Chapter 1

Conservation of Mass and Energy

One of the most fundamental laws in science is the conservation of mass and energy. This law states that mass (matter) and energy cannot be created or destroyed. This means the total matter and energy in the universe always stays the same.

1.1 Conservation of Mass

Since matter cannot be created or destroyed, a chemical reaction does not change the mass of the reactants as they form products. Consider the reaction between vinegar and baking soda, which produces carbon dioxide, water, and sodium acetate:

acetic acid
common name: vinegar

dihydrogen monoxide
common name: water

$$NaHCO_3 + CH_3COOH \rightarrow NaCH_3COO + H_2O + CO_2$$

sodium bicarbonate
common name: baking soda

sodium acetate

carbon dioxide

The reactants are labeled with red, and the products with blue. This equation is *balanced*: that is, it shows the same number of each element on each side of the arrow. This shows that the atoms are not created or destroyed during a chemical reaction; they are only rearranged. Take a minute to count up each element on each side. You should find there are 5 hydrogens, 1 sodium, 3 carbons, and 5 oxygens on each side.

Now, let's look at an *unbalanced* chemical reaction. As you know, hydrogen and oxygen combine to form water. Additionally: hydrogen and oxygen both exist as *diatomic gases*. When we say "oxygen gas" or "hydrogen gas", we mean the diatomic molecules, O_2 and H_2, respectively. Here is an unbalanced chemical reaction between hydrogen gas and oxygen gas to form water:

$$H_2 + O_2 \rightarrow H_2O$$

How do we know this equation is unbalanced? Count up the elements: there are two oxygen atoms on the reactant side, but only one on the product side. This violates the conservation of matter: that oxygen atom cannot just disappear!

1.1.1 Balancing Chemical Reactions

We solve this by *balancing* the chemical reaction: adjusting the number of products and reactants to comply with the Law of Conservation of Matter. You'll learn strategies for balancing chemical reactions in Sequence 2, but for now we'll briefly balance this chemical reaction so that it complies with the Law of Conservation of Matter. You may be tempted to simply add a lone oxygen atom to the products side:

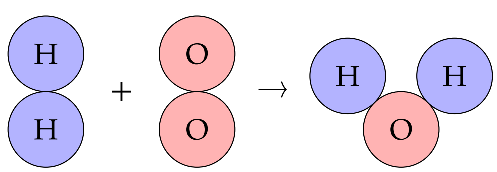
$$H_2 + O_2 \rightarrow H_2O + O$$

The major reason this is incorrect is that oxygen does not exist as a lone atom - as discussed above - so it doesn't make sense to have a lone oxygen as a product. So maybe we should add a molecule of oxygen gas to both sides?

$$H_2 + O_2 \rightarrow H_2O + O_2$$

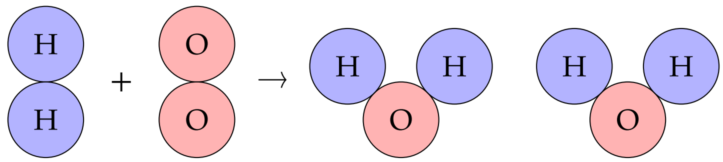
Well now we have the same problem we started with: the oxygens are unbalanced. When balancing chemical reactions, we can only add *whole molecules* that are already in the reaction. Let's take another look at our unbalanced reaction with some molecular models for visualization:

$$H_2 + O_2 \rightarrow H_2O$$



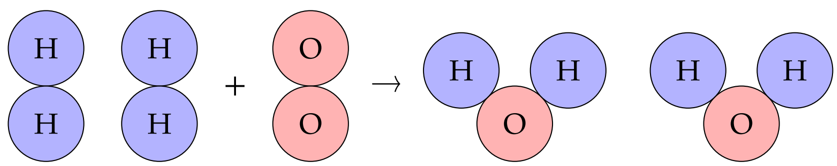
You can clearly see we need more oxygens on the product side. Since we can only add *whole molecules*, our only option is to add another water. We do this by adding a coefficient of 2 in front of H_2O in our equation, which indicates 2 water molecules (just like $2x$ means two x's):

$$H_2 + O_2 \rightarrow 2H_2O$$



We've fixed our oxygen problem: now there are two oxygen atoms on both sides. But now we have a hydrogen problem: there are 2 on the reactant side and 4 on the product side. We can address this by adding another hydrogen gas molecule to the reactant side:

$$2H_2 + O_2 \rightarrow 2H_2O$$



And now we have the same number of hydrogens and oxygens on each side! Notice we have all the same reactants and products that we started with, but now in ratios that reflect the conservation of matter.

