Unit 2: **Thermodynamics**

Laboratory Investigations:

- Calculating Thermal Conductivity
- Heat Engine
- Hair Dryer Efficiency

Estimated Time: *20 days*

Guiding Questions: ▼ How are heat and temperature explained on a molecular level? ▼ How do gas molecules exert pressure on the walls of a container? ▼ How is the expansion of a gas related to mechanical work? ▼ What is entropy, and how is it related to the irreversibility of most real-world processes?

Learning Objectives	Materials	Instructional Activities and Assessments
Make predictions of the dynamical properties of a system undergoing a collision by application of the principle of linear momentum conservation and the principle of the conservation of energy in situations in which an elastic collision may also be assumed. [LO 5.D.1.6, SP 6.4] Classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum and restoration of kinetic energy as the appropriate principles for analyzing an elastic collision, solve for missing variables, and calculate their values. [LO 5.D.1.7, SP 2.1, SP 2.2] Classify a given collision situation as elastic or inelastic, justify the selection of conservation of linear momentum as the appropriate solution method for an inelastic collision, recognize that there is a common final velocity for the colliding objects in the totally inelastic case, solve for missing variables, and calculate their values. [LO 5.D.2.5, SP 2.1, SP 2.2]	**Web** "Collision Lab"	**Instructional Activity:** Students individually work with the simulation to explore the characteristics of one-dimensional elastic and inelastic collisions. They collect data to calculate and compare system momentum and system kinetic energy before and after collisions with varying degrees of inelasticity. Students then write a paragraph defining the characteristics of elastic collisions, and they justify their claims about elastic collisions with evidence from their data.
		Instructional Activity: Students in small lab groups work with the advanced activity in the simulation to explore the characteristics of two-dimensional elastic and inelastic collisions. After they have compared system momentum and kinetic energy for different collision types, they use the simulation to construct a model that would represent an ideal gas in a container. They must describe in writing how their model is representative and what its limitations are.
		Formative Assessment: Students individually describe in writing the type of collision they think occurs in a container of ideal gas. They consider collisions between individual gas molecules and collisions between gas molecules and the walls of the container. They must articulate the reasons they have selected a particular collision type. After writing their individual statements, students in small groups combine their descriptions to produce group reports, which are presented to the class for discussion.

I monitor the discussion, guiding it where necessary, to ensure the class understands that collision of ideal gas molecules is elastic. The discussion informs my decisions about next instructional steps.

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Learning Objectives	Materials	Instructional Activities and Assessments
Design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables. [LO 7.A.3.2, SP 3.2, SP 4.2] Analyze graphical representations of macroscopic variables for an ideal gas to determine the relationships between these variables and to ultimately determine the ideal gas law $PV = nRT$. [LO 7.A.3.3, SP 5.1] Treating a gas molecule as an object, analyze qualitatively the collisions with a container wall and determine the cause of pressure, and at thermal equilibrium, quantitatively calculate the pressure, force, or area for a thermodynamic problem given two of the variables. [LO 7.A.1.2, SP 1.4, SP 2.2] Extrapolate from pressure and temperature or volume and temperature data to make the prediction that there is a temperature at which the pressure or volume extrapolates to zero. [LO 7.A.3.1, SP 6.4, SP 7.2] Make claims about how the pressure of an ideal gas is connected to the force exerted by molecules on the walls of the container, and how changes in pressure affect the thermal equilibrium of the system. [LO 7.A.1.1, SP 6.4, SP 7.2]	**Web** "Gas Properties"	**Instructional Activity:** Students first use the simulation to visualize the behavior of an ideal gas at the molecular level. They then propose a mechanism, consistent with considering molecules as objects, by which the ideal gas exerts pressure on the container walls. They also make claims based on evidence for a specific collision type (elastic or inelastic) between molecules in an ideal gas and between gas molecules and the container wall. **Instructional Activity:** Students investigate the interdependence of volume, pressure, and temperature for an ideal gas, using measurement tools in the simulation to collect data and create graphs. Students construct written responses describing what the physical consequences would be if (a) gas molecules underwent inelastic collisions, (b) gas molecules did not exert forces on each other during collisions, and (c) gas molecules exerted long-range attractive forces on each other. Students also identify what they think is the cause of the repulsive force that exists between molecules of an ideal gas and other gas molecules and between gas molecules and the container wall. They must justify their answers.

