4: Thermodynamics

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4A: Thermal Properties Of Matter

4A10. Thermometry

Show & Tell Thermometers (4A10.10) -- Choose from the following:

- liquid (mercury or alcohol)
- bimetallic coil (large or small)
- liquid crystal (aquarium type) -- thermometer strip indicates temperatures from 66° F to 84° F by color changes)

Liquid Crystal Sheets (4A10.50) -- large sheets of temperature-sensitive liquid crystals change color with changing temperature.

See also Galileo's Thermometer (Thermal Expansion of Air) (4E10.11).

4A20. Liquid Expansion

Thermal Expansion of Water (4A20.10) -- a 1 liter flask filled with colored water has a long glass tube protruding up from the neck. A gas flame is placed under the flask and thermal expansion forces water up the tube.

Negative Expansion Coefficient of Water (4A20.30) -- a 2 liter flask of colored water with a glass tube inserted through the stopper is kept in a bath of ice water until the temperature of the water in the flask has fallen to 0° C. The water level in the vertical tube is noted, and the flask and tube are removed from the ice bath. As the temperature of the flask water rises above 0° C, the water level in the tube drops until the water has warmed to about 4° C, the temperature of maximum density, then begins to rise. Demonstrates why ice floats, and always forms at the top surface of the water.

Density of 4° C Water (4A20.35) -- a mixture of ice and water in a beaker is placed on a styrofoam insulation pad. After coming to equilibrium, a large display thermometer can be used to show that the water up around the ice is at 0° C, while the denser water at the bottom is at 4° C.

4A30. Solid Expansion
Bimetallic Strip (4A30.10) -- two dissimilar metal strips bonded together and fastened to a handle. When heated, the strip bends because of the different expansion rates of the metals.

Bimetallic Coil -- same as the bimetallic strip in concept, but helical in form. The coil is heated and moves a large indicator arrow as it expands.

Thermostat Model (4A30.11) -- working model of a thermostat with a lamp heater and a bimetallic strip.

Ball and Ring (4A30.21) -- a metal ball and ring on handles are constructed so that the ball will just pass through the ring at room temperature. The ball is heated and will not pass through the ring. The ball and ring are both heated and the ball now passes through the heated ring.

Ball and Hole (4A30.22) -- a ball which is too large to pass through a hole in a square metal plate will pass easily through the hole after the plate has been heated in a flame. Many students expect the hole to shrink upon heating, but it actually expands along with the rest of the plate.

Heated Wire (4A30.60) -- a thin wire supported at both ends is electrically heated and the wire sags in the middle.

4A40. Properties of Materials at Low Temperatures

Elasticity at Low Temperatures (4A40.15) -- a lead spring is dipped in liquid nitrogen and hooked on a vertical stand. A weight is attached to the end of the spring and set into oscillation - the spring will oscillate when cold, but as it warms up its elastic limit is lowered and the weight sags onto the table.

Smash Stuff in Liquid Nitrogen (4A40.30) -- Cool flowers, racquetballs, fruit, etc. in liquid nitrogen. Please bring your own items (no watermelons).

4A50. Liquid Helium

4B: Heat And The First Law

4B10. Heat Capacity and Specific Heat

Calorimeter (4B10.26) -- Show & Tell version of a double-walled aluminum calorimeter with hole on top for thermometer, used for heat of fusion of water, etc.

Specific Heat (Quantitative) (4B10.28) -- three equal masses of metal shot (aluminum, steel, and lead) are placed in pop cans and heated in boiling water until they are all at 100°C. They are then each dumped into equal masses of water and stirred, then the final temperature of each is read with a large display thermometer. Reasonable (10%) figures for the heat capacities of the metals can be obtained from the data. The results will always be slightly on the low side due to heat losses during transfer, but are good to 10-15%.

Specific Heat (Rods and Wax) (4B10.30) -- cylinders of lead, brass, and aluminum are heated in boiling water, then lifted onto a block of paraffin. The plugs melt through the wax with speeds approximately proportional to their heat capacities.

Ruchardt's Experiment for γ (4B10.70) -- A steel ball in a precision tube oscillates as gas escapes from a slightly over pressurized flask. By measuring the oscillation frequency, you can determine the ratio $\gamma = C_p/C_v$. Note: Please talk to us in advance.
4B20. Convection

Convection D-Tube (4B20.10) -- a large glass tube in the shape of a “D” is filled with water and heated by a burner near one bottom corner. The resulting circulating convection current is shown by adding drops of dye to the water.

