Chapter 1

The Energy Called Heat

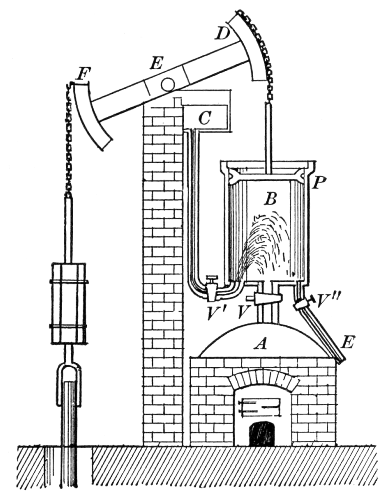

Figure 1.1 Newcomen engine from *Practical physics for secondary schools. Fundamental principles and applications to daily life,* by Newton Henry Black and Harvey Nathaniel Davis, publ. 1913 by Macmillan and Company, p. 219

When Thomas Newcomen and his partner John Calley built the first piston steam engine 1712, there was not a physicist alive who could have explained how it worked. Newcomen and Calley built the engine to pump water out of a mine at the Conygree Coalworks in central England. At the time, there were no powered machines working in the mines – all work was done by laborers and horses. The mine did have a sort of steam pump that used condensing steam to suck ground water out of the mine, preventing the mine from flooding. However, this steam pump was not working and Newcomen was called to fix it. The fix he devised, shown in figure 1.1, was actually an entirely new design. Figure 1.1 shows his new engine in its resting position. On the left is a simple pump driven by a large weight. When the weight is lifted, water flows into the bottom of the pump, deep in the mine (not shown). When the heavy weight is lowered, it forces water up a pipe to the surface. Then the weight must be lifted again.

Lifting the weight is the job of the engine on the right. Water in the boiler A is heated by a fire below. When the valves V and V'' are opened (with valve V' closed), steam rises into the cylinder B forcing any air out through the valve V''.

Once the cylinder is filled entirely with steam, the cylinder is sealed by closing valves V and V''. Then the valve V' is opened briefly, allowing cold water from the tank C to spray into the cylinder, as shown in figure 1.1. This spray cools the cylinder and the steam, causing the steam to condense into liquid water again. All of the steam condenses into a tiny volume of water, which collects with the sprayed water at the bottom of the cylinder. No air is allowed back into the cylinder, and all of the steam has condensed, so the cylinder is almost empty, with near vacuum above the small pool of water at the bottom.

Outside the cylinder is the atmosphere, pushing in from all sides. Most importantly, the atmosphere pushes down on the movable piston which forms the top of the cylinder in figure 1.1. The downward pressure P produces a huge downward force F on the piston.

$$F = PA,$$

where A is the piston's area. (In this chapter we will use P for pressure, not power.) The SI unit for pressure is a pascal, defined by

$$1\,\mathrm{Pa} = 1\,\mathrm{N/m^2}.$$

Example 1.1 A working replica of Newcomen's engine operates at a museum near the site of Newcomen's original. The piston's radius is 26 cm. What is the force exerted on the piston by the atmosphere?

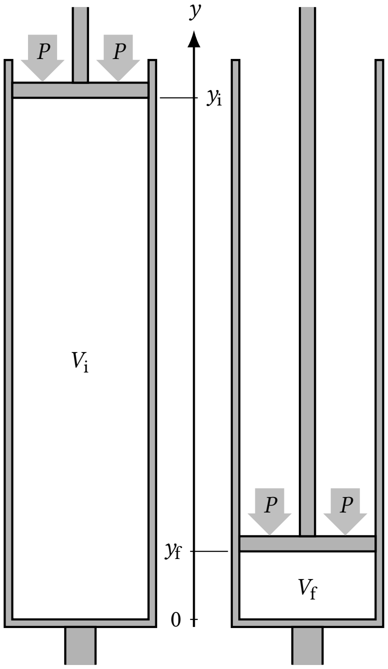

FIGURE 1.2 The downward power stroke of Newcomen's atmospheric engine is driven by atmospheric pressure pushing down on the piston.

