

## Answers to Physics 176 One-Minute Questionnaires

Lecture date: February 1, 2011

### **Why do scientists in different fields argue over the sign of work and heat?**

“Argue” is too strong a word. I don’t know the history of why different conventions or choices of notation have been in thermodynamics or in other fields. Since the choices of sign for  $W$  and  $Q$  are really quite arbitrary, it is no surprise that different people have made different choices and then it is a political game of which researcher or journal or country has the most clout scientifically. And then there are communities like chemists, engineers, and physicists who largely don’t coordinate their educational efforts and so differences are maintained.

### **I am still confused about the distinction between heat and work. For example, if I light a candle below some container of gas, am I doing work on or adding heat to the system?**

Heat is a transfer of energy caused by a temperature difference between two objects. If you light a candle below a container of gas, you are transferring heat energy to the gas in two ways: by convection of hot air that rises above the candle flame and comes in contact with the gas container; and by radiation, the light from the hotter candle strikes the gas container and raises its temperature. (The gas container also radiates light in the form of blackbody radiation and so transfers some heat back to the candle via radiation.)

The hot air rising from the candle can also do work, for example it can flow past a toy pinwheel and cause the pinwheel to spin. (This increases the kinetic energy of the pinwheel.) But if the hot rising air simply comes in contact with a container, it does no work on the container and so transfers energy only as heat.

### **I’m still confused about adiabatic processes, and how you begin with isothermal curves. Could you explain precisely why you have to begin with isothermal curves when explaining adiabatic processes?**

A related question was “Would you explain again why the adiabatic curve has to lie above an isothermal curve?”

Sorry if this was confusing.

There was actually no need to relate the discussion of an adiabatic process to isothermal curves in the  $PV$  plane, all of the insights can be worked out directly from the key formulas that  $V^\gamma P = \text{constant}$  and  $T^{f/2}V = \text{constant}$  for an adiabatic process.

What I was describing in lecture was a pedagogical insight about why, during compression, an adiabatic curve must lie above an isothermal curve, when both processes start at the same initial point  $(V_0, P_0)$  in the  $PV$  plane. Schroeder gives the same argument on page 25, see Figure 1.12 of the text. The idea is that you can think of the positive quadrant of the  $PV$  plane (where  $P > 0$  and  $V > 0$  as completely filled by adjacent constant-temperature hyperbola curves  $P = [NkT]/V$ . If you start at some initial point  $(V_0, P_0)$  and follow a process for which the temperature increases (let's say over a tiny change  $\Delta V$  in volume), then the curve you are following must rise above the constant temperature curve that passes through the point  $(V_0, P_0)$ . Similarly, if you make a small change in  $\Delta V$  that causes the temperature to drop, you must be following a curve that lies below the constant-temperature hyperbola that passes through your initial point. From this simple observation, you can get some intuition about what the shape of the curve must be, e.g., that adiabatic compression curves have to rise faster than (lie above) isothermal compression curves.

That adiabatic compression curves lie above isothermal ones is an insight perhaps more useful for engineers, it tells us that we can transfer more energy to a gas via an adiabatic compression and we can get more work out of a gas by an isothermal expansion (which always lies above an adiabatic expansion curve starting at the same location). In practice, no one bothers with isothermal processes because they are too slow since you have to change the system in tiny steps, with long waits between steps (long compared to a thermal relaxation time) to keep the temperature constant.

### **If equipartition is wrong, why do we keep using it?**

The world is really hard to understand and so it is useful to keep a variety of simple models at your finger's tips to provide some intuition about what is going on. Many models, although wrong, often have some useful truth in them or invoke a helpful insight and so are worth keeping.

So although equipartition is wrong, it is simple and turns out to give the right magnitude of the heat capacity  $C$  (of order the gas constant  $R$  for a mole of material) and it helps us to appreciate why the thermal energy  $kT$  seems to be so important. And it is correct in the case of considering the

thermal energy associated with the center of mass of a molecule, one gets  $(3/2)kT$  for liquids as well as for gases with polyatomic molecules.

Similarly, high school chemistry and physics books still teach the Bohr model of the hydrogen atom even though we have known since about 1920 that the Bohr model is conceptually flawed and just plain wrong. (As one example, an electron orbiting a proton must generate a circular current which in turn must generate a magnetic moment, but experiments showed long ago that hydrogen atoms do not have an orbital magnetic moment in their ground state.) Yet the Bohr model provides a simple intuitive picture, links classical physics to quantum phenomena, and gives the correct hydrogen quantum levels with a modest calculation. It is still useful to know the Bohr model long after you have learned to solve the more complicated and less intuitive Schrodinger equation.

