The Third Heat: Pictet's Experiment

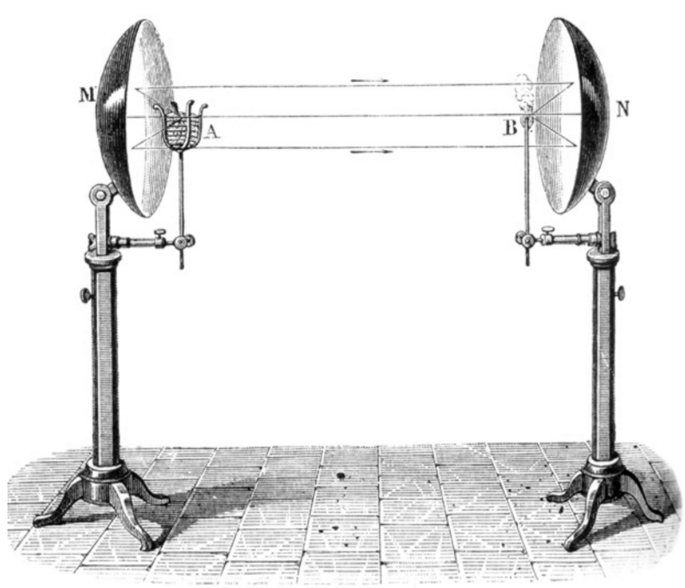
Intro

Let us think for a moment about how heat appears to us as a sensation. We can feel what we know of as conduction–A hand on a hot pan. We can feel convection–a fire warming a room. But we also sense a different kind of heat. When opening a furnace door we feel heat IMMEDIATELY, much faster than air molecules around the furnace could reach us.

We also feel the heat of the sun. Stepping out of full shade on a hot day makes things immediately hotter. How does that work? Is that energy we experience part of the light we can see? The sun is certainly bright, and so is a hot furnace. But plenty of hot things don't emit light. Humans are pretty warm and we don't visibly glow. Neither does a hot pan one might reach for.

Let's travel back in time to 1790. We don't know that the light we see is just a tiny slice of a broad spectrum of energy, most of which is invisible to us. It is ten years before the first bit of this spectrum outside our visual experience will get isolated and examined scientifically.

What we have is a suspicion that beyond conduction (touching that hot pan), and convection (feeling the heat of a fire roil through the air), there is a ***third heat****, one which travels quickly like light. To turn this suspicion into knowledge, scientists turn to* ***experiments****. We are going to conduct one today like it would have been done 230 years ago.*



Pair of parabolic mirrors in brass
Traité de physique, Ganot, Paris, 1884

The Science Behind Reflection of Heat

Pictet's experiment is the name given to a series of experiments performed in 1790 by Marc-Auguste Pictet which demonstrated radiative heat transfer and reflection of radiated heat from objects that were not visibly glowing, ten years before the isolation of infrared light from sunlight and half a century before modern theories of black-body radiation were developed.

After measuring an increase in temperature from the reflected heat of an object, a colleague suggested to

Pictet that he insert a very cold object and see what happens. Snow was brought into the laboratory and placed where the hot object had been. To Pictet's surprise, the temperature of the thermometer *went down*.

Some scientists at the time struggled with this result because they held a misconception noted in students of heat transfer today, that cold objects–those which feel cold to the touch–emit or radiate coldness akin to how we sense radiant heat from hot objects. Others, who knew that cold was the absence of heat, incorrectly inferred from this that the temperature should remain the same, and had to update their intuition.

The experiment was a way to move beyond apprehending radiant heat with our senses to measuring it with tools. What we would now call heat flux from an object could be reflected by mirrors, and focused following the same rules of optics that visible light did. Infrared cameras like those on the James Webb Space Telescope that today help us peer further into the past than we have seen before operate on principles demonstrated here.

Suggested placement of the lesson

The demonstration of Pictet's experiment can be useful for a range of students. This lesson plan has been designed to allow instructors the option to teach the material at a variety of levels. While the key question, "how is heat reflected and focused by mirrors" is relatively simple, the questions the demonstration prompts students to ask can be productive even for students with a fair amount of experience in physics.

