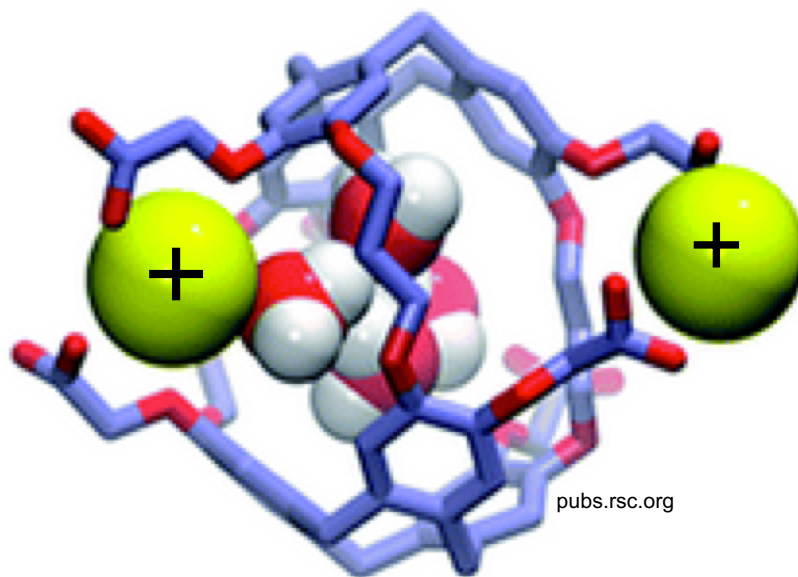
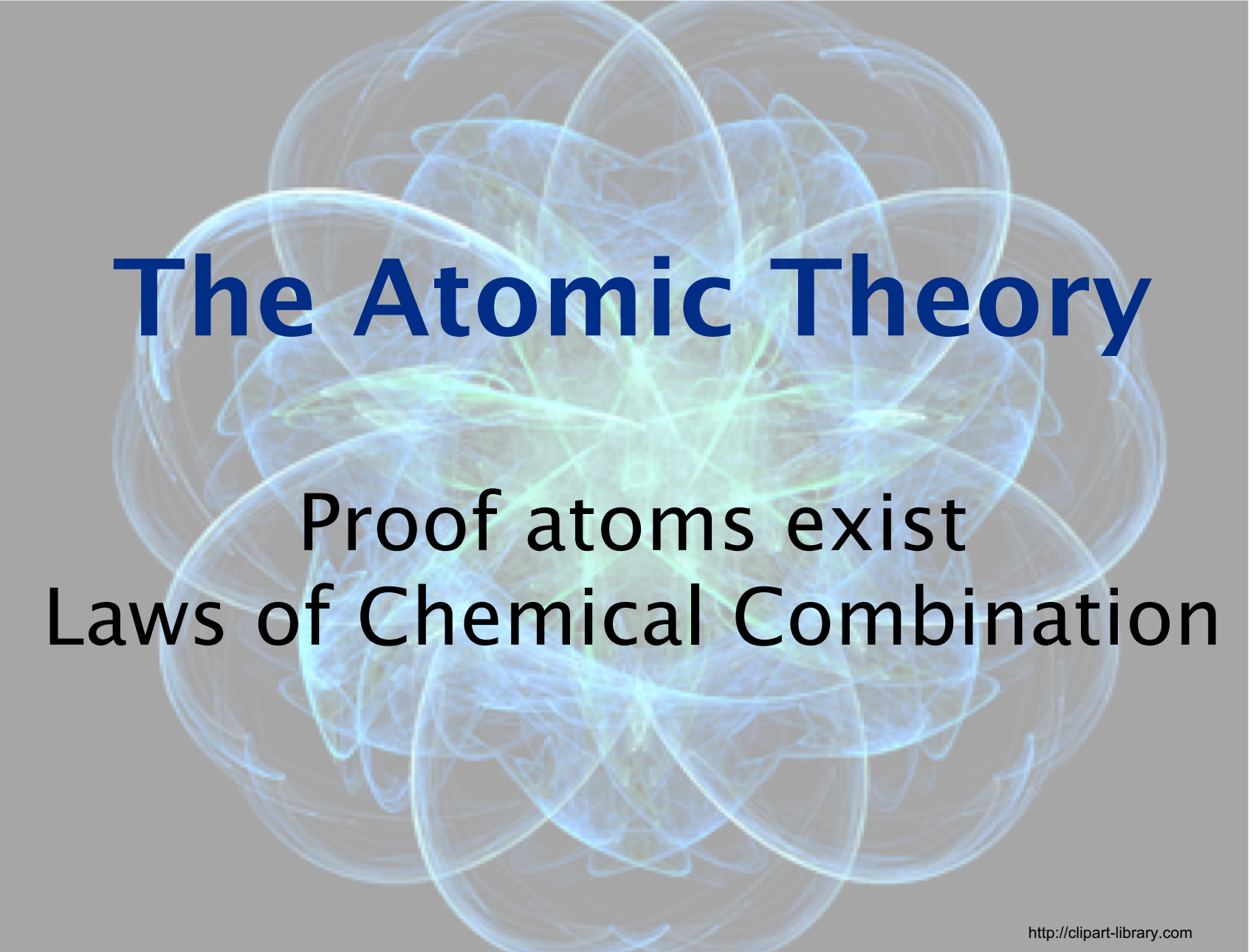


