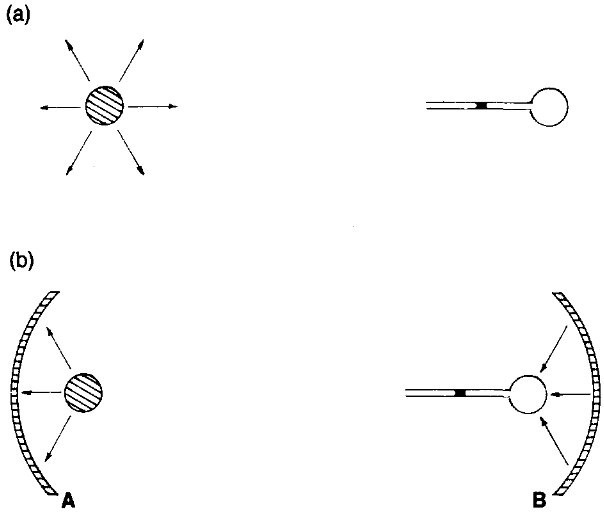

Fig. 5. For use in explaining Pictet's experiment.

Let us note that every object—even a cold object—continually emits radiation. Each object also continually receives radiation that has been emitted by the objects surrounding it. The energy emitted per unit time by a given object depends both upon the object's temperature and the properties of its surface. A highly polished metal mirror is a very poor absorber of infrared radiation; it is also, consequently, a poor radiator. Thus we may safely ignore any emission or absorption of radiant heat by the mirrors themselves. The sole function of the mirrors then consists in the reflection of the radiation that is incident upon them.

Consider first the version of the experiment involving a flask of boiling water. This flask emits radiation in all directions, as shown schematically in Fig. 5(a). A negligible part of this radiation is received directly by the air thermometer, which has but a small cross-sectional area and which is placed at a considerable distance from the flask. In Fig. 5(b), we imagine the mirrors to be placed so that the focus of mirror A lies in the flask, and the focus of B in the bulb of the thermometer. Now we direct our attention toward that part of the radiation from the flask which happens to strike mirror A. This radiation will, after two reflections, impinge on the bulb of the thermometer. This is radiation that the thermometer did not receive prior to the introduction of the mirrors. Of course, the thermometer also receives radiation from other objects in the room. The introduction of mirror B effectively eliminates the right third or half of the room as a source of radiation for the thermometer. The effect of the mirrors is therefore to replace a part of the ambient radiation that formerly impinged on the thermometer by the more intense radiation from the flask. The thermometer therefore grows a little warmer.

The version of the experiment involving a flask of snow may be explained in a similar way. Before the mirrors are introduced, the air thermometer receives radiation from all the objects in the room surrounding it. After the introduction of the mirrors, the radiation from the right third or half of the room is cut off from the thermometer by mirror B. This relatively high-temperature radiation is replaced by the radiation from the flask of snow. The thermometer now receives less energy per unit time than previously. The thermometer, initially at room temperature, now radiates away more energy than it absorbs, and so suffers a decrease in temperature.

V. PICTET'S EXPERIMENT AS A LECTURE DEMONSTRATION

Figure 1 illustrates the essential features of the experiment. Many university physics departments are no doubt equipped with all that is required. The mirrors need not be of very high optical quality, but if they are of glass they must be front-surface reflectors, as glass is a strong absorber of both hot and cold emanations—a point made quite clearly by Pictet himself.[54]

In an arrangement designed by J. Davis and used at the University of Washington, the reflectors are 25 cm in diameter, with focal lengths of about 2 cm. A brass sphere, which may be heated over a Bunsen burner or plunged into liquid nitrogen, serves as the hot or cold object and is mounted on a stand at the focus of one reflector. At the focus of the other is a thermopile, which is connected to a projection galvanometer so that changes in temperature can be observed by a large audience. Full-scale deflection of the galvanometer is achieved for the radiation of both hot and cold.

Those without large reflectors and adequate temperature-sensing equipment should not despair, for perfectly acceptable homemade apparatus can be assembled in a few hours and for a few dollars. The homemade equipment, by dispensing with such historical anomalies as liquid nitrogen and projection galvanometers, actually results in a demonstration that is more pleasing and convincing.

For the cold object, a glass beaker of ice water works well enough. Glass, being a good absorber of infrared radiation, is also a good emitter. A metal can should not be used unless the metal is blackened. Colder temperatures can be obtained, if necessary, by using ice and salt, or by using dry ice.