Convection Currents (Projection) (4B20.40) -- convection currents from a hot wire in a small water cell are projected onto a screen using a simple Schlieren optics system.

Convection with Overhead (4B20.45) -- a bunsen flame held between the overhead and screen clearly shows convection currents rising from the flame.

4B30. Conduction

Thermal Conductivity (4B30.12) -- five rods of different composition are attached to a steam chamber to provide equal temperatures at the bases of the rods. The rods are covered with wax, which melts and peels off as the rods heat up. Relative rates of heat conduction can be deduced from the rates at which the wax melts on each rod. The five materials in order of decreasing conductivity are: copper, aluminum, brass, steel, and glass.

4B40. Radiation

Leslie Cube (4B40.30) -- a brass cube filled with hot water has four different faces: one is plain brass, one painted white, one painted glossy black, and one painted flat black. A thermocouple connected to a projection galvanometer is positioned near the Leslie cube and the cube is rotated on its base so that each face passes in front of the thermocouple. A different rate of radiation is seen from each face.

Radiation from Hot and Cold Bodies -- two parabolic reflectors are aligned facing each other on the lecture table, with a thermopile at the focal point of one of the reflectors and a heated sphere at the other. A projection galvanometer’s deflection shows the transmission of heat by radiation. Replace the hot sphere with a sphere dipped in liquid nitrogen and the galvanometer will deflect in the opposite direction.

Two Can Radiation (4B40.40) -- Shiny and flat black cans filled with cool water warm up (15 minutes), or cool off when filled with boiling water (45 minutes).

Please see Section 6: Optics for more electromagnetic radiation demonstrations.

4B50. Heat Transfer Applications

Insulation (Dewar Flasks) (4B50.10) -- four dewar flasks (thermos bottles) are filled with boiling water and a thermometer and cork are placed in each mouth. Each flask has a different degree of insulation, and these are (from worst to best): unsilvered without vacuum between the walls, silvered without vacuum, unsilvered with vacuum, and silvered with vacuum. Water is left cooling until the end of the period, then temperature of each flask is read on a thermometer and relative rates of heat transfer are inferred from the different temperatures.

Water Balloon Heat Capacity (4B50.25) -- a lit match may be held directly beneath a water balloon without burning through the balloon, due to the high heat capacity of the water. In contrast, an air balloon explodes immediately on contact with the flame.

Leidenfrost Effect (4B50.30) -- Pour water into a hot pan, or pour liquid nitrogen on the floor.
4B60. Mechanical Equivalent of Heat

Drill and Dowel (4B60.55) -- a wooden dowel held in an electric drill chuck is ground against a large flat piece of wood. The friction between the two produces heat, smoke, etc.

Cork Popper (4B60.70) -- a motorized rotating hollow shaft holds a thimbleful of water and is sealed with a stopper. Wooden arms are squeezed together on either side of the rotating shaft, and the heat generated by friction boils the water and pops the cork.

4B70. Adiabatic Processes

Fire Syringe (4B70.10) -- A thick glass tube with a plunger has a small two match heads in the bottom. If the plunger is rapidly pushed in, the heat of compression ignites the match heads with a bright flare.

Cloud Flask (4B70.20) -- a flask containing a small amount of water has a large rubber bulb attached to the side. If the bulb is squeezed and released, a cloud will form in the flask, but only if a small amount of smoke is added first to act as condensation centers.

Temperature Change with Compression (4B70.31) -- a small plastic syringe contains a small thermocouple probe in the tip that connect to a large display thermometer. If the syringe is compressed rapidly, a temperature rise is seen on the thermometer. Pulling the plunger up rapidly lowers the temperature of the air inside.

4C: Change Of State

4C10. PVT Surfaces

PVT Surface Model - Carbon Dioxide (4C10.10) -- a three dimensional model showing various PVT states of carbon dioxide.

PVT Surface Model - Water (4C10.10) -- a three dimensional model showing various PVT states of water.

PVT Surface Model - Ideal Gas (4C10.10) -- a three dimensional model showing various PVT states of an ideal gas.

