Explaining hot and cold

Models of heat transfer

We are likely to speak about how hot or cold something is. People tend to use the word *heat* to mean whatever is in something that makes it seem warm, and to associate a "lack of heat" with cold. But heat is not a substance.

Hot and cold may seem to be determined by measurement (a thermometer) but there is more to it than that. You can provide counterexamples: When you step out of bed during winter, would you rather put bare feet down on a tile floor or a carpeted floor? Most people know the answer, but don't necessarily recognize that the surfaces are the same temperature.

A simple experiment with several large ceramic tiles and swatches of equal-sized carpet squares (and two thermometers) will help them with this. Put one thermometer, a stack of tiles, and a stack of an equal number carpet squares (remnants are often available free) in the refrigerator freezer before the end of school one day. Also put a stack of tiles and the other thermometer into the refrigerator. The next morning, take the temperature reading from the thermometers and use your fingers to sense which feel colder or warmer. The thermometer readings say they're the same temperature, but there is apparently a difference between the measured temperature and the object's sensual reaction to temperature.

Something dynamic had to happen to make us "feel" the cold. That thing is known as heat transfer. Heat is what flows from the warmer object to the colder object.

Why do things feel cold? Most people designate objects with a high thermal conductivity (such as tiles or most metals) as cold and objects with a low thermal conductivity (such as carpet, paper, or insulating material) as warmer (or at least not so cold as those other objects). People and teachers with experience with saunas know it works the other way as well. Metal ladles (high thermal conductivity) feel very hot, while wood benches (low thermal conductivity) do not.

The key is recognizing that people's skin is at a temperature of about 35 °C, so when a person touches something at a lower temperature, heat will flow from the warmer object (the person) to the colder object. The bigger the temperature difference, the bigger the heat flow (colder tile from freezer vs. warmer tile from refrigerator). The bigger the thermal conductivity, the bigger the heat flow (tile from freezer vs. carpet remnant from freezer). The heat transferred from your foot is quickly distributed over the tile because of its relatively high conductivity. So the foot on the tile loses heat, while the foot on the rug experiences much less loss of heat, because it is not conducted away from the foot as rapidly.

Touching something that's really cold can make a person feel cold. It drains energy. People who have their energy drained away because of cold environment and insufficient body covering can die of exposure (as in the case of those who were floating in life jackets in cold water around the Titanic in the movie one of my daughters has already seen five times). When people get cold, they may shiver to warm themselves again. That shivering is movement of muscles that leads to increased motion of the molecules making up our bodies.

All the atoms in our bodies are in motion because they are at a temperature above absolute zero, which has the least amount of energy (and of amplitude) possible. (Because of zero point motion, there is motion even at absolute zero.) The greater the motion, on average, the greater the amount of *thermal energy* an object has (this may be roughly characteristic of the "energy content" of the object).

Conduction

You and a few friends can model thermal energy and heat transfer. Divide into two (standing) groups, "colds" and "hots," standing somewhat apart. (The two groups should have an equal number of people for this analogy to work.)

Have the "hots" and "colds" randomly move their bodies up and down at the about the same frequency, but the "hots" should move their ups and downs (amplitudes) through a greater distance than the "colds." There is more thermal energy in the "hots." We want the "hots" to be jittering, and the "colds" to be relatively quiet. Have the two subgroups come into contact. The "hots" who are in contact with the "colds" should jostle their cold counterparts. The pushy "hots" who are near the edge should decrease their jittering motion, and the "colds" in contact with them should increase theirs. The warmer neighbors of the "edge hots" can jostle them more, jittering a little less in consequence, while making the "edge hots" jitter more again. Meanwhile, the "edge colds" could jostle their colder neighbors, jittering them more while decreasing their jitters. This process continues until the group is pretty much all jittering with the same amplitude (all at the same temperature). By cooling (by being in contact with the cold group), the warm group members (the ones near the contact point) should decrease their amplitudes while the cold ones will increase their amplitudes a little (near that point and later, on the average).

Conduction, illustrated above, is only one method of transfer of thermal energy. The other two methods of heat transfer are convection and radiation.