Chapter 2:

Atoms, Molecules, and Ions





The Atomic Theory

Proof atoms exist
Laws of Chemical Combination

Atomic Theory of Matter: Dalton (1808)³

1. All matter is composed of tiny particles called atoms
2. All atoms of a given element are identical, but atoms of different elements differ in size, mass, & chemical properties

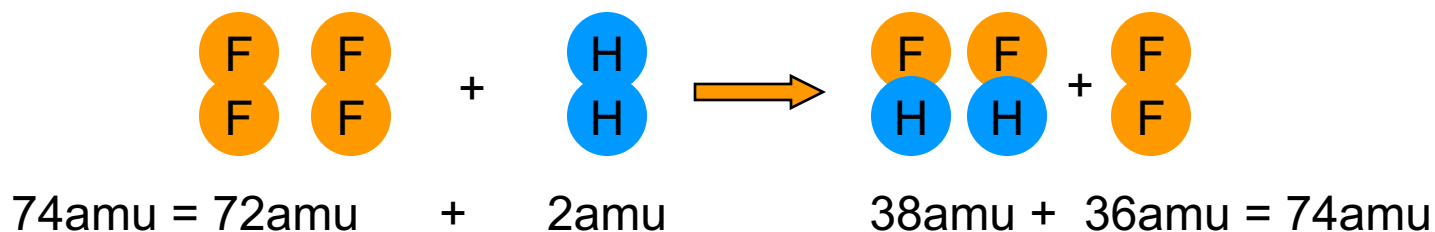


Fluorine atom: 18 amu



Hydrogen atom: 1 amu

3. Compounds are formed when atoms of different elements combine in fixed proportions.



4. A chemical reaction involves atomic rearrangement.
No atoms are created or destroyed.

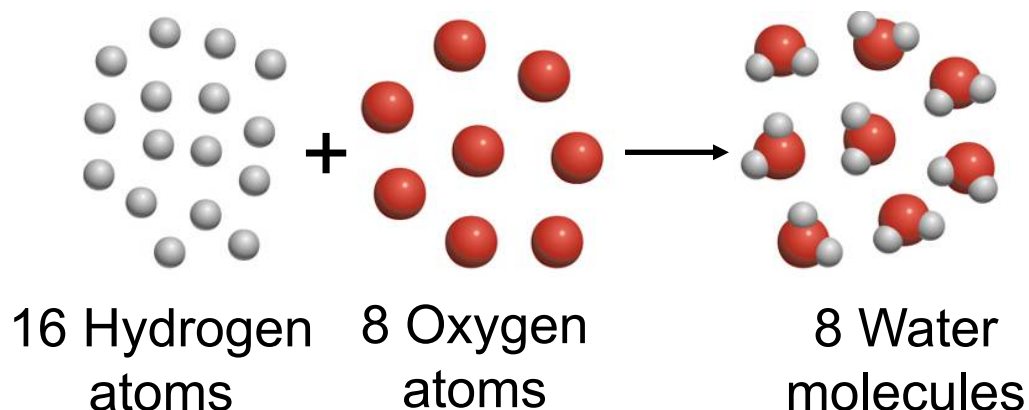
Law of Definite Proportions – Joseph Proust 1799

4

- Supports Part 3 of Atomic Theory

A compound will always have same chemical composition

- Each product is formed from definite proportions of reactants



**Water is
ALWAYS
 H_2O**

- Same mass proportions & atomic ratios of elements present

Law of Multiple Proportions

If the same two elements can combine to form more than one compound:

- The **masses** of one element combine with a fixed mass of the second element.
- The combination is in a ratio of **small whole numbers**.

