CHE 1031: General Chemistry I

2. **Atoms, molecules & ions**

   2.1: Early ideas about atomic theory

   2.2: Evolution of atomic theory

   2.3: Atomic structure & symbolism

   2.4: Chemical formulas

   2.5: The periodic table

   2.6: Molecular & ionic compounds

   2.7: Naming chemical compounds → *covered in lab*

2. Atoms, molecules & ions

2.1: Early ideas about atomic theory

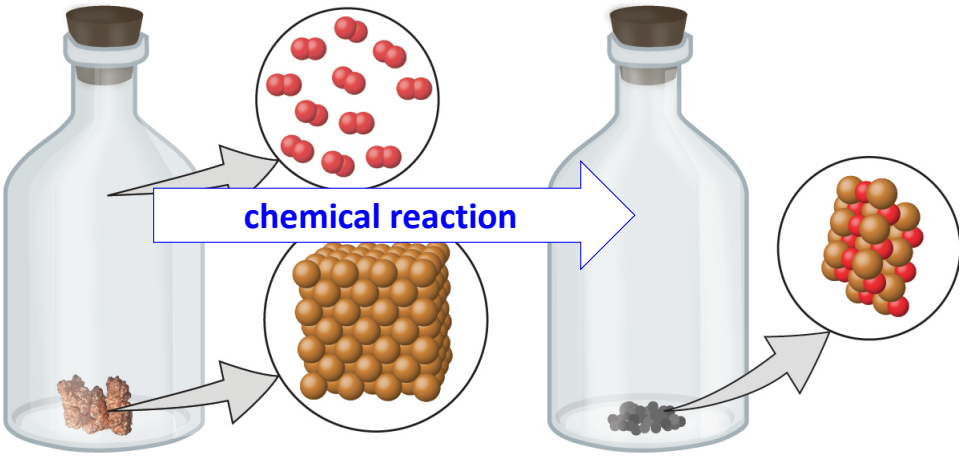
- State the postulates of Dalton's atomic theory
- Use postulates of Dalton's atomic theory to explain the laws of definite & multiple proportions

Dalton's atomic theory

1806, English school teacher John Dalton used **experiments** to revive the ancient concept of a universal element of matter & proved the existence of the atom.

1. Matter is composed of tiny particles called **atoms***: smallest unit of an element that can participate in chemical change.*
2. Every element is made of one type of atom with a characteristic mass. All atoms of one element are identical.
3. The atoms of each element differ & are found only in that element.
4. A compound is made by combining atoms of two or more elements at a constant, whole-number ratio.
5. Chemical reactions neither create nor destroy atoms, but rearrange them to create new substances.

Visualize a chemical reaction



The elements copper and oxygen

The compound copper(II) oxide

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Obeying Dalton's postulates?

Do the chemical reactions shown here obey the five postulates of Dalton's atomic theory? If not, why?

1

Nope.
Matter is not conserved as the product is missing two atoms, one blue, one green.

Yes!
Matter is conserved here.

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Law of definite proportions

Aka **Law of constant composition:**
all samples of one compound have the same elements in the same proportion by mass, or the same atomic ratio

sample*	carbon (g)	hydrogen (g)	mass ratio (C : H)
A	14.82	2.78	5.33 : 1.00
B	22.33	4.19	5.33 : 1.00
C	19.40	3.64	5.33 : 1.00

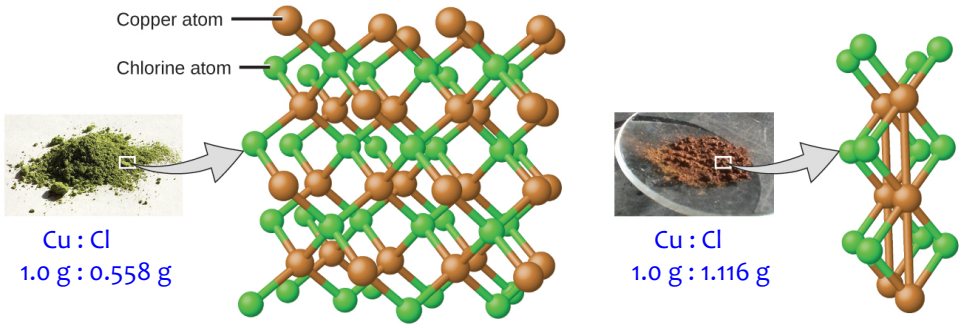
*isooctane, C8H18

Dalton knew of this work done by the French chemist Joseph Proust.

Law of multiple proportions

Law of multiple proportions: *two elements can be combined in a number of different proportions or ratios to create a number of different compounds*

- *Multiple proportions produce multiple compounds*



Here Dalton riffed on Proust's work, adding his own experiments.

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Try this

Compounds A & B are both clear & odorless gases.
A sample of compound A is found to contain 4.27 g of C and 5.69 g of O. A sample of compound B is found to have 5.19 g of C and 13.84 g of O.
Are A & B examples of the law of definite proportions, the law of multiple proportions, or neither?

2

A $\frac{5.69 \text{ g O}}{4.27 \text{ g C}} = \frac{1.33 \text{ g O}}{1.00 \text{ g C}}$

B $\frac{13.84 \text{ g O}}{5.19 \text{ g C}} = \frac{2.67 \text{ g O}}{1.00 \text{ g C}}$

A & B illustrate the law of multiple proportions.

