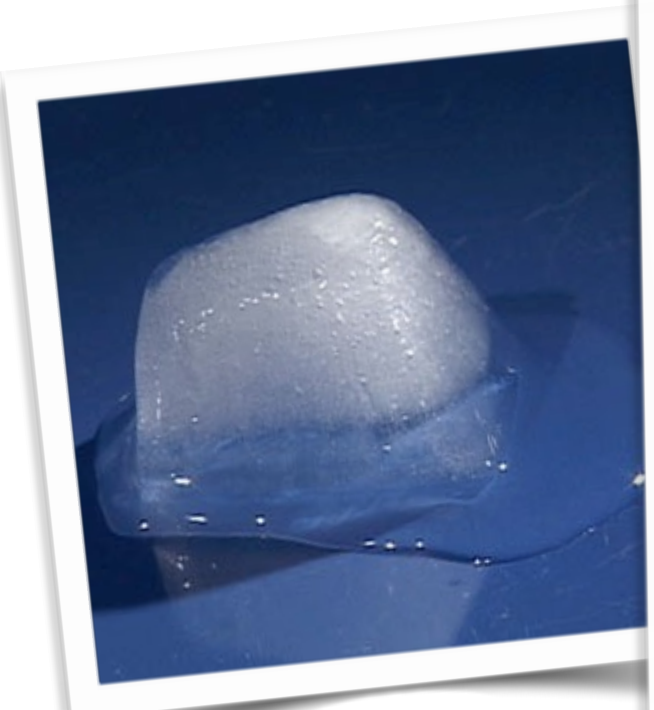
CHEM 100
Principles Of Chemistry



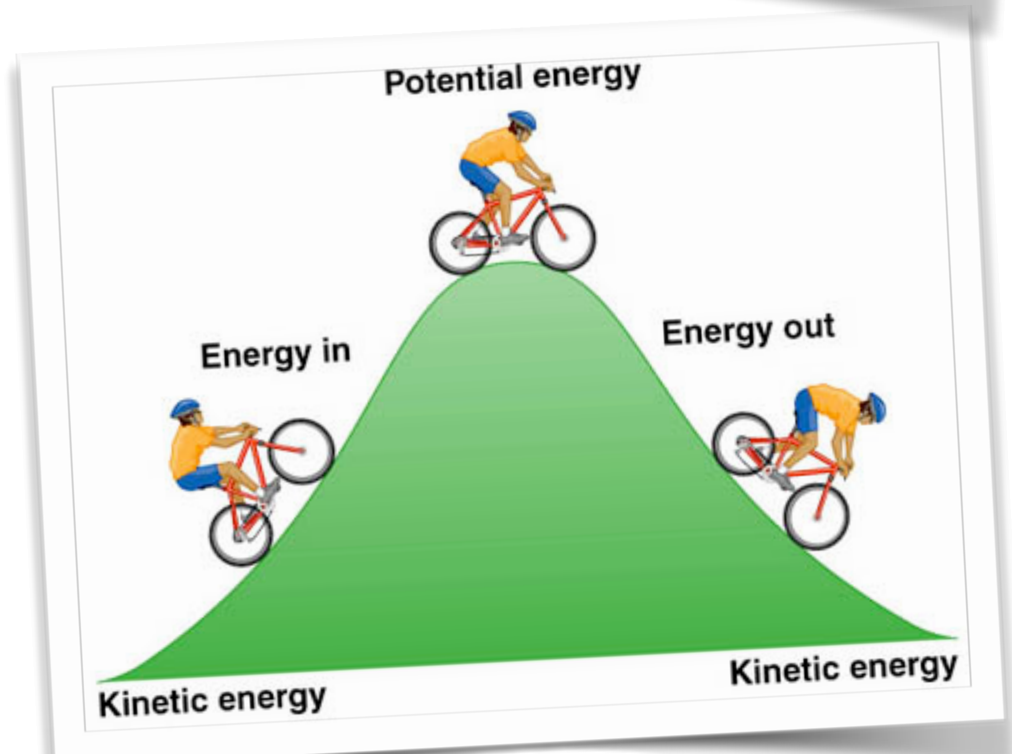
Chapter 4 - Chemical And Physical Changes

4.1 Energy

- Almost all physical and chemical changes involve the **transfer** or **conversion** of energy
- **Kinetic energy** (**KE**) is the energy of motion
  – The faster an object moves, the higher its KE
- **Potential energy** (**PE**) is stored energy because of position
  – Gravitational PE increases when an object is raised
  – Mechanical PE increases when a spring is stretched
  – Electrostatic PE increases when oppositely-charged particles are pulled apart
- KE is frequently converted to PE and vice versa

Energy Conversion

- At the top of the swing set arc, PE is maximum and KE is minimum
- At the middle of the swing set arc, PE is minimum and KE is maximum
- At the bottom of the hill, PE is minimum
- At the top of the hill, PE is maximum
- **Mechanical work** is required to convert KE to PE