Convection

A similar model of convective heat transfer can also be developed. Have a subgroup of volunteers leave the group of "hots" (still moving up and down) and join the "colds." Some energy has left the "hots" and moved to the "colds." The people who moved between the groups have carried the energy with them (they have transferred energy between the groups). The "hot" group has a bit less thermal energy (fewer people there) and so has cooled a little; the "cold" group has a bit more thermal energy and has warmed a little. [With an addition of cookies—chemical energy—in the possession of the "hot" group, this energy transfer can be made even more vivid. The people traveling as heat from hot to cold can bring and distribute the chemical energy of cookies among the "cold" group, symbolizing the transfer of thermal energy among atoms that actually occurs. Atoms in the "cold" material will increase their amplitudes on average when the heat arrives.]

Both conduction and convection involve the presence of matter. Energy is transferred using the material itself, either passively (conduction) or actively (convection).

Radiation

In radiation, thermal energy is transferred through the space between objects at different temperatures. The space may contain matter or not; either way energy is transferred by radiation. The word for radiation comes from the spoke of a wheel. Radiation is energy transferred by streaming away from one object toward a colder object somewhere else.

A model for this using people could be a group that gathers at the center, jiggling. Other people may be scattered about some distance away. The jigglers at the center now run outward from the center and bring their energy to the lower-temperature people some distance away.

An example: the campfire

An example that combines all these in one is a campfire. If you hold one end of a burning stick (not the burning end!) you will eventually feel it getting hotter. This is heat transfer by conduction. If you hold your hand above the fire (but not too close!), it will be warmed by convected air. If you are somewhere in the vicinity, you will feel the side toward the fire getting warmer by radiation.

I am much indebted to Mario Iona for his cogent advice on this subject. This material was adapted from an article “Explaining hot and cold” originally published in *AURCO J.* **6**, 61 (2000).

There is no such thing as "heat energy"

We have used *heat* only for the energy transferred between the objects at different temperatures, and *thermal energy* to describe the "energy content" of the objects. That is the correct way to characterize these quantities. In some circles, "heat energy" is incorrectly used to mean "energy content," when heat is not something contained within an object, but rather energy transferred by the object. There is no such thing as "heat energy," while there really is thermal energy.

The reason lies in the definition of heat itself, and in two other types of energy: thermal energy and internal energy. In order to define heat, we must define a reservoir (sometimes known as a heat reservoir or an energy reservoir). This is an object or material at a uniform temperature that is so large that removing a small amount of energy or adding a small amount of energy does not change anything (or at least not very much). Heat is energy transferred between systems at different temperatures. (Objects at different temperature transfer thermal energy.) The colder object becomes hotter and the hotter becomes colder.

Thermodynamics and temperature

The study of systems in which thermal properties change is known as *thermodynamics*. Perhaps the gentle reader has already heard of the three laws of thermodynamics, paraphrased as

1. "Energy is conserved."

2. “You can’t win, you can only lose or break even.”

3. “You can’t even break even.”

To that, physicists have added a “zeroth law,” which describes how temperature is defined.

Suppose there are three objects, A, B, and C. The objects A and B are reservoirs and are in thermal equilibrium, which means that when they are in contact there is no net exchange of thermal energy between them. The two objects are now separated. If object C is brought up and found to be in thermal equilibrium with object A, say, then if objects B and C are placed in contact, it will be found that they are also in equilibrium with one another.

A device that measures temperature is known as a *thermometer*. Temperatures are measured by allowing the thermometer and the system to come to thermal equilibrium. Two objects are said to be in a state of *thermal equilibrium* if there is no net interchange of thermal energy between those objects when they are brought into thermal contact. The measurement of the temperature of the thermometer therefore also gives a measurement of the temperature of the system. In this setup, the object C acts as the thermometer.

A real thermometer (like object C) is originally calibrated by placing it in equilibrium with various objects at various known temperatures. The temperatures are marked in some way (most thermometers we are acquainted with have a mercury or alcohol column whose height is different at different temperatures, and the heights corresponding to various know temperatures are marked). Temperature is measured by putting the calibrated thermometer together with, say, object B and waiting for equilibrium to be established.

Then objects B and C are in thermal equilibrium and the calibrated reading of the temperature may be read off.

We now define the property of thermal systems that determines whether or not they are in thermal equilibrium as the temperature: Two systems that are in thermal equilibrium with each other must have the same temperatures. Thermal equilibrium is the state in which there is no net interchange of thermal energy between objects. In practice, temperature is measured by assigning numbers to systems we designate as cold or hot and by using thermal equilibrium.