A final note: if atoms are in parentheses followed by a subscript, the subscript applies to every atom in the parentheses. For example, zinc nitrate, $Zn\left(NO_3\right)_2$ is made of 1 zinc, 2 nitrogens, and 6 oxygens.

Exercise 1 Balanced and Unbalanced Reactions

Classify the following chemical reactions as balanced or unbalanced. If it is unbalanced, state what element(s) are not conserved.

1. $NiCl_2 + 2NaOH \rightarrow Ni\left(OH\right)_2 + 2NaCl$
2. $HgO \rightarrow Hg + O_2$
3. $BaSO_4 + 2C \rightarrow 2BaS + CO$
4. $Cd\left(NO_3\right)_2 + H_2S \rightarrow CdS + 2HNO_3$

Working Space

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1.2 Conservation of Energy

Just like matter, energy is also conserved: it cannot be created or destroyed, only change forms. You'll learn more about the types of energy in a subsequent chapter, Work and Energy. The transformation of energy from one type to another drives our modern world: your phone transforms electrical potential energy into light and sound energy, a nuclear power plant transforms nuclear energy to electrical energy, and your car transforms chemical potential energy (in the gasoline) into kinetic energy (motion).

1.2.1 Friction, Heat, and Energy "Loss"

Imagine rolling a ball across a flat surface: you have given the ball some kinetic energy in its motion. If the kinetic energy were conserved, the ball would keep rolling at the same speed forever, as long as it was on a flat surface. Experience tells us this isn't what happens: the ball will eventually come to a stop. Why doesn't this violate the Conservation of Energy?

Friction is the force that opposes motion: whenever you slide two objects past each other, friction transforms kinetic energy into heat. Rub the palms of your hands together. You should feel warmth, a product of the friction between your hands. As the ball in the example above rolls, it also experiences friction between itself and the ground. The friction slowly transforms the kinetic energy of the ball into heat, causing the ball to lose kinetic energy. When all of the ball's kinetic energy is transformed to heat, the ball comes to a rest. So, the kinetic energy of the ball wasn't destroyed and didn't disappear: it became heat.

In fact, nearly all energy in the universe will eventually be transformed to heat, resulting in the inevitable "heat death" of the universe. Here is a short video about heat, entropy, and the heat death of the universe: https://www.youtube.com/watch?v=gOWt_Hq3yrE/.

1.2.2 Energy Conservation in Falling Objects

When an object is positioned above the ground, it has *gravitational potential energy*. The potential energy is proportional to the mass of the object, the strength of the gravitational field, and the object's height above the ground:

$$E_p = mgh$$

where m is the mass of the object in kg, g is the acceleration due to gravity ($9.8m/s^2$ on Earth), and h is the height above the ground in meters.

Example: What is the gravitational potential energy of a 5.0 kilogram bowling ball in the hand of a bowler (approximately 1.2 meters high)?

Solution: The mass is 5.0 kg, the height is 1.2 m, and we assume the bowler is on Earth, so g is 9.8 $\mathrm{m/s^2}$:

$$E_p = (5.0\mathrm{kg})\left(9.8\mathrm{m/s^2}\right)(1.2\mathrm{m}) = 59\mathrm{J}$$

Here is a new unit: *joules*, represented by a capital J. A joule is a unit of energy, and it is the same as $\frac{\mathrm{kg \cdot m^2}}{\mathrm{s^2}}$.

If the bowler were to drop that ball, it would lose potential energy and gain *kinetic energy*. The kinetic energy of an object is proportional to its mass and the square of its speed:

$$E_k = \frac{1}{2}mv^2$$

where mass is in kg and speed (v) is in m/s. You can quickly check that the units still come out to a joule! If there is no air resistance, then as an object falls all of its potential energy is converted to kinetic energy. (If you'd like to explore what happens when friction is accounted for, you can play with this PhET simulation: `https://phet.colorado.edu/en/simulations/energy-skate-park`.)

Example: If the bowling ball were dropped, what would it's speed be right before it hits the ground? (Neglect air resistance.)

