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Teaching thermodynamics with Physlets® in introductory physics

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Abstract

This paper describes the use of interactive, Physlet®-based curricular material designed to help students learn concepts of thermodynamics with a particular focus on the use of kinetic theory models. These exercises help students visualize ideal gas particle dynamics and engine cycles, make concrete connections between mechanics and thermodynamics, and develop a conceptual framework for problem solving. Examples of curricular material from thermodynamics will be presented as well as the Web address for its download.

(Some figures in this article are in colour only in the electronic version)

Introduction

During the usual progression in introductory physics from mechanics to thermodynamics and then to electromagnetism, students find that they must increasingly visualize abstract representations of physical systems. This transition from concrete to abstract representations becomes particularly apparent in thermodynamics. Thermodynamics, the study of thermal properties in physics, seeks to connect macroscopic properties of matter (such as temperature and pressure) to microscopic properties (such as momenta and energies) of the constituent particles. Computer simulations are a powerful way to provide more concrete connections between microscopic and macroscopic properties of a system through enhanced visualization[4]. However, the technology must be incorporated into the classroom in ways that are pedagogically sound so that the technology contributes to student learning instead of simply being entertaining.

Physlets®, scriptable Java applets with physics content [2], are interactive simulations that combine sophisticated technology with pedagogy. Physlet-based exercises have simple animations without flashy, distracting images, allowing students to focus on the desired concept. Because Physlets are scriptable, they can be modified for local use. However, they are not simplistic; the physics computations at the heart of the Java programs are rich with complex physics content. Using Physlets to animate static text illustrations and problems can make complex topics easier for students to conceptualize.

In our experience both using and developing Physlet-based exercises across the introductory physics curriculum [3, 4] and in advanced classes [5], we have identified three primary advantages to Physlet-based interactive exercises:

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[3] Present address: Western Carolina University, Cullowhee, NC 28723, USA

[4] See the discussion of a simulation modelling molecular kinetics in a compressed syringe developed to help explain an associated classroom demonstration [1].

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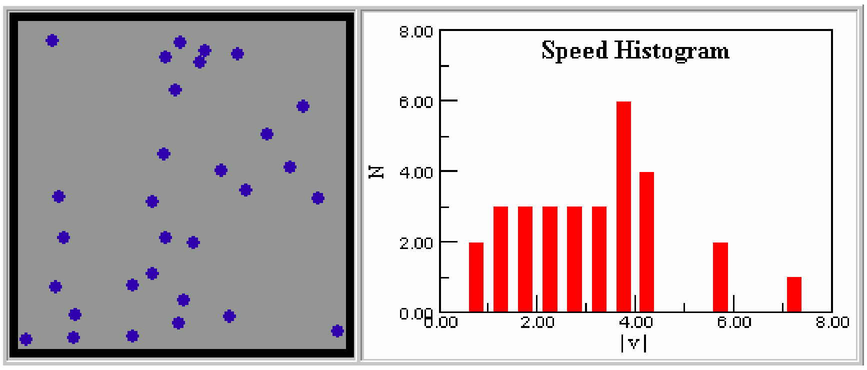

Figure 1. Gas particles confined to a box shown with the particles' instantaneous speed distribution.

Physlet-based activities provide an interactive visualization of abstract concepts. Physlets are dynamic in nature and are able to model abstract concepts in ways not accessible through other means. Being able to see, rather than being told about, the properties of a system is helpful to students. When asked, students list better visualization of concepts as the main advantage of Physlet-based exercises.

Physlet-based activities force students to move beyond novice problem-solving strategies. Students often use a 'plug-and-chug' method of problem-solving when they analyse a problem by looking for a formula and then substituting the numbers given into the equation. Since students must take their own 'data' from the Physlet (either from a table, from a graph, or by clicking in the animation), Physlet-based exercises make it less likely that a 'plug-and-chug' approach would be successful and thereby encourage students to adopt a concept-first approach to problem solving.

Physlet-based activities provide a quick way for students to see the effects of changing the parameters of different systems. Because Physlet-based exercises can provide feedback to students, the exercises make learning interactive. Physlets are embedded into HTML documents, so that many Physlet-based exercises allow students to change parameters by including a text box that allows students to type values in, by including different scenarios that students can access by pushing HTML buttons, or by including a slider (another Physlet) that allows students to slowly vary a parameter. Additionally, students can explore Physlet-based exercises whenever they have an available computer because they can be delivered on a CD or via the Web through a Java-enabled Web browser. With easy access, then, the interactive nature of Physlet-based activities makes them fun for students, who can indulge their curiosity by trying new ideas.

