes this sentence: "If the force acts toward a single center, the object's path may curve into an orbit around the center." Although we include in the curriculum a homework assignment that deals with nonlinear motion, the main focus of Chap. 2 is on motion in one dimension.

[31] M. McCloskey, in *Mental Models*, edited by D. Gentner and A. L. Stevens (Erlbaum, Hillsdale, NJ, 1982).

[32] R. Gunstone and M. Watts, in *Children's Ideas in Science*, edited by R. Driver, E. Guesne, and A. Tiberghien (Taylor & Francis, London, 1985), pp. 85–104.

[33] The PET developers decided to focus only on speed-time graphs rather than distance-time, velocity-time, and/or acceleration-time graphs because the evidence gathered from speed-time graphs would be sufficient to support the target ideas for the chapter. Also, the Newton's second law benchmark, around which the chapter was developed, focuses on change in speed, not change in velocity.

[34] The version of PET that the students in the case study used was an earlier draft of the published version of PET. However, the substance of Chap. 2, Act. 1, that the students used was very similar to the final version that was published.

[35] There is no evidence in the full transcript as to why Ashlie ultimately agreed with Amara, although it is possible that she remembered this idea from a previous physics course. She did not bring up this idea in her discussions with the other two members of the group.

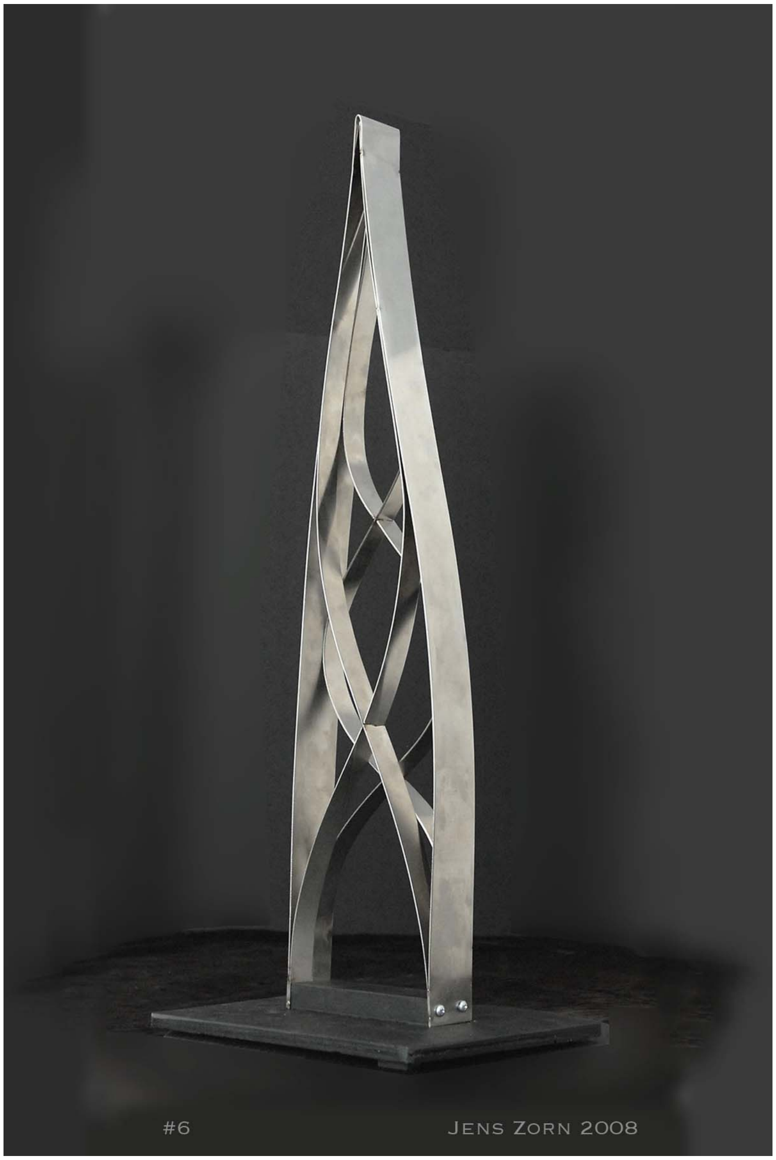
[36] The question showed images of the four students whose ideas are described. We omitted the images to save space.

[37] The average normalized gain is defined as the ratio of the actual average gain $(\%\langle\text{post}\rangle-\%\langle\text{pre}\rangle)$ to the maximum possible average gain $(100-\%\langle\text{pre}\rangle)$ (Ref. 23).

[38] W. K. Adams, K. K. Perkins, N. Podolefsky, M. Dubson, N. D. Finkelstein, and C. E. Wieman, "A new instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey," Phys. Rev. ST Phys. Educ. Res. **2** (1), 010101 (2006).

[39] K. K. Perkins, W. K. Adams, N. D. Finkelstein, S. J. Pollock, and C. E. Wieman, “Correlating student attitudes with student learning using the Colorado Learning Attitudes about Science Survey,” in 2004 Physics Education Research Conference Proceedings, 790, edited by J. Marx, P. Heron, and S. Franklin (AIP, Melville, NY, 2005), pp. 61–64.

[40] A version of PSET, suitable for large-enrollment classes, was developed with support from NSF (Grant No. 0717791). Information about this *Learning Physical Science* curriculum is available from the first author.



Boundary Conditions

This steel sculpture depicts eigenfunctions defined by a zero value at one boundary and by a zero slope at the other. Designed for Miami University in Oxford, Ohio, the sculpture celebrates the success and lasting importance of George Arfken’s classic text Mathematical Methods for Physicists, a book that originated as notes for his lectures at Miami and that is still a standard text, worldwide, more than forty years after its first publication. This sculpture was created by Jens Zorn, Professor of Physics at the University of Michigan.