Answers to Physics 176 One-Minute Questionnaires

Lecture date: February 24 and March 15, 2011

Why does the term $(\partial S_R/\partial E)_{N,v}(-E_S)$ become $e^{-E_s/(Kat_R)}$ in calculating the probability for the system to be in a state with energy E_s?

Please take a look at my class lecture notes dated March 15, pages 10-12, where I hopefully answer this question to your satisfaction. If not, I will be glad to meet with you and go through the details.

In general, how does one calculate the partition function Z

You will soon see several examples for which the partition function can be evaluated in a concise mathematical form, say for the Einstein solid, the paramagnet, for an ideal gas consisting of molecules rather than atoms, and for a long polymer that assembles out of monomers.

For most cases, however, one either tries to obtain an approximation to the exact partition function or one tries to evaluate the partition function numerically. The latter is fairly easy to do even for physical systems that are much too hard to study mathematically (analytically) in a useful way.

How do we measure the mass of stars such as Betelgeuse?

The preferred way to measure the mass of some remote star is to see if it is part of a binary star system (two stars orbiting each other, most stars in the sky are members of multiple star systems, our Sun is an exception). By observing several features of the stars such as the Doppler shifts of their light with respect to Earth (which gives the component of the speeds of motion toward or away from Earth) and especially whether one star passes in front of and behind the other star, one can deduce various details of the orbits of the stars and so the relative mass of the stars.

Betelgeuse does not have an orbiting companion so instead one deduces its mass less accurately (in the 10-20% range) by using an important astronomical plot called the Hertzsprung-Russell diagram (see the Wikipedia article "Hertzsprung-Russell diagram"). This is a plot of a star's luminosity (total light power emitted per second) versus the star's surface temperature (which can be deduced from a knowledge of the distribution of light frequencies, since most stars act as ideal blackbody radiators of light). When one plots many stars on this diagram, rather remarkably the points do not lie spread out over an area but lie along a thin well-defined curve known as the "main sequence"; these are the stars that are burning hydrogen in their cores. It then turns out that the mass of a star is tightly correlated with a star's position on the main sequence (as worked out by theory and by testing the theory with binary star systems), so a measure of how bright Betelgeuse is (easy to carry out, just count photons coming out of the telescope pointed at Betelgeuse) and its surface temperature gives the approximate mass of Betelgeuse.

Why is it necessary for there to be a cold reservoir in a heat engine?

The answer is that practical engines have to be cyclic devices that return to their original state after one cycle. If you think about it, I think you will realize that cyclic devices are the only way to produce steady work over an arbitrarily long period of time (over many engine cycles) *and* have the engine be a compact object that would fit say in a car or airplane.

An example of a non-cyclic device could be letting a heavy rock attached to a rope fall down a tall cliff. The force on the rope can do work as the rock falls but the work comes to an end when the rope extends to its full length; you then have to haul the rock back up and rewind the rope to get another burst of work.

For a heat engine, you can get work by just adding heat to the engine, but at some point the engine has moved its parts as far as possible (say some piston has been pushed as far as possible) and then the work comes to an end. You then need a cold reservoir to bring the engine back to its original state, with the piston compressed and ready to push again.

Chapter 4 of Schroeder has a clear and interesting discussion of ideal and practical heat engines.

Could you explain the reservoir/engine diagram in relation to a car?

Section 4.3 of Schroeder has a good discussion of realistic engines and I would recommend that as a place to learn about more realistic heat engines.

Is superconductivity related to the third law of thermodynamics?

No, superconductivity is a novel quantum state that arises when certain systems (typically metals) are cooled sufficiently, but the mechanism that produces superconductivity does not require a system to be arbitrarily close to absolute zero, nor does it depend on the heat capacity becoming arbitrarily small at low temperatures.

Superconductivity arises from the paradoxical fact that electrons can actually have a weak attractive interaction when moving about inside a crystal lattice. Roughly, as an electron moves past some positive nucleus, the position of the nucleus is changed a little bit (it moves just a tiny bit toward the negative electron). A second electron that passes near the same nucleus can have its path changed in such a way that the second electron basically acts like it was attracted to the first electron. At sufficiently low temperatures, such that the weak energy of attraction between electrons becomes comparable to or bigger than kT, pairs of electrons can actually form weakly bound states called "Cooper pairs" and these Cooper pairs act like a new kind of particle that can condense into the novel superconducting state.

Give precise definition of extensive/intensive variables?

Not sure what to say beyond what I mentioned in lecture or what Schroeder mentions in his text. You simply increase the amount of system present (say by welding two blocks of metal together to form a single block, or by combining two cups of water together in a single container) and then ask how certain macroscopic variables have changed experimentally or conceptually. You don't really need to double the amount of system, you just have to change the amount by some constant factor λ and then see if some variable of interest also changes by a factor of λ, implying extensive behavior, or doesn't change at all, implying intensive behavior.

If one has some mathematical expression, say for $U = U(N, P, T)$ or $S = S(U, V, N)$ you can test whether the expression is extensive or intensive by replacing each extensive variable by some constant times the variable. For entropy $S = S(U, V, N)$, you would make the substitution

$$U \to \lambda U, \quad V \to \lambda V, \quad N \to \lambda N, \tag{1}$$

and, after simplifying the expression, see if the original expression $S(U, V, N)$ is now λS:

$$S(\lambda U, \lambda V, \lambda N) = \lambda S(U, V, N). \tag{2}$$

This is satisfied by the Sackur-Tetrode equation for example.

A function that satisfies this relation is called "first-order homogeneous", see the Wikipedia entry "homogeneous function" for further information. A precise mathematical definition of "extensive" variable is that the variable can be written as a first-order homogeneous function of known extensive variables. Certain variables like N and V are obviously extensive since they just involve geometric concepts (points, volume), quantities like U and S are extensive only to the extent that interacting subsystems interact weakly and there are rare cases where U and S are not extensive.

If a variable is a function of state variables, is it also a state variable?

Yes (and that would have made a good true-false question). A thermodynamic variable of state depends just on the instantaneous properties of the equilibrium system, not on the history of how the system was brought to its current state. A function of such variables is also a state variable. So far in this course, the only non-state variables we have seen are heat Q and work W, their values depend distinctly on the details of how some process is carried out.

Do you think there should be a history of physics course in the university physics curriculum?

I do, I think such a course could be interesting and it would help students appreciate how slow, difficult, and interesting scientific progress can be, even for the brightest minds living at any given time.

If you feel you would like to see such a course, you should email the Associate Chair, Professor Teitsworth, at `teitso@phy.duke.edu` and express your interest.

In the real world, what does $C_P(T=0) \to 0$ mean? Could you give an exemplary system?

Not sure I understand this question. Do you mean why does the heat capacity go to zero at $T = 0$? A practical consequence of the heat capacity vanishing is that it is impossible to bring a physical system to exactly absolute zero. The reason is that one can write the definition $C = Q/\Delta T$ in the form $\Delta T = (1/C)Q$, i.e., a small amount of heat Q added to a system will cause a big increase in the temperature ΔT. As one tries to cool some sample to lower and lower temperature, tiny stray amounts of heat can cause the temperature of the sample to rise.

You mentioned in passing about how computers are limited by the heat engine efficiency $\epsilon = 1 - T_c/T_h$. How does that work?

This is a rich modern topic, will try to explain it later in the course or give you some references to think about when it comes time for students to write 1-page summaries of some recent application of 176 material. The ideas are especially associated with the names of Rolf Landauer and Charles Bennett (who did their work in IBM's basic research group at Yorktown, NY), who first thought hard about what was the minimal amount of energy needed to carry out a sequence of computations.