

In this section: we learn about one of the fundamental achievements of physics, namely the understanding that temperature measures the energy of the random motions of atoms. This insight is fundamental to understanding atmospheres and, in later chapters, stars.



Figure 7.3. Ludwig Boltzmann was one of the giants of physics at the transition from the nineteenth to the twentieth century, when the foundations of modern physics were laid. In Boltzmann's time, not all physicists accepted that matter was composed of atoms. Many of the ideas Boltzmann used go back to Bernoulli, who argued that pressure could be caused by the random motion of small particles, and that this would naturally explain the increase of pressure with temperature. But Boltzmann put mathematics to these ideas, and turned them into a testable physical theory. By doing this, Boltzmann made a great step toward establishing the reality of atoms. Unfortunately, Boltzmann's story is a good deal more tragic than that of most other physicists: in his middle age, ill and depressed, at least partly by the resistance his ideas had met among older physicists, he committed suicide. He never understood that he had completely converted the younger generation of physicists to his point of view, and he did not know that his theories were actually on the verge of experimental verification. Image courtesy Österreichische Zentralbibliothek für Physik.

temperature T , then at absolute temperature $2T$ and the same pressure it will have volume $2V$.

Why there is a coldest temperature: the random nature of heat

Although the universal nature of the absolute zero of temperature has been verified over and over again in laboratory experiments, there might be something unsatisfying about our approach to it so far: we have no real explanation, no real understanding of how this can be. A more satisfying explanation was provided by Boltzmann, whom we mentioned earlier in this chapter.

Boltzmann was the principal founder and exponent of the branch of physics that we now call **statistical mechanics**. (Other important contributions were made, independently, by James Clerk Maxwell – whom we will meet in Chapter 15 – and by the American physicist Willard Gibbs, 1839–1903.) Boltzmann showed that *all* the known properties of simple gases could be explained if one took the view that a gas was composed of atoms that moved randomly about inside a container, frequently colliding with each other and with the walls of the container. He showed that pressure was the result of the forces of all the small atoms hitting the walls randomly. To make his calculation work, he needed to make only one simple assumption about the relationship between the average kinetic energy of an atom in the gas[†] $\langle K \rangle_{\text{avg}}$ and the absolute temperature:

$$\langle K \rangle_{\text{avg}} = \left\langle \frac{1}{2}mv^2 \right\rangle_{\text{avg}} = \frac{3}{2}kT, \quad (7.3)$$

where we have used Equation 6.8 on page 54, the definition of the kinetic energy for an atom of mass m . The constant k is called *Boltzmann's constant*, and it has the value

$$k = 1.38 \times 10^{-23} \text{ kg m}^2 \text{ s}^{-2} \text{ K}^{-1}.$$

Equation 7.3 is the quantitative form of the relation between temperature and kinetic energy that I referred to at the beginning of this chapter. We study Boltzmann's argument in more detail in Investigation 7.2 on page 78.

The idea that kinetic energy should be proportional to temperature was not just an arbitrary assumption. What Boltzmann showed was that when a large collection of atoms move and collide randomly, they tend to share out their kinetic energy equally: when a rapidly moving and a slowly moving atom collide, they usually both bounce off with speeds somewhere in between. This is so similar to what happens when hot and cold bodies are placed into contact, that Boltzmann drew what was to him an obvious conclusion: temperature essentially *is* the kinetic energy of a typical atom of the gas.

This leads, of course, to a simple explanation of *why* bodies in contact tend to approach the same temperature: their atoms at the point of contact tend to share energy, and when they collide with atoms behind them inside their respective bodies, this sharing tends to make all energies – hence both temperatures – the same. Moreover, and this is where our real interest is in this section, Boltzmann gives us a natural explanation for absolute zero: absolute zero is the temperature at which there is no longer any random kinetic energy inside the body. At absolute zero, all the atoms are perfectly at rest with respect to each other. The fact that this lowest temperature should be the same for all bodies is obvious in this picture.

Why does absolute zero lead to zero volume? Remember that in Charles' law the pressure is held constant, so there is always some pressure from outside on the

[†]The use of angle brackets $\langle \dots \rangle_{\text{avg}}$ is a conventional notation for a statistical average (also called the **mean**) over a large number of random events. In this case the average is over random motions of molecules.