Can you?

(1) State all the postulates of Dalton's atomic theory?

(2) State the law of definite proportions describe how it relates to molecular formulas?

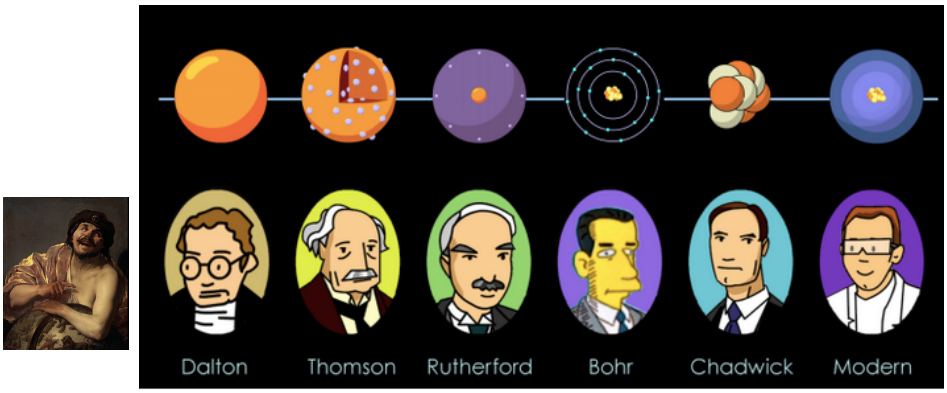
(3) Explain the law of multiple proportions & give an example?

2. Atoms, molecules & ions

2.2: Evolution of atomic theory

- Outline milestones in the development of atomic theory
- Summarize & interpret the results of the experiments of Thomson, Millikan & Rutherford
- Describe the three subatomic particles of atoms
- Define isotopes & give examples of several elements

Atomic structure timeline



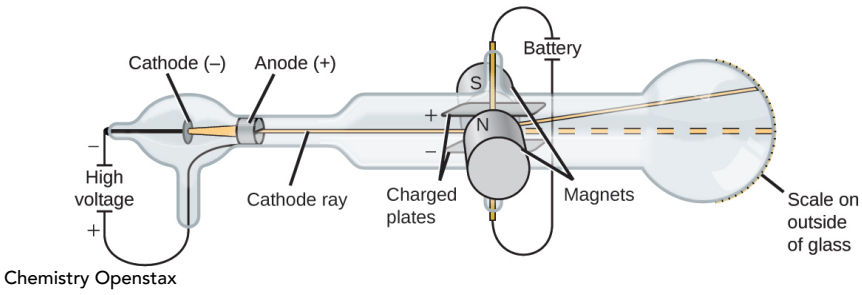
400 BC **1808** **1897** **1911** **1913** **1932**

Note that a lack of **technology**, not a lack of intelligence or human imagination, kept our knowledge of the atom from advancing more quickly.

Thomson discovers electrons

1897, JJ Thomson used a cathode ray tube to discover the first **subatomic particle**, the **electron**.

- Partially evacuated glass tube containing a cathode & anode.
- When electricity is applied, a **cathode ray** flowed from the cathode toward the anode.
- Magnets deflected the beam, showing it was negatively charged.
- Calculations showed the particle was much lighter than an atom.



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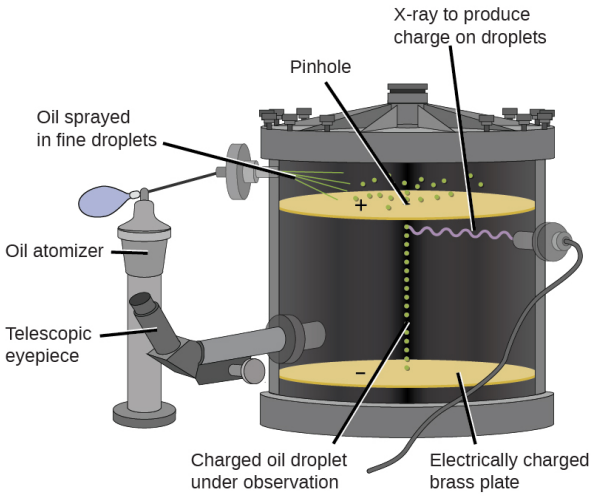
Millikan discovers electron's charge

1909, Robert Millikan coated tiny droplets of oil with electrons & determined their charge.

- The speed at which e-coated oil droplets fell could be changed by an electric field.
- Calculations showed that electrons have a **charge of 1.6 E-19 Coulombs & mass of 9.107 E-28 g.**



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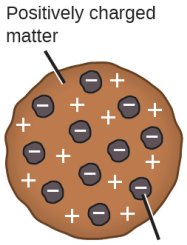
New model for the atom?

So, where were the electrons located? Competing models:

Plum pudding model
(Thomson)
The atom is a positively charged mass, studded with randomly placed & negatively charged electrons.



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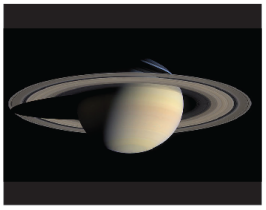
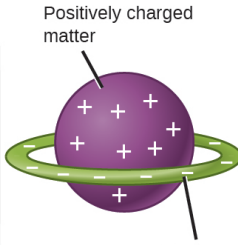
Saturn model
(Nagaoka)
The atom is a positively charged mass, orbited by negatively charged electrons.

