Energy vs. temperature vs. heat:

Using negative heat capacities to clarify the distinctions

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U, Q, and T

Internal energy (U): Energy associated with all the microscopic components of a system, excluding bulk motion of the system as a whole.

Heat (Q): Spontaneous transfer of energy to a system due to a temperature difference, carried through microscopic mechanisms.

Temperature (T): A measure of the tendency of a system to spontaneously give energy to its surroundings. (Thermal equilibrium between two systems = No spontaneous energy flow.)

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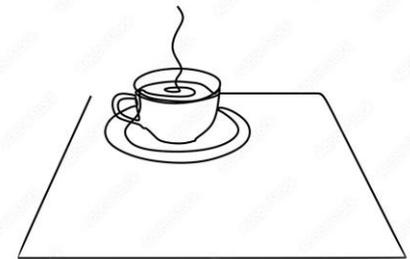
Relations between U, Q, and T

Students in an introductory thermodynamics course are exposed to an array of equations relating these quantities:

$$\Delta U = Q + W \qquad Q = C\,\Delta T \qquad Q = m\,c\,\Delta T$$

$$Q_V = n\,C_V \Delta T \qquad Q_P = n\,C_P\,\Delta T \qquad \Delta U = n\,C_V \Delta T$$

Most problems they encounter about these quantities can be solved by applying these equations, creating an "illusion of understanding".

The finer conceptual distinctions seem irrelevant when, after all, these equations seem to say that U, Q, and T "go together". (Just different ways of talking about how hot something gets, duh!).

"Explain your reasoning" conceptual questions in exams often show that all these concepts remain conflated/confused, even if the equations can be applied correctly.

Wealth-generosity analogy for U and T

Illuminating analogy (from Schroeder's Introduction to Thermal Physics):

"Temperature is to energy as generosity is to wealth"

Temperature is the tendency to spontaneously give away energy, not energy in itself.

Most people are careful with money if they have little, and become happier to give it away the more they have.

In the same way, most systems have more temperature the more energy they have. For ideal gases, this results in the simple proportionality formula that students are familiar with.

Heat Capacity (defined as $C = Q/\Delta T$) is **positive.** If the system gains energy through heat (all other things equal) the temperature will increase.

Negative heat capacities?

Distinguishing clearly between energy and temperature opens the possibility of a physical system for which energy and temperature are **anti-correlated** rather than correlated.

For such a system, spontaneously **giving away** energy (Q < 0) would result in an **increase** in temperature (ΔT > 0). A negative heat capacity!

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Analogy: a miserly rich person that becomes more carefree the less money they have.

Is there a simple example of such a system, that can be explained in a few minutes, and at the level appropriate for intro physics students?
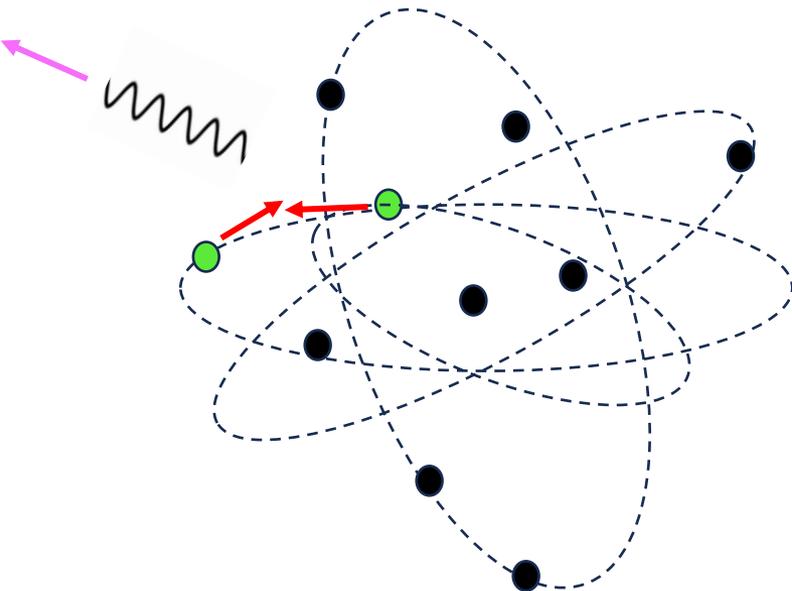

Disneyplus.com

Example: Interstellar gas cloud

Collection of atoms/molecules floating in space, bound by their collective gravity.