During this activity, I encourage students to apply classical mechanics concepts of Newton's third law, conservation of linear momentum, and conservation of energy to the molecular level.

Students should remember ideal gas laws from chemistry. It is advisable to remind them of ideal gas behavior but not to spend too much time on it. In AP Physics, we are more interested in how a container of ideal gas can function as a heat engine.

Thermodynamics

(continued)

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Learning Objectives	Materials	Instructional Activities and Assessments
Design a plan for collecting data to determine the relationships between pressure, volume, and temperature, and amount of an ideal gas, and to refine a scientific question concerning a proposed incorrect relationship between the variables. [LO 7.A.3.2, SP 3.2, SP 4.2] Analyze graphical representations of macroscopic variables for an ideal gas to determine the relationships between these variables and to ultimately determine the ideal gas law $PV = nRT$. [LO 7.A.3.3, SP 5.1] Treating a gas molecule as an object, analyze qualitatively the collisions with a container wall and determine the cause of pressure, and at thermal equilibrium, quantitatively calculate the pressure, force, or area for a thermodynamic problem given two of the variables. [LO 7.A.1.2, SP 1.4, SP 2.2] Extrapolate from pressure and temperature or volume and temperature data to make the prediction that there is a temperature at which the pressure or volume extrapolates to zero. [LO 7.A.3.1, SP 6.4, SP 7.2] Make claims about how the pressure of an ideal gas is connected to the force exerted by molecules on the walls of the container, and how changes in pressure affect the thermal equilibrium of the system. [LO 7.A.1.1, SP 6.4, SP 7.2]	**Supplies** Empty aluminum soda can, tongs, hot plate, ice water bath	**Instructional Activity:** I place a small amount of water in an empty soda can, heat it to boiling over a burner, and quickly invert the can so the opening is under water in the ice water bath. The can suddenly implodes. Working in small groups, students then critique the phrase "Nature abhors a vacuum" as an explanation for this phenomenon. They must justify the phrase, or come up with an alternative explanation, using appropriate physics concepts. Student teams write their explanations and present them to the class for discussion.
	Print O'Kuma, Maloney, and Hieggelke, Heat and Thermodynamics Ranking Tasks, pp. 110, 114, 118, 120–121	**Formative Assessment:** Working in groups, students solve and present the solutions to different ranking task problems involving heat and thermodynamics.

I encourage discussion during the presentations and monitor explanations for correct use of the ideal gas law. The discussion informs my decisions about next instructional steps.

Guiding Questions: ▼ How are heat and temperature explained on a molecular level? ▼ How do gas molecules exert pressure on the walls of a container? ▼ How is the expansion of a gas related to mechanical work? ▼ What is entropy, and how is it related to the irreversibility of most real-world processes?

Learning Objectives	Materials	Instructional Activities and Assessments
Make predictions about the direction of energy transfer due to temperature differences based on interactions at the microscopic level [LO 4.C.3.1, SP 6.4] Describe the models that represent processes by which energy can be transferred between a system and its environment because of differences in temperature: conduction, convection, and radiation. [LO 5.B.6.1, SP 1.2] Construct an explanation, based on atomic-scale interactions and probability, of how a system approaches thermal equilibrium when energy is transferred to it or from it in a thermal process. [LO 7.B.1.1, SP 6.2] Design an experiment and analyze data from it to examine thermal conductivity. [LO 1.E.3.1, SP 4.1, SP 4.2, SP 5.1]		**Instructional Activity:** I show video clips of "Demonstrations in Physics with Julius Sumner Miller – Heat and Temperature Parts 1 and 2." (These videos can easily be found online.) Miller is particularly good at explaining thermodynamics concepts. After watching the video clips, students use appropriate physics concepts to discuss each of the demonstrations.
	Web "Physics/Chemistry – Heat Energy"	**Instructional Activity:** In teams, students explore this site to answer questions such as the following: (a) How does temperature difference affect heat transferred between two systems in contact? (b) By what mechanism do the molecules of one system transfer heat to the molecules of another system? (c) How does conservation of momentum apply to heat transfer? (d) How does conservation of energy apply to heat transfer? (e) What conditions must exist for thermal equilibrium to be established? (f) How do conduction, convection, and radiation differ in the way they cause heat to be transferred from one system to another? Student teams focus on the questions that interest them the most and report their findings to the class for discussion.
	Supplies Polystyrene cups, glass beakers, steel cups, aluminum cups, water, thermometers, calipers, hot-water baths, ice baths, stopwatches	**Instructional Activity:** Students in collaborative lab groups design a procedure to collect data that can be used to calculate the thermal conductivity of Styrofoam, glass, steel, and aluminum. They collect data, perform calculations, and compare the results to standard values. A full or partial written lab report is submitted.