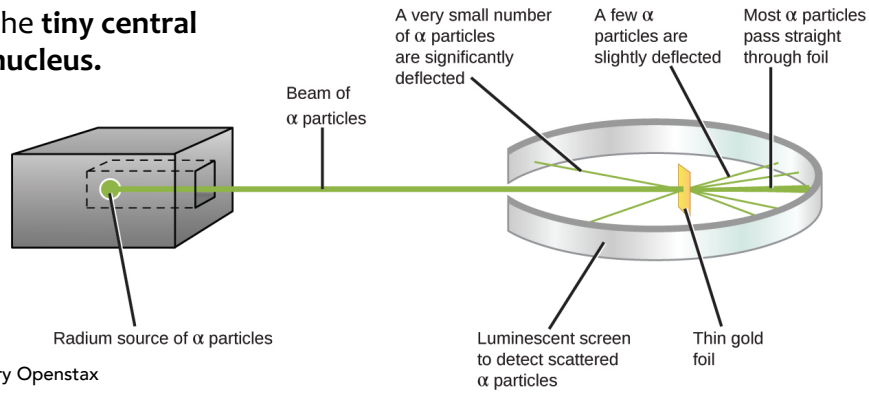




Rutherford goes nuclear

1911, Ernest Rutherford's gold foil experiment shows that Nagaoka's model is better → **'nuclear' model of the atom.**

- Heavy alpha particles were aimed at gold foil 1-2 atoms thick.
- Most particles passed through without deflection, showing that most of the atom held light electrons.
- All dense material is in the **tiny central nucleus.**



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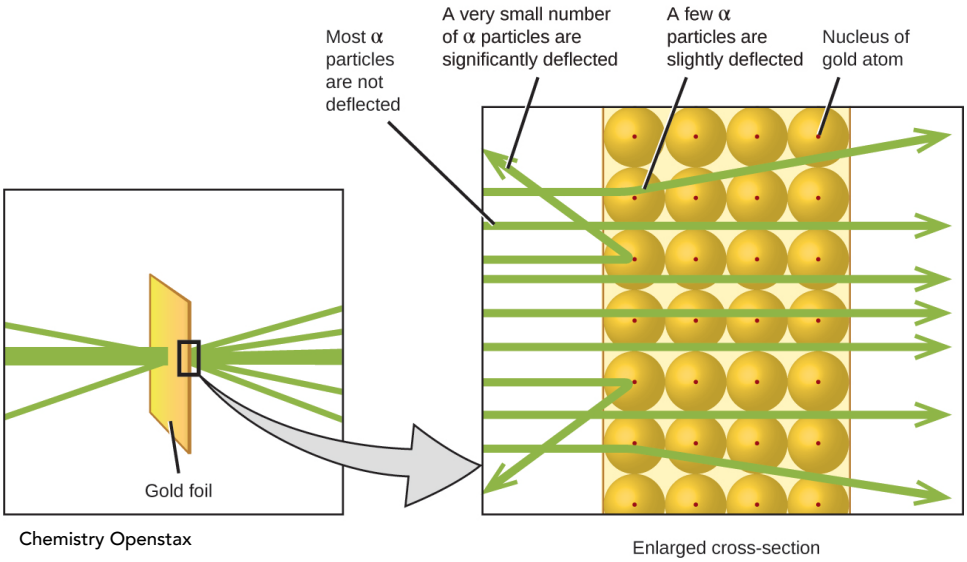
The nuclear model

How tiny is the nucleus?

The size of a tiny pea suspended in the world's largest stadium.



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Isotopes

Isotopes: *atoms of the same element that differ in mass*

Isotopes have the same number of protons & electrons, but the number of neutrons differs.

Neutrons are heavy, uncharged particles that – together with positively charged protons – are found in the nucleus.

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Can you?

(1) Explain how Thomson used a cathode ray tube to discover the electron?

(2) Describe the essential difference between Thomson's plum pudding model and Nagaoka's Saturn model?

(3) Explain how the nuclear model was developed from the data Rutherford collected in his gold foil experiment?

(4) Explain how isotopes differ from 'standard' atoms of an element?

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2. Atoms, molecules & ions

2.3: Atomic structure & symbolism

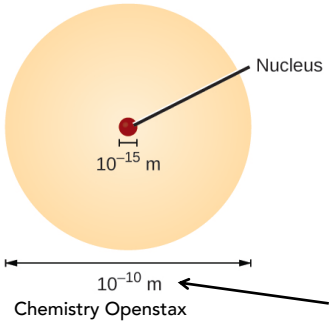
- Write & interpret symbols that depict atomic number, atomic mass and charge of atoms & ions
- Define the atomic mass unit & average atomic mass
- Calculate average atomic mass & isotopic abundance

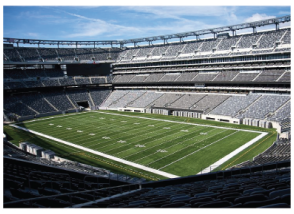
Picturing atoms

Most of the volume of the atom is occupied by electrons & is called the **electron cloud**.

The tiny & dense **nucleus** is located in the center of the atom & holds all of the heavy particles: **protons** & **neutrons**.

If an atom is the size of a superdome stadium, the nucleus is the size of a blueberry.





The angstrom (Å; 1 E-10 m) is used to measure atoms.

