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Cool It!

Activities with liquid nitrogen can stimulate bracing physics discussions.

by John H. Lehman

When scientific truths conflict with our students' observations and intuition, we ask them to trust our explanations. But can our explanations match the excitement and imagery students are accustomed to from movies and television? How, for example, do you explain impulse momentum or gas laws on Monday morning to students who saw rockets rumbling through cinematic space on Saturday night?

Heat, energy, resistance, kinetics—such topics challenge not only our students' imagination but also our own ability to explain them in interesting ways. What teachers need is a vehicle that holds the students' attention while it helps to explain the underlying physics principles. *Cryogenics*, the study of low-temperature phenomena, is such a vehicle.

The National Bureau of Standards (NBS) has developed a series of cryogenics activities (some of which I offer below) suitable for investigating the principles of magnetism; heat and energy; atoms and molecules; resistance, current, and power; and the ideal gas law. The activities require a cryogenic liquid, such as liquid nitrogen, and a collection of objects or simple devices. When cooled to cryogenic temperatures, each object or device illustrates a particular principle of physics. (See Ways & Means on page 30 for more about the equipment needed.) If you purchase or build the items as you introduce the corresponding topics to your curriculum, you can spread your expenses out over time. Because the activities are versatile, schools with similar interests could collect the items together.

Cryogenics is sometimes referred to as "the science of cold." However, *cold* is a relative term. When speaking of cryogenics, we are typically interested in phenomena occurring from absolute zero, or about -273°C, to about -150°C. Liquid nitrogen, with a boiling point at standard atmospheric pressure of -195.8°C, is often used to demonstrate low-temperature phenomena.

Other types of cryogenic liquids are available, but nitrogen is an economical choice. As mysterious as it looks, liquid nitrogen is fairly common and relatively cheap. Due to the low temperature of liquid nitrogen, it is mandatory to avoid direct contact both with the liquid itself and with objects that have been immersed in or have contained liquid nitrogen—even for short periods of time. When liquid nitrogen touches human flesh, it can freeze the water in the cells, causing severe frostbite.

The activities below are intended as demonstrations to be performed by teachers only. Teachers should wear thick, insulating gloves and eye protection at all times while handling liquid nitrogen, and students should wear eye protection and watch the demonstrations from at least 3 meters away. Also, as liquid nitrogen boils, it produces nitrogen gas. Breathing nitrogen gas, which is odorless, tasteless, and colorless, can result in suffocation. Caution and common sense are advised.

Never keep liquid nitrogen more than 36 hours. Oxygen from the air is condensed to a liquid within the liquid nitrogen. Hence, if left standing, liquid nitrogen slowly accumulates oxygen, and the mixture becomes a strong oxidizing agent. Leave the container uncapped; in a closed container sufficient pressure can develop to burst the container, sending pieces flying. After your demonstrations are complete, dispose of any leftover liquid nitrogen by pouring it on the ground outdoors.

Balloon

A balloon can demonstrate the ideal gas law, energy exchange, and molecular interactions. To begin, use a funnel to pour some liquid nitrogen into an insulated tray. Inflate and tie a balloon, making the balloon small enough to be submerged or doused with liquid nitrogen. If you fill the balloon using an air compressor, the balloon will contain air—78 percent nitrogen, 21 percent oxygen, and small amounts of other gases. If you inflate the balloon with your breath, the balloon will contain slightly less oxygen and slightly more carbon dioxide.

Ways & means

At the heart of the cryogenics activities is liquid nitrogen. Liquid nitrogen is available from welding and hospital supply houses at prices starting at less than $2/liter and dropping to about $1.50/liter for larger quantities. All of the demonstrations would not require more than 4 liters. The rest of the items required can be bought, borrowed, and scavenged according to your budget.