In this paper, we will describe some Physlets that illustrate these advantages for thermodynamics. These can be accessed at webphysics.davidson.edu/physlet_resources/.

Ideal gas in a box: microscopic models

For ideal gases, the visualization aids available from Physlets are particularly useful in developing a microscopic model of gas particles in a box. Figure 1 shows an example of a Physlet-based activity that uses a molecular dynamics Physlet to show the microscopic model and a data-analysis Physlet to show a histogram of the particles' instantaneous speed distribution. The model consists of hard disks which collide elastically with the walls and with each other, modelling a two-dimensional ideal gas. Since Physlets are dynamic, students can see the moving particles (representing gas atoms) and their different velocities, which are ever changing due to collisions with the walls and each other. This example makes the constantly changing speeds explicit as students see a dynamically changing Maxwell–Boltzmann distribution in the histogram. In this particular exercise, as students adjust the temperature by typing a new value into a text box, they can see the changes in the speed histogram. This can quickly dispel the student belief that all the gas atoms in a

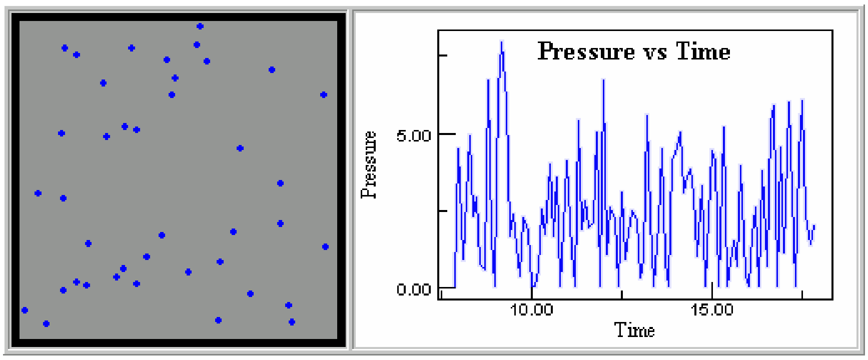

Figure 2. Gas particles in a box with a graph of instantaneous pressure on the walls versus time.

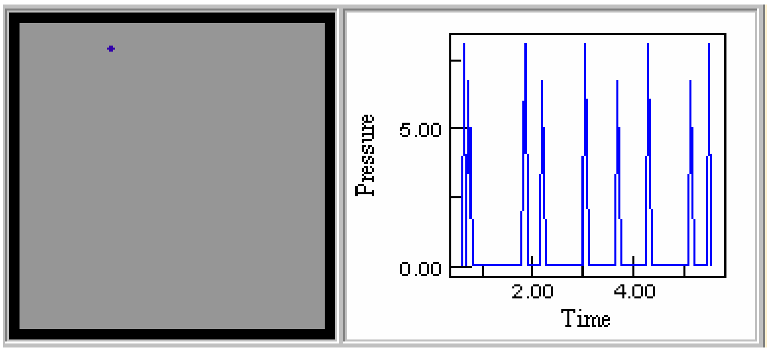

Figure 3. A single gas particle in a box with a graph of instantaneous pressure on the walls versus time.

box are stationary or have the same speed[5]. It also gives students a clearer picture of why the particles' speeds are constantly changing (because of constant collisions) and the need for a defined characteristic speed, whether it be rms, average or mean speed. As teachers, we can (and often do) tell all of this to students, but they are more likely to remember and understand this concept if they see and interact with a model.

In the activity shown in figure 2, students can change both the temperature and the number of particles, which helps them make the connection between the properties of individual particles (momenta and kinetic energies) and the macroscopic quantities of the associated thermodynamic system (pressure and temperature). Students still see the particles in a box, but now they view a graph of the pressure versus time. The pressure on the walls of the box is from the force due to collisions of individual particles with the walls of the box.