Protons, neutrons & electrons

Compare the atom's three subatomic particles:

particle	location	charge (C)	charge	mass (amu)	mass (g)
electron	cloud	- 1.602 E-19	-1	0.00056	0.00091 E-24
proton	nucleus	+ 1.602 E-19	+1	1.00727	1.67363 E-24
neutron	nucleus	none	0	1.00866	1.67493 E-24

C is Coulomb, a unit of electric charge.
Amu is atomic mass unit, an arbitrary & comparative unit of mass.

Atomic number & mass

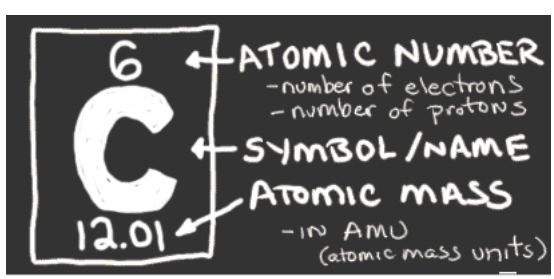
Atomic number: *the unique identifier for each atom*

- *the number of protons in each element*
- *also number of electrons in an atom*

Atomic mass: *the mass of each atom (amu or g/mole)*

- *roughly = #p + # n*

Number of neutrons: *= atomic mass – atomic number*



http://www.chem4kids.com/files/elements/006_shells.html

Calculating atomic contents

Iodine is atomic number 53 and has a mass of 127 amu.
Iodine gains one electron to form iodide ions, I^{-1}.
How many protons, neutrons & electrons are there in an iodide ion?

3

Iodine atoms & iodide ions both have 53 protons.

- *The number of protons in an atom never changes.*

Iodine **atoms** have the same number of protons & electrons, so 53 electrons. But iodide **ions** have gained one electron to create the charge of -1. So, iodide ions have 53 + 1 = 54 electrons.

The number of neutrons = 127 – 53 = 74

- *The number of neutrons is the same in atoms & ions.*

Try this

An ion of platinum has a mass number of 195 and has 74 electrons.
How many protons & neutrons does it have?
What is its charge?

4

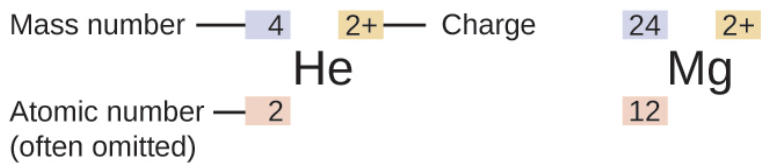
Pt has atomic number 78, so it has 78 protons.

With 74 electrons, it's lost 4 electrons & must have a charge of +4.

Neutrons = 195 – 78 = 117

Isotope symbols

While atoms are represented by a letter or two, the symbol for an isotope must also include **isotopic mass**, since the mass of an isotope can be lighter or heavier than that of other atoms of the same element.



Magnesium (Mg) has three isotopes with masses of 24, 25 & 26:

^{24}Mg, ^{25}Mg, ^{26}Mg *'magnesium 24"*

All isotopes of Mg have 12 protons. Numbers of **neutrons** differ:

^{24}Mg 24 – 12 = 12 n
^{25}Mg 25 – 12 = 13 n
^{26}Mg 26 – 12 = 14 n

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Isotope abundance

Each element can have a number of **different isotopes** and they occur at **different abundances** or frequencies (%).

element	symbol	atomic #	# p	# n	mass (amu)	%
hydrogen	^{1}H	1	1	0	1.0.....	99.9885
deuterium	^{2}H	1	1	1	2.0141	0.0115
tritium	^{3}H	1	1	2	3.01605	trace
helium	^{3}He	2	2	1	3.01603	0.00013
	^{4}He	2	2	2	4.0026	<100
carbon	^{12}C	6	6	6	12.0000	98.89
	^{13}C	6	6	7	13.0034	1.11
	^{14}C	6	6	8	14.0032	trace

Chemistry Openstax

Average atomic mass

The frequency of isotopes for each elements determines the **average atomic mass** shown in the periodic table.

- Weighted average takes frequency & mass into account.

average atomic mass = Σ (isotopic mass)(isotopic frequency)

Boron occurs in two isotopes: 19.9% have a mass of 10.0129 amu & 80.1% have a mass of 11.0093.
Calculate the average atomic mass of boron.

5

average atomic mass = (10.0129)(0.199) + (11.0093)(0.801)

= 10.8110 amu

Remember to move the decimal 2 places when multiplying by a percentage.

Try this

A meteorite found in central Indiana contains traces of neon gas picked up from solar wind. Analysis shows 91.84% ^{20}Ne (19.9924 amu), 0.47% ^{21}Ne (20.9940 amu), and 7.69% ^{22}Ne (21.9914 amu).
Calculate the average atomic mass of neon in solar wind.

6

= (19.9924)(0.9184) + (20.9940)(0.0047) + (21.9914)(0.0769)

= 18.3610 + 0.09867 + 1.6911 = 20.1508 amu

Tougher!