I evaluate student discussion for understanding that elastic collisions between molecules are involved in the transfer of thermal energy. Students should also understand that thermal equilibrium does not mean that all molecules have the same kinetic energy but rather that there is an average kinetic energy for all molecules in the system.

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Learning Objectives	Materials	Instructional Activities and Assessments
Qualitatively connect the average of all kinetic energies of molecules in a system to the temperature of the system. [LO 7.A.2.1, SP 7.1] Connect the statistical distribution of microscopic kinetic energies of molecules to the macroscopic temperature of the system and relate this to thermodynamic processes. [LO 7.A.2.2, SP 7.1]	**Web** "Gas Properties"	**Instructional Activity:** Students use the simulation introduced earlier in this unit for another study. After they add gas molecules to the chamber, they add or remove heat and collect data on molecular speed, kinetic energy, and temperature. Groups present answers to the following questions: (a) How does molecular speed depend upon temperature? (b) How does molecular kinetic energy depend upon temperature? (c) Do all the molecules have the same speed or kinetic energy? (d) Does a given molecule have the same speed or kinetic energy over time? (e) How does the average speed and kinetic energy vary over time at constant temperature? (f) What differences do you observe between light and heavy gas molecules at the same temperature? (g) How is energy transferred from one molecule to another?
Describe and make predictions about the internal energy of systems. [LO 5.B.4.1, SP 6.4, SP 7.2] Predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. [LO 5.B.7.1, SP 6.4, SP 7.2]		**Instructional Activity:** I explain to students that the "internal energy" of a gas describes the energy it can exchange in the form of heat or work. They use their understanding of the molecular model of an ideal gas to propose which of the variables in $PV = nRT$ are most directly related to internal energy.
	Print O'Kuma, Maloney, and Hieggelke, Heat and Thermodynamics Ranking Tasks, pp. 113, 115–117, 121	**Formative Assessment:** In small collaborative groups of two or three, students construct answers in writing to these conceptual exercises. Students present their answers to the class, prompting discussion.

I offer direct feedback on the exercise to individual students or to the entire class when the class is unable to arrive at a correct consensus answer.