The compound bar (about $6) and the ball and ring apparatus (about $9) can be ordered from an educational supply catalog. The lead spring you can make from lead solder wire (about $4/ounce). While wearing plastic gloves, wrap the lead wire around a pencil. Remove the pencil and you have a lead spring. The steam engine is relatively expensive, about $65. Some hobby stores still sell them, as do some educational supply companies. A steam engine is not essential, but it's nice if you've got the money. Most of the equipment you can find in a hardware store: large rubber bands ($1.50 each), a funnel ($5 each), leather gloves ($12/pair), and tongs ($2/pair).

Living things, such as a carnation or a banana, are entertaining additions to the demonstrations, and they cost less than a dollar. Cooling them in liquid nitrogen and then shattering or breaking them makes for a dramatic comparison with their counterparts at room temperature. Try the same with a hollow rubber ball.

A few items are just not available commercially and have to be built. For the lead bell and the metal tray, the best approach is to walk into your school's machine shop with some decent drawings of what you want done and some samples, if you have them. Maybe the shop instructor in your school will have students construct them as a project. Otherwise, with materials and labor, the items could cost you as much as $100 from a commercial shop. You'll probably get a blank stare when you ask for a lead bell. An existing bell can be used as a casting mold. (If you are melting lead or casting the bell yourself, work under a hood. If you make the bell from sheet lead, wear plastic gloves while handling the metal.)

While you are at the shop, have an insulated metal tray made. The tray should be big enough to hold the bell and any other item you will cool in the liquid nitrogen. Or, to build one yourself, solder some sheet metal to form a tray about the size of a cigar box, or use a square cake pan. Insulate the tray or cake pan by building another tray of insulating foam around the first tray. Tape the foam in place to ensure a tight fit.

The light bulb apparatus you will probably need to make. Most of the basic materials are on the shelf in your storage cabinet or are available at a hardware store: a few meters of #30 bare wire ($1), a plastic bobbin (5¢ each), a petri dish, a female and a male banana plug ($1.50 each), a size D battery ($1.25 each), 60 centimeters of #22 insulated wire ($2), a flashlight bulb ($1.25 each), a chassis box ($4), a small lamp fixture ($2.50), and a battery holder ($1.50).

Put the light bulb in the lamp fixture, and screw the lamp fixture onto the chassis box. Attach the female banana plug to the chassis box, and rivet the battery holder to the chassis. Connect one lead of the battery holder to the lamp fixture. Attach the other lead to one lead of the female banana plug. Put the battery in the battery holder, and attach the remaining lead on the lamp fixture to the remaining lead on the female banana plug. Wrap the bare copper wire around the bobbin, leaving the two ends of the wire exposed. Connect each end of the wire to the male banana plug. (See the photo on page 33.)

When you are ready to do the demonstration, set the wire coil in the petri dish, pour some liquid nitrogen into the petri dish, and insert the male banana plug into the female plug.

Finally, if your equipment is going to travel, you'll need a box for everything. A photography case or a hardshell suitcase works well for about $70. A cardboard box works just as well if you don't have far to go.

—*J.H.L*

The composition of the air in the balloon characterizes the behavior of the air at low temperatures. When you lower the temperature to -196°C, the balloon collapses. The air doesn't escape; it merely condenses. Your students will be able to see a little liquid in the balloon after it has collapsed. The liquid appears because at -196°C, the temperature is low enough to liquefy all the gaseous components of the air.

If the bath were liquid oxygen, which boils at -183°C, only the oxygen and carbon dioxide portions of the air would condense, because the temperature is not low enough to liquefy the other gaseous components. With an ice-water bath, the temperature is not low enough to condense the gaseous content, but the balloon would shrink some.

Now fill the balloon with a gas such as helium, which has a boiling temperature of -269°C. Then submerge the balloon in liquid nitrogen. The balloon will contract as the helium in the balloon responds to a decrease in temperature with a decrease in volume. But no condensation will be observed, since -196°C is not cold enough to liquefy helium.

Ball and ring apparatus

A ball and ring apparatus allows you to demonstrate thermal expansion. The apparatus consists of a brass ring and a brass sphere, each mounted on a steel rod. Demonstrate that when the ball and ring are at the same temperature, you can slip the ball through the ring easily. Then submerge the ring in liquid nitrogen. Remove it, and try to slip the ball through the ring; the ball won't fit. Let the ring return to room temperature; the ball now slips easily through. (Students are often surprised that the hole in the ring increases with temperature; they think that as the material expands, the hole should shrink. This misconception is common and worth

– Photo by Lloyd Wolf

exploring in the classroom.)