If you look back at your physics education, you will see that it consists mainly of first learning wrong simple models and then correcting that in upper-level course with more complicated (but still partially wrong) models. Thus the Schrodinger equation is a giant improvement towards understanding atomic and molecular structure but fails when energies of particles become comparable to their rest mass or when photons are involved.

**What's the quantum mechanical reason that equipartition breaks down?**

We will discuss this in detail in class. I can tell you when equipartition breaks down and quantum mechanics is needed, it is when the thermal energy  $kT$  becomes comparable to or smaller than the typical spacing  $\Delta E$  between energy levels of the system of interest. Why and how it breaks down requires specific calculations which you will soon learn how to do.

**If the definition of an adiabatic process is that there's no heat transfer, how come there's a temperature change?**

Conservation of energy in the form  $\Delta U = W + Q$  says that the internal energy  $U$  of a system can change in two ways, by the transfer of energy via heat  $Q$  or by the transfer of energy via work  $W$ . In an adiabatic process,  $Q = 0$  (no heat is exchanged) but that still allows the internal energy to increase or decrease via changes in  $W$ . But since  $U = Nf(kT/2)$  by the equipartition theorem, changes in  $U$  correspond to a change in temperature  $T$ . So you can increase the temperature of a gas by doing work on a gas (say compressing it) even though no heat is exchanged with the surroundings.

**Why does the experimental  $C_V$  curve for  $H_2$  cut off at great enough temperatures, before we can approach  $(7/2)R$ ?**

Diatomic hydrogen  $H_2$  starts to disassociate into hydrogen atoms at temperatures above about 3,000 K so experimental data can't be obtained beyond that range.

**What order of magnitude of  $T$  is required for  $kT > 2mc^2$ ? How can particles be created?**

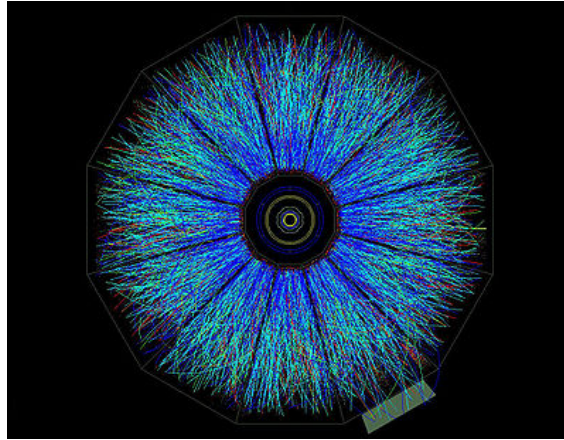
You know enough to do this calculation. The lowest mass stable particles are electrons (let's ignore neutrinos, which are now known to have a tiny mass but of an unknown value). Since the mass of an electron is  $10^{-30}$  kg to the nearest power of ten, particle-antiparticle creation starts to be substantial for a gas (plasma) of electrons and protons when the thermal energy  $kT$  is of order the electron rest mass energy  $mc^2$ , that is when the temperature exceeds about

$$T > \frac{m_e c^2}{k} \approx \frac{10^{-30} \text{ kg} \times (3 \times 10^8 \text{ m/s})^2}{10^{-23} \text{ J/K}} \approx 10^{10} \text{ K}, \quad (1)$$

to the nearest power of ten. (You should get in the habit of always giving the units of numbers in a scientific calculation, helps to avoid errors caused by inconsistent units.)

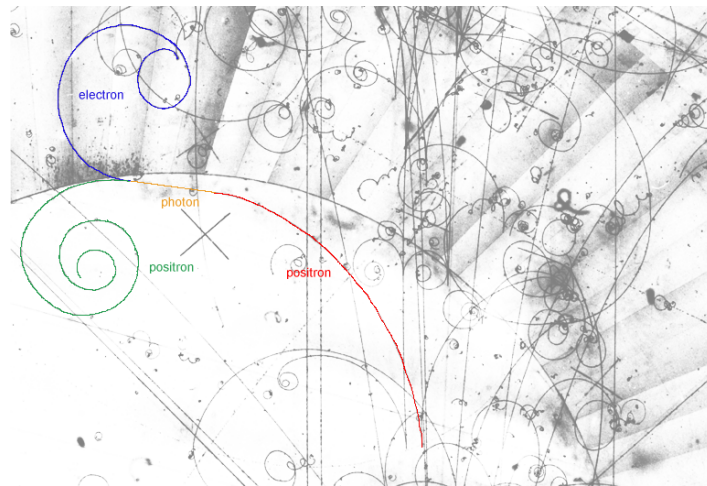
This temperature existed in the early hot universe when the universe was filled with nearly exactly equal amounts of matter and antimatter, constantly annihilating and reappearing. The highest natural temperatures that I know of currently in the universe occur in the centers of large-mass stars where fusion reactions raise the temperature to over  $10^9$  K. Nearly as hot are the accretion disks around black holes and neutron stars which can reach temperatures of about  $10^8$  K in extreme cases.