For middle school science students learning about modes of heat transfer, the demonstration can prompt students to inquire about the role and nature of radiative heat transfer. Those classrooms may choose to skip questions about the determination of the focal point and questions about how much thermal radiation is collected by the mirrors. However, a review of these principles can be achieved without calculus and only some trigonometry[1]. Further, while heat flux impinges on an area, the discussion can be simplified by considering only a two-dimensional mirror and object setup.

While not covered directly in this lesson plan, asking students to consider different material choices for the hot object can prompt discussions about the relative role of emissivity and reflectivity of objects with respect to radiative heat transfer, a subject with concept inventories have shown to be a common source of student misconceptions.

[1] We assume spherical mirrors and only consider objects at the focal point of these mirrors, simplifying the calculations.

Key Terms

Focal Point: The point at which parallel light rays passing through a lens or reflected from a curved mirror converge, or the point from which they appear to diverge after refraction or reflection by the lens or mirror. Also called the focus or the principal focus.

Concave: Curving inwards. A concave mirror is one in which the reflecting surface is formed from the interior surface of a sphere or paraboloid. For this lesson, we treat all concave mirrors as spherical.

Black-body radiation: Thermal radiation emitted by an ideal, non-reflective object, dependent only on the object's temperature.

Infrared: Electromagnetic radiation just below the range of visible light. Sometimes referred to as "thermal radiation" or "radiative heat".

Conduction: The process by which heat is directly transmitted through a substance when there is a difference of temperature or of electrical potential between adjoining regions, without movement of the material.

Convection: Movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, denser material to sink under the influence of gravity, which consequently results in the transfer of heat.

Radiative heat transfer: Transfer of energy via thermal radiation, i.e., electromagnetic waves. This occurs across a vacuum or any transparent medium (solid, fluid, or gas). Thermal radiation is emitted by all objects at temperatures above absolute zero, due to random movements of atoms and molecules in matter.

KEY QUESTION:

How is heat reflected and focused by mirrors?

Getting Started

The goal of this lesson is for students to understand Pictet's counterintuitive science experiment first performed in 1790, showing the reflection of radiative heat by mirrors and the apparent reflection of cold. Some main objectives are to encourage the students to be creative, to think like scientists and engineers, and to give them a space where they are free to speculate about the results of the science demonstration without having the pressure of saying their guess in front of their peers.

Materials Needed:

- 2 concave mirrors
- 1 temperature sensing device
- A hot object
- A cold object
- Objects to hold the concave mirrors, thermometer, and heat source in place

If you do not have the exact materials, you can follow our associated experimental setup document which provides budget-friendly alternatives for how to demonstrate the experiment best.

Demonstration Setup

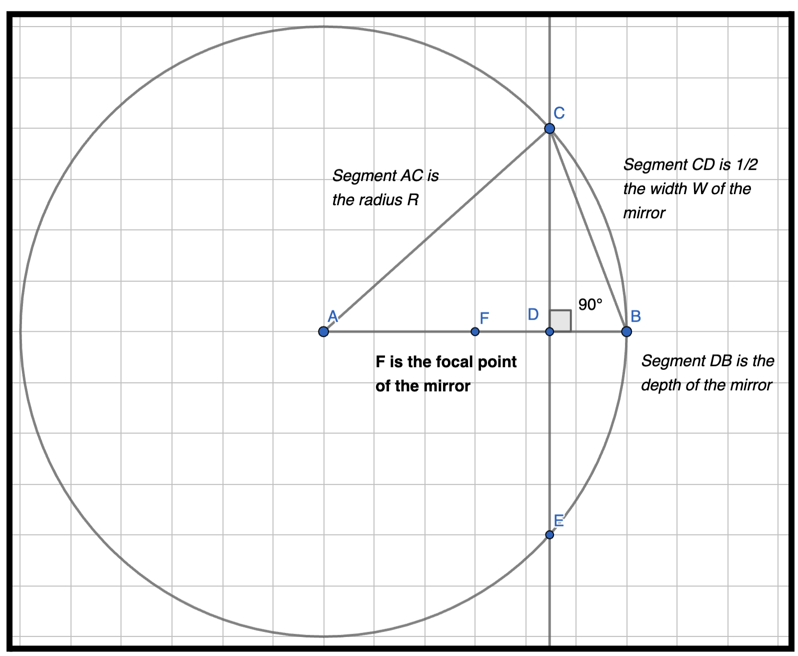
See the associated experimental setup document.