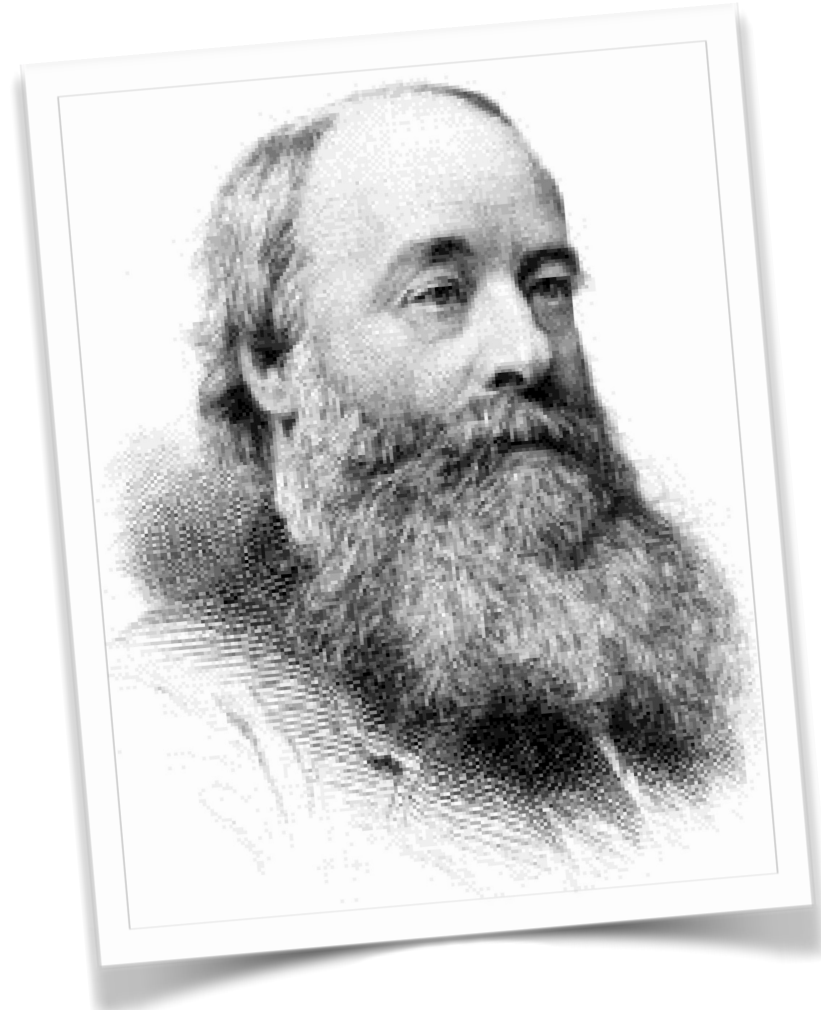
Types of Energy

- Mechanical work is done by exerting a **force** over a **distance**
  - Energy is simply the capacity to do work
- Other kinds of energy commonly encountered are:

1. **Radiant** (light) **energy**
   - Solar panels, photosynthesis
2. **Chemical energy**
   - Explosions, powering a car, using a gas stove
3. **Thermal** (heat) **energy**
   - Cooking on a stove, melting metal
4. **Electrical energy**
   - Turning on a light, powering a stereo, running a vacuum cleaner

The First Law of Thermodynamics

- The **first law of thermodynamics** states **energy is neither created nor destroyed, only converted from one form to another**
- The SI unit of energy is the **joule** (J)
  - The human heart uses 2-3 J every second
- Other non-SI units of energy are:
- **calorie** (1 cal = 4.184 J exactly)
- **Calorie** (food calorie) (1 Cal =



James Joule
(1819-1889)

Calories And Joules

$$19{,}600\ \mathrm{Cal} \times \frac{1000\ \mathrm{cal}}{1\ \mathrm{Cal}} \times \frac{4.184\ \mathrm{J}}{1\ \mathrm{cal}} = 82\ \mathrm{MJ}$$

- A person requires about 8.4 MJ (2000 Calories) per day
  - The Nathan's record corresponds to eating almost 10 days worth of food
- 1 lb of body fat stores about 15 MJ of energy
  - Equivalent to adding about 5.5 lbs of fat in a single meal!

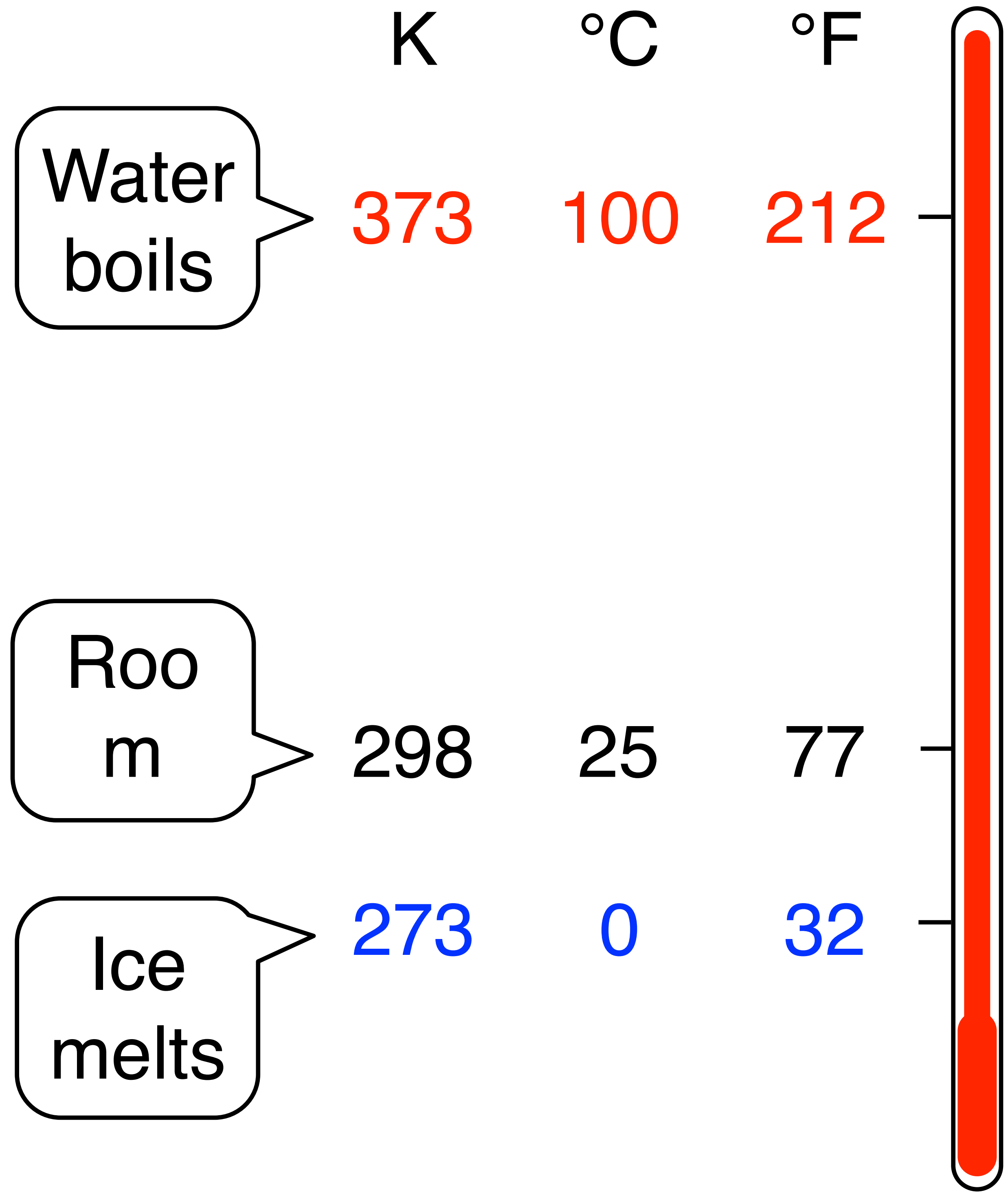
Nathan's hot dog eating contest winner 2008

4.2 Energy Changes

- When a process involves the absorption of heat, the **temperature** increases
- Temperature scales include the **Celcius** (°C), Fahrenheit (°F) and **Kelvin** (K)

$$t_{^\circ F} = (t_{^\circ C} \times \frac{9}{5}) + 32$$

$$t_K = t_{^\circ C} + 273.15$$



What Is Temperature?

