# CHAPTER 12
# Thermodynamics


**Figure 12.1** A steam engine uses energy transfer by heat to do work. (Modification of work by Gerald Friedrich, Pixabay)

## Chapter Outline



**INTRODUCTION** Energy can be transferred to or from a system, either through a temperature difference between it and another system (i.e., by heat) or by exerting a force through a distance (work). In these ways, energy can be converted into other forms of energy in other systems. For example, a car engine burns fuel for heat transfer into a gas. Work is done by the gas as it exerts a force through a distance by pushing a piston outward. This work converts the energy into a variety of other forms—into an increase in the car's kinetic or gravitational potential energy; into electrical energy to run the spark plugs, radio, and lights; and back into stored energy in the car's battery. But most of the thermal energy transferred by heat from the fuel burning in the engine does not do work on the gas. Instead, much of this energy is released into the surroundings at lower temperature (i.e., lost through heat), which is quite inefficient. Car engines are only about 25 to 30 percent efficient. This inefficiency leads to increased fuel costs, so there is great interest in improving fuel efficiency. However, it is common knowledge that modern gasoline engines cannot be made much more efficient. The same is true about the conversion to electrical energy in large power stations, whether they are coal, oil, natural gas, or nuclear powered. Why is this the case?

The answer lies in the nature of heat. Basic physical laws govern how heat transfer for doing work takes place and limit the maximum possible efficiency of the process. This chapter will explore these laws as well their applications to everyday machines. These topics are part of *thermodynamics*—the study of heat and its relationship to doing work.

# 12.1 Zeroth Law of Thermodynamics: Thermal Equilibrium

### Section Learning Objectives

*By the end of this section, you will be able to do the following:*

- Explain the zeroth law of thermodynamics

## Section Key Terms

| | |
|---|---|
| thermal equilibrium | zeroth law of thermodynamics |

We learned in the previous chapter that when two objects (or *systems*) are in contact with one another, heat will transfer thermal energy from the object at higher temperature to the one at lower temperature until they both reach the same temperature. The objects are then in **thermal equilibrium**, and no further temperature changes will occur if they are isolated from other systems. The systems interact and change because their temperatures are different, and the changes stop once their temperatures are the same. Thermal equilibrium is established when two bodies are in *thermal contact* with each other—meaning heat transfer (i.e., the transfer of energy by heat) can occur between them. If two systems cannot freely exchange energy, they will not reach thermal equilibrium. (It is fortunate that empty space stands between Earth and the sun, because a state of thermal equilibrium with the sun would be too toasty for life on this planet!)

If two systems, A and B, are in thermal equilibrium with each another, and B is in thermal equilibrium with a third system, C, then A is also in thermal equilibrium with C. This statement may seem obvious, because all three have the same temperature, but it is basic to thermodynamics. It is called the **zeroth law of thermodynamics**.

### TIPS FOR SUCCESS

The zeroth law of thermodynamics is very similar to the transitive property of equality in mathematics: If a = b and b = c, then a = c.

You may be wondering at this point, why the wacky name? Shouldn't this be called the *first* law of thermodynamics rather than the *zeroth*? The explanation is that this law was discovered after the first and second laws of thermodynamics but is so fundamental that scientists decided it should logically come first.

As an example of the zeroth law in action, consider newborn babies in neonatal intensive-care units in hospitals. Prematurely born or sick newborns are placed in special incubators. These babies have very little covering while in the incubators, so to an observer, they look as though they may not be warm enough. However, inside the incubator, the temperature of the air, the cot, and the baby are all the same—that is, they are in thermal equilibrium. The ambient temperature is just high enough to keep the baby safe and comfortable.

### WORK IN PHYSICS

### Thermodynamics Engineer

Thermodynamics engineers apply the principles of thermodynamics to mechanical systems so as to create or test products that rely on the interactions between heat, work, pressure, temperature, and volume. This type of work typically takes place in the aerospace industry, chemical manufacturing companies, industrial manufacturing plants, power plants (Figure 12.2), engine manufacturers, or electronics companies.

Figure 12.2 An engineer makes a site visit to the Baghdad South power plant.

The need for energy creates quite a bit of demand for thermodynamics engineers, because both traditional energy companies and alternative (*green*) energy startups rely on interactions between heat and work and so require the expertise of thermodynamics engineers. Traditional energy companies use mainly nuclear energy and energy from burning fossil fuels, such as coal. Alternative energy is finding new ways to harness renewable and, often, more readily available energy sources, such as solar, water, wind, and bio-energy.