The human race can briefly produce plasmas with this temperature by colliding two high-energy gold nuclei, e.g., using the Large Hadron Collider. The collision produces a tiny short-lived plasma fireball consisting of many new particles that emerge from the energy, see this picture



and read the related Wikipedia article “Relativistic Heavy Ion Collider”. Each of the colored “threads” is the path of one of the roughly 10,000 particles that were created out of vacuum by the collision of two gold nuclei.

As to how particles can be created: I would just say that this possibility is predicted by relativistic quantum mechanics and is observed experimentally; I don’t know of any simple intuitive picture to give you about how it occurs. (In turn, have you ever wondered where the photon comes from when an excited atom deexcites to its ground state? The photon also appears out of nowhere—it did not exist prior to the atom deexciting—and it appears in the same quantum mechanical way that particles and antiparticles appear when enough energy is available.) Here is a famous bubble chamber picture



which shows the creation of an electron (blue curve) and antiparticle positron (green curve) as a photon (red curve) scatters off an invisible nucleus. There

is a strong magnetic field perpendicular to the image which causes the particles to spiral in opposite directions but in similar ways, indicating that the particles have opposite charges but equal masses

**Adiabatic processes in quantum mechanics approximations are taken to be slow processes. Why is there a difference between the definitions?**

I don't know the history of how the word adiabatic became associated with classical mechanics, quantum mechanics, or with thermodynamics, it would be interesting for someone to track this down.

As you point out, the word has two different meanings in physics, "no transfer of heat" for thermal physics and "a slow change of a system parameter" for a classical or quantum system. A simple and famous example of a mechanical adiabatic change would be a mass swinging from a rope (a simple pendulum) such that the length of the rope is slowly shortened over time, say by pulling the rope slowly through a hole in the ceiling. This turns out to be an historically interesting theoretical problem because one is not able to calculate the lowest-order correction to the period by perturbation theory, it turns out that the solution has the form of a class of functions  $e^{-1/x}$  that have a zero Taylor series around  $x = 0$  and so small corrections can not be calculated by standard (easiest) theoretical methods. These kinds of functions turn out to be common in thermal physics, e.g., we will see many times expressions of the form  $e^{-E/(kT)}$  that have a zero Taylor series with respect to temperature  $T$  around  $T = 0$ .

**What is the reason that diamond has such an abnormally high thermal diffusivity?**

It is related to the fact that diamond is the strongest material known in that it can scratch all other substances but can not be scratched itself: carbon-carbon bonds are extremely strong for reasons that I will let the chemists explain. But the connection between bond strength and thermal diffusivity is not simple, too complicated to explain here in a useful way.

**Could you explain the methodology for counting degrees of freedom for different structures?**

I gave an explanation of this on pages 13-14 of my January 27 lecture notes, which I posted here:

with notes for other lectures. If those notes are not helpful, I would be glad to meet with you and explain this further.

**Is there an ideal brain size (for intelligent life)? It seems like a larger brain should perform better but may be inefficient at a certain point.**

I don't think we know enough about brains to pose this question in a reasonable way. From an evolutionary point of view, the brain of any animal is ideal if the animal is able to survive by using its brain to solve the usual problems of survival such as finding food, avoiding being eaten, finding a mate, and reproducing. Thus the 1 mm long nematode *C. elegans* has a nervous system consisting of exactly 302 neurons and there is a cluster of these neurons that roughly act like a brain. This worm is able to survive successfully over many generations so I would say that it has an ideal brain for its needs.

As you likely know, humans do not have the biggest brains in the animal kingdom, whales and elephants have bigger brains by mass and volume. We don't even have the biggest ratio of brain mass to body mass, which is a commonly used criterion for predicting intelligence, there are some birds like ravens that exceed our ratio (and some ravens are actually astoundingly smart, more so than cats and dogs).