Safety

The experiment uses hot and cold objects. The simplest hot object to use is a candle–precautions for handling open flame are required. A glass of ice water is sufficient for a cold object, but the effect will be more dramatic the colder the object is. The use of dry ice or liquid nitrogen to cool a metal object requires precautions in the classroom.

Before starting the demonstration with students, consider these questions

How do light rays reflect off concave mirrors?



In setting up and discussing the experiment, discussing how visible light is reflected by mirrors can motivate where the objects and thermometer are placed relative to the mirrors. For concave mirrors, light radiating from the focal point of a mirror will reflect perpendicular to the axis of the mirror. Calculating this focal point, because it comes from these nearly parallel rays, can use the small angle or paraxial approximation, and no calculus or overt trigonometry is needed. The distance of the resulting focal point F is F = R / 2 where R is the radius of the imaginary sphere that the mirror forms a part of.

If a light bulb is placed at the focus of a spherical mirror, a cone of that light is collected in the mirror and reflected in a beam. But the light from which isn't captured by the beam falls off with the square of the distance from the source. This is how the headlights of a car can shed light at a distance but the same light held in the air would illuminate only a short distance.

What are the ways we can feel the sensation of heat?

This is a broad question that can be answered by students from their experience. Prompt them to think about touching hot objects and feeling the heat of a fire to get them to think about conduction and convection. For radiative heat transfer, this may require some additional prompting. Students may or may not have experience with a furnace or kiln—if they do, ask about how quickly they feel the heat from these objects at a distance. If they do not, prompt them to think about stepping into the sun on a windy day. The heat felt in that scenario cannot be via convection and must come from something else.

Does heat bounce off mirrors like light rays?

This can be posed to almost any student. After discussing the above, prompt students to think about roasting meat or vegetables. We often "tent" a roast by wrapping it in foil. What purpose might this serve? After removing a hot object from the oven, it will cool to room temperature if left alone. Covering the object in foil insulates it. If heat is transmitted via conduction or convection alone, it might serve to wrap an object in paper. Why do people use foil in their kitchens instead?

This question can be extended to a discussion of the characteristics of an object, specifically emissivity and reflectivity. However, for classes that have not discussed these topics, a general discussion can still be valuable.

Does the transfer of "cold" exist separate from the transfer of heat?

The range of human sensation provides an important anchor for understanding the world, but it can mislead us. We tend to think of objects that are warm to the touch as "hot" and those that appear cold as "cold" and students can hold the misconception that this split in sensation means a split in function or behavior.

One way to motivate questions like these can be to hand out cold packs that have just come out of a freezer as well as cold packs that have been allowed to come to room temperature. Objects at room temperature will not cause a strong sensation but cold objects will.

Another way to move this question forward is to have students discuss the implications of a hypothesis that cold objects emit or radiate coldness. If an object "gives off" cold, does a colder object give off more? Does a hot object also give off cold? When might an object stop giving off cold and instead give off heat? Probing questions like these can help students steer themselves to a conclusion that heat transfer occurs across a difference in temperature, rather than being connected to the sensation of hot and cold.

What is black-body radiation?

Where the demonstration is performed with a heated object (not a candle), students can be prompted to inquire about what features of the object aside from its temperature determine the amount of thermal energy transmitted. A “perfect” black-body emitter will give off the maximum amount of energy at a given temperature, while an object painted white will give off far less.

A comparison of those two situations is not the only question that can be posed. One of the key goals of the original experiment was to determine whether or not an object that was not visibly glowing gave off thermal radiation. In the “hot” stage, this can be shown with a hot object, but in the “cold” and “reset” stages, radiation of heat from the thermometer to the environment is observed. Here students can see that something that is roughly room temperature can radiate heat.

Setting the Stage: Fostering Inquiry-Based Learning

Prior to demonstrating the experiment–either during class or as a take-home assignment beforehand–distribute the attached hypothesis worksheet. The questions ask students to make simple predictions about the behavior of the system during the experiment. The main goal is to get students to advance a prediction and articulate their reasons why they did so.

