PhyzGuide: Compleat Guide to Heat

WHY BOTHER: WHAT'S SO HOT ABOUT HEAT?

Without heat, you would die. So heat is an important quantity. Without an understanding of heat, life would be pretty miserable. Consider a few of the conveniences made possible by the application of the concept of heat: home heating and cooling, internal combustion (what makes automobiles go, at least for now), home electricity, anything made of any kind of metal or plastic (including nails that hold together things made of wood, like houses and schools). I'm leaving out many things, but I hope you can see the relevance of understanding heat.

WHAT IT IS AND WHAT IT ISN'T

Heat is not internal energy. What is internal energy? **Internal energy** is the total energy possessed by the particles in a sample. This includes the total kinetic energy due to the random motion of the particles—translational, rotational, and vibrational—as well as the potential energy the particles have due to the positions they have relative to each other. Like mass, volume, and thus density, internal energy is a quantity a body can have. The symbol for internal energy is U, and it is measured in joules.

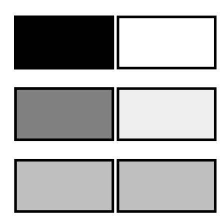
Heat is the internal energy that is *transferred* from a hotter object to a colder object. Like force, heat is not something that can be possessed by a body. Rather, it is energy in transit between objects. When an object gains internal energy as the result of a heating process, its temperature tends to rise. Likewise, when an object loses internal energy as the result of a heating process, its temperature tends to fall. I use the word "tends" because these are not the only results possible (stay tuned). But again, keep in mind that it is incorrect to think of an object as *possessing* heat. Take a moment to digest that, because it's tough to make that a part of your working knowledge. (Many textbooks even get this one wrong!) The symbol for heat is Q, and it is measured in joules.

Heat is not temperature. **Temperature** can be thought of as the average kinetic energy of the random translational motion of the particles in a sample. The symbol for temperature is T, and it is measured in kelvins.

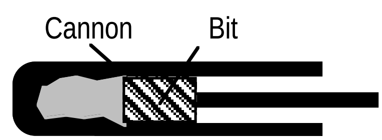
If you understand these definitions, you will never again say something like, "It's hot because it has lots of heat." Hot refers to something with a relatively high temperature, but heat is not something that can be possessed. Internal energy can be possessed. So you may say, "It's hot because it has a lot of internal energy."

THE HISTORY OF HEAT: WHERE THE CALORIE COMES FROM

Long ago, the quantity we now call internal energy was thought to be an invisible, massless fluid called caloric. **Caloric** was the fluid of heat. Hot objects possessed excess caloric, cold objects lacked it. If a hot object and a cold object were placed in contact, the caloric fluid would flow from the region of abundance to the region of deficit. Caloric theory made good sense and was the product of intelligent examination of nature. But like many scientific models, it was replaced by a superior model: kinetic theory.



The invisible caloric fluid flows from hot objects to cold objects in the caloric theory of heat.



The brass cannon is spun around a fixed bit. A sharp blade scrapes off MORE material than a dull blade, yet generates LESS heat in the process.

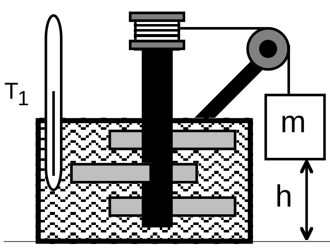
Caloric's downfall began in the eighteenth century, initiated by a carousing, womanizing American Tory named Benjamin Thompson. After fleeing the colonies, Thompson landed a job in the Bavarian army. His job was to bore cannons for the army. So he told the cannons about the time he was lost in the jungle... er, no—he was in charge of drilling out the centers of cannons. While boring cannons, Thompson found not only that high temperatures were produced in the process, but that the temperature produced was *inversely proportional* to the amount of scrapings. Caloric theory predicted that higher temperatures would be generated if more scrapings were produced. Yet a dull bit produced few scrapings and very high temperatures, while a sharp bit produced a lot of scrapings without raising the temperature as much.

The fundamental meaning of Thompson's findings was that *the generation of a high temperature is associated with mechanical work:* part of the energy that went into turning the cannon about the bit "turned into" internal energy. Dull bits resulted in more internal energy because high friction forces meant more work had to be put in to turn the cannons. Scientists were left uneasy and tried not to think about Thompson's findings. (Thompson was later bestowed with the title of Count Rumford.)

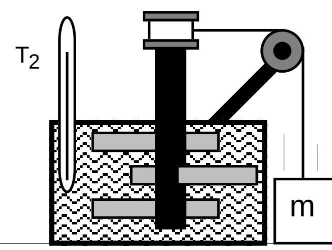
Caloric theory was finally put to rest by the findings of James Prescott Joule and subsequent work in heat theory and conservation of energy. But while caloric theory reigned, a unit of heat called the calorie was developed. The calorie is still in use today. One calorie of heat will raise the temperature of one gram of water by one Celsius degree. A food calorie, the Calorie, is 1000 calories or 1 kilocalorie.

Joule found a specific relation between mechanical energy and temperature. His experimental apparatus was a weight attached to a paddlewheel which was immersed in water. As the weight fell due to gravity, it turned the paddlewheel in the water. Joule noticed that this churning increased the temperature of the water. The increase in temperature of the water was directly proportional to the initial gravitational potential energy of the weight. This finding established kinetic theory as the superior model for understanding heat, internal energy, and temperature.

Actually, it would be more correct to say it *re-established* kinetic theory. Just as the ancient Greek knowledge of the Earth's sphericity was lost somewhere in the middle ages and re-established with the voyages of Renaissance explorers, so too the kinetic theory of heat held by Renaissance scientists was supplanted by caloric theory in the Age of Reason only to be re-established after the work of Rumford and Joule.



Initially, the mass m has gravitational potential energy (*PE=mgh*) and the water is at some temperature T_1



After the mass falls, it has given up its potential energy, and the temperature of the water has increased to T_2

CONSERVATION OF ENERGY IN JOULE'S PADDLECUP

Work is done to raise the weight. The work increases the potential energy of the weight. When the weight is released, it loses its potential energy along its descent. But that energy is transformed to the kinetic energy of the paddlewheel. The paddlewheel eventually stops. The weight no longer has potential energy and the paddlewheel no longer has kinetic energy. The energy was given to the water molecules. The increase in their random motion can be measured as an increase in temperature. Energy is conserved.

THE NITTY AND THE GRITTY: UNITS OF HEAT

Since heat is associated with energy, the units of heat are units of energy. In the SI system, the unit is the joule (named after guess who?). However, other units are also commonly used. Here is a partial listing.

- A **joule** is the SI unit of energy and therefore the SI unit of heat. [J]
- A **calorie** (from "caloric") is the amount of heat needed to raise the temperature of 1g of water by 1°C (specifically from 14.5°C to 15.5°C). [cal]
- A **Calorie** (with a capital "C") is one kilocalorie = 1000 calories ≡ amount of heat needed to raise the temperature of one kilogram of water by 1°C (specifically from 14.5°C to 15.5°C). This is a "food calorie." [Cal]
- A **British thermal unit** is the amount of heat needed to raise one pound of water one Fahrenheit degree (from 63°F to 64°F). [Btu]

1 cal = 4.186 J = 0.004 Btu 1 kcal = 4186 J 1 Btu = 778 ft·lb = 252 cal = 0.252kcal