

## 8.1: Work

### Learning Objectives

- To know the relationship between energy, work, and heat.

One definition of energy is the capacity to do work. There are many kinds of work, including mechanical work, electrical work, and work against a gravitational or a magnetic field. Here we will consider only mechanical work and focus on the work done during changes in the pressure or the volume of a gas.

### Mechanical Work

The easiest form of work to visualize is mechanical work (Figure 8.1.1), which is the energy required to move an object a distance  $d$  when opposed by a force  $F$ , such as gravity:

$$w = F d \quad (8.1.1)$$

with

- $w$  is work
- $F$  is opposing force
- $d$  is distance

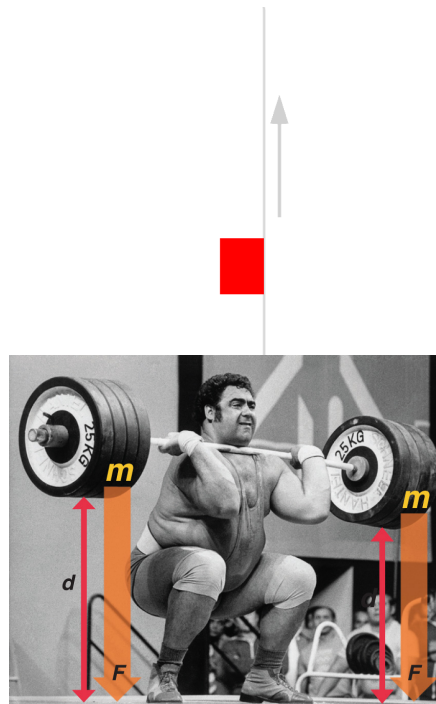


Figure 7.4.1: One form of energy is mechanical work, the energy required to move an object of mass  $m$  a distance  $d$  when opposed by a force  $F$ , such as gravity.

Because the force ( $F$ ) that opposes the action is equal to the mass ( $m$ ) of the object times its acceleration ( $a$ ), Equation 8.1.1 can be rewritten to:

$$w = m a d \quad (8.1.2)$$

with

- $w$  is work
- $m$  is mass
- $a$  is a acceleration, and
- $d$  is distance

Recall from that weight is a force caused by the gravitational attraction between two masses, such as you and Earth. Hence for works against gravity (on Earth),  $a$  can be set to  $g = 9.8 \text{ m/s}^2$ ). Consider the mechanical work required for you to travel from the first floor of a building to the second. Whether you take an elevator or an escalator, trudge upstairs, or leap up the stairs two at a time, energy is expended to overcome the opposing force of gravity. The amount of work done ( $w$ ) and thus the energy required depends on three things:

1. the height of the second floor (the distance  $(d)$ );
2. your mass, which must be raised that distance against the downward acceleration due to gravity; and
3. your path.

## Pressure-Volume (PV) Work

To describe this pressure-volume work ( $PV$  work), we will use such imaginary oddities as frictionless pistons, which involve no component of resistance, and ideal gases, which have no attractive or repulsive interactions. Imagine, for example, an ideal gas, confined by a frictionless piston, with internal pressure ( $P_{int}$ ) and initial volume  $V_i$  (Figure 7.4.2). If  $P_{ext} = P_{int}$ , the system is at equilibrium; the piston does not move, and no work is done. If the external pressure on the piston ( $P_{ext}$ ) is less than  $P_{int}$ , however, then the ideal gas inside the piston will expand, forcing the piston to perform work on its surroundings; that is, the final volume ( $V_f$ ) will be greater than  $V_i$ . If  $P_{ext} > P_{int}$ , then the gas will be compressed, and the surroundings will perform work on the system.