Once you have the demonstration set up, responses in class work best in small groups. Even though for practical purposes there will likely be only one demonstration in the classroom, student reflection and discussion in groups helps them advance and process speculation about the outcome.

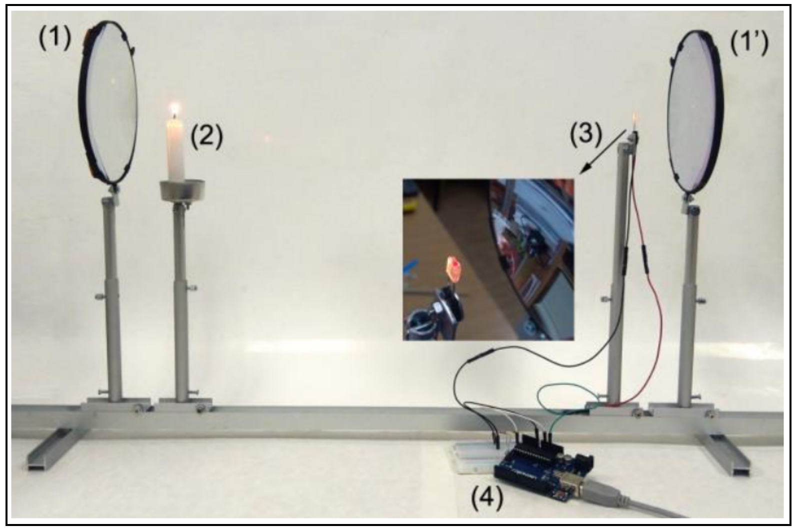
Have the students discuss amidst their group and decide which hypothesis they think is best. Make sure that each group has a spokesperson for their group that can share their hypothesis’ - science happens in community!

Next, have a class discussion where each team reflects to the class their hypothesis and discuss in class the potential consequences of each. After demonstrating the experiment with a hot object, ask groups to review the outcomes and report on how the system behavior deviated from what they expected. Most groups are likely to produce a “correct” answer at this stage–ie a hypothesis that says that the temperature at the sensor will go up with a reasonable explanation as to why.

When you repeat this process with the cold object, answers are more likely to vary both in predicted outcome and rationale.

Demonstration of the experiment

The demonstration has roughly three stages: hot, reset, and cold.



Pictured is the setup for Pimpas et al. (2017), which recreated the experiment using a candle and a thermocouple.

Hot:

Place a hot object in the focus of one mirror and ask students to pay attention to changes in the temperature sensor at the other focus. The temperature should increase immediately (if slowly) when the hot object is placed in the focus.

At this stage, one common student misconception is that the hot object is heating the sensor simply due to proximity rather than via reflection of radiant heat by the two mirrors. There are two interventions which can be useful here.

You may remind students of the inverse square law for radiation–the heat flux for a given area at a 10 cm distance (the distance from the hot object to the mirror) will be ~80 times the heat flux for the same area at 90 cm distance (the distance from the hot object to the thermometer for a 1 m distance setup). This has the advantage of allowing you to prompt discussion and computation of the relative heat flux.

There is a more direct route at this point, however. While the hot object is in focus, slide an opaque object between the hot object and its mirror (a sheet of printer paper will do). This has the effect of blocking all radiated heat from reaching the mirror but leaving the side facing the thermometer clear. If it was proximity to the heat source, not reflected radiant heat which caused the temperature increase the temperature should be expected to continue to rise. Instead, it can be observed to fall.

Reset:

After removing the hot object, have the students observe that the sensor returns to room temperature. The sensor will transfer heat to its environment until it is at thermal equilibrium.

This stage is a place to prompt students for discussion of what that environment is for the sensor. When heat is transferred in the form of infrared radiation, a portion of that reaches the mirror and is reflected. That reflected portion is lost to the environment without something in the other focus.

Cold:

Demonstration of a cold object placed near the focal point of the left mirror. Note the rough positioning of the cold object and the precise positioning of the sensor.

Once the sensor is at room temperature, ask students to make a prediction as to what will happen when a cold object is placed in the other focus. Defer the question as to why until after the demonstration.

After placing a cold object in the focus, observe carefully the change in temperature at the sensor. The decrease in temperature will be less than the increase with a hot object. For a water-ice object at ~ 0 ℃ the change will happen slowly. With an object cooled well below 0 ℃ it will happen faster. However, the temperature should go down.