Cool the ring again, but this time, cool the ball along with the ring. This time the ball slips through the ring.

Since the ball and ring are constructed of the same material, their contraction and expansion are identically proportional to the change in temperature. The contraction that students observe is the result of less intense thermal vibrations of the metal atoms, as energy in the form of heat is removed as the metal cools. Have students watch for the evidence of a transfer of energy—an increase in the boiling activity of the liquid nitrogen as the ball and ring are submerged in the nitrogen.

Different materials contract and expand different amounts for the same temperature change. This relative expansion of the material per degree Celsius is referred to as the *expansion coefficient* of the material. The expansion coefficient has been determined for many materials. With this coefficient it is possible to predict the contraction or expansion in volume or length for a given change in temperature.

Rubber band

You can use liquid nitrogen to demonstrate the glass transition of a material. Rubber is a polymeric material. Unlike the behavior of most of the other items in the NBS demonstrations, a rubber band's behavior is based on molecular interactions that may be less obvious to students than some of the other phenomena observed at low temperatures.

At room temperature, rubber is pliable and deformable. The ability of the rubber to bend, stretch, and then recover its original shape without any permanent deformation is a process of kinking and unkinking on the molecular level. The kinking and unkinking of the long molecular chains takes place freely as long as the rubber is above its *glass temperature,* which is about -75°C.

But, cool the rubber in liquid nitrogen and the kinking and unkinking will not take place. Cooled below its glass temperature, the rubber will maintain the shape that it was in as it crossed the -75°C mark. When the rubber band warms to room temperature, it will reassume its original shape and flexibility.

First, stretch the rubber band on tongs, and cool it by dipping the tongs in the liquid nitrogen. After a few seconds, lift it out, and carefully separate the rubber band from the tongs. The rubber band will maintain its stretched shape until it warms. If you tap the rubber band with a hammer, it will break.

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One way to consider the action of the rubber is to visualize the locked arms of a wrestler restraining an opponent. (The wrestler's arms represent the long chains of the rubber molecules.) As the opponent struggles (as we pull on the rubber band and then cool it), the wrestler tires (loses energy) and his grip lengthens (the rubber band stretches). If the wrestler is unable to redouble his efforts (if the rubber molecules are not sufficiently warmed), he will not be able to tighten his grip on his opponent (the rubber can't kink and stays stretched). If the opponent is able to take advantage of the situation (if you tap the frozen rubber with a hammer), he may lose his grip altogether (the rubber band will break). The rubber as it warms and regains its original shape is analogous to the wrestler regaining his strength and getting his grip back.

Compound bar

A compound bar demonstrates thermal expansion. The bar consists of two strips of metal bonded together. One side is steel; the other side is brass.

At room temperature, the bar is straight. Dip the bar in liquid nitrogen, and students will observe that the bar arches. It arches because the two metals have different rates of thermal contraction and different expansion coefficients. To help students visualize the effect, ask them to imagine what would happen to the two strips of metal if the strips were unbonded and cooled to the same temperature. As long as there is no heat transfer lag, the two strips would each shrink to a different length, but remain straight.

Lead bell and spring

Bells are typically made of brass, and springs are often made of steel wire. For the environment in which they are used—temperatures around 20°C—the materials serve their functions quite well. Lead, however, has a lattice structure different from that of other pure metals, and it does not behave typically. At 20°C, lead is very malleable and ductile, characteristics not very useful for a bell or a spring.

John H. Lehman is a mechanical engineer and a member of the Optical Electronic Metrology group at the National Bureau of Standards, Division 724.02, 325 Broadway, Boulder, CO 80303. He is also involved with the Career Awareness and Resource Education (CARE) program, located at Division 360.42 at the National Bureau of Standards. CARE promotes science, math, and engineering career awareness.