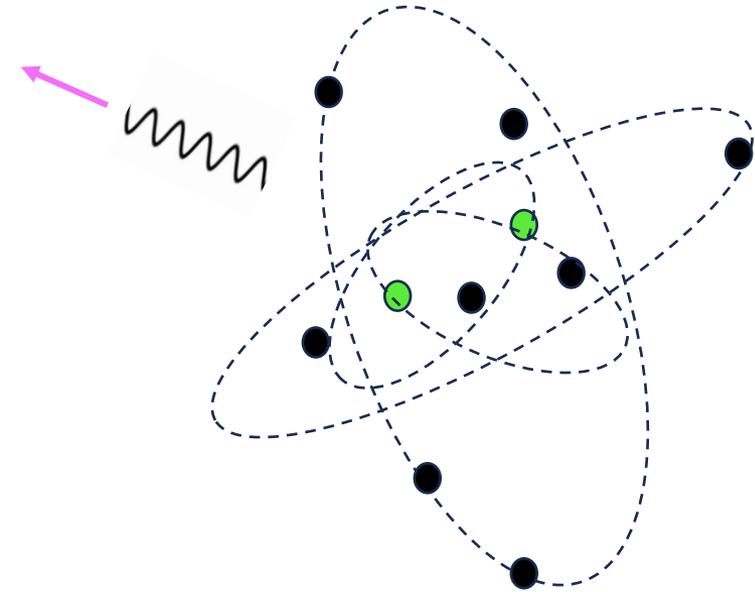Each particle is in orbit around the collective center of mass.

Occasionally, two particles randomly collide.

Collisions are **inelastic**: particles decrease their overall energy.

Energy lost is emitted as radiation (leaving the system).
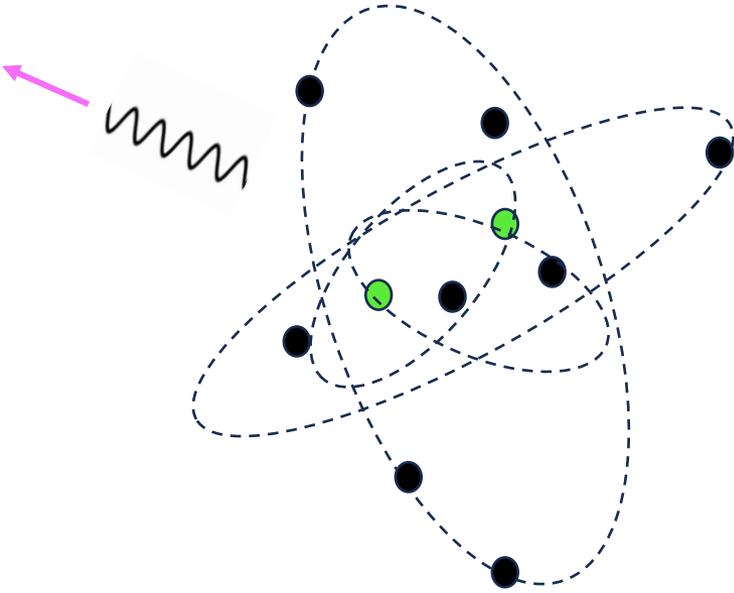
Interstellar gas cloud (cont.)

After colliding and losing energy, particles settle into orbits closer to the center, deeper into the "potential well".

The system has **lost energy**.

What happened to its temperature?

Interstellar gas cloud (cont.)

After colliding and losing energy, particles settle into orbits closer to the center, deeper into the "potential well".

The system has **lost energy**.

What happened to its temperature?

As particles settle into orbits closer to the center, they have **more** chances of randomly colliding.

Orbits closer to the center have also higher speeds, which means collisions emit more radiation.

The tendency to radiate away energy to the empty space surrounding the cloud (i.e., the temperature) has **increased.**

Interstellar gas cloud (cont.)

In conclusion: as the cloud spontaneously radiates energy (Q < 0) and decreases its overall energy (ΔU < 0), its temperature increases (ΔT > 0)!

Negative heat capacity.

Not a purely academic or theoretical example! **This is how stars are born.**

Straightforward, accessible, intuitive example highlighting the conceptual distinction between temperature and energy.

No need to invoke the virial theorem or other advanced notions!

Do students care?

Included 10-15 minutes of class with a version of the material above, as part of PHYS 204 (General Physics II) at Harford Community College.

Standard calculus-based course covering thermodynamics, electricity and magnetism. Most students take it as part of an engineering career path.

<u>Anonymous</u> survey completed online for extra credit asked students:

Slides 25-29 in Lecture 6 (describing an interstellar gas cloud as an example of a system in which temperature and energy are anti-correlated rather than correlated) can be considered a "bonus" topic for the course, with the purpose of clarifying the interrelations and distinctions between temperature and energy by going beyond the simple systems we dedicate most attention to (such as the ideal gas).