The neurons in brains are expensive to maintain metabolically, e.g., in humans, a brain consumes about 20% of your daily food consumption yet constitutes less than 2% by body mass. So there can be a penalty for letting brains get too big, you need to find more food to keep the brain working. Many people have pointed out that the human race is the first species to be capable of wiping out all other species including itself (nuclear warfare, biological warfare) and that is a powerful argument that having a brain that is too big and powerful is actually dangerous.

**Are humans optimal in terms of approaching the  $kT$  limit? If so, why us? If not, what could be improved?**

Individual neurons do seem to operate optimally in that their membrane voltages are close to that allowed by equipartition, of order 50 mV in magnitude. But it is not known whether a large group of neurons, like the 100 billion neurons in an adult human brain, all work in an optimal way

from a thermodynamic point of view. There has been much recent theoretical work which suggests that optimality plays a big role in brain anatomy, e.g., neurons and groups of neurons evolve to arrange their shape, size, connections, and dynamics to so as to minimize metabolic cost while maintaining flexibility to connect to one another. Identifying optimality principles will be an especially hot field in about ten years as connectomic projects currently underway start to give us the full wiring diagrams of complete brain regions.

**Is there any physical reason why the efficiency of computers can't approach the efficiency of the brain? Or is simply that nobody's figured out how to do it yet?**

There was a related question: "Is the fact that our neurons are so thermally efficient a reason why computers likely never be as powerful/efficient as our brains?"

There is no reason why artificial computers can not approach the efficiency of biological brains, but it is clear from neurobiology why this is not going to happen soon.

One reason that brains are so powerful compared to silicon computers is that a neuron is able to connect to (share information with) as many as 50,000 other neurons in an intricate three-dimensional network. Current silicon technology can barely connect one transistor to about ten other transistors and the technology is primarily two dimensional. So biological brains, because of the way they self-assemble themselves from individual cells, are greatly more flexible and capable than silicon computers (per volume and per energy consumed). There is no reason why we can't eventually invent self-assembling silicon digital computers but that turns out to be a difficult technology to invent.

At a molecular level, neurons are able to change dynamically the strength and properties of connections with other neurons by synthesizing new proteins and destroying existing ones. This is another capability that silicon computers lack, they can not modify their connections after being constructed and this is perhaps one reason why brains can learn rather easily while computers so far can not.

**What determines the timescale of the lifespan of organisms?**

I don't know. I know some timescales that are relevant, e.g., bacteria have to live a bit longer than it takes time to replicate its DNA (say 30 minutes)



but I don't know why it takes 30 minutes to replicate a bacterial DNA. Some aspects of lifespan are determined by non-physical reasons such as evolution, e.g., biologists believe that mammals (and other species) have become programmed by evolution to become old and die so that older animals don't compete with young animals for food and mates. But why humans live 60-70 years and flies live 30 days before senescence becomes fatal, I don't know.

**Describe the  $PV$  diagram of the universe.**

I don't think that this is a meaningful question. A  $PV$  diagram applies to changes in an equilibrium system whose properties can be characterized by an equilibrium pressure  $P$  and volume  $V$ . We know from observation that the entire universe is expanding (space itself is increasing in volume, something not easily understood unless you are familiar with Einstein's general relativity theory) and that the expansion is accelerating. This means that the universe is far from equilibrium and so it is not clear how to define  $P$  nor even how to define  $V$  since we don't know whether our universe contains a finite or infinite amount of space.

**Does the temperature of an object falling in vacuum change?**

Does this question relate to the PRS question asked in class, about the ball on the string that lowers its center of mass by a tiny amount as it expands?

You have to ask this question carefully to get an answer. For example, if I drop a ball on the Moon (which has no atmosphere to a good approximation), the ball will heat up slightly as it falls. The reason has to do with tidal effects: because the ball has a finite extent, gravity pulls with different strengths on different parts of the ball (which are not all the same distance from the center of the Moon) and this causes a flexing of the ball throughout its interior as it falls, and this flexing will generate some heat via friction, although only a very tiny amount of heat for a ball in a laboratory falling a meter or less in height.

In some cases, this tidal heating can be substantial. Thus you might know that the moon Europa orbiting Jupiter is believed to have a giant liquid ocean under an ice crust (and people are greatly excited to explore that ocean and see if there is any life). The ice has melted and stays melted because of tidal heating from Jupiter's strong gravitational field, a consequence of Europa's elliptical orbit. Similarly Jupiter's moon Io has frequent volcanic eruptions, generated by tidal heating and squeezing.