A sensitive air thermometer may be quickly constructed from a flask, a one-hole stopper, and a bent glass tube, as shown in Fig. 6. A bead of colored water or alcohol is inserted in the glass tube before the stopper is seated in the neck of the flask. A small card, marked with uniform but otherwise arbitrary divisions, may be taped to the tube to make the motion of the water more apparent. The glass of the flask is probably already a sufficiently good absorber of infrared radiation; but a curl of black paper inserted in the flask may increase absorption somewhat. The thermometer should respond instantly to the touch, or even the close proximity, of the hand. If it does not, one of the two seals (of the stopper in the flask, or of the tube in the stopper) is probably not air-tight.

The thermometer just described is quite sensitive and can be easily observed by the whole audience in even a rather large room. But as the thermometer is rather bulky,

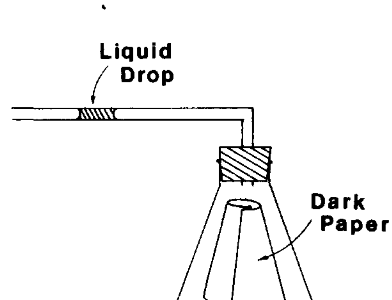

Fig. 6. A simple air thermometer.

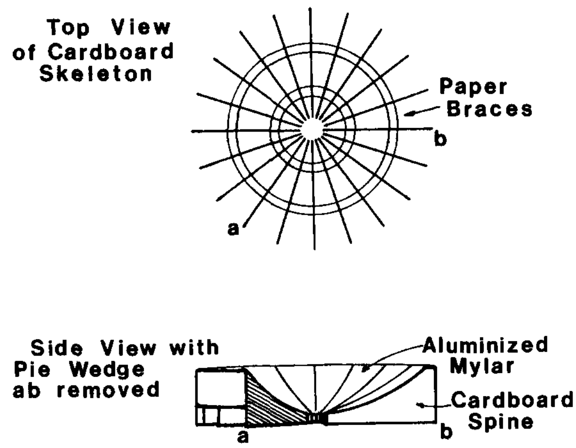

Fig. 7. Design of an inexpensive mirror for reflecting cold emanations.

it requires the use of mirrors of fairly long focal length. Since the mirrors need be of only minimal quality, they can be made from a sheet of aluminized mylar. Cardboard spines are cut with the appropriate circular or parabolic shape, as shown in Fig. 7. (Our reflectors are approximately 55 cm in diameter and have a focal length of 15 cm.) These spines are then fastened together with strips of stiff paper to form the skeleton of the reflector, as shown. Paper strips are then pasted to the skeleton, completely covering it. This provides added sturdiness and a base on which to apply the aluminized mylar. The mylar is fastened in thin, wedge-shaped pieces with double-stick tape. The finished mirror will, of course, have many little warps and bubbles and will be completely unsuitable for optical experiments, but it will be more than adequate for experiments with radiant heat. The large diameter of the reflector more than compensates for the imperfections of its surface.

ACKNOWLEDGMENTS

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[1] Thomas Charles Hope (1766–1844), professor of chemistry at the University of Edinburgh for nearly 50 years. John Playfair (1748–1819), best known today for his *Illustrations of the Huttonian Theory of the Earth* (Edinburgh, 1802). Appointed professor of mathematics in 1785, he exchanged this chair for the chair of natural philosophy in 1805. Dugald Stewart (1753–1828) succeeded his father Matthew Stewart as professor of mathematics. He is said to have been a successful teacher but to have groaned at the prospect of teaching Euclid for the thirteenth time. In 1785 he transferred to the chair of moral philosophy.

[2] Rumford's account of this experiment is given in his "Historical Review of the Various Experiments of the Author on the Subject of Heat," first published in French in his *Mémoires sur la chaleur* (Paris, 1804). The English version appears in *The Collected Works of Count Rumford*, edited by S. C. Brown (Harvard University, Cambridge, 1968–1970), Vol. I, pp. 443–496. The repetition of Pictet's experiment is found on pp. 477–478 of Brown's edition. Rumford had long espoused vibrationist views [see M. Watanabe, "Count Rumford's First Exposition of the Dynamic Theory of Heat," Isis **50**, pp. 141–144 (1959)]; but it was in Edinburgh in 1800 that he first publicly asserted an analogy between heat and sound.

[3] For an overview, see E. S. Cornell, "Early Studies in Radiant Heat," Ann. Sci. **1**, 217–225 (1936). The account by A. Wolf, *A History of Science, Technology, and Philosophy in the Eighteenth Century* (George Allen & Unwin, London, 1952), 2nd ed., pp. 206–212, is based largely on Cornell's article.