- **Temperature** is a measure of the **average kinetic energy** of the atoms, molecules or ions
- What happens when the temperature of a solid rises?
- Solid particles are held in place by electrostatic forces
  - **Solid particles** are fixed but may vibrate in place
- The particles eventually have enough energy to overcome the attractions and the solid **melts**
  - **Liquid particles** move easily but remain close together on average
- At high temperature, the KE overcomes all

Changes Of State

- A **solid** has fixed shape and volume, is not easily compressed and particles are fixed by attractions
- A **liquid** has fixed volume but no fixed shape, is not easily compressed and particles are held by attractions but able to move past each other
- A **gas** takes the volume and shape of its container, is compressible and has widely-spaced particles moving rapidly

Using Equations As Shorthand

- For any process we can write

$$A \text{ (Initial State)} \xrightarrow{\text{Physical Change}} B \text{ (Final State)}$$

$$A \text{ (Reactants)} \xrightarrow{\text{Chemical Change}} B \text{ (Products)}$$

- For a chemical change the product is a new substance (element, compound or molecule)
- For a physical change the final state is <u>not</u> a new substance

A physical change

$$H_2O(s) \rightarrow H_2O(l)$$

Many physical changes are reversed by changing temperature/pressure

(s) = solid
(l) = liquid
(g) = gaseous
(aq) = aqueous

Endothermic And Exothermic Processes

- When ice melts, energy must be added to overcome the attraction between the molecules
- Heat-absorbing processes are called **endothermic** processes

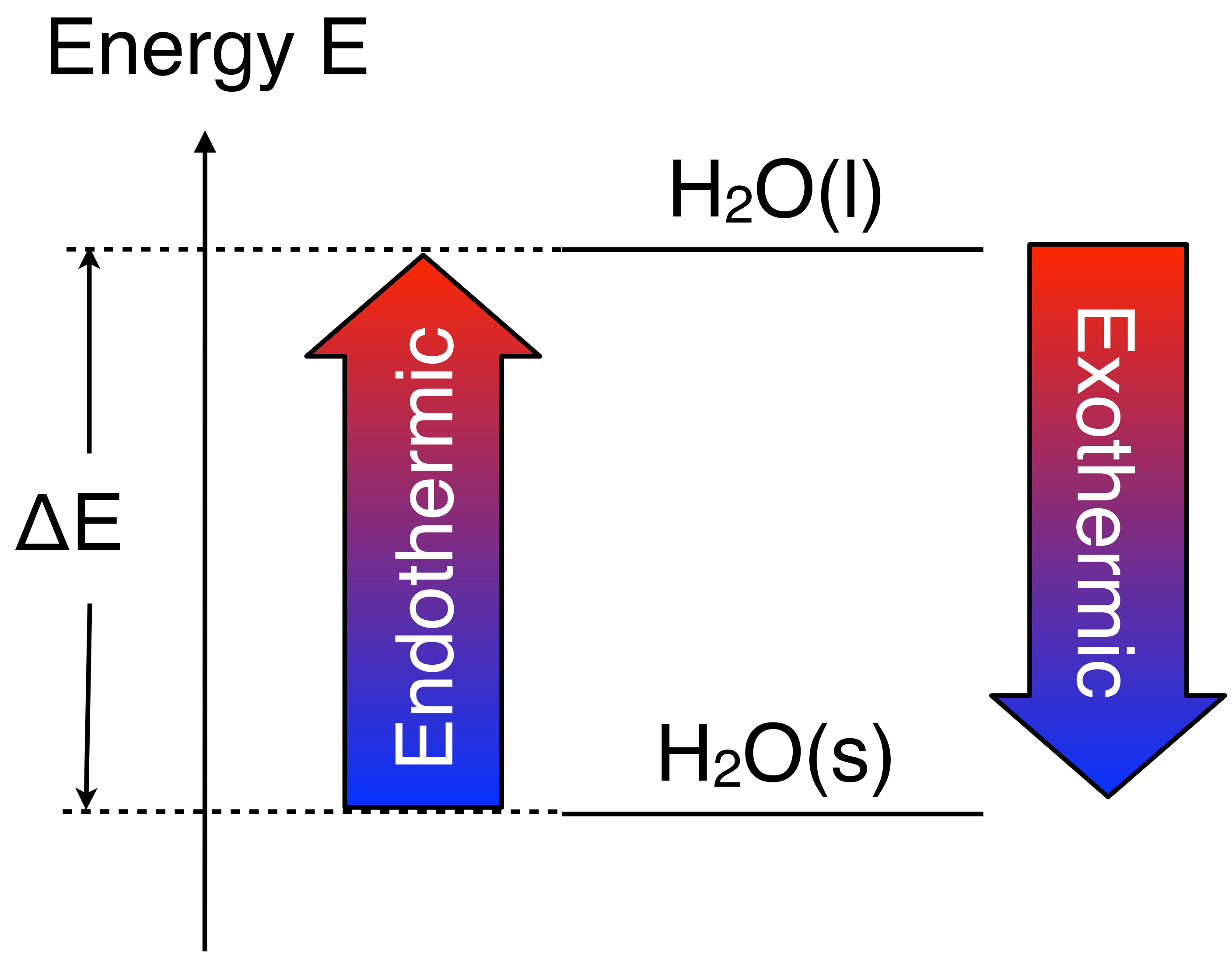
$$\text{Heat} + H_2O(s) \rightarrow H_2O(l)$$

- If we reverse the process, energy must be released
- Heat-releasing processes are called **exothermic** processes

$$H_2O(l) \rightarrow H_2O(s) + \text{Heat}$$

Energy Level Diagrams

- Alternately, we could draw an **energy level diagram**
- If we add energy to ice to melt it, liquid water must contain more energy than ice <u>at the same temperature</u>