Solution: Ignoring air resistance, according to the Law of Conservation of Energy, the kinetic energy of the ball right before it hits the ground must be equal to the gravitational potential energy of the ball right before its release. Therefore:

$$mgh = \frac{1}{2}mv^2$$

We can eliminate an m from both sides and rearrange to solve for v:

$$v = \sqrt{2gh} = \sqrt{2\,(9.8\mathrm{m/s^2})\,(1.2\mathrm{m})} = \sqrt{23.52\frac{\mathrm{m^2}}{\mathrm{s^2}}} = 4.8\frac{\mathrm{m}}{\mathrm{s}}$$

The ball will have a speed of 4.8 m/s just before it hits the ground.

Exercise 2 Kinetic and Potential Energy

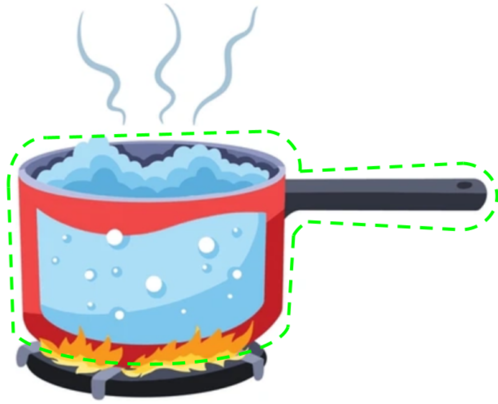
Working Space

1. How fast should you toss a ball straight up if you want it to reach your friend on the second floor (3.7 meters above you)?
2. Your little brother is teasing you from a treehouse 5.0 meters off the ground. If your slingshot can shoot a pebble at 15 m/s, can you hit your little brother?
3. A 63-kg roller-blader rolls down a hill. If the hill is 8.0 meters high and she reaches the bottom of the hill with a speed of 11.2 m/s, how much energy was converted to heat through friction?

Answer on Page 11

1.3 Types of Systems

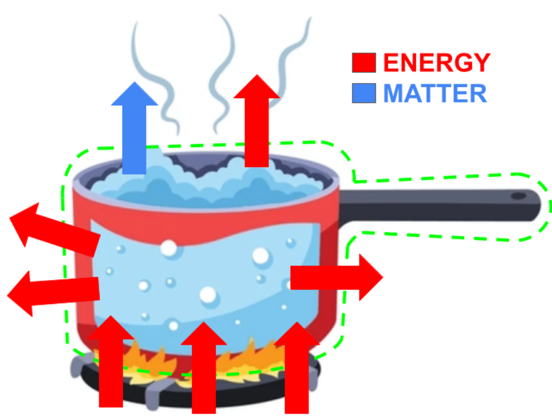
We classify systems based on the flow of matter and energy. A *system* is a set of interconnected elements. Your body is a system, as is a television or a boiling pot of water. Scientists define systems by separating the parts of the system from the rest of the universe, usually called ”the surroundings”. You can represent this separation with a dashed line. Here is a diagram defining a pot of boiling water as a system:



Everything inside the dashed line is the system: the pot and the water boiling in it. Everything outside the dashed line is the surroundings: the stove, the air around the pot, etc. Defining a system is *arbitrary*: there isn't one hard and fast definition of a system. Think of your school: you could look at the system of a classroom, the system of a hallway and all the classes connected to it, or the entire school building. How you define a system depends on what you're studying.

1.3.1 Open Systems

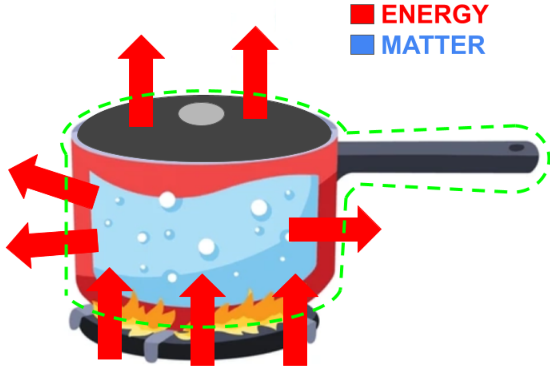
An *open system* allows for matter and energy to cross the imaginary boundary between the system and its surroundings. The uncovered pot of boiling water is an example of an open system. Energy enters the system as heat from the stove, and leaves the system as heat in the steam rising from the pot. Notice that steam rising: see how it crosses the imaginary boundary? The steam is matter *leaving the system*. Since matter and energy can cross the boundary between the system and its surroundings, the uncovered boiling pot is an open system.



The system also loses energy through the sides of the pot: if you touched the pot, it would feel hot, which means heat energy can also leave the system through the sides of the pot. This is due to the collision between air particles (the surroundings) and the outside of the pot (the system). With every collision, a little heat is transferred from the pot to the air. This is why your hot drink gets cold if you leave it out, even if you don't add any ice.

