Heat Is Not What the Object Contains

A common student answer

A student writes that the hotter cup "has more heat" than the cooler one. It is an easy line to mark down and move past. But the looseness is not really in the word; it sits in a picture of heat as something a body holds — a quantity that can be poured in, kept inside, and carried about. The student is not being careless with vocabulary. They are using a model. Naming the model rather than the slip gives a teacher a sharper way to hear what the student is claiming, and a clearer target to correct. It is worth knowing where that model comes from, because for a long time it was the considered view of serious scientists.

Heat is not the same as temperature

Begin with the part of the model that is easiest to dislodge: the sense that "hot" and "amount of heat" are one and the same.

Put a small beaker and a large beaker of water on the bench, both filled from the same tap. A thermometer reads the same in each. Now warm them over identical flames until each has risen by ten degrees. The large beaker takes longer, and requires a greater transfer of energy from the flame. The two begin at the same temperature and undergo the same temperature rise, yet the energy transferred is plainly different.

A sharper version of the same point: take ice at its melting temperature and warm it gently. While it melts, the thermometer holds steady. Energy is transferred to the ice the whole time, but the reading does not move until the last of it is gone.

So the thermometer does not report the amount of energy involved. It reports a state — how hot the water is, not how much energy it has. The relevant energy here is internal energy, and that depends on more than temperature: on how much substance is present, what the substance is, and whether it is solid, liquid, or gas. For the same water in the same state, the larger beaker has the greater internal energy. Set different materials side by side and the comparison is no longer so simple.

The older view: caloric

The student's "heat flows in and stays there" is an old idea. For much of the eighteenth and early nineteenth centuries, many scientists understood heat as a kind of fluid — invisible and weightless, present in greater quantity in a warmer body, passing of its own accord from the warmer to the cooler until the two evened out. A larger body held more of it. It could drive a solid to melt or a liquid to boil. And, grouped as it was with the chemical elements, it could be neither created nor destroyed. This fluid was called caloric.

This was not a foolish idea. It accounted for the way warmth spreads and equalises, for the extra warming a larger object needs, for melting and for boiling. For the ordinary run of heating and cooling, it worked.

When a student says that heat flows into an object and is held there, the error is an intelligible one — it is the caloric picture.

The problem of friction

The fluid picture began to strain when people looked closely at friction. In the boring of cannon, the metal grew warm and stayed warm for as long as the boring continued; with the work kept up long enough, the surrounding water could be brought to the boil. If warmth were a finite store held inside the metal, there ought to be a limit to how much could be drawn from it. There seemed to be none. As long as mechanical effort was supplied, the warming went on.

At first sight, this looked as though the rubbing was making heat. The careful reading is different: the work done against friction was raising the internal energy of the metal and the water. Nothing was being let out of a store.

Joule’s paddle wheel

The decisive work was done in the 1840s by James Joule, in a long series of painstaking experiments. The clearest of them is also the simplest. A falling weight is connected by cords to a set of paddles inside an insulated vessel of water; as the weight descends, the paddles turn and stir the water, and the water grows slightly warmer. The rise is small — Joule needed a finely divided thermometer and great care with insulation, and he corrected for what little warmth escaped. Run with different weights and different liquids, the result came out the same: a fixed relation between the work done by the falling weight and the rise in temperature, which Joule called the mechanical equivalent of heat.

It is worth being exact about what this experiment shows, because it is often summarised as “work converted into heat,” and that summary misleads. The falling weight does work on the water-and-paddle system. The measured rise in temperature records an increase in the system’s internal energy. There is no hotter body to transfer energy into the water by heating; the work raises its internal energy directly.

Heat, work, and internal energy

What Joule’s work, and the long argument around it, eventually settled was a precise way of speaking about thermal things. Four terms carry the load, and keeping them apart removes most of the confusion.

Temperature is a state: how hot a body is, what a thermometer reads. Internal energy is a system property, depending on amount, material, temperature and state. Heat is energy transferred from one body to another because of a temperature difference between them. Work is energy transferred by other means — by a force acting through a distance, as the falling weight acts on the paddles.

Heat and work, then, are ways energy crosses the boundary of a system; in the cases discussed here, the system’s internal energy is what changes. And heating is not the only route to a higher internal energy: doing work on a body raises it just as well, which is exactly what the paddle wheel shows.

Return to the cup. What a warm cup has is internal energy; "heat" refers to something different — energy in transit between bodies that differ in temperature. The mistake is to treat it as a quantity the cup keeps. A student who writes that the cup "has more heat" can be led to "has more internal energy."

What comes next

Once heat is understood as a transfer rather than a stored fluid, and once doing work and heating are seen as two entries in a single energy account, a sharper question comes into view. If energy is conserved, and heat is energy transferred across a boundary because of a temperature difference, why can a cyclic heat engine never turn all the energy transferred in by heating into useful work? Some of it must always be passed on to a colder place. That constraint, and the reason for it, is the subject of the next article.

Sources

Paul Sen, Einstein's Fridge: How the Difference Between Hot and Cold Explains the Universe (Scribner, 2021).

Arnold B. Arons, Teaching Introductory Physics (Wiley, 1997) — Ch. 5, esp. §§5.5 and 5.10.