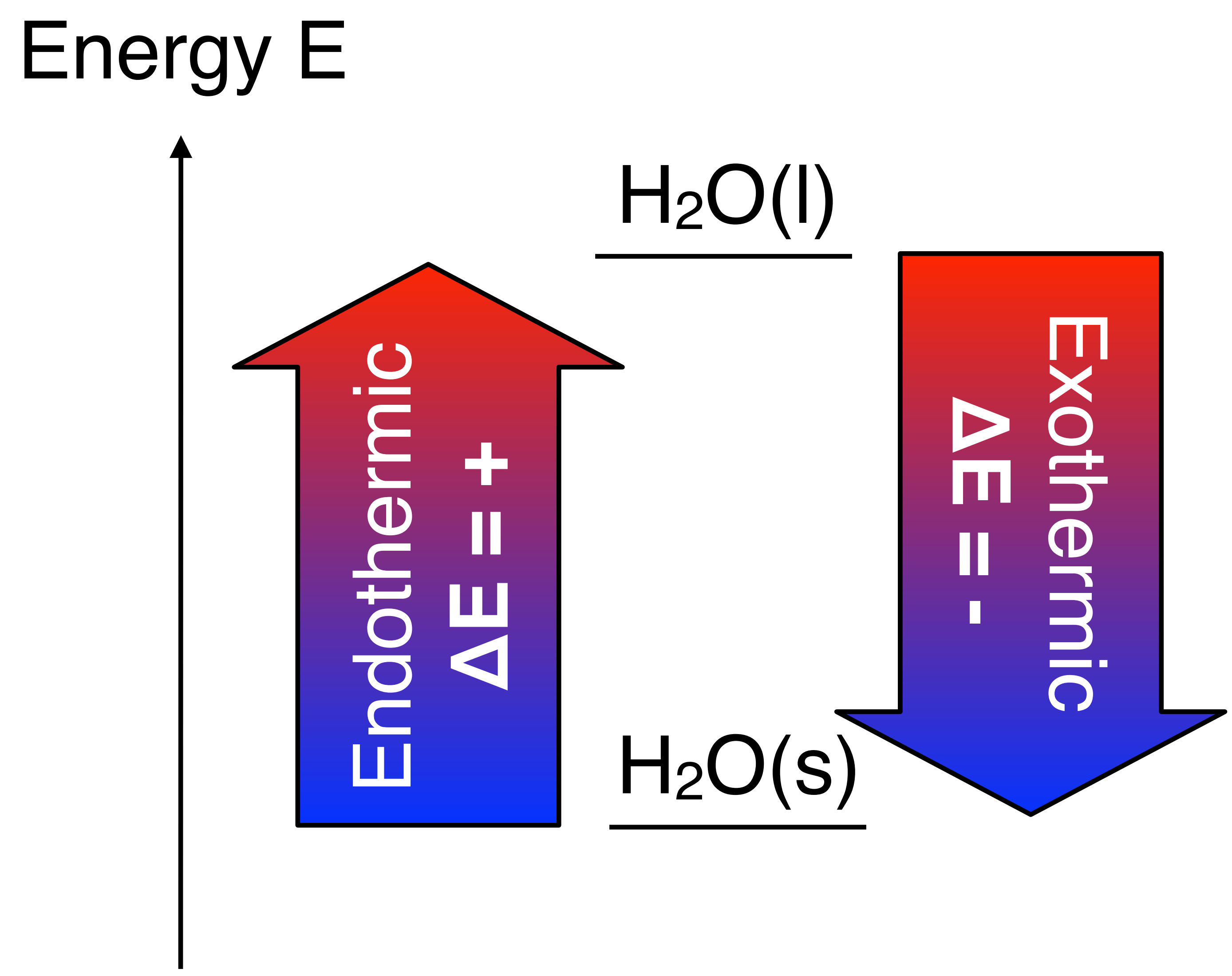
Δ (delta) means "change" or "difference"

ΔE And Energy Changes

- Changes in quantities are always written

$$\Delta E = E_{final} - E_{initial}$$

- For an **endothermic** process, $E_{final} > E_{initial}$ so ΔE is a **positive** quantity
- For an **exothermic** process, $E_{final} < E_{initial}$ so ΔE is a **negative** quantity



In this class you won't learn how to predict if a process is exo- or endothermic

Energy And Temperature Changes

- For a single state of matter, adding **heat** (**q**) causes a **temperature change** (**ΔT**) that must depend on the mass of the object (m)

$$q \propto m \cdot \Delta T$$

- Turning the proportionality into an equality

$$q = c \cdot m \cdot \Delta T$$

  where c is called the **specific heat** of the object

- q has units of J, m has units of g, ΔT has units of °C so c has units of J/g·°C
  - c represents the amount of heat required to raise the temperature of 1 g of the object by 1 °C

Energy And Temperature Changes

Q How much heat is released when a 105 g Cu block cools from 52 °C to 21 °C (c = 0.385 J/°C·g)?

A The equation is

$$q = c \cdot m \cdot \Delta T$$

where c = 0.385 J/°C·g, m = 105 g and $\Delta T = T_{final} - T_{initial}$ = 21 °C - 52 °C = -31 °C

So

$$\begin{aligned} q &= c \cdot m \cdot \Delta T \\ &= 0.385 \frac{J}{°C \cdot g} \times 105\ g \times (-31\ °C) \\ &= -1253.175\ J \\ &= -1.3\ kJ \end{aligned}$$

Minus sign means heat released

2 significant figures

Specific Heat And Temperature Changes

- A material with strong attractions between the particles will require more energy to cause the particles to vibrate
- The material will have a higher specific heat
  - Metals heat up easily
  - Water heats up less easily
  - Ice heats up more quickly than water
  - Aluminum pans heat up more quickly that the water inside

Substance	Specific Heat (J/g·°C)
$H_2O(l)$	4.18
$H_2O(s)$	2.05
Al(s)	0.902
Cu(s)	0.385
Au(s)	0.128
Fe(s)	0.45

4.3 More Conservation Laws

- **Antoine Lavoisier** discovered that the total mass is conserved in a chemical reaction
  - 103.4 g of reactants produces 103.4 g of products
- This is called the **law of conservation of mass**
- Recently it has been found that there are very tiny changes in total mass when energy is released or absorbed by a chemical reaction

Antoine Lavoisier
(1743-1794)

More Conservation Laws

- For an exothermic reaction, the total mass of products is very slightly less than the mass of reactants
  - The mass is converted to released energy
- For an endothermic reaction, the total mass of products is very slightly greater than the mass of reactants
  - The absorbed energy is converted to mass
- The law is now called the **law o conservation of mass and**

Albert Einstein
(1879-1955)

The difference can be ignored in this class

4.4 Chemical Reactions And Chemical Equations

- Chemical equations are shorthand for providing all relevant information for a chemical or physical change
- A **word equation** is the first step:

Carbon solid + oxygen gas → carbon monoxide gas

- If we substitute chemical formulas for the words we make an **unbalanced chemical equation**

$$C(s) + O_2(g) \rightarrow CO(g)$$

- This equation is <u>unbalanced because it does not have the same number of atoms on each side of the arrow</u>