[4] This experiment was performed, for example, by Zahn, Hoffman, Scheele, and Lambert. See Wolf, *History*, pp. 206–209. The experiment is mentioned by Saussure as one that is "well known": H.-B. de Saussure, *Voyages dans les Alpes* (Neuchatel, 1779–1796), Vol. 2, p. 353.

[5] Johann Heinrich Lambert (1726–1777), best known to mathematicians for his proof of the irrationality of π and e. In physics, his name is attached to (1) the exponential decrease of the intensity of light passing through a homogeneous absorbing medium, as well as to (2) Lambert's cosine law, which states that the intensity of light emitted by a diffusely radiating plane surface is proportional to the cosine of the angle between the line of sight and the normal to the surface. Lambert's investigations into the measurement, radiation, and reflection of heat are reported in his *Pyrometrie oder vom Maasse des Feurers und der Wärme* (Berlin, 1779).

[6] Carl Wilhelm Scheele (1742–1786), the extraordinarily productive and talented chemist from Swedish Pomerania. His research on gases culminated in his discovery of oxygen in advance of Priestly. This work, as well as his investigation into radiant heat, was reported in his *Chemische Abhandlung von Luft und dem Feuer* (Upsala and Leipzig, 1777; 2nd ed., Leipzig, 1782). A French translation by Dietrich was published in 1781 with the approbation of the Académie des Sciences, under the title, *Traité chemique de l'air et du feu* (Paris, 1781), through which Scheele's work became widely known in France and in French Switzerland. The German edition of 1782 has been reprinted as Vol. 58 of Ostwald's *Klassiker der exakten Wissenschaften* (W. Englemann, Leipzig, 1894). There is an English translation in L. Dobbin, *The Collected Papers of Carl Wilhelm Scheele* (G. Bell & Sons, London, 1931).

[7] Lambert, *Pyrometrie*, Sec. 378. The use of a pane of glass to halt the progress of radiant heat was a standard experiment. It had already been demonstrated a hundred years before by Mariotte: *Histoire de l'Académie Royale des Sciences depuis son établissement en 1666 jusqu'à 1686, Vol. I* (Paris, 1733), p. 344. Mariotte also showed that the heat from the sun differed from that of a fire, in that it was not stopped by glass. The notion of obscure heat also seems to have been in the air at the time that Lambert wrote. G. Buffon distinguished between luminous and obscure heat in his *Histoire naturelle, générale et particulière...Supplément, Vol. I* (Paris, 1774), p. 32. Buffon produced a "rather strong" heat without any light at the focus of a mirror by interposing a plate of iron between the mirror and a fire (p. 42, note o.)

[8] Scheele, *Chemische Abhandlung*, Secs. 56–57.

[9] See Ref. 8, Secs. 58, 69.

[10] These biological sketches of Saussure and Pictet are drawn largely from the articles in the *Dictionary of Scientific Biography*, edited by C. C. Gillispie (Scribner's, New York, 1976) and in the Michaud *Biographie universelle* (Paris, 1843-?). The latter is also an excellent source of information on the many minor 18th and early 19th century scientists who cannot be found in any other standard biographical reference work. For Saussure there is also a biography: D. W. Freshfield, *The Life of Horace Benedict de Saussure* (E. Arnold, London, 1920).

[11] M.-A. Pictet, *Essai sur le feu* (Geneva, 1790). Translated into English by W. B. [elcombe] and published as *An Essay on Fire* (London, 1791). Pictet intended to write a series of *Essais de physique*. The treatise on fire, which was the only one completed, is sometimes cited by this title as well.

[12] The thermometer was of mercury. Neither Saussure nor Pictet specifies the kind of degree used. Thus one should assume the degree of the 80-degree scale (Réaumur) which Pictet used as a matter of course. Pictet did, however, possess at least one thermometer adapted to Farenheit's scale, made by Ramsden in London, which he used on occasion (*Essai sur le feu*, Sec. 53).

[13] Louis Bertrand (1731–1812), Swiss geologist and mathematician, and a student of Euler's. In 1761 Bertrand was appointed to the chair of mathematics at the Academy of Geneva. He wrote memoirs on probability theory and the binomioal formula but is best known for the treatment of the theory of parallels that formed a part of his *Développements nouveaux de la partie élémentaire des mathématiques* (Geneva, 1778). At the time of the revolution in Geneva (1793), Bertrand resigned his chair and retired to a country village, where he occupied himself with geology and produced his rather fantastic *Renouvellements périodiques des continents terrestres* (Hamburg, 1799; Geneva, 1803). He returned to Geneva