The everyday scale of temperature is the Celsius scale, named for Swedish astronomer Anders Celsius (1701-1744), who designed the first temperature scale separated by one hundred degrees of temperature in 1742. As defined today, the Celsius temperature scale has its zero at the triple point of water (where water, ice, and water vapor are at equilibrium in a vacuum), a temperature negligibly different from the freezing point of water on Earth’s surface, and sets 100 °C as the boiling temperature of water at sea level. A degree Celsius (°C) is one-one hundredth of the interval between these two points. In this Celsius scale, ice melts at 0 °C, a cool day might have a temperature of 10 °C, room temperature is about 20 °C, a heat wave would have temperatures around 30 to 40 °C, and human body temperature is 37 °C (skin temperature is about 35 °C).

The *absolute temperature scale,* or Kelvin scale, is named for William Thomson, Lord Kelvin (1824-1907), who contributed mightily to the understanding of thermal systems. He was the first person to realize that there is an absolute minimum temperature at -273 °C, which he proposed in 1851. The kelvin (K) is equal in size to the degree Celsius. There is no “degree” associated with the name of the unit in the Kelvin scale. The zero of the absolute scale, absolute zero, is at 0 K = -273.15 °C. Thus, 0 °C is at a temperature of 273.15 K.

Heat and thermal energy

The word *heat* refers to energy in transit between objects at two different temperatures. Heat is not a separate form of energy, but an artifact of the transfer of energy to an object by virtue of a temperature difference.

No object has a “heat content,” as was first shown by the American inventor Benjamin Thompson (1753-1814), also known as Count Rumford, in 1798. During this period, he was arms maker for the King of Bavaria. He did an experiment in which he had workers drill out a cannon bore, which they did by turning a large drill into the solid iron cannon; the bore boiled cooling water as long as the drill was turned. The amount of energy to boil water that could come off the cannon was essentially infinite; it didn’t come from the cannon itself, but rather from the work the drill did.

An object may, however, be assigned a *thermal energy*, just as it can be assigned a potential energy. The unit of thermal energy and of heat in the International System is the joule (J). The units of energy are consistent across all uses and always given in terms of joules. This is a consequence of the identification of thermal energy as a form of energy. (This unit replaces old units of energy for virtually all uses. This means that in science it is no longer acceptable to use the calorie or kilocalorie (food calorie); all energies are measured in joules.) Thermal energy is the total energy of motion of all the molecules in an object.

There is evidence of the molecular basis of matter in *Brownian motion.* Grains of pollen in water, when observed under a microscope, seem to jitter around with a life of their own. They jitter because they are at a very high temperature compared to the lowest temperature possible, absolute zero. Molecules have thermal energy. The amount of energy is reflected in their kinetic energies. On average, the higher the temperature, the faster the molecules of the matter move. In solids, this is just a bouncing motion, since the atoms are fixed into place by interatomic "springs". In liquids, the same result is found. The tiny unseeable water molecules go flying around. Sometimes they hit the pollen molecule so hard that it bounces visibly away as a result of the collision. Thus, Brownian motion is evidence for the existence of unseen molecules that bang around hitting other molecules. This explanation for Brownian motion was first offered by Albert Einstein in a famous paper from the year 1905.

The molecules in air do a similar thing. The molecules are always moving around. The only way they interact is by bumping into one another. It is clear that, even if all molecules had the same speed at an initial instant, soon thereafter, they would be hitting other molecules in direct collisions, in glancing collisions, and so on. The molecules would soon have a range of speeds. There is a most probable speed, which depends on temperature, but molecules may have many speeds. Gas molecules move at average speeds of kilometers per second.