Balancing Chemical Equations

- To balance a chemical equation we add numbers (**coefficients**) <u>before</u> the chemical formulas

$$C(s) + O_2(g) \rightarrow CO(g)$$

- Notice that there are two O atoms on the left but only one O atom on the right?
  - Any chemical formula without a coefficient is assumed to be 1
- We can balance by adding a coefficient of ½ before O_2

$$C(s) + \frac{1}{2}\, O_2(g) \rightarrow CO(g)$$

- Now we have a **balanced chemical equation**

Balancing Chemical Equations

- In general, balanced chemical equations are written with the smallest <u>integers</u> as coefficients
- We can achieve this by multiplying all coefficients by 2

$$C(s) + \tfrac{1}{2}\, O_2(g) \rightarrow CO(g)$$

- Becomes

x 2

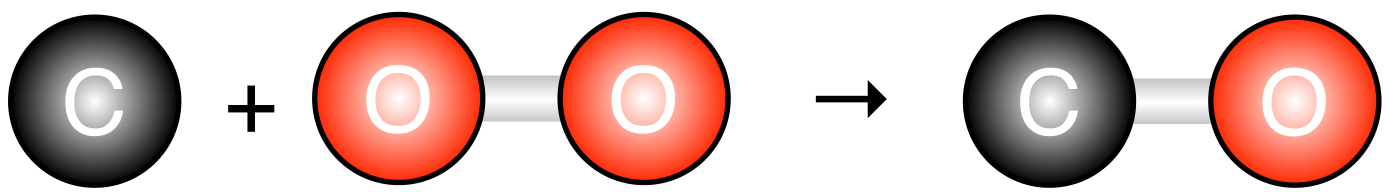
$$2\, C(s) + O_2(g) \rightarrow 2\, CO(g)$$

  - Now we have a **fully balanced chemical equation**
  - Note you <u>cannot alter the chemical formulas</u> to balance an equation, only the coefficients!

Balancing Chemical Equations

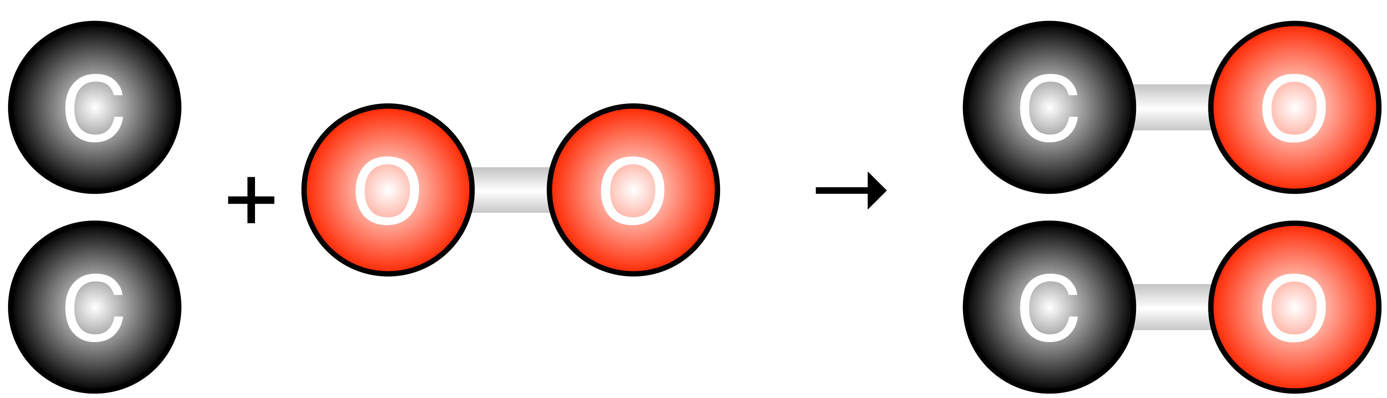
- Let's put this into pictures:

$C(s) + O_2(g) \rightarrow CO(g)$ — Unbalanced



$C(s) + \frac{1}{2} O_2(g) \rightarrow CO(g)$ — Balanced

$2\,C(s) + O_2(g) \rightarrow 2\,CO(g)$ — Fully balanced



Test Yourself: Chemical Equations

Q Write a balanced chemical equation for the reaction of lithium metal and chlorine gas making lithium chloride

A Word equation:

Lithium solid + chlorine gas → lithium chloride solid

Unbalanced chemical equation:

$$Li(s) + Cl_2(g) \rightarrow LiCl(s)$$

Balanced chemical equation:

$$Li(s) + \tfrac{1}{2}\, Cl_2(g) \rightarrow LiCl(s)$$

Fully balanced chemical equation:

$$2\, Li(s) + Cl_2(g) \rightarrow 2\, LiCl(s)$$

Test Yourself: Chemical Equations

Q Write a balanced chemical equation for the reaction of calcium metal and oxygen gas making calcium oxide solid

$2\ Ca(s) + O_2(g) \rightarrow 2\ CaO(s)$

Test Yourself: Chemical Equations

Q Write a balanced chemical equation for the reaction of nitrogen gas and oxygen gas making dinitrogen tetroxide gas

$N_2(g) + 2\ O_2(g) \rightarrow N_2O_4(g)$

Test Yourself: Chemical Equations

Q Write a balanced chemical equation for the reaction of solid sulfur and oxygen gas making sulfur trioxide gas

$2\ S(s) + 3\ O_2(g) \rightarrow 2\ SO_3(g)$

Test Yourself: Chemical Equations

Q Write a balanced chemical equation for the reaction of aqueous silver nitrate and aqueous sodium chloride making silver chloride solid and aqueous sodium nitrate

$AgNO_3(aq) + NaCl(aq) \rightarrow AgCl(s) + NaNO_3(aq)$

Test Yourself: Chemical Equations

Q Write a balanced chemical equation for the reaction of aqueous hydrochloric acid and iron making iron (II) chloride and hydrogen

$2\ HCl(aq) + Fe(s) \rightarrow FeCl_2(s) + H_2(g)$

4.5 Classification of Chemical Reactions

- Chemical reactions are grouped into similar types, ones that follow similar patterns
- We will look at:

1. **Combination** reactions
2. **Decomposition** reactions
3. **Combustion** reactions
4. **Displacement** reactions