1 - How interesting/engaging did you find this topic?

2 - Would you have preferred if this amount of class time had been dedicated instead to doing an additional practice problem on one of the other topics covered?
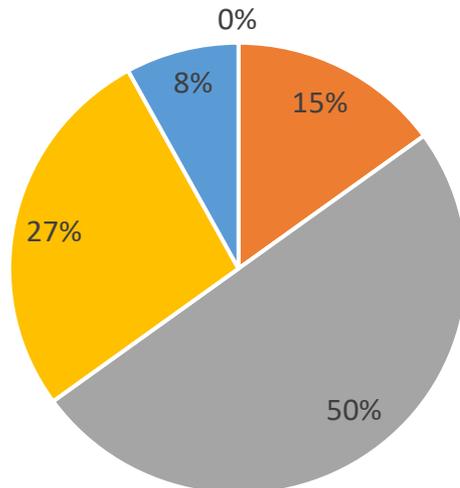
Student response

Question 1:
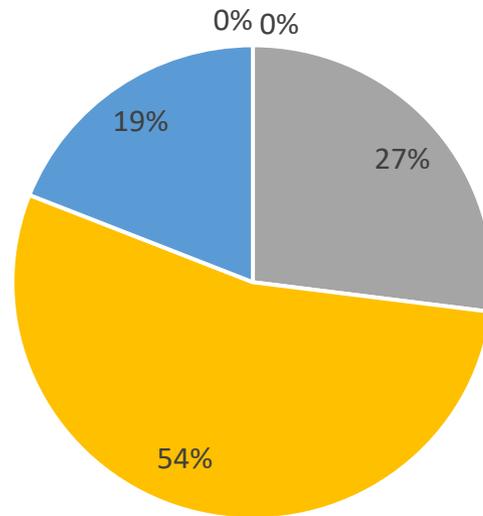
- ■ Substantially less interesting than the average course topic
- ■ A bit less interesting than the average course topic
- ■ About as interesting than the average course topic
- ■ A bit more interesting than the average course topic
- ■ Substantially more interesting than the average course topic

Question 2:

- ■ Strong preference for this amount of class time to be dedicated to an additional practice problem.
- ■ Weak preference for this amount of class time to be dedicated to an additional practice problem.
- ■ Roughly indifferent between this topic and an additional practice problem.
- ■ Weak preference for this topic over an additional practice problem.
- ■ Strong preference for this topic over an additional practice problem.

Total number of responses: 26.

Extra discussion: Equilibrium vs. disequilibrium

Usually, when two systems can freely exchange energy, energy flowing spontaneously from the higher T to the lower T one leads towards **thermal equilibrium.**

Students might assume that this is part of the definition of temperature, but it is not! Only true with positive heat capacities!

With negative heat capacities, the temperature difference would spontaneously become larger and larger rather than smaller and smaller.

Natural tendency is to **disequilibrium**!

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This explains structure formation (stars/galaxies/clusters) after the Big Bang!

See e.g. Wallace (arxiv:0907.0659, 2009) for a lucid discussion.

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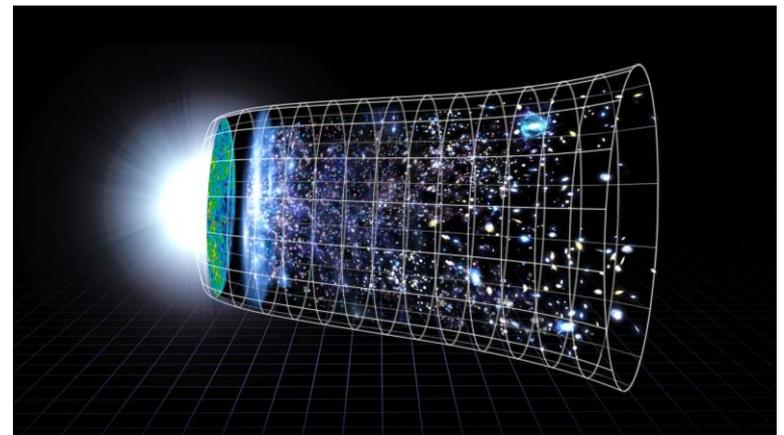
Summary

- A self-gravitational gas cloud is a conceptually simple example of a physical system with negative heat capacity.

- Dedicating a small amount of class time to this discussion can highlight the conceptual distinctions between temperature, heat, and internal energy.

- According to an (unscientific) student response survey, students appreciate this inclusion and would not have preferred additional practice problems.

- With more class time, the discussion could be extended to include the overall tendency to disequilibrium in gravitational systems and its importance for the evolution of the Universe.