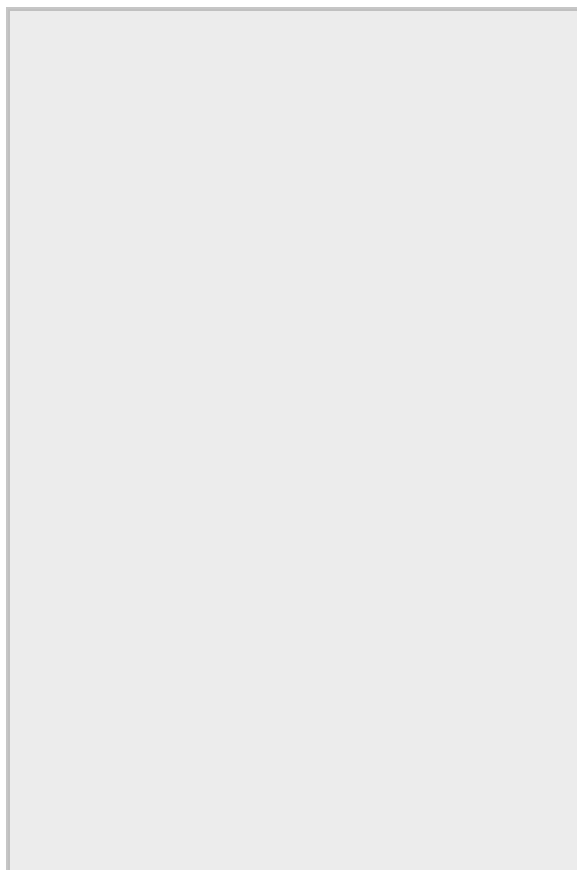


Figure 7.4.2: PV Work. Using a frictionless piston, if the external pressure is less than  $P_{int}$  (a), the ideal gas inside the piston will expand, forcing the piston to perform work on its surroundings. The final volume ( $V_f$ ) will be greater than  $V_i$ . Alternatively, if the external pressure is greater than  $P_{int}$  (b), the gas will be compressed, and the surroundings will perform work on the system.

If the piston has cross-sectional area  $A$ , the external pressure exerted by the piston is, by definition, the force per unit area:

$$P_{ext} = \frac{F}{A} \quad (8.1.3)$$

The volume of any three-dimensional object with parallel sides (such as a cylinder) is the cross-sectional area times the height ( $V = Ah$ ). Rearranging to give  $F = P_{ext} A$  and defining the distance the piston moves ( $d$ ) as  $\Delta h$ , we can calculate the magnitude of the work performed by the piston by substituting into Equation 7.4.1:

$$w = Fd = P_{ext} A \Delta h \quad (8.1.4)$$

The change in the volume of the cylinder ( $\Delta V$ ) as the piston moves a distance  $d$  is  $\Delta V = A \Delta h$ , as shown in Figure 7.4.3. The work performed is thus

$$w = P_{ext} \Delta V \quad (8.1.5)$$

The units of work obtained using this definition are correct for energy: pressure is force per unit area (newton/m<sup>2</sup>) and volume has units of cubic meters, so

$$w = \left( \frac{F}{A} \right)_{ext} (\Delta V) = \frac{\text{newton}}{\text{m}^2} \times \text{m}^3 = \text{newton} \cdot \text{m} = \text{joule} \quad (8.1.6)$$



Figure 7.4.3: Work Performed with a change in volume. The change in the volume ( $\Delta V$ ) of the cylinder housing a piston is  $\Delta V = A \Delta h$  as the piston moves. The work performed by the surroundings on the system as the piston moves inward is given by  $w = P_{ext} \Delta V$ .

If we use atmospheres for  $P$  and liters for  $V$ , we obtain units of  $\text{L} \cdot \text{atm}$  for work. These units correspond to units of energy, as shown in the different values of the ideal gas constant  $R$ :

$$R = \frac{0.08206 \text{ L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} = \frac{8.314 \text{ J}}{\text{mol} \cdot \text{K}} \quad (8.1.7)$$

Thus  $0.08206 \text{ L} \cdot \text{atm} = 8.314 \text{ J}$  and  $1 \text{ L} \cdot \text{atm} = 101.3 \text{ J}$ .

Whether work is defined as having a positive sign or a negative sign is a matter of convention. Heat flow is defined from a system to its surroundings as negative; using that same sign convention, we define work done by a system on its surroundings as having a negative sign because it results in a transfer of energy from a system to its surroundings. This is an arbitrary convention and one that is not universally used. Some engineering disciplines are more interested in the work done on the surroundings than in the work done by the system and therefore use the opposite convention. Because  $\Delta V > 0$  for an expansion, Equation 7.4.4 must be written with a negative sign to describe PV work done by the system as negative:

$$w = -P_{ext} \Delta V \quad (8.1.8)$$

The work done by a gas expanding against an external pressure is therefore negative, corresponding to work done by a system on its surroundings. Conversely, when a gas is compressed by an external pressure,  $\Delta V < 0$  and the work is positive because work is being done on a system by its surroundings.

#### Note: A Matter of Convention

- Heat flow is defined from the system to its surroundings as **negative**
- Work is defined as by the system on its surroundings as **negative**

#### Outside Links

- Gasparo, Frances P. "Remembering the sign conventions for  $q$  and  $w$  in  $\Delta U = q - w$ ." J. Chem. Educ. 1976: 53, 389.
- Koubek, E. "PV work demonstration (TD)." J. Chem. Educ. 1980: 57, 374. '

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