The piston's area is $A = \pi r^2 = \pi(0.26m)^2 = 0.212\,\mathrm{m}^2$. *The force is*

$$\begin{aligned} F &= PA \\ &= (1.01 \times 10^5\,\mathrm{Pa})(0.212\,\mathrm{m}^2) \\ &= (1.01 \times 10^5\,\mathrm{N}/\cancel{\mathrm{m}^2})(0.212\,\cancel{\mathrm{m}^2}) \\ &= 21\,000\,\mathrm{N}. \end{aligned}$$

This downward force acting on the right side of figure 1.1 is enough to lift a weight of over 2000 kg *on the left.*

The atmosphere's pressure drives the piston downward. This downward motion is the engine's power stroke. It pulls down on the chain at D in figure 1.1, rocking the large lever FED around the pivot E. That lifts the chain at F, raising the large weight.

Once the weight is lifted, the valve V is opened, allowing the water to flow down into the boiler. Hot steam from the boiler fills the cylinder B again, allowing the piston to rise and the weight to fall. The whole process is then be repeated, spraying cold water into the cylinder to condense the steam for the power stroke. (Since the cylinder is filling with steam directly from the boiler, valve V'' does not need to be opened each cycle.)

Newcomen's design included mechanisms that used the motion of the top beam to open and close the valves automatically at precisely the right times in the cycle. (These mechanisms are not shown in the diagrams.) This allowed the engine to operate continuously, performing each cycle in about five seconds and doing as much work as a team of several horses or dozens of men. Many mines upgraded to Newcomen's reliable and powerful engine. Dozens were installed in Britain and eventually in other parts of Europe.

The engines could be built in a variety of sizes, depending on the mine's needs. Engineers developed the concepts of work and power to quantify their engines' productivity, so they could build the right size engine.

EXAMPLE 1.2 The replica of Newcomen's engine in example 1.1 has a piston that travels approximately 1.8 m inside the cylinder, shown in figure 1.2. Like Newcomen's original, it operates at a rate of one cycle every five seconds. Find the work done by the atmosphere on the engine and the average power.

The work can be calculated using the force form example 1.1 and a displacement of 1.8 m .

$$W = F\Delta y = (21\,000 \times 10^4\,\mathrm{N})(1.8\,\mathrm{m}) = 38\,000\,\mathrm{J}.$$

The force and displacement are in the same direction, so the work is positive. In figure 1.2 they are both pointed in the negative direction, so we also could have written both as negative. The answer would be the same.
Power is the rate at which the work is done.

$$\frac{W}{\Delta t} = \frac{38\,000\ \text{J.}}{5\ \text{s}} = 7500\ \text{W}$$

While we used the piston's area and displacement to calculate the work, all that is actually needed is the pressure and the cylinder's change in volume. The volume of the cylinder in figure 1.2 is $V = Ay$, where A is the piston's area and y is its height. Taking care with signs, we should write the downward force as $F = -PA$, since pressure and area are positive, but the force is in the negative direction.

$$W = F\Delta y = -PA(y_\mathrm{f} - y_\mathrm{i}) = -P(Ay_\mathrm{f} - Ay_\mathrm{i}) = -P(V_\mathrm{f} - V_\mathrm{i}) = -P\Delta V$$

The negative sign deserves some explanation. During the engine's downward power stroke, the volume inside the cylinder is decreasing, so ΔV is negative. The pressure is positive, so the work formula $W = -P\Delta V$ will give positive work for the downward power stroke, as it should.

Work was a new concept to physicists in the eighteenth century – remember, the *vis viva* debate was raging at this time – but the ideas behind the engine's forceful power stroke were well understood. Atmospheric pressure, force, and displacement were all basic physics knowledge at that time.