This connection becomes particularly apparent when students run this animation with only one particle, as shown in figure 3, and note that there is a pressure value only when the particle collides with a wall. A corresponding table allows students to compare a time average of this instantaneous pressure with the pressure predicted by the ideal gas law. As students verify that the change in momentum of one particle averaged over time corresponds to the 'pressure', they begin to understand that the pressure in a gas is due to the motion of many particles, and that gases, through their individual gas particles, exert forces in all directions, a concept not well understood by many students entering introductory physics classes[6]. Furthermore, by changing the temperature, students can watch the particles to see the corresponding change in speeds and how that results in an increased pres-

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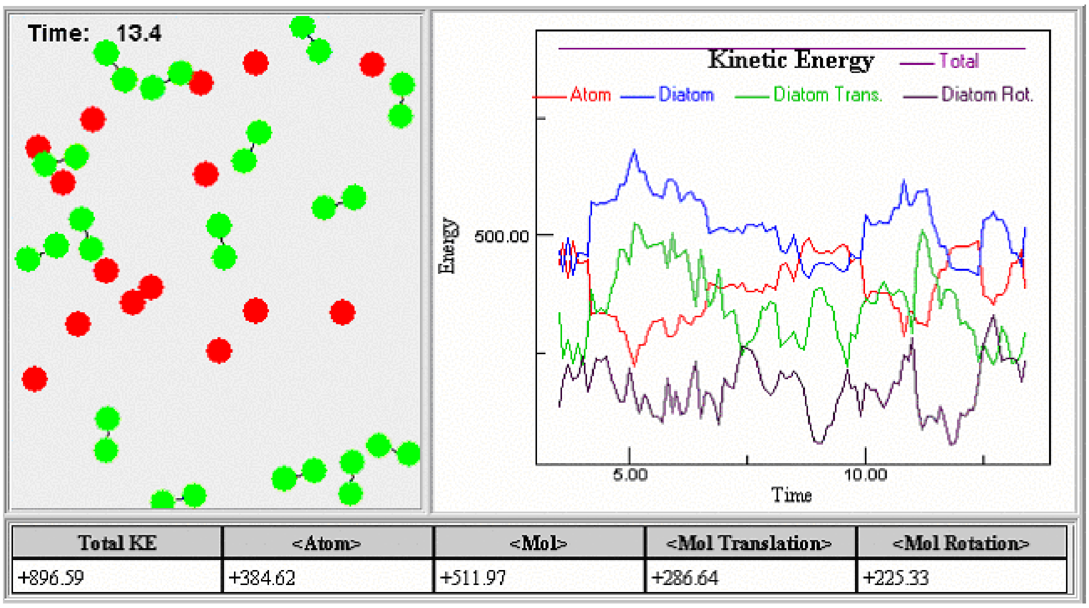
[5] Nussbaum and Novick found that only about one half of 14-year-old students who had a particulate model of air used the idea of the intrinsic motion of air molecules to explain pressure and the filling-up of space; they further found that even in high school the same percentage of students failed to use the idea of intrinsic particle motion to explain pressure properly [6, pp 126–32].

[6] Driver *et al* found that only one third of the 16-year-olds in their study recognized that air pushes in all directions [7].



Total KE	<Atom>	<Mol>	<Mol Translation>	<Mol Rotation>
+896.59	+384.62	+511.97	+286.64	+225.33

Figure 4. Total energy and average kinetic energies of monatomic and diatomic molecules used to demonstrate the equipartition theorem. Java applet by Ernesto Martin and modified by Wolfgang Christian [9].

sure. We have used this Physlet as the basis for a guided exercise that takes students through the typical kinetic theory development and shows that $\frac{1}{2}k_BT$ per degree of freedom is related to the average kinetic energy of the gas particles (Exploration 20.1 in *Physlet Physics* [8]).

When this particular Physlet-based activity was introduced in one class, it drew a spontaneous verbal response from one student: “wow—this is the coolest thing I’ve ever seen!” We assume that the Physlet was not really the ‘coolest thing’ this student had ever seen, but that he was commenting on the interactivity and the feedback from the Physlet as he changed the number of particles and temperature of the ensemble. It made ideal gases come alive for him in ways he had not seen before.