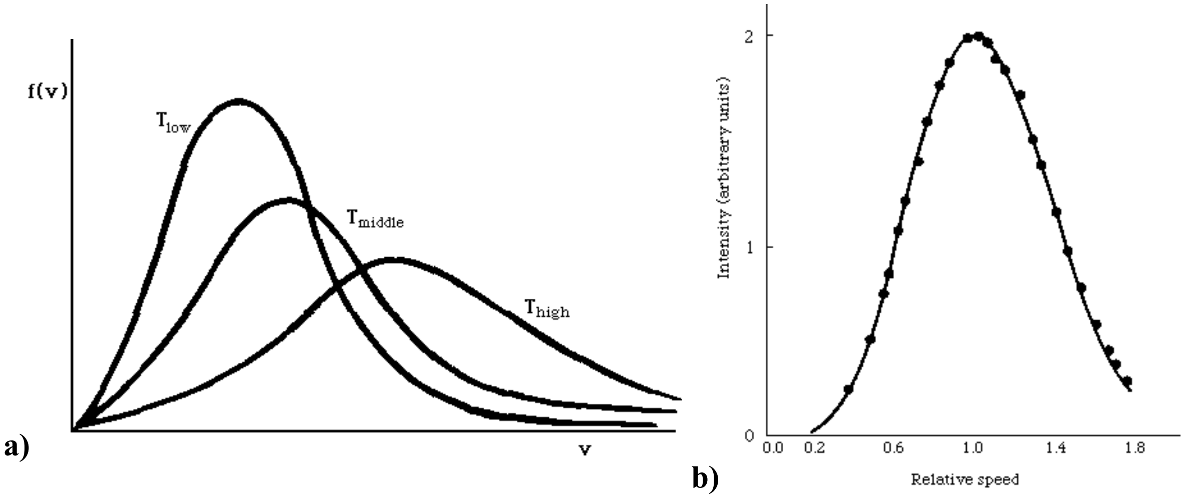

Fig. E07.2.1 The Maxwell-Boltzmann distribution for several temperatures. b) Actual data (•) from a gas (thallium vapor) at 870 K compared to the Maxwell-Boltzmann prediction (line).

James Clerk Maxwell (1831-1879) in 1859 derived the distribution of molecular speeds that corresponded to an ideal gas, and Ludwig Boltzmann in 1871 extended this to the distribution of energies in arbitrary systems. As a result it is now called the *Maxwell-Boltzmann distribution*. The picture above shows the Maxwell-Boltzmann distribution function, which gives the relative number of particles in some speed range. Notice that the distribution begins at zero for zero speed and rises to a maximum, then falls for higher speeds.

Molecules are small: The typical size of a molecule is 10^{-10} m. To get an idea how small this is, a small plastic 35-mm film canister holds about 10^{25} molecules of water, a very large number. The US national debt is about $5 trillion. If for each dollar of national debt, we had an amount equal to the national debt, we would have 2.5×10^{25} dollars. There are that many water molecules in two 35 mm film canisters! Put another way, 10^{25} seconds would be 20 million ages of the universe.

We can't see these small objects, but we can see their effects, as in Brownian motion. It is no surprise that we can't see the molecules moving, they are so small. But they do move and their motion produces thermal energy. The pictures above indicate that, while we can't know what any individual molecule is doing, the molecules trade their energy with one another and do not lose it. This energy content is the thermal energy.

The amount of thermal energy, denoted ΔQ, transferred as heat between two objects of different temperature depends on the difference in the objects' temperature, ΔT. More thermal energy can be transferred between two objects if the temperature difference between them is greater than between two other objects for which the temperature difference is smaller.

Generally (but not always), an object experiencing a transfer of thermal energy that increases that object's energy will experience a rise in temperature. Conversely, most objects transferring away thermal energy will undergo a decrease in temperature. If thermal energy is gained by an object, ΔQ for that object is positive, and its temperature increases. If thermal energy is lost by an object, ΔQ for that object is negative, and its temperature decreases. In general (but not always), the greater the transfer of thermal energy to or from an object, the greater the change in that object's temperature. The exception referred to above occurs if the object is in the process of changing from a solid to a liquid (or vice versa) or a liquid to a gas (or vice versa). Thermal energy transferred to or from an object undergoing one of these changes doesn't result in an increase or decrease in temperature.

The reason the object does not change temperature is that the energy is going into changing the potential energy of individual molecules of material, releasing them from bonds or creating bonds. This is a change in the potential energy of the molecules of matter. To take this behavior into account, physicists have invented the term *internal energy* to refer to both the thermal energy and the potential energy of the molecules of a material. This assures everyone that energy is conserved in these processes (including phase changes).

In sum, thermal energy refers to the kinetic energy of the atoms and/or molecules in matter. Internal energy refers to the total kinetic and potential energy in a material. Heat is thermal energy that is being transferred between two objects at different temperatures. There is no such thing as "heat energy"!

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