Naturally occurring chlorine has two isotopes, ^{35}Cl (34.96885 amu) and ^{37}Cl (36.96590 amu). The average atomic mass is 35.453 amu. *Calculate the abundance (frequency) of each chlorine isotope.*

7

$35.453 = (34.96885)(x) + (36.96590)(1-x)$

$35.453 = (34.96885x) + (36.96590) - (36.96590x)$

$1.99705x = 1.513$

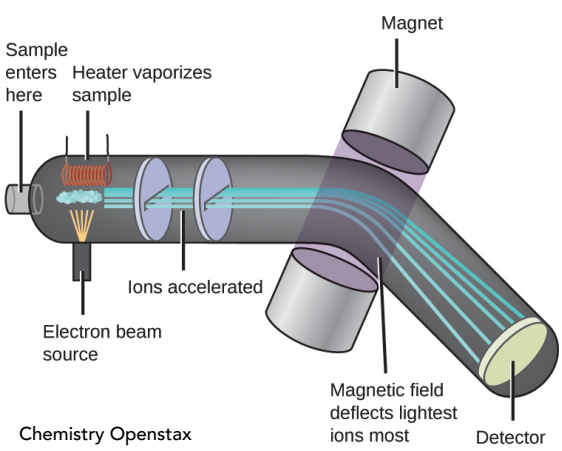
$x = \frac{1.513}{1.99705} = 0.70576$ So, $1 - x = 0.2424$

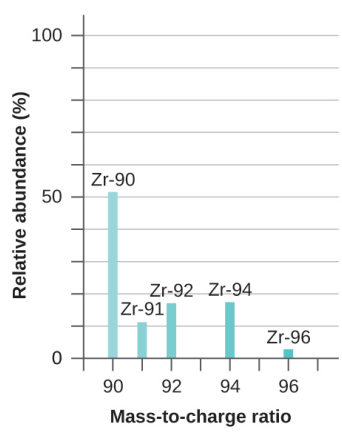
$^{35}Cl = 70.576\%$
$^{37}Cl = 24.24\%$

Mass spectrometer

An incredibly useful instrument called a **mass spectrometer** can determine the presence & frequency of elements & isotopes in a sample whose identity is unknown.

- *see CSI*





Can you?

(1) Describe the nuclear model of the atom?

(2) List the three subatomic particles, their relative masses & charges?

(3) Give the number of protons, neutrons & electrons found in any atom using the periodic table?

(4) Describe the number added to an atomic symbol to identify an isotope?

(5) Calculate average atomic mass from isotopic mass & frequency?

(6) Give a basic description of how a mass spec separates isotopes?

2. Atoms, molecules & ions

2.4: Chemical formulas

- Symbolize the composition of molecules using molecular formulas & empirical formulas
- Represent the bonding arrangement of atoms within molecules using structural formulas

Molecular formulas

Molecular formula: *the exact types & numbers of atoms in a molecule*

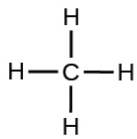
- Subscripts give the number of each atom in the molecule.
- No subscript means there's a single atom.

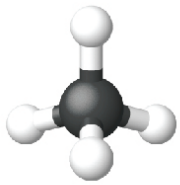
Structural formula: *shows how the atoms in a molecule are connected or bound together*

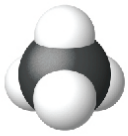
Ball & stick: *shows geometry of bonded atoms*

Space-filling: *shows relative sizes of bonded atoms*

CH_4







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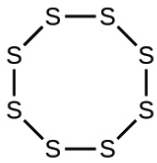
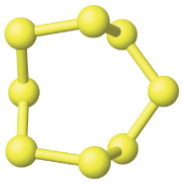
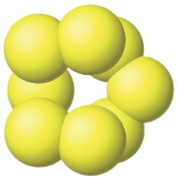
Examples

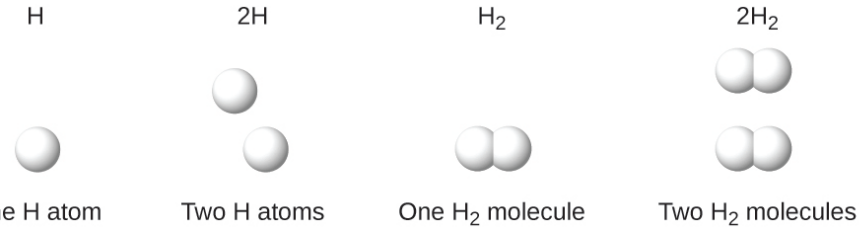
In nature **sulfur** is found as S_8, called elemental sulfur.







In nature **hydrogen** is found as hydrogen gas, H2.



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Empirical formula

Empirical formulas are simplified versions of molecular formulas.

- *The simplest whole-number ratio of atoms in a molecule.*

TiO_2 (titanium dioxide) is the empirical formula for the molecule shown below & used as a sunblock.

- Note that the molecule can include <u>many</u> <u>repeats</u> of the empirical formula.

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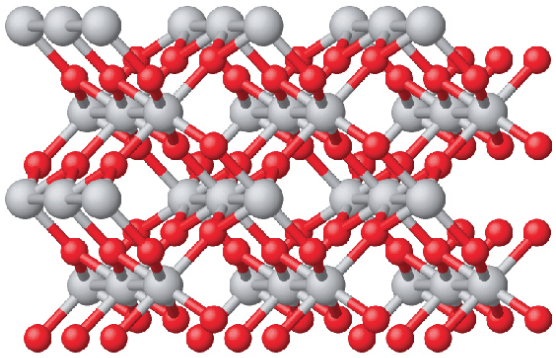
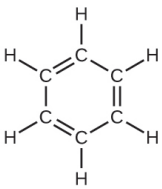
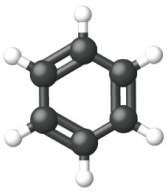
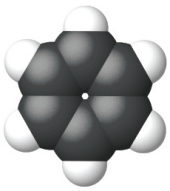


Molecular & empirical formulas?