The upward stroke was where physicists would have started struggling. The piston is lifted by the heavy weight, but this is only possible because steam is allowed into the cylinder, as shown in figure 1.3. The steam, also at atmospheric pressure, pushes up on the bottom of the piston, balancing the downward force of the outside atmosphere so the piston can rise. The steam is clearly doing work as it lifts the piston against the downward force of the atmosphere, but where does the steam get the energy? Clearly, the energy is from the fire, but it is not obvious how the energy of the fire turns into work done on the piston.

Daniel Bernoulli's *Hydrodynamica* appeared in 1838. In this great work, he brought together physicists' *vis viva*, engineers' work, and his own ideas about potential energy. He also offered an insightful and correct model of a gas like steam. He described the gas as being made of many tiny parts, now called molecules, that bounce around furiously – ricocheting off of the containers walls and off of each other, as shown in figure 1.4. In this model, the tiny molecules are spread throughout the container, but they occupy very little of the space. It looks as if the piston and the weight at the top

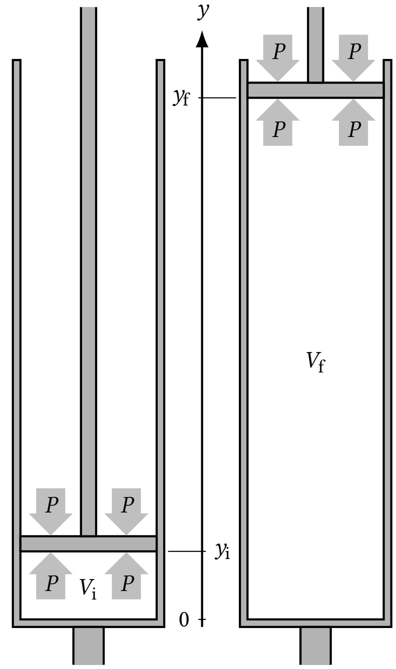

FIGURE 1.3 Steam entering the cylinder provides an upwards force on the piston. It is then lifted by the heavy weight on the left of figure 1.1.

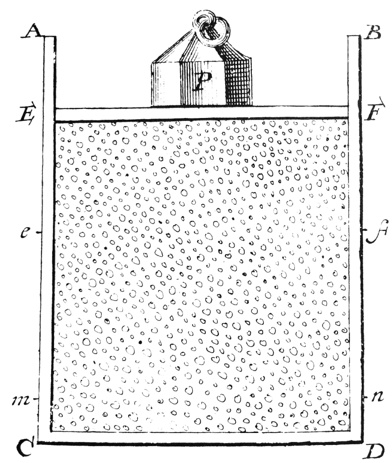

FIGURE 1.4 Daniel Bernoulli's description of a gas. The gas molecules are not packed together. Still, their frequent collisions with the piston hold the piston and weight aloft.

of figure 1.4 will fall, packing the molecules together at the bottom of the cylinder. Bernoulli realized that if the molecules are traveling fast enough, their repeated impacts on the bottom of the piston will provide enough tiny impulses to keep the piston from falling. This became known as the kinetic theory of gasses because it is the molecule's motion that causes the pressure against the sides of the container. The molecules' sizes and shapes are of little consequence.

Example 1.3 Daniel starts a fire under his
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The work can be calculated using the force form example 1.1 and a displacement of 1.8 m .

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$$\frac{W}{\Delta t} = \frac{38\,000\,\mathrm{J.}}{5\,\mathrm{s}} = 7500\,\mathrm{W}$$

Bernoulli took several important steps in developing this model, but this part of *Hydrodynamica* was largely ignored for a century. Physicists were not interested in engines, and engineers were not reading physics treatises. Steam engines and many mistaken models of heat spread widely into the early nineteenth century.

Energy and Temperature in solids

$$E_{\mathrm{therm}} = 3nRT$$

The motion which we call heat

Boltzmann: On the Nature of Gas Molecules

It is an interesting fact that thermal energy tends to spread out equally into every accessible place. The average amount of energy stored in each place is proportional to the temperature, and is given by the formula $\frac{1}{2} k_{\mathrm{B}} T$. Boltzmann's constant, kB, is the same in all situations. It is defined as exactly.

$$k_{\mathrm{B}} = 1.380649 \times 10^{-23}\ \mathrm{J/K}$$

You should think of k_B as a conversion from kelvins to joules. Kelvins are just another unit for measuring average energy. A kelvin is a very tiny amount of energy!