4C20. Phase Changes: Liquid-Solid

Regelation (4C20.30) -- a block of ice is supported at ends and a thin wire with weights attached is hung over the top. Pressure from the wire raises the melting temperature of the ice, and the wire will pass through the block without cutting it in two (the ice refreezes behind the wire) within 15 to 30 minutes. Ice skating and the making of snowballs are two examples of regelation at work.

Exothermic Reaction -- a small pouch contains a solution of water and a salt that dissolves endothermically (absorbs heat as it dissolves). When a small snapper inside the pouch is popped, the salt comes out of solution, releasing the heat it had absorbed while dissolving. The pouch can be recharged by placing it in boiling water until the salt dissolves. This is a commercial item used by campers for supplemental warmth. Please give plenty of notice for this demonstration.

4C30. Phase Changes: Liquid-Gas

Boil Water Under Reduced Pressure (4C30.10) -- a special long-necked spherical flask with a concave depression in its bottom is filled with water and boiled to drive out the air. The flask is then capped with a cork and thermometer (which shows the water is boiling at 100° C), turned upside down, and cooled by filling the hollow with ice. The resulting pressure reduction causes the water to boil at a reduced temperature (80-90° C or lower).
Liquid Nitrogen in a Balloon (4C30.35) -- a small amount of liquid nitrogen is poured into a balloon and allowed to evaporate and expand.

Hand Boiler -- convoluted glass tube contains a small amount of a volatile liquid. Heat from your hand will boil the liquid and the vapor pressure will force it to flow to the opposite end of the tube. Note: This is small and not very viewable for a large class.

4C31. Cooling by Evaporation

Cryophorus (4C31.10) -- A partially evacuated glass tube that contains some water in the bulb on one end. The other empty end is placed in liquid nitrogen and the change in pressure causes the water to boil and then freeze.

Freezing Water by Evaporation (Triple Point) (4C31.20) -- air pressure is lowered almost to vacuum over a small sample of water, which begins to boil. Evaporation in vacuum lowers temperature of the water until it reaches the triple point at .01° C. Water then boils and freezes almost simultaneously - displayed on the overhead projector.

Drinking Bird (4C31.30) -- commercial novelty item. Dip the bird's beak into a beaker of water, then let it go. Evaporation of the water from the wet beak cools the beak, lowering the vapor pressure of the liquid inside and drawing it up into the head. That overbalances the bird and it tips into the water for a “drink.” In that position, the liquid inside flows back into the lower bulb, which rights the bird and starts the cycle over. Note: This is not very visible for a large class without using a camera and monitor.

4C32. Dew Point and Humidity

4C33. Vapor Pressure

4C40. Sublimation

Sublimation of CO2 (4C40.10) -- CO2 is solidified by dipping a balloonful in a container of liquid nitrogen. The balloon is cut open to show the solid CO2, which sublimates directly to the gaseous state.

4C45. Phase Changes: Solid-Solid

4C50. Critical Point

Critical Point of CO2 (4C50.10) -- liquid CO2 in a glass tube at high pressure is close enough to the critical point that warm air from a hair dryer will complete the transition. The tube is displayed with a video camera and the meniscus is seen, but when the tube is heated the meniscus slowly fades and disappears as the liquid CO2 goes through a gradual transition to a high-pressure gas. A turbulent mixture of liquid and gas with equal densities is seen above and below the meniscus point.

Critical Opalescence (4C50.20) -- a mixture of triethylamine and water in a tube is hand warmed and passes through the liquid/gas critical point. The liquid is clear at first, then clouds up as the critical point is reached; a sparkly meniscus forms at the phase interface.

4D: Kinetic Theory

4D10. Brownian Motion

Brownian Motion (4D10.10) -- a small chamber is filled with smoke and observed with a video camera and TV. See also Molecular Motion Demonstrator (4D30.20).

4D20. Mean Free Path
4D30. Kinetic Motion

**Molecular Motion Demonstrator (4D30.20)** -- A small variable speed motor shakes a four-sided frame mounted over a glass plate on the overhead projector. Various sized plastic and metal balls placed in the frame bounce randomly about, simulating molecular motion. Concepts which may be demonstrated include temperature, equipartition of energy, diffusion, and Brownian motion.