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Learning Objectives	Materials	Instructional Activities and Assessments
Describe and make predictions about the internal energy of systems. [LO 5.B.4.1, SP 6.4, SP 7.2] Predict qualitative changes in the internal energy of a thermodynamic system involving transfer of energy due to heat or work done and justify those predictions in terms of conservation of energy principles. [LO 5.B.7.1, SP 6.4, SP 7.2]		**Instructional Activity:** I explain that the first law of thermodynamics is a version of the law of conservation of energy in which heat and mechanical work are both taken into account. Assuming a container of ideal gas as a system, students draw a graphic model representing the first law of thermodynamics, using arrows to represent energy exchange as heat or work between the system and its environment. Students then express the first law of thermodynamics in equation form.
Make claims about the interaction between a system and its environment in which the environment exerts a force on the system, thus doing work on the system and changing the energy of the system. [LO 5.B.5.4, SP 6.4, SP 7.2] Predict and calculate the energy transfer to (i.e., the work done on) an object or system from information about a force exerted on the object or system through a distance. [LO 5.B.5.5, SP 2.2, SP 6.4] Design an experiment and analyze graphical data in which interpretations of the area under a pressure-volume curve are needed to determine the work done on or by the object or system. [LO 5.B.5.6, SP 4.2, SP 5.1] Create a plot of pressure versus volume for a thermodynamic process from given data. [LO 5.B.7.2, SP 1.1] Use a plot of pressure versus volume for a thermodynamic process to make calculations of internal energy changes, heat, or work, based upon conservation of energy principles (i.e., the first law of thermodynamics). [LO 5.B.7.3, SP 1.1, SP 1.4, SP 2.2]	**Supplies** Heat engine/gas law apparatus (e.g., the PASCO TD-8572, a commercial gas law apparatus consisting of a piston with a platform that can raise and lower weights, a submersible air chamber, tubing, and one-way check valves), two 1000 mL beakers for hot and cold water, ruler, pressure gauge, calipers, masses (20, 50, 100, 200 g), hot plate, ice	**Instructional Activity:** Using the apparatus in combination with hot- and cold-water reservoirs, students demonstrate how the flow of heat through a heat engine can be harnessed to perform mechanical work by lifting a weight. Students collect and graph pressure-versus-volume data for the gas (air). They compare the work done in lifting the weight, $F(\Delta y)$, to the area under the *PV* curve for a complete cycle and estimate thermodynamic efficiency. Students explain in writing how their mathematically and graphically determined mechanical work for each process is related to the fundamental concept that work is force multiplied by distance.
	Web "The AP Physics B Exam": 2010 Form B, Question 4; 2009 Form B, Question 4; 2007 Form B, Question 5; 2006 Form B, Question 5	**Formative Assessment:** I provide practice problems from published AP examinations. Students use accompanying scoring rubrics to correct their own work. It is important to continue emphasizing fundamental concepts of molecular kinetic energy and its relationship to internal energy and temperature throughout formative assessment exercises.

If you have only one gas law apparatus, the investigation may be done as a demonstration during which data is collected for independent analysis by students. Remind students that the bounded area on a PV graph is related to net work, and ask them to tell you why this is so. Using the definitions of pressure and work, guide them to show that $W_g = P\Delta V$.

While Physics B free-response questions are not reliable representatives of the questions on the AP Physics 2 Exam, some Physics B questions, such as those cited here, can provide a starting point for physics teachers to develop their own formative assessment questions.

Students submit their corrected problems, including a verbal analysis of mistakes they made. I provide feedback on their original work and their analysis.

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(continued)

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Learning Objectives	Materials	Instructional Activities and Assessments
Connect qualitatively the second law of thermodynamics in terms of the state function called entropy and how it (entropy) behaves in reversible and irreversible processes. [LO 7.B.2.1, SP 7.1]	**Supplies** Pieces of cotton fabric (old T-shirts may be used), water, mass balances, hair dryers with known power ratings, timers	**Instructional Activity:** In small groups, students use hair dryers to partially dry wet fabric; from the power rating of the hair dryers, the drying time, and the amount of water evaporated, students determine hair-dryer efficiency. They discuss whether a hair dryer that is 100 percent efficient could be invented.
	Web "Second Law of Thermodynamics"	**Instructional Activity:** Working in small groups, students explore the Web, beginning with the resource given, for information on the second law of thermodynamics, entropy, and reversible and irreversible processes. Each group of students researches all three topics and is responsible for coming up with examples of reversible and irreversible processes, which they must describe in terms of the associated entropy changes. The students return to the hair-dryer discussion and assess the feasibility of a 100 percent efficient hair dryer in terms of the second law of thermodynamics. I monitor discussions for correct application of the concepts of entropy (disorder) and irreversibility.
All of the learning objectives in this unit are addressed in this summative assessment.	**Web** "AP Physics 2 Practice Exam"	**Summative Assessment:** An exam consisting of several multiple-choice questions and one free-response problem is given to assess mastery. Exam questions are selected or adapted from the practice exam provided by the College Board.

All of the guiding questions for this unit are addressed in this summative assessment.