- In many cases, knowing the type of chemical reaction

Reaction of wood and oxygen - a combustion reaction

Decomposition Reactions

- In a **decomposition reaction** a <u>single substance breaks down</u> to make <u>two or more new substances</u>

$$AB \rightarrow A + B$$

  – These are the opposite of combination reactions

- Examples include

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

$$2\ H_2O_2(l) \rightarrow 2\ H_2O(l) + O_2(g)$$

$$6\ NaHCO_3(s) \rightarrow 3\ Na_2CO_3(s) + 3\ H_2O(l) + 3\ CO_2(g)$$

- Again, the specific products are difficult to predict

Combination Reactions

- In a **combination reaction**, <u>two or more substances</u> react to form <u>a single product</u>

$$A + B \rightarrow AB$$

- Examples include

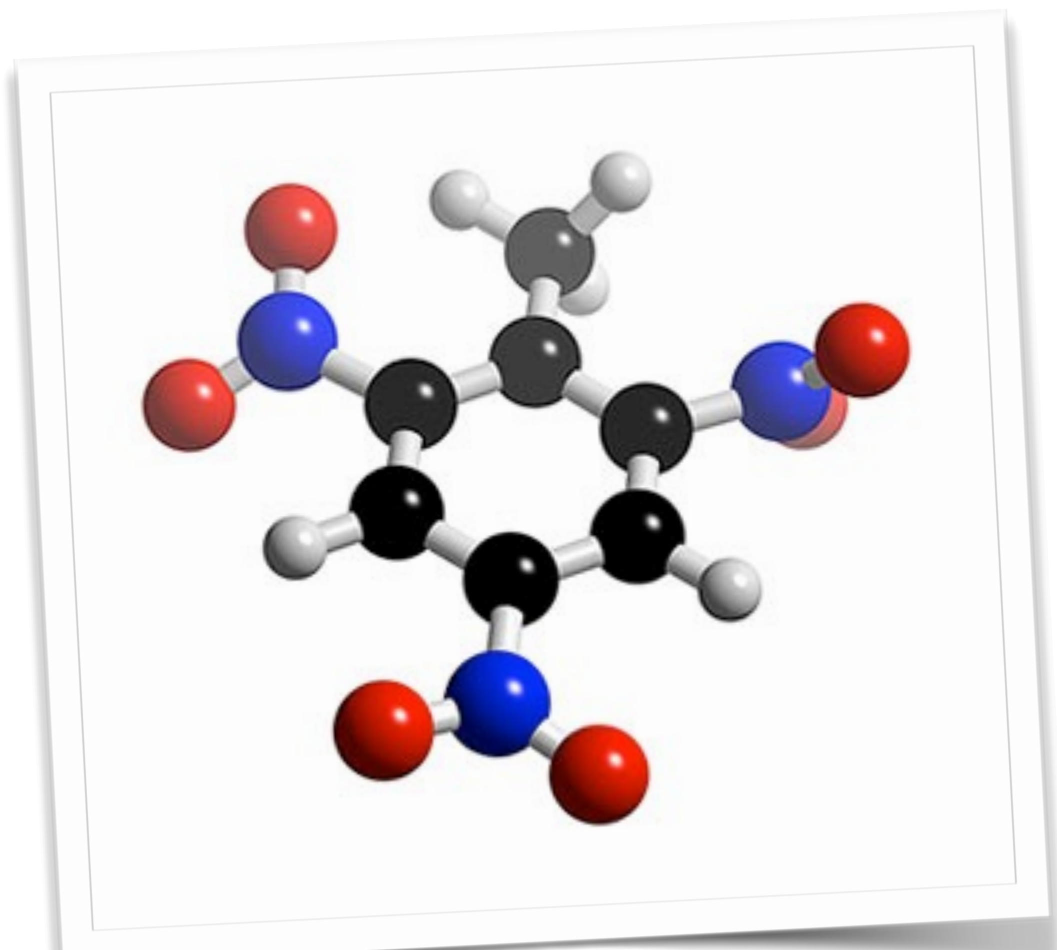
$$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(l)$$
$$N_2(g) + 2\ O_2(g) \rightarrow 2\ NO_2(g)$$
$$Ti(s) + O_2(g) \rightarrow TiO_2(s)$$

- The chemical formula of molecular compound products are difficult to predict but ionic compounds are straightforward

Decomposition Reaction

- Many explosives are decomposition reactions
- The decomposition reaction for trinitrotoluene (TNT) is

$$2\ C_7H_5N_3O_6(s) \rightarrow 3\ N_2(g) + 5\ H_2O(l) + 7\ CO(g) + 7\ C(s)$$



Combustion Reactions

- In a **combustion reaction** a compound containing C and H (a **hydrocarbon**) or C,H and O only reacts with oxygen

Unbalance

$$C_xH_y + O_2(g) \rightarrow CO_2(g) + H_2O(l)$$

$$C_xH_yO_z + O_2(g) \rightarrow CO_2(g) + H_2O(l)$$

- The reactants may be solids, liquids or gases
- Many combustion reactions are exothermic
- C_xH_y and $C_xH_yO_z$ include many fuels such as natural gas (CH_4), gasoline (mostly C_8H_{18}) and sugar ($C_{12}H_{22}O_{11}$)

Combustion Reactions

- Examples include

$$CH_4(g) + 2\ O_2(g) \rightarrow CO_2(g) + 2\ H_2O(l)$$

$$2\ C_8H_{18}(l) + 25\ O_2(g) \rightarrow 16\ CO_2(g) + 18\ H_2O(l)$$

- When balancing combustion reactions, start with C and H atoms by adding coefficients in front of $CO_2(g)$ and $H_2O(l)$, respectively
- Then balance O by adding coefficients in front of the $O_2(g)$ reactant