4D40. Molecular Dimensions

4D50. Diffusion and Osmosis

**Diffusion (4D50.20)** -- An upside-down porous clay bottle with tubing leading out of the bottom and into a test tube of water is placed under an inverted beaker. Natural gas or helium is introduced into the beaker, and the osmotic pressure between the two gases forces air out of the bottle and down the tubing, so that bubbles are seen coming from the end of the tubing. After the cup fills entirely with natural gas, a new equilibrium is reached and the bubbles stop.

**Bromine Diffusion (4D50.45)** -- Glass tubes containing bromine and bromine/air are cooled in liquid nitrogen and allowed to warm back up to show rates of diffusion. The bromine only tube will diffuse faster than the bromine/air mixture.

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4E: Gas Law

4E10. Constant Pressure

**Galileo's Thermometer (Thermal Expansion of Air) (4E10.11)** -- Air expansion in a glass bulb causes liquid level in a vertical tube below the bulb to drop - qualitative only.

**Helium Balloon in Liquid Nitrogen (Charles's Law / Volume vs. Temperature) (4E10.22)** -- A helium balloon is drenched with liquid nitrogen. As the helium shrinks in volume, the balloon loses buoyancy and comes to rest on the table. As the helium warms up, the balloon expands and begins to float again. Note: Constant pressure here is atmospheric pressure.

4E20. Constant Temperature

**Boyle's Law (Pressure vs. Volume) (4E20.10)** -- A syringe is connected to a dial pressure gauge on the overhead projector. A decrease in volume of the syringe causes an inversely proportional increase in the pressure. An increase in the volume results in a decrease in the pressure.

4E30. Constant Volume

**Gay-Lussac's Law (Pressure vs. Temperature) (4E30.10)** -- A hollow metal sphere is attached via tubing to a pressure gauge on the overhead projector. The sphere is immersed in water baths of various temperatures (boiling, room temperature, and ice water) and the corresponding pressure is noted. The data can be extrapolated to absolute zero if desired.

**Constant Volume Gas (Pressure Thermometer) (4E30.20)** -- Constant volume is maintained by adjusting a water column, and pressure is read from the height of water in the other leg of the tube. Qualitative only, and only usable for small changes in pressure.

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4F: Entropy And The Second Law

4F10. Entropy

**Mixing and Unmixing (4F10.10)** -- The area between two acrylic coaxial cylinders is filled with glycerin and red dye. When the inner
cylinder is rotated, the dye appears to be mixed but is distributed in a fine one armed spiral sheet. Reversing the direction of inner cylinder rotation will cause the original dye pattern to reappear. Note: Please talk to us about this first.

**Entropy Pennies** -- a tray is filled with pennies painted green on the tails and red on the heads. If the tray is shaken the pennies begin to flip at a rate dependent on the magnitude of the shaking. Eventually an equilibrium is reached, with approximately equal numbers of reds and greens. Further shaking will not, of course, return them to their original state. If only a few pennies are used, they will occasionally return to their original state, showing the dependence upon the number of particles in the system.

See also Gaussian Distribution (1A20.10).

**4F30. Heat Cycles**

**Heron's Engine (or Hero's Engine) (4F30.01)** -- working model of the first primitive steam engine. A glass globe containing a small amount of water is heated with a flame. The steam produced comes out through two arms and spins the globe.

**Stirling Engines (4F30.10)** -- Choose from the engines listed below.

- **Stirling Engine (Heavy Duty)** -- A heavy duty Stirling engine. This is the biggest engine, but perhaps the least instructive because of low visibility.

- **Stirling Engine (Transparent Pistons)** -- a new model Stirling engine has glass cylinders so the power and displacement pistons can be viewed (a video camera helps, and an animation of the process is available on The Video Encyclopedia of Physics Demonstrations).

- **Stirling Engine (Hot & Cold)** -- This one runs off any sort of a temperature differential, and doesn't need much of a $\Delta T$. It will run on a cup of hot water, or (in reverse) on a block of ice. As the temperature differential decreases with time, the engine slows down. Doesn't need a flame, so it's useful to show that hot and cold reservoirs are all it takes to produce work from heat.

- **Stirling Engine (Hand-Held)** -- our newest Stirling engine is so well machined and balanced that it can run off the heat from your hand. Quite impressive.

**Cutaway Steam Engine (4F30.31)** -- cutaway model of a steam engine shows the steam chamber, piston, valves, etc.