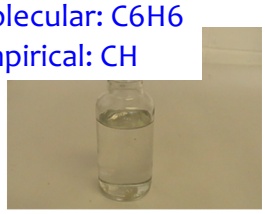
Benzene:







molecular: C_6H_6
empirical: CH



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Acetic acid:

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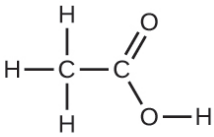
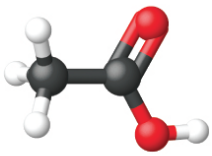
molecular: $C_2H_4O_2$
empirical: CH_2O





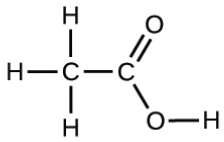
Structural isomers

Structural isomers: *distinct & different molecules that share the same molecular formula but have different structural formulas*

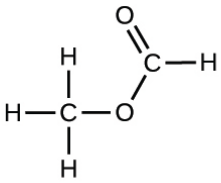
- Isomers have different physical & chemical properties

colorless liquid
sharp, pungent odor
m.p. 16-17C
b.p. 118C
density 1.049 g/mL

colorless liquid
pleasant 'ethereal' odor
m.p. -100c
b.p. 32c
density 0.98 g/mL



Acetic acid
$C_2H_4O_2$



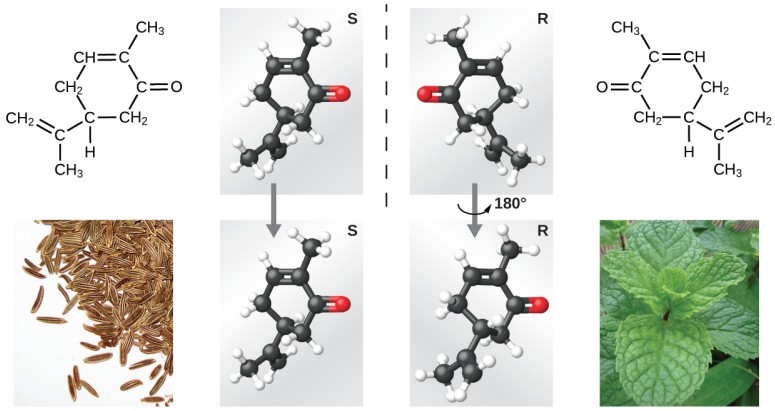
Methyl formate
$C_2H_4O_2$

Chemistry Open:

Spatial isomers

Spatial isomers: *distinct & different molecules that share the same molecular formula and structural formulas, but different arrangements in 3D space*

- Many properties are the same but others differ.



(+)-Carvone
$C_{10}H_{14}O$

(–)-Carvone
$C_{10}H_{14}O$

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Can you?

(1) Describe the differences between molecular formula, empirical formula, structural formula, ball & stick models & space-filling models?

(2) Derive empirical formulas from molecular formulas?

(3) Explain why structural isomers have distinct physical & chemical properties?

(4) Describe the difference between structural isomers & spatial isomers?

2. Atoms, molecules & ions

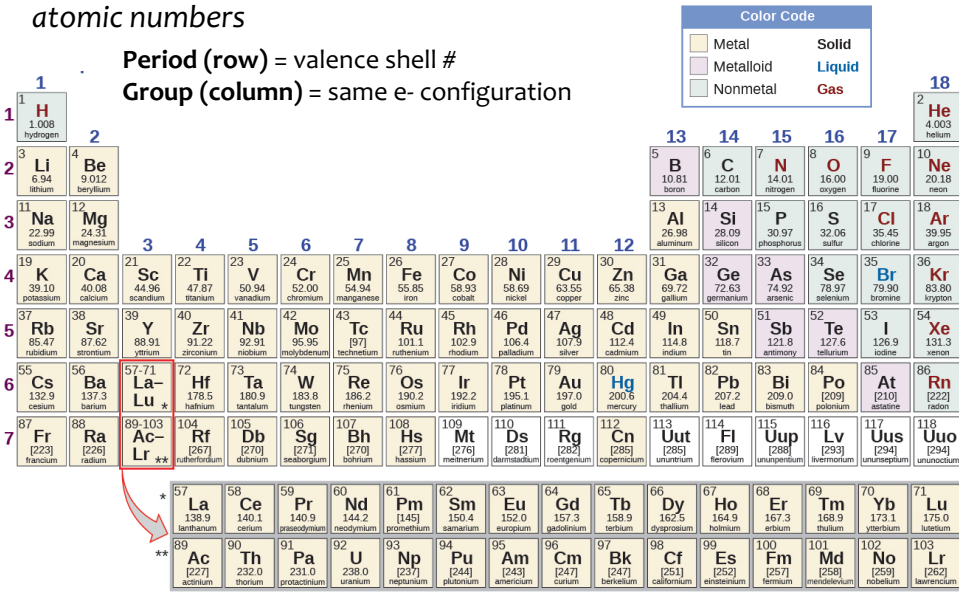
2.5: The periodic table

- State the periodic law & explain the organization of elements in the periodic table
- Predict general properties of elements based on their location in the periodic table
- Identify metals, nonmetals & metalloids by their properties and/or location in the periodic table