A thermodynamics engineer in the energy industry can find the most efficient way to turn the burning of a biofuel or fossil fuel into energy, store that energy for times when it's needed most, or figure out how to best deliver that energy from where it's produced to where it's used: in homes, factories, and businesses. Additionally, he or she might also design pollution-control equipment to remove harmful pollutants from the smoke produced as a by-product of burning fuel. For example, a thermodynamics engineer may develop a way to remove mercury from burning coal in a coal-fired power plant.

Thermodynamics engineering is an expanding field, where employment opportunities are expected to grow by as much as 27 percent between 2012 and 2022, according to the U.S. Bureau of Labor Statistics. To become a thermodynamics engineer, you must have a college degree in chemical engineering, mechanical engineering, environmental engineering, aerospace engineering, civil engineering, or biological engineering (depending on which type of career you wish to pursue), with coursework in physics and physical chemistry that focuses on thermodynamics.

**GRASP CHECK**

What would be an example of something a thermodynamics engineer would do in the aeronautics industry?

a. Test the fuel efficiency of a jet engine
b. Test the functioning of landing gear
c. Test the functioning of a lift control device
d. Test the autopilot functions

## Check Your Understanding

1. What is thermal equilibrium?
    a. When two objects in contact with each other are at the same pressure, they are said to be in thermal equilibrium.
    b. When two objects in contact with each other are at different temperatures, they are said to be in thermal equilibrium.
    c. When two objects in contact with each other are at the same temperature, they are said to be in thermal equilibrium.
    d. When two objects not in contact with each other are at the same pressure, they are said to be in thermal equilibrium.

2. What is the zeroth law of thermodynamics?

a. Energy can neither be created nor destroyed in a chemical reaction.
b. If two systems, A and B, are in thermal equilibrium with each another, and B is in thermal equilibrium with a third system, C, then A is also in thermal equilibrium with C.
c. Entropy of any isolated system not in thermal equilibrium always increases.
d. Entropy of a system approaches a constant value as temperature approaches absolute zero.

# 12.2 First law of Thermodynamics: Thermal Energy and Work

### Section Learning Objectives

*By the end of this section, you will be able to do the following:*

- Describe how pressure, volume, and temperature relate to one another and to work, based on the ideal gas law
- Describe pressure–volume work
- Describe the first law of thermodynamics verbally and mathematically
- Solve problems involving the first law of thermodynamics

## Section Key Terms

| | | | | |
|---|---|---|---|---|
| Boltzmann constant | first law of thermodynamics | ideal gas law | internal energy | pressure |

## Pressure, Volume, Temperature, and the Ideal Gas Law

Before covering the first law of thermodynamics, it is first important to understand the relationship between **pressure**, volume, and temperature. Pressure, $P$, is defined as

$$P = \frac{F}{A}, \tag{12.1}$$

where $F$ is a force applied to an area, $A$, that is perpendicular to the force.

Depending on the area over which it is exerted, a given force can have a significantly different effect, as shown in Figure 12.3.

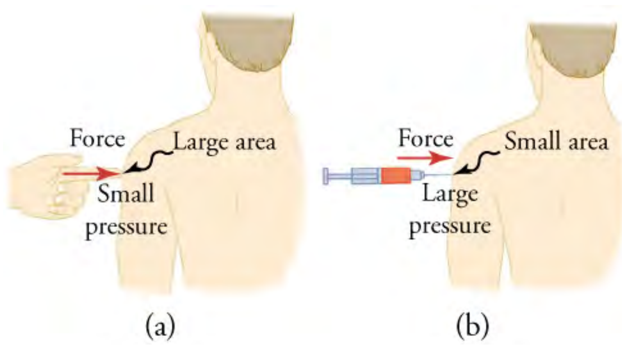


**Figure 12.3** (a) Although the person being poked with the finger might be irritated, the force has little lasting effect. (b) In contrast, the same force applied to an area the size of the sharp end of a needle is great enough to break the skin.

The SI unit for pressure is the *pascal*, where $1\ \text{Pa} = 1\ \text{N/m}^2$.

Pressure is defined for all states of matter but is particularly important when discussing fluids (such as air). You have probably heard the word *pressure* being used in relation to blood (high or low blood pressure) and in relation to the weather (high- and low-pressure weather systems). These are only two of many examples of pressures in fluids.

The relationship between the pressure, volume, and temperature for an ideal gas is given by the **ideal gas law**. A gas is considered ideal at low pressure and fairly high temperature, and forces between its component particles can be ignored. The ideal gas law states that

$$PV = NkT. \tag{12.2}$$

where $P$ is the pressure of a gas, $V$ is the volume it occupies, $N$ is the number of particles (atoms or molecules) in the gas, and $T$ is