After students observe the drop in temperature, you can insert a piece of paper between the cold object and its mirror just as you did the hot object. The temperature at the sensor should rise.

At this point, you should ask student groups to speculate why the introduction of the cold object causes a temperature drop at the sensor. Remind them of their explanations as to why a hot object caused the temperature to go up.

Discussion

There are a few ways to motivate discussion of an explanation of why the temperature at the sensor drops.

Ask students to imagine a different setup: a temperature sensor in a bath of liquid where a cold object has been inserted. In this thought experiment, the temperature of the bulk fluid will drop until it reaches equilibrium. This sidesteps the question of reflection but prompts students to imagine the sensor as part of a system.

Remind students that one phenomenon shown by the hot object demonstration and the reset is that all objects radiate some heat to their environment. Setting up the mirrors as we did means that some portion of that radiated heat is captured by the mirrors. With no object in focus, all radiant heat passing the focus comes from the environment. When a cold object is placed in the focus instead, the portion of that heat flux that would otherwise be reflected by the mirror is greatly reduced.

Because the features of the experimental setup are known, the above discussion can also include a calculation of how much of the system is comprised of the two mirrors.

- The fraction of the circle with center F and radius R/2 (arc CBE in the above diagram) can be computed by doubling the angle FCD.
- Angle FCD can be computed by taking the inverse tangent of (W/2)/(F - depth). The distance F, depth of the mirror, and width of the mirror are known. For a mirror with a depth of 0.51 cm and a width of 9 cm, the focal length is 10 cm, which gives an angle of ~30 degrees. Doubling that leaves 60 degrees.
- Dividing this from the imaginary circle around the temperature sensor gives the proportion of the radiation leaving the sensor which reaches the mirror. It also gives, conversely, the rough proportion of thermal radiation reaching the opposite mirror which will be focused on the sensor. For our example mirror this is 1/6th of the total radiation in the system.

In effect, a cold object will radiate much less heat than the surrounding environment over the arc CBE that is focused on the sensor. Without an object in focus, this radiation comes entirely from the environment which at the start of the demonstration is in equilibrium with the sensor.

Related heat transfer concepts:

- Temperature vs. Heat – Concept inventories from Jacobi et al. 2003 and Prince et al. 2012

Corresponding Extension Activities

[Hypothesis Worksheet]
[Suggested Diagrams Handout]

Suggested Resources

- Pictet's experiment on the English Wikipedia created for this lesson covers historical context for the experiment and links to peer-reviewed sources.
- "Are There Rays of Cold?", an undated video demonstration in Russian released in 2015 from the Moscow Engineering Physics Institute.

References

Concept inventories for heat transfer

Prince, M., Vigeant, M. and Nottis, K. (2012), Development of the Heat and Energy Concept Inventory: Preliminary Results on the Prevalence and Persistence of Engineering Students' Misconceptions. Journal of Engineering Education, 101: 412-438. https://doi.org/10.1002/j.2168-9830.2012.tb00056.x

A. Jacobi, J. Martin, J. Mitchell and T. Newell, "A concept inventory for heat transfer," 33rd Annual Frontiers in Education, 2003. FIE 2003., Westminster, CO, USA, 2003. https://doi.org/10.1109/FIE.2003.1263338

Recreations of the experiment

Evans, James; Popp, Brian (1985). "Pictet's experiment: The apparent radiation and reflection of cold" (PDF). *American Journal of Physics*. 53 (8): 737–753.

Pimpas, Alexander; Mihova, Gergana M.; Andreeva, Andreana I.; Zografov, Nikolay N. (2017). "Trapping Radiant Cold Via Mirrors" (PDF). *Journal of Physics and Technology*. 1 (2): 65–69.

General Reference

Lemons, D. S., Shanahan, W. R., Buchholtz, L. J. (2022). On the Trail of black-body Radiation: Max Planck and the Physics of His Era. United Kingdom: MIT Press. ISBN: 9780262047043

The Pictet Cabinet: The art of teaching science through experiment (PDF), a 2011 pamphlet from the Musée d'histoire des sciences de la Ville de Genève (Museum of the History of Science of the City of Geneva)