The molecule in the cylinder has three places for energy, $K_x = ½mv_x^2$, $K_y = ½mv_y^2$, and $K_z = ½mv_z^2$. If the temperature of the gas is T, then the molecule with have $½\,k_BT$ of energy in each of these places. Add more molecules and there are more places for the energy, three places per molecule. Even though $½\,k_BT$ is a very small amount of energy, a large number of molecules can store a significant amount of energy. Be careful with hot things!

7. What is PV if there are N molecules with an average vertical kinetic energy $K_y = ½\,k_BT$ per molecule? T is the temperature of the gas. The pressure will be N times greater, so the new PV is

$$PV = 2NKy \;=\; NkBT$$

8. What is PV if there are n moles of gas in the cylinder? Use the definition $R = N_Ak_B$ where N_A is Avogadro's number and R is the gas constant, both of which you remember fondly from chemistry. Also recall $N \;=\; nN_A$. Your result should look familiar.

$$PV \;=\; nNAkBT \;=\; nRT$$
$$PV \;=\; nRT$$

9. At temperature T, what is the total energy in the gas. Assume that the molecules' kinetic energy is the only energy in the gas. (For simple, monoatomic gasses this is an excellent assumption.) Call the total energy U, even though it is actually kinetic energy. Everyone uses U for the internal energy of the gas. The total energy in the gas is N times the Kinetic energy of a single atom

$$U = NK \;=\; N(K_x \;+\; K_y \;+\; K_z) \;=\; N(½\,k_BT + ½\,k_BT + ½\,k_BT\,) \;=\; (3/2)Nk_BT \;=\; (3/2)RT,$$

n this activity you will use Boltzmann's insight to find the amount of energy required to heat 63.55 g of copper from 20°C to 100°C. (Why 63.55 g? Because working with four significant figures builds character.) Boltzmann tells us that the energy in every available spot is ½kBT, where kB = 1.381×10-23 J/K. You need to find out how many spots there are in 63.55 g of copper. The number of spots can be found with a simple model of copper. Imagine that the copper atoms are arranged is a simple cubic lattice, and that each atom is connected to its immediate neighbors by springs. Every atom is connected to the atom on its left and its right, in front and in back, above and below. The atoms can bounce around a bit, but they are always pushed back towards their home position by the springs.

1. Some of the thermal energy is stored in the bouncing kinetic energy of the copper atoms. There are three types of kinetic energy for each atom. List the three symbols for these.

2. For a lattice containing a large number of copper atoms, how many springs are there per atom? (Hint: There are not six springs per atom!) Explain, with a picture if you like.

3. How many thermal energy spots are there per atom?

4. Find the thermal energy per atom for copper at room temperature (20°C = 293 K).

5. Find the thermal energy per atom for copper at 100°C = 373 K.

7. What is the specific heat capacity of copper in J/g °C? (For comparison, the specific heat capacity of water is 4.2 J/g °C.)

> For all simple solids with the exception of carbon, [boron], and silicon the product $M\Gamma$ is not very different from 6; it is between 5.22 and 6.9. The values obtained for h are between 1.78 and 2.34. On average, then, the total heat supplied is twice as great as that to increase the mean living force, half of which is used for work, if the forces acting on an atom are proportional to the removal of it from its position of rest. For solids, this is likely to be the case with some approximation. If one wanted to use the latter formula, one could insert the theoretical value $Ap/\rho T$ for $\gamma' - \gamma$. The result is a similar one. From the composite solid bodies, which obey Neumann's law, it must be assumed that each of its atoms really has three kinds of mobility. For simple or compound bodies, however, which deviate significantly from Dulong-Petit or Neumann's laws, it could perhaps be assumed that two or more atoms are so firmly connected that the number of types of mobility of the system they form is smaller than the three-fold number of its atoms. [p.108-9]