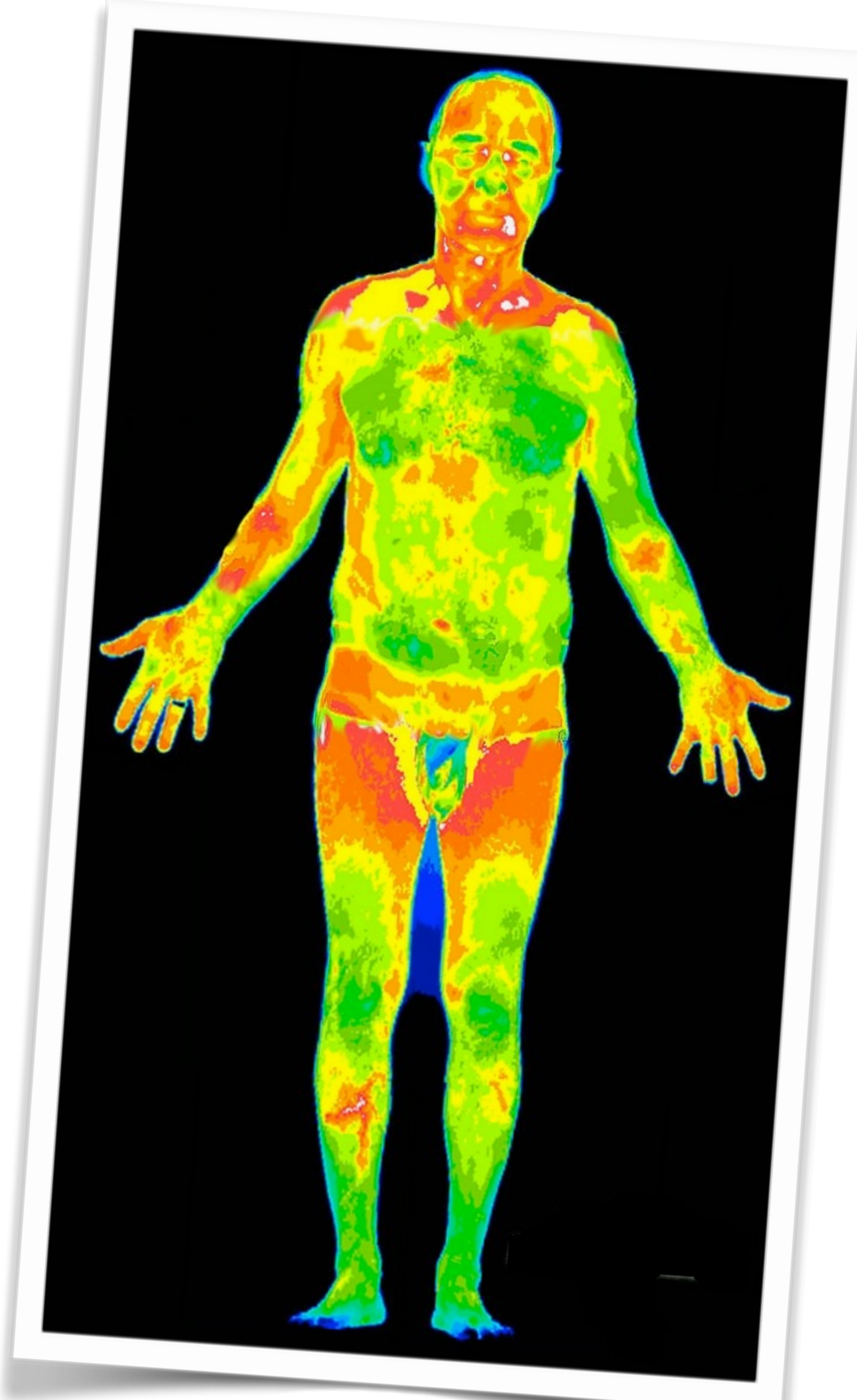
Test Yourself: Chemical Equations

Q Write a balanced chemical equation for the combustion of sugar ($C_{12}H_{22}O_{11}$)

$C_{12}H_{22}O_{11}(s) + 12\ O_2(g) \rightarrow 12\ CO_2(g) + 11\ H_2O(l)$

Combustion Reactions

- Combustion reactions inside human cells produce $CO_2(g)$ and $H_2O(g)$ which are exhaled
- The energy released drives many biochemical reactions and keeps us warm
  - The human body releases about 100 J/s (100 Watts) at rest and 1000 J/s (1000 Watts) during a fast sprint



Displacement Reactions

- In a **single displacement reaction**, atom A displaces atom B from compound BC to form two new substances

$$A + BC \rightarrow AC + B$$

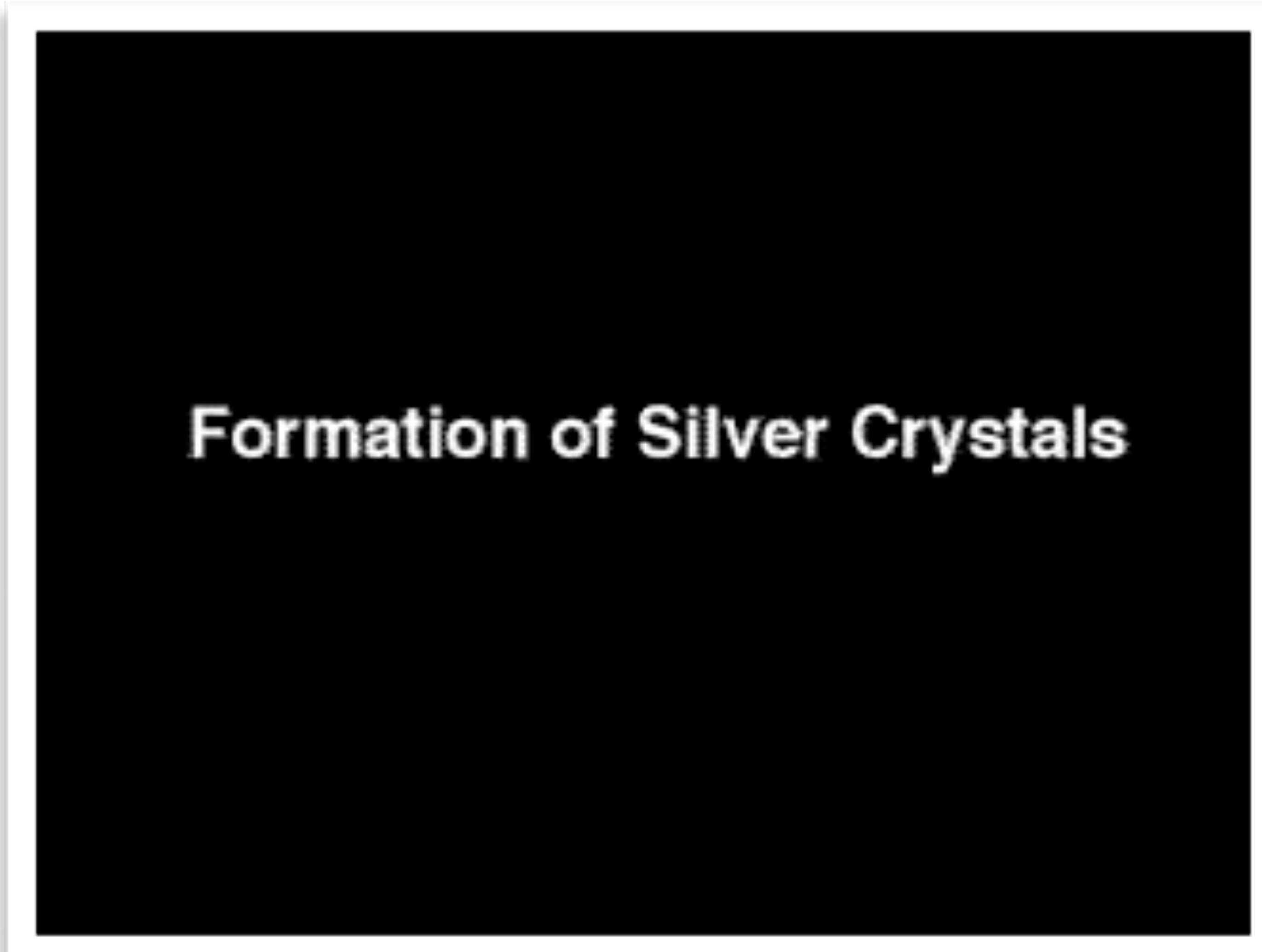
- Both atoms A and B must be metals, hydrogen or halogens
- Examples include