Periodic law

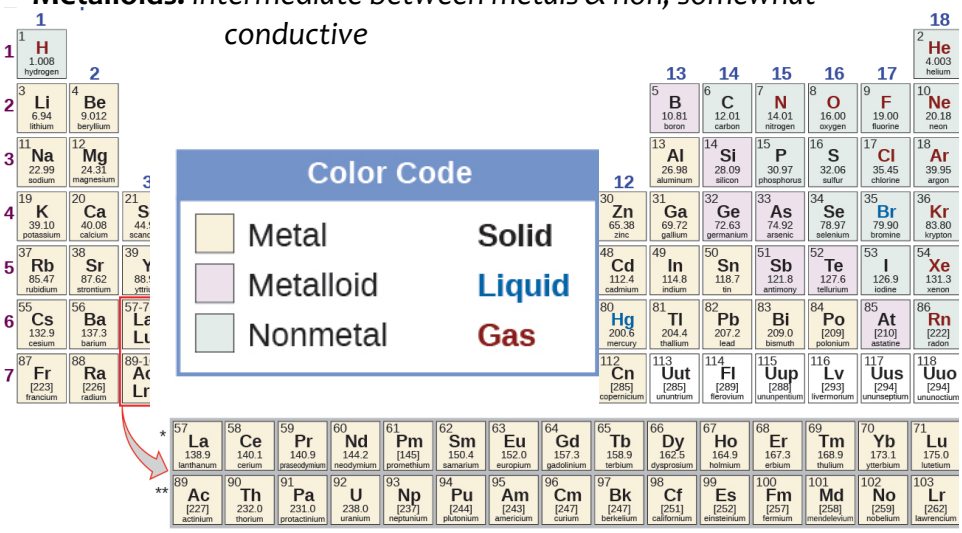
Periodic law: *properties of elements are periodic functions of their atomic numbers*

Period (row) = valence shell #
Group (column) = same e- configuration



Metals, nonmetals & metalloids

Metals: *shiny, malleable, ductile, conduct electricity & heat*
Nonmetals: *dull, poor conductors of electricity & heat*
Metalloids: *intermediate between metals & non; somewhat conductive*



Can you?

(1) State the periodic law?

(2) Describe what is common to elements in the same column vs. those in the same row?

(3) Describe the location of metals, non-metals, transition metals and metalloids in the periodic table and the differences between these types of elements?

(4) Locate these types of elements in the periodic table?
- Alkali metals
- Alkali earth metals
- Halogens
- Noble gases

2. Atoms, molecules & ions

2.6: Molecular & ionic compounds

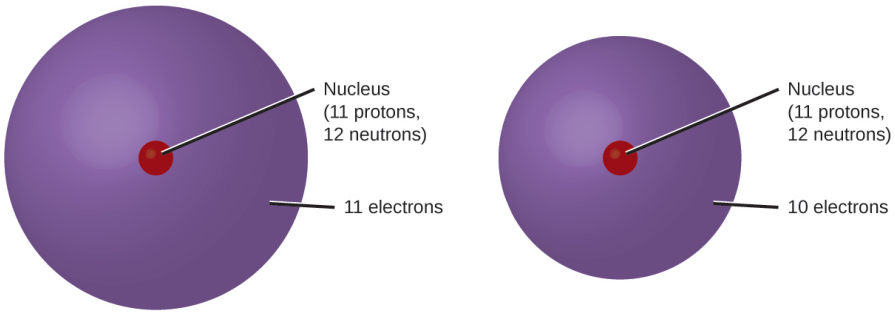
- Define ionic & molecular (covalent) compounds
- Predict the type of compound formed from elements based on their location within the periodic table
- Determine formulas for simple ionic compounds

Monoatomic ions

Monoatomic ions: *single atoms that have lost or gained electrons & are therefore electrically charged*

Metals: *lose enough e- to leave the number of e- of the preceding noble gas; become + cations*

Nonmetals: *gain enough e- to give the number of e- of the next noble gas; become - anions*



Na atom Na^+ ion

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Predicting ionic charge

Notice the **pattern** that relates charge to column.

9

- *Why is charge consistent within a column?*

Because of the periodic law!
There is a consistent pattern relating the number of electrons for the element in each column position to the number of electrons in the noble gas of that row.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1																		He
2	Li^+	Be^{2+}												C^{4-}	N^{3-}	O^{2-}	F^-	Ne
3	Na^+	Mg^{2+}											Al^{3+}		P^{3-}	S^{2-}	Cl^-	Ar
4	K^+	Ca^{2+}				Cr^{3+} Cr^{6+}	Mn^{2+}	Fe^{2+} Fe^{3+}	Co^{2+}	Ni^{2+}	Cu^+ Cu^{2+}	Zn^{2+}			As^{3-}	Se^{2-}	Br^-	Kr
5	Rb^+	Sr^{2+}									Ag^+	Cd^{2+}				Te^{2-}	I^-	Xe
6	Cs^+	Ba^{2+}								Pt^{2+}	Au^+ Au^{3+}	Hg_2^{2+} Hg^{2+}					At^-	Rn
7	Fr^+	Ra^{2+}																

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Try these

Some antiperspirants use an element with 13 protons that has 10 electrons when it forms an ions? 10

What is the element & what is its ionic charge?