Students can also begin to see the limitations of modelling gases with the idealized picture of elastically colliding point particles simply by changing the size of the gas particles. As the particles get bigger (and their volume is no longer negligible in relation to the size of the container), they effectively reduce the volume of the chamber so the pressure calculated by the ideal gas law ($P = Nk_BT/V$) will be smaller than the actual pressure for a chamber with an effectively reduced volume. In the Physlet-based activity, students can see that the time between collisions decreases so that the change in momentum per unit time increases, thereby increasing the pressure.

By using a Physlet that models a mixture of monatomic and rigid-rotor diatomic molecules (figure 4 [9]) in a two-dimensional box, students can extend their understanding of kinetic theory, particularly of the equipartition of energy. As shown in figure 4, the graph shows the individual contributions to the total kinetic energy from the atoms and the diatomic molecules (from translational and rotational motion). In this exercise, we ask students: if there are 15 atoms in this two-dimensional box, how many diatomic molecules are needed for the contributions to the total kinetic energy from both types of particles (atoms and diatomic molecules) to be equal (on average)? Since students can try a variety of answers, they can get immediate feedback on their answers to discover that ten molecules is the correct answer. This exercise leads to a better understanding of the equipartition theorem. Notice that, to solve this problem, students need to first recognize that the average temperature for the particles in the box is the same (the atoms cannot somehow stay hotter than the molecules). Then, they need to understand the equipartition of energy, recognizing that the translational motion of each atom and diatomic molecule contributes $\frac{1}{2}k_BT$ for each dimension (it is a two-dimensional

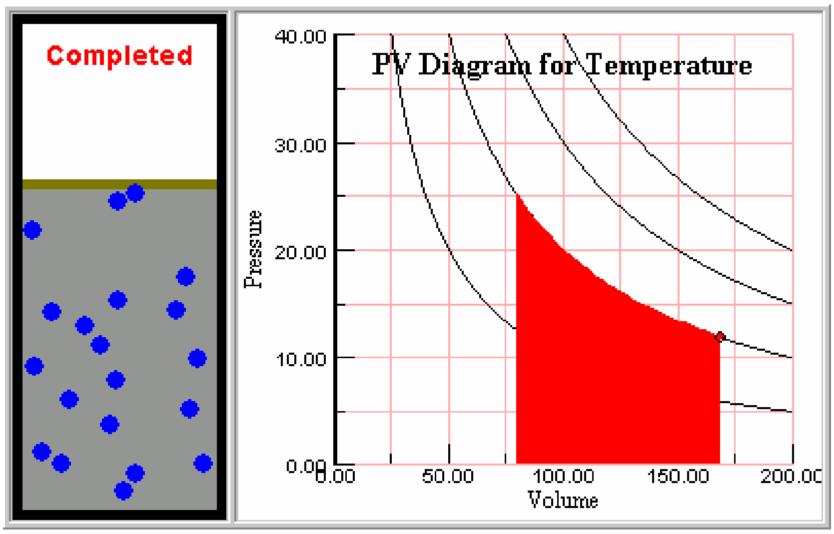


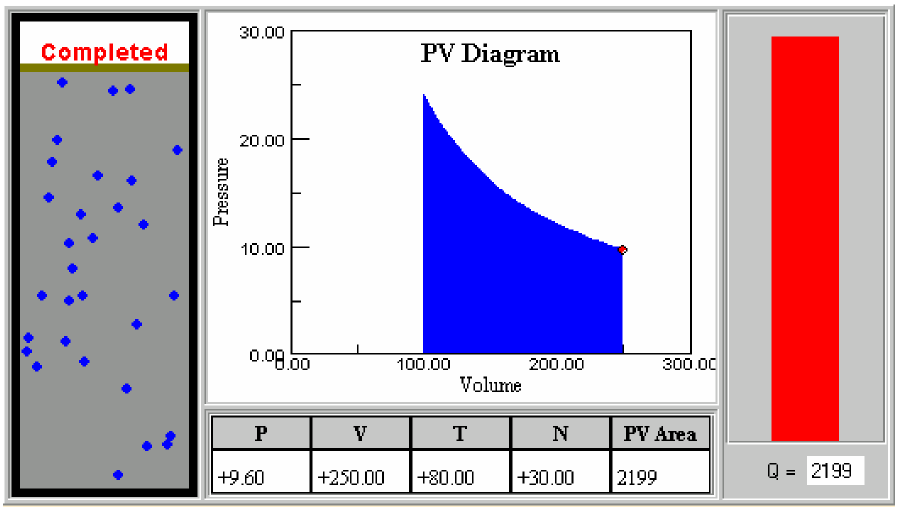
Figure 5. PV diagram for isothermal expansion.