1.3.2 Closed Systems

A *closed system* allows for the transfer of energy but not the transfer of matter. If we put a lid on this pot, it would become a closed system.



Notice that the difference between an open and closed system is the flow of *matter*: open systems allow for the movement of matter, while closed systems do not. However, energy can still enter and leave closed systems. Sealed containers that aren't insulated are good examples of closed systems - a car with the windows up and doors closed.

1.3.3 Isolated Systems

An *isolated system* does not allow for the flow of matter *or* energy in or out of the system. There is no such thing as a truly isolated system - in reality a small amount of energy can be transferred even through the best thermal insulators. However, for well-insulated systems, it can be a good approximation to model that system as isolated. A simple example would be a sealed, well-insulated coffee thermos. The transfer of heat energy between the coffee in the thermos and the thermos' surroundings is so slow that we can ignore that small amount of transfer and approximate the thermos as an isolated system.

1.3.4 Classifying Systems

To quickly categorize a system as open, closed, or isolated, ask yourself two questions:

1. Can matter enter or leave the system?
2. Can energy enter or leave the system?

If your answer to the first question is yes, you know automatically the system is open. If no, move to the second question. If energy can enter or leave, the system is closed. If not, the system is isolated. Sometimes, textbooks and exams will describe a system as "well-insulated". This is directing you to assume any transfer of energy between the system and surroundings is negligible, and that you should treat the system as an isolated system.

Exercise 3 Open, Closed, and Isolated Systems

Classify each system as open, closed, or isolated. Justify your answer.

1. The human body
2. Earth
3. Your cell phone
4. A well-insulated cooler with the lid sealed
5. A well-insulated cooler with the lid open
6. A bottle of soda before it is opened to be drunk

Working Space

Answer on Page 11

Appendix A

Answers to Exercises

Answer to Exercise 1 (on page 3)

1. balanced
2. unbalanced; oxygen
3. unbalanced; barium, sulfur, oxygen, and carbon
4. balanced

Answer to Exercise 2 (on page 6)

1. $v = \sqrt{2gh} = \sqrt{2\left(9.8\mathrm{m/s^2}\right)\left(3.7\mathrm{m}\right)} = 8.5\mathrm{m/s}$
2. $h = \frac{v^2}{2g} = \frac{\left(15\frac{m}{s}\right)^2}{2\left(9.8\frac{m}{s^2}\right)} = 11.5\mathrm{m}$. You can hit your little brother, since you could shoot the pebble as high as 11.5 m and he is only 5.0 m above you.
3. We know that $E_{p,initial} = E_{k,final} + E_{losttofriction}$. Therefore, $E_{losttofriction} = E_{p,initial} - E_{k,final} = mgh - \frac{1}{2}mv^2 = (63\mathrm{kg})\left(9.8\frac{m}{s^2}\right)(8\mathrm{m}) - \frac{1}{2}(63\mathrm{kg})\left(11.2\frac{m}{s}\right)^2 = 4939.2\mathrm{J} - 3951.4\mathrm{J} = 988\mathrm{J}$.

Answer to Exercise 3 (on page 9)

1. The human body is an open system because matter can enter (food, water, oxygen) and leave (waste, carbon dioxide, sweat) your body.
2. The Earth is an open system because matter can enter (asteroids falling, spaceships returning) and leave (space vehicles and astronauts). On the other hand, the Earth can be well-approximated as a closed system. Before the 20th Century, humans had no way to deliberately expel matter from the Earth, and the mass of asteroids that are pulled in by the Earth's gravity is negligible compared to the Earth. Therefore, in the right circumstances, it would be appropriate to model the Earth as a closed system. (It is closed because energy in the form of sunlight is constantly entering

the system.)

3. A cell phone is a closed system - you don't put any matter in or take it out of your phone, but it constantly uses battery and then is recharged, showing that energy enters and leaves your phone.
4. Since the cooler is described as well-insulated and the lid is closed, it can be approximated as an isolated system. Scientific equipment, like bomb calorimeters, rely on this approximation.
5. With the lid open, matter can enter and leave and therefore the cooler is an open system (yes, even though it is well-insulated).
6. A sealed bottle of soda is a closed system - the soda and carbon dioxide can't escape, but energy in the form of heat can be transferred in and out of the system (the contents of the bottle will lose heat if you put it in the fridge and gain heat if you leave it in the sun).

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