The element with 13 p+ must be aluminum.
An ion of aluminum with 10 e- would have a charge of +3; 3 more p+ than e-.
The preceding noble gas is neon, element 10, so the Al^{+3} ion 'wants' 10 e-

Magnesium & nitrogen can react to form an ionic compound.

Predict the charges for each ion. 11

Mg is a metal in row 3. It 'wants' to have the same number of e- as the preceding noble gas, Ne, element 10. So, Mg loses 2 e- creating Mg^{+2} cation.

N is a nonmetal in row 2, element number 7. It 'wants' to have the same number of e- as the noble gas in its row 2, Ne, element 10. So, N gains 3 e- creating N^{-3} anion.

Polyatomic ions

Polyatomic ions: *charged molecules, a group of bonded atoms with an electric charge*

Most are **oxyanions:** *a non-metal combined with oxygen atoms, creating a unit with a negative charge*

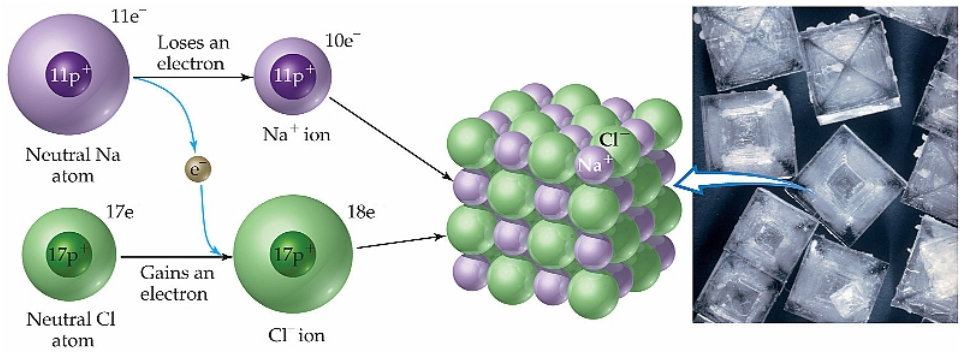
We'll cover this in detail in lab.

Name	formula
ammonium	$NH4^{+1}$
hydronium	$H3O^{+1}$
peroxide	$O2^{-2}$
hydroxide	OH^{-1}
acetate	$CH3COO^{-1}$
cyanide	CN^{-1}
azide	$N3^{-1}$
carbonate	$CO3^{-2}$
bicarbonate	$HCO3^{-2}$
nitrate	$NO3^{-1}$
nitrite	$NO2^{-1}$
sulfate	$SO4^{-2}$

Ionic compounds

Ionic compounds: *form when metals react with nonmetals, causing transfer of electrons from metals to nonmetals, creating ions with opposing & attractive forces that bond via charge or ionic bonds.*

- Motivation? Ions are more stable, have a lower energy, than atoms & so both atoms are stabilized.
- Notice that e- transfer obeys the law of conservation of mass.



Formulas of ionic compounds

When atoms ionize to form ionic compounds, cations & anions combine at **ratios** that create a **neutral, uncharged compound**.

- Formulas of ionic compounds are always 'empirical'.

Sapphires are formed from the ionic compound aluminum oxide. What's its formula?

13

Al^{+3}_{2} O^{-2}_{3}

+6 -6 → Al_2O_3

Odd & even charges make it challenging to create a net charge of zero.

- Least common product? 2 x 3 = 6

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Try these

What's the formula of a compound formed from sodium and sulfur?

14

Na^{+1}_{2} S^{-2}

+2 -2 → Na2S

What's the formula of a compound formed from calcium and the polyatomic ion dihydrogen phosphate?

15

Ca^{+2} $H_2PO_4^{-1}{}_{2}$

+2 -2 → $Ca(H_2PO_4)_2$

Molecular compounds

Molecular compounds: *form when non-metals share electrons, creating covalent bonds*

Properties?
Often gases, liquids with low boiling points or solids with low melting points

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Ionic or molecular?

Predict whether these compounds are ionic or molecular: 16

KI	Ionic: metal + non
H_2O_2	molecular: H acting as a nonmetal
$CHCl_3$	molecular: all nonmetals
$Li_2(CO_3)$	ionic: metal + nonmetal polyatomic anion

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Can you?

(1) Define the terms ion, cation and anion?

(2) Differentiate between monoatomic and polyatomic (and oxyanions) ions?

(3) Use the periodic table to predict the charge of monoatomic ions?

(4) Explain why the formation of cations and anions is inextricably linked?

(5) Add subscripts to create proper (empirical) formulas for ionic compounds?

(6) Identify ionic vs. molecular vs. compounds by their formulas?

Lecture 2, Atoms, etc.: terms to know

actinide
alkali metal
alkali earth metal
alpha (α) particle
anion
atomic mass
atomic mass unit
atomic number
cation
chalcogen
chemical symbol
covalent bond
covalent compound
Dalton's atomic theory
electron
empirical formula
group
halogen
inert gas
inner transition metals
ion
ionic bond
ionic compound
isomer
isotope
lanthanide
law of constant composition
law of definite proportions
law of multiple proportions
main group element
metal
metalloid
molecular compound
molecular formula
monoatomic ion
neutron
noble gas
nomenclature
nonmetal
nucleus
oxyanion
period
periodic law
periodic table
pnictogen
polyatomic ion
proton
spatial isomer
structural formula
structural isomer
transition metal