box), and that the rotational motion of the diatomic molecule contributes another $\frac{1}{2}k_BT$. Therefore, each individual atom, on average, contributes k_BT to the total energy with each molecule contributing, on average, $\frac{3}{2}k_BT$. Thus, for equal contributions to the total kinetic energy from the atoms and molecules, the ratio of atoms to molecules needs to be 3:2. Because it is not clear from the Physlet what data are relevant, students must think about what is happening in the animation before deciding what data to use. Forcing students to conceptualize in the process of working the problem keeps them from simply picking up an equation, dropping numbers into it and hoping to get the correct answer.

Ideal gas in a box with a movable piston: dynamic *PV* diagrams

With Physlets, the tools that students use to analyse macroscopic properties of a gas, such as pressure and volume, need not be separated from the microscopic picture of a box teeming with moving, colliding particles. Students can compare these two models by observing a dynamic expansion in both a gas container and a PV diagram. Furthermore, as shown in figure 5, the work done (area under the curve) is clearly shown. These types of exercises help students understand why we use PV diagrams, especially when they can see the dynamic connections between the diagram, the particles in a box and the work done by the gas. Additionally, students get a much better sense of the difference between the different named thermodynamic processes (isobaric, isothermal, isochoric, adiabatic) if they can directly compare them as in this exercise; it gives them a strong visual context. On an end-of-the-semester survey in two introductory physics classes (total of 39 students), over 70% of students either agreed or strongly agreed with the statement that this particular exercise (and a related problem) ‘helped me visualize and understand concepts presented in class’. One student reported going back to this particular Physlet-based exercise while reviewing for the exam; while another found that it ‘helped put the meaning of these terms [the different thermodynamic processes] together’.

Another common student difficulty is determining the heat capacity of gases undergoing several different thermodynamic expansions, all with the same heat input. To determine the heat capacity, students must determine the information they need as they find which expansion has the biggest change in temperature, how much work is done and the connection to heat capacity. The questions addressed are fundamental to understanding the laws of thermodynamics and do not necessarily involve looking for an equation to explain what happens. Thus, this Physlet-based activity helps students develop a conceptual understanding using their knowledge of work and energy in conjunction with kinetic theory. Notice that



P	V	T	N	PV Area
+9.60	+250.00	+80.00	+30.00	2199

Q = 2199

Figure 6. Finding the change in entropy.

these exercises continually and explicitly bring kinetic theory into ideal gas law problems. This highlights the physics associated with ideal gases[7] and also addresses, indirectly, students' questions about why it is necessary for them to study ideal gas laws in physics if they have already done so in chemistry.

We use similar Physlet-based exercises for entropy-related questions in order to discourage 'plug-and-chug' approaches. Consider the problem shown in figure 6 (Problem 21.7 in *Physlet Physics* [8]), which asks students to calculate the change in entropy during the expansion. This is a standard and straightforward question. However, in the Physlet version of the problem, the student must first determine the type of process, noting initial and final conditions, before being able to calculate the change in entropy. In this case, since it is an isothermal process, calculating the change in entropy does not require any calculus. However, it is not immediately apparent what data are needed to solve the problem, especially since the usual cues from a textbook problem (i.e., 'for an isothermal expansion from a volume of 100 cm^3 to 250 cm^3. . . ') are missing.

Ideal gas and engine cycles

Understanding how to read PV diagrams is crucial in analysing engine cycles as well. Once students are familiar with PV diagrams, we use them again to illustrate engine cycles by explicitly showing when the gas is in contact with a hot or a cold reservoir. The Physlet can easily (and visually) connect the dynamics of the expansion and compression with the path on the PV diagram and with the net work associated with the complete engine cycle. Then, we can ask students to do 'typical' engine efficiency calculations without naming the expansions and giving the temperatures of the hot and cold reservoirs, thereby requiring that the students have a deeper understanding of the material in order to approach the problem.

Particularly useful in connecting the abstract PV diagram with a real engine is the Otto Engine Physlet [13] shown in figure 7. To understand this connection, students need to work through the complete cycle. The Physlet allows students to do this easily, stopping at various points throughout the cycle and repeating the cycle until they fully understand the engine and its relationship to the PV diagram. As the piston moves up and down in the animation, the point on the PV diagram is shown until the complete path is drawn.