$$Fe(s) + CuSO_4(aq) \rightarrow FeSO_4(aq) + Cu(s)$$

$$Mg(s) + 2\ HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$$

$$Ca(s) + 2\ H_2O(l) \rightarrow Ca(OH)_2(aq) + H_2(g)$$

Displacement Reactions



$$Cu(s) + 2\,AgNO_3(aq) \rightarrow Cu(NO_3)_2(aq) + 2\,Ag(s)$$

Cu^{2+} = Blue

Displacement Reactions

- In a **double displacement reaction**, cations A and C swap places with anions B and D to form two new substances

$$AB + CD \rightarrow AD + CB$$

- Cations A and C and anions B and D may be monatomic or polyatomic
- Examples include

$$AgNO_3(aq) + HCl(aq) \rightarrow HNO_3(aq) + AgCl(s)$$

$$Na_2SO_4(aq) + BaCl_2(aq) \rightarrow BaSO_4(s) + 2\ NaCl(aq)$$

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$$

4.6 Solubility Of Ionic Compounds

- In double displacement reactions some ionic substances produced are (aq) and some (s)
- In other words, some ionic substances are **soluble** in water
  - They dissolve and are shown as (aq)
- Some ionic substances are **insoluble** in water
  - They don't dissolve and are shown as (s)
- An insoluble product formed in aqueous solution is called a **precipitate**

$$3\ CaI_2(aq) + 2\ Li_3PO_4(aq) \rightarrow 6\ LiI(aq) + Ca_3(PO_4)_2(s)$$

Displacement Reactions

- Double displacement precipitation reactions are sometimes desirable because products can be separated easily by filtering

$$Pb(NO_3)_2(aq) + 2\ KI(aq) \rightarrow 2\ KNO_3(aq) + PbI_2(s)$$

Insoluble yellow PbI_2 forming in $KNO_3(aq)$

Precipitation Reactions

$$NaCl(aq) + AgNO_3(aq) \rightarrow NaNO_3(aq) + AgCl(s)$$

$$NaI(aq) + AgNO_3(aq) \rightarrow NaNO_3(aq) + AgI(s)$$

Precipitate

Solubility Of Ionic Compounds

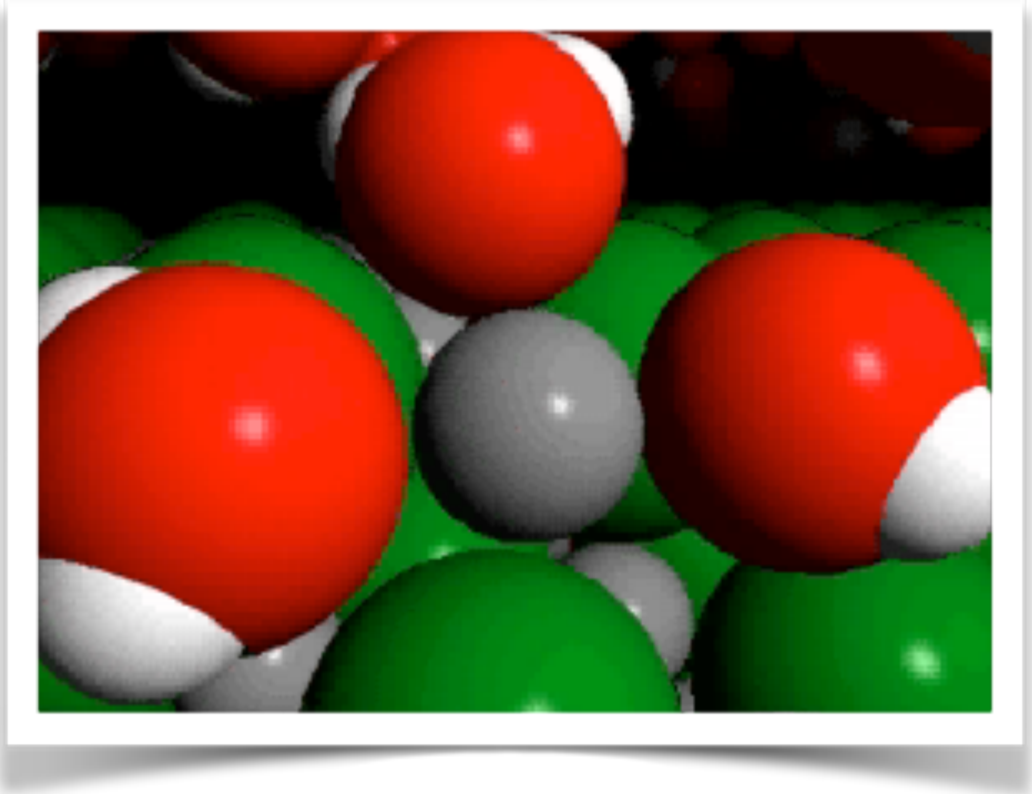
- How do we predict whether an ionic substance will be soluble or insoluble?

1. The **solubility rules** list the solubility of major types of cations and anions
   - For example, all nitrates are soluble in water
   - But there are many exceptions and the list is long
2. Another approach relies on gauging the <u>strength of the attraction</u> between the oppositely-charged ions
   - When an ionic compound dissolves, the ions are separated and free to move in the solution

Solubility Of Ionic Compounds

- How does an ionic compound dissolve?

1. Water molecules cluster around the ions
2. If the ions are held together weakly, water molecules are able to cluster around the ion and separate it
3. The ion travels through the solution with water clustered around it



Soluble NaCl dissolving in water

Solubility Of Ionic Compounds

- Coulomb's law tells us that the force between oppositely-charged ions increases with q_1 and q_2 (the charges of the ions)
  - The lower the charge, the weaker the attraction
- **Compounds containing +1 and/or -1 ions** tend to be **soluble**
  - Main exceptions are compounds containing +2 or +3 cations and OH^-
- **Compounds containing only +2/+3 and -2/-3 ions** tend to be **insoluble**
  - Main exception is compounds containing SO_4^{2-}

Test Yourself: Solubility

- Are the following ionic compounds likely to be

Formula Unit	Cation	Anion	Soluble?
$NaBr$	Na^{+}	Br^{-}	Yes
$MgCl_2$	Mg^{2+}	Cl^{-}	Yes
$NiSO_4$	Ni^{2+}	SO_4^{2-}	Yes (exception)
$MgCO_3$	Mg^{2+}	CO_3^{2-}	No
Na_2CO_3	Na^{+}	CO_3^{2-}	Yes
Al_2O_3	Al^{3+}	O^{2-}	No