Experimental and Material Setup Instructions

Introduction

The experiment involves the observation of reflected radiant heat, first from a hot or heated object to a temperature sensor and then from a temperature sensor to its environment. The magnitude of the effect observed depends on two main factors:

1. The amount of energy released as radiant heat by the hot object or thermometer
2. The proportion of that energy reflected and transmitted by the mirrors the system

The greater the magnitude of this effect, the more temperature deflection is seen by the sensor. An increase in energy released can be achieved by heating an object with a given emissivity to a higher temperature and an increase in the energy reflected can be achieved through mirrors which capture a larger fraction of the heat radiated by the object (larger mirrors or mirrors with a longer focal length will capture more of this radiation, see below)

During the performance of the “hot” stage of the demonstration, the effect is strong enough to be observed even with a relatively less sensitive system; however, the effect in the “cold” stage is less dramatic, and less sensitive setups may require more time to observe a change.

Setup

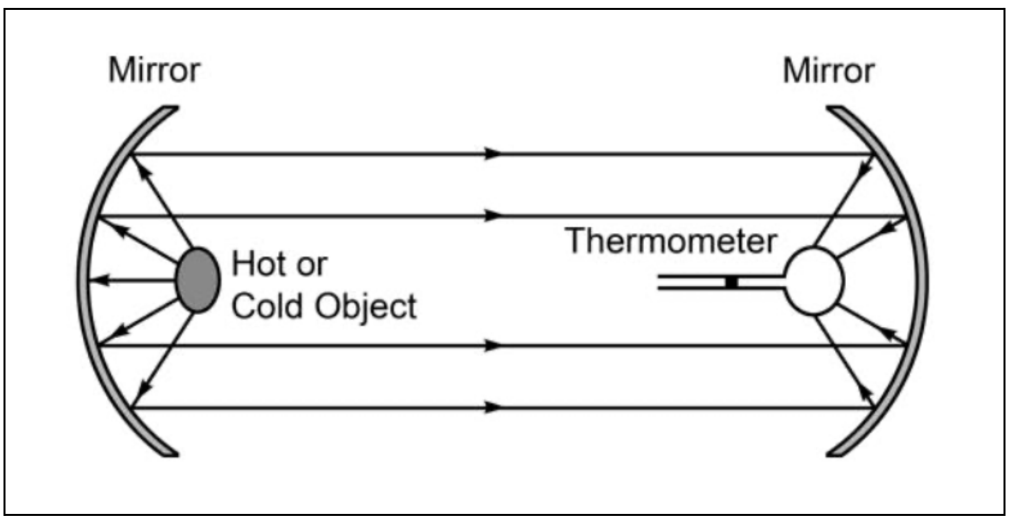


Diagram of setup from Pimpas et al. 2017

The two concave mirrors are set up at a distance of 1 to 2 meters[1] facing one another perpendicular along their optical axes. At the focal point for one mirror, a temperature sensor is fixed. The focal point of the other mirror is where the hot or cold object is placed.

Our suggested hot and cold objects are large enough that they need not exactly be at the focal point, but the target size of thermometers is small.

Determination of the focal point can be made during the experimental setup using visible light by placing a light bulb at the focus of one mirror and aligning the temperature sensor at the point where the visible light is focused by the other mirror.

Mirror sizing

The purpose of the mirrors is to collect light to or from a focal point. A larger mirror will collect relatively more heat than one with a smaller diameter, and a deeper mirror will collect more than a shallow mirror of the same diameter. This experiment has been replicated with mirrors of diameter 8-25 cm with varying focal lengths. Larger and deeper mirrors will collect more heat flux and allow for the use of less sensitive temperature sensors.

The distance to the focal point can be determined from the width *W* of the mirror and its depth *D*. Knowing those, the focal length is $((W/2)^2 + D^2) \times (1/4D)$. For our supplied instructions for a 16 cm wide mirror with a depth of 1.67 cm, the distance is 10 cm.

Mirror material and dimension

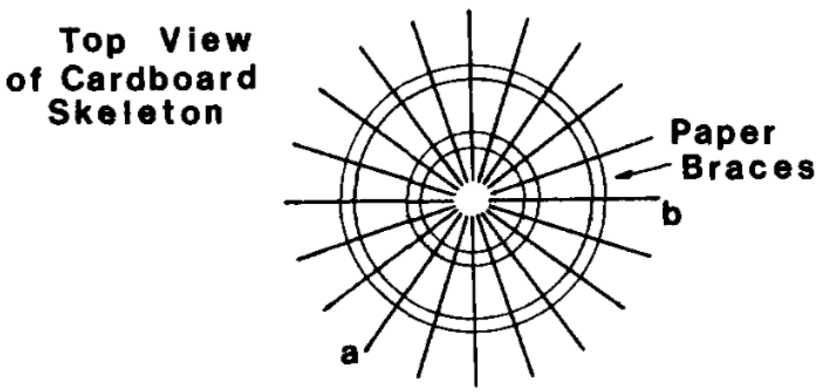
This experiment has been performed in modern times with three kinds of mirrors:

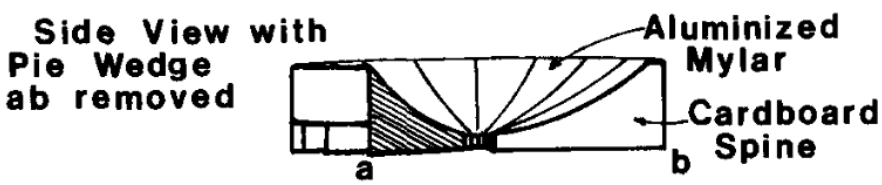
1. Mirrors made from a structural backing material coated in aluminum or Mylar. Physicists at the University of Washington cut cardboard ribs to the desired size and arc and covered them with Mylar. We created mirror structural backing in a 3D printer, sanded the surface, and applied high-gloss aluminum spray paint.
2. Silvered glass mirrors. Researchers at Sofia University in Bulgaria used small mirrors for their recreation. They did not report the dimensions of the mirror but we used small commodity concave mirrors purchased on Amazon.
3. Formed polished metallic mirrors were used by instructors at the Moscow Engineering Physics Institute for their recreation. Not having access to these we did not attempt to replicate this choice.

The size and shape of these mirrors differ. UW physicists used deep 55 cm diameter mirrors with a focal length of 15 cm, while those at Sofia University used what appears to be shallow, ~ 10 cm mirrors. As noted above, the size and shape impact the amount of infrared radiation reflected, but the material choice also has an impact. However, both Mylar tape and aluminum spray paint have very high values of reflectivity and should be appropriate.

[1] Distances shorter than 1 meter run the risk of implying to students that the hot and cold object is influencing the temperature sensor by simply being near it. Longer distances are possible, but errors in position and orientation grow with distance.

Evans and Popp 1985 p. 751 contains instructions for the creation of a cardboard mirror backing, seen here:





For a width of 55 cm and a focal length of 15 cm, the desired depth of the mirror is roughly 18cm.

Temperature sensor

The temperature-sensitive instrument may be a consumer-grade digital temperature sensor (e.g. the MCP9808 which has a precision of 0.25 ℃ over 2 seconds), a mercury thermometer, or a thermocouple. University of Washington physics teachers constructed galvanometers in 1985.

The choice of sensor is linked to other choices. In general, larger and deeper mirrors will require less sensitive instruments as will very hot or very cold objects. If you are planning to use relatively small mirrors and cold objects at the temperature of water ice, a sensitive thermocouple might be better than a digital temperature sensor.

A major advantage of the thermocouple and digital sensor over a mercury thermometer is the ability to transmit the results to a display. An advantage of a thermocouple over either choice of thermometer is relatively higher[2] sensitivity, while thermometers in general have the advantage of interpretability. With a thermocouple, students must be introduced to the system of measurement and must recognize that a deflection in current represents a deflection in the instrument.

---

[2] Most commodity thermocouples have a rated temperature sensitivity similar to the MCP9808, but in our experience deflections in temperature less than the rated sensitivity can reliably be observed.

Hot objects

One of two options has been used in the modern recreation of the experiment

1. A metal sphere or slug roughly 2-3 cm in diameter heated to more than 200 ℃. Much larger and it will occlude too much of a 9 cm diameter mirror. Smaller and it will have reduced heat capacity.
2. A small open flame, for instance, a candle or a Bunsen burner.

The original experiment showed objects radiated heat at lower temperatures as they seemed to radiate heat *and* light at very high temperatures. This is one of the earliest experimental demonstrations of black-body radiation, decades before much of the theory was developed in the mid-19th century. The use of a candle for a hot object is much simpler, but it will not allow you to as easily demonstrate black-body radiation, because the candle flame is also emitting visible light.

Cold objects

Two options are available:

1. Using water ice, including snow or a glass of ice water at roughly 0 ℃.
2. Cooling an object with a refrigerator, dry ice, or liquid nitrogen to temperatures well below 0 ℃.

A colder object will show a relatively more dramatic effect. An object cooled with liquid nitrogen can be roughly -190 ℃ and will emit much less heat through radiation than the same object cooled to 0 ℃. However, the effect can be demonstrated with a sensitive thermometer even with a glass of ice water.

Material cost estimates

A variety of material choices were presented with the possibility that some classrooms may have access to certain elements of the apparatus available. Choices of mirror, heat source, and temperature sensor can be mixed and matched based on what is on hand or available at low cost. Estimates of material cost for sensors and mirrors are below, rounded to the nearest dollar.

Mirrors:

- Concave mirrors are available on Amazon. We used 10 cm mirrors with a focal length of 15 cm: $24
- 3D printed mirror cost feedstock for 16 cm mirrors: $2
- We used recycled cardboard and paper. New cardboard for a roughly 20 cm diameter mirror: $6

Sensors:

- MCP9808 High Accuracy I2C Temperature Sensor Breakout Board, available from AdaFruit: $5
- 0.56" 4-Digit 7-Segment Display w/I2C Backpack - Yellow, available from AdaFruit: $10
- Stainless Steel thermocouple, available from Amazon: $13

Material instructions and links

Project materials and code are available on Github in the public domain: github.com/Protonk/Pictet. This repository also contains an excerpt from Evans and Popp 1985 detailing their experimental replication, shared as fair use.