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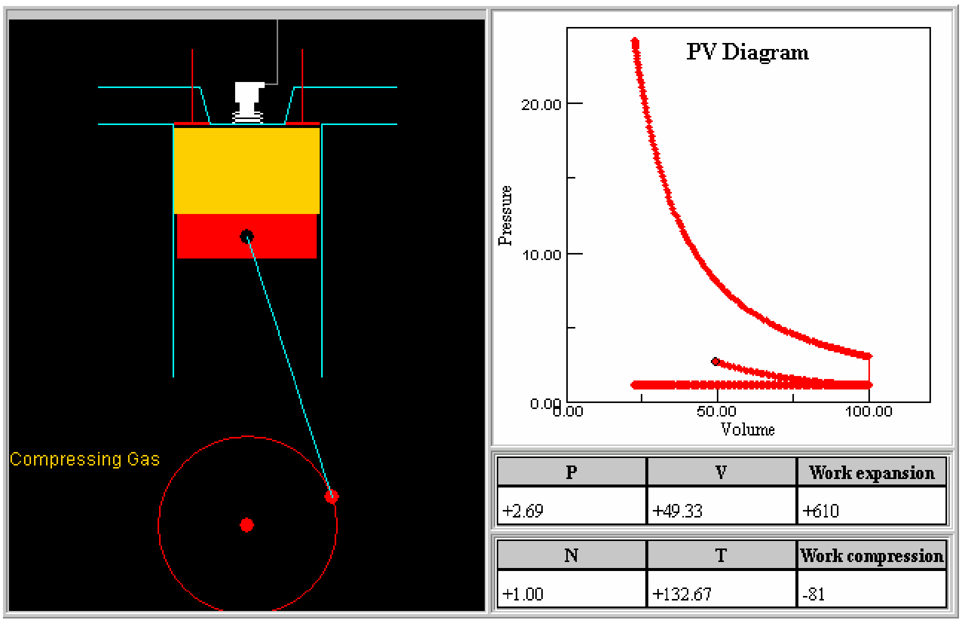
[7] Although Loverude *et al* argue against early introduction of kinetic theory based on their research on student understanding in thermodynamics [10], Nussbaum's research on children's understanding of physical concepts suggests that a particulate matter model for gases could profitably address students' conceptual difficulties [6, pp 143–4]. Similarly, authors of two articles in the recent Thermodynamics–Statistical Mechanics theme issue of the *American Journal of Physics* argue for early introduction of microscopic models in introductory physics [11, 12].



P	V	Work expansion
+2.69	+49.33	+610

N	T	Work compression
+1.00	+132.67	-81

Figure 7. Otto Engine Physlet [13].

Students can quickly determine the efficiency of this engine and it helps them connect the abstract PV diagrams of physics and chemistry to a simplified version of real-world combustion engines in their automobiles.

Summary

We have used Physlets to develop exercises that help students study thermodynamics by providing them with dynamic connections between graphs and thermodynamic processes, by modelling 'real-world' applications, specifically showing engine processes and their associated heat and work diagrams, and by allowing students to see the effects of changing parameters on systems. In so doing, Physlets help students visualize abstract concepts and make connections between mechanics and thermodynamics. These thermodynamic exercises also challenge students to move away from 'equation shopping' and to consider the type of problem (e.g., What type of thermodynamic process does the problem animate?) and required information (e.g., What data do I need to collect from the animation?) before simply plugging numbers into an equation. In the process, students develop a more solid conceptual understanding of thermodynamic processes in introductory physics.

Physlets are free for non-commercial use. The Physlet-based materials described in this paper are available to instructors who wish to use them in their courses simply by going to webphysics.davidson.edu/physlet_resources/ and following the links to this paper. This website also contains resources and links to a variety of Physlets available for educational use. For instructors who wish to modify Physlets or script their own Physlet-based exercises, *Physlets: Teaching Physics with Interactive Curricular Material* [2] is a good starting point, while *Physlet Physics: Interactive Illustrations, Explorations and Problems for Introductory Physics* [8] provides a collection of ready-to-run Physlet-based exercises that span the introductory physics curriculum.

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