Open face sandwich

1 bread + 1 filling

1:1 ratio



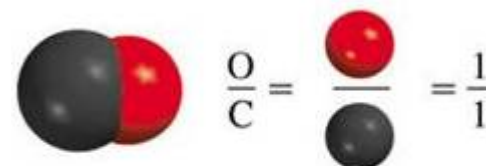
Regular sandwich

2 bread + 1 filling

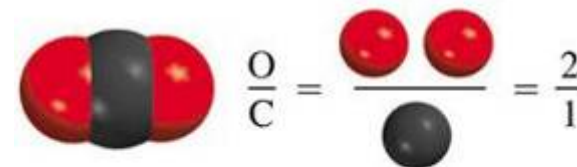
2:1 ratio



Carbon monoxide



Carbon dioxide



Compounds are formed when atoms of different elements unite in fixed proportions

Law of Conservation of Mass

Total mass is constant during a chemical reaction

Mass of reactants must exactly match mass of products



2lbs potatoes + 3 ounces milk + 1 ounce butter = 2.25 lbs mashed potatoes

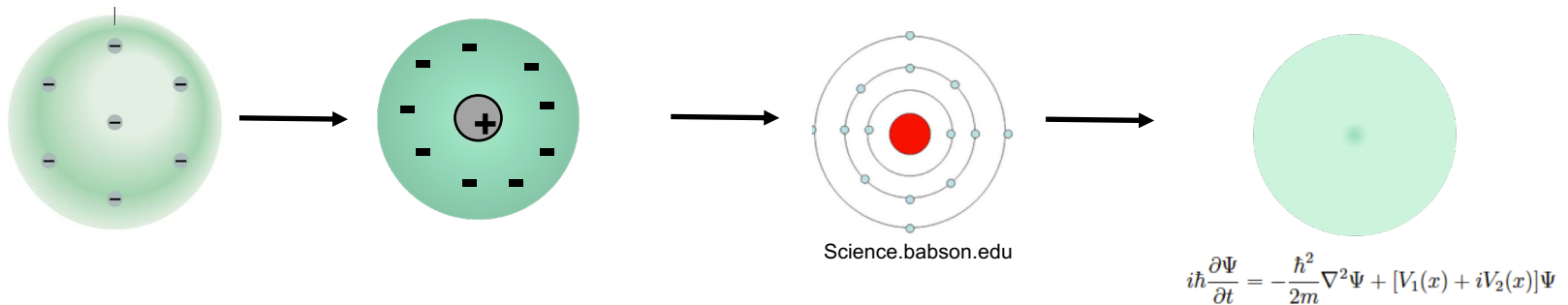
Called mass balance



**Matter cannot be created or destroyed
in chemical reactions!**

Structure of the Atom

What's on the inside?!?

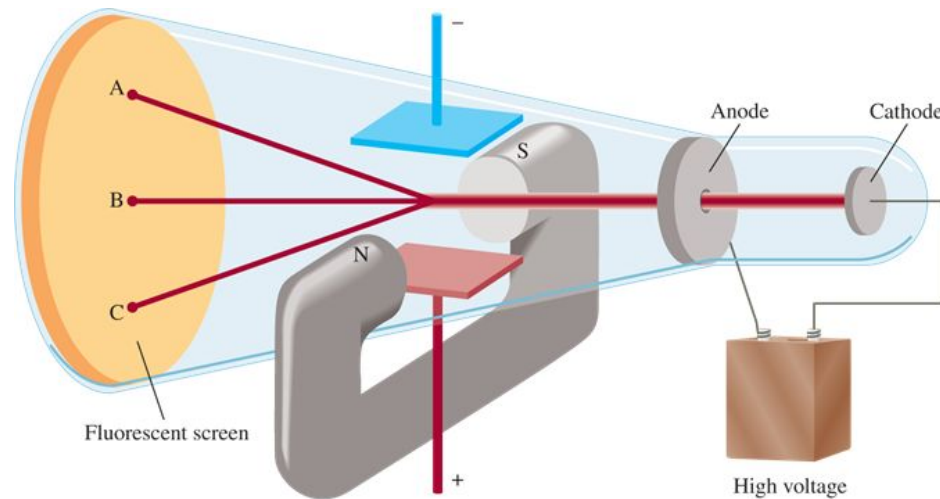


The Electron and Cathode Rays (1890's)

Electricity causes ray to be deflected in a vacuum

Few molecules: minimal molecular interference

Applied magnetic field or electric field deflects ray



Ray is attracted to positively (+) charged anode, so it must be made of negatively (-) charged particles

Atom not smallest piece of matter – had charged “things” inside!

Millikan Oil Drop Experiment

Determination of charge and mass of electron

JJ Thompson:

Ratio of cathode ray particle's charge to mass

$$= -1.76 \times 10^8 \text{ C/g}$$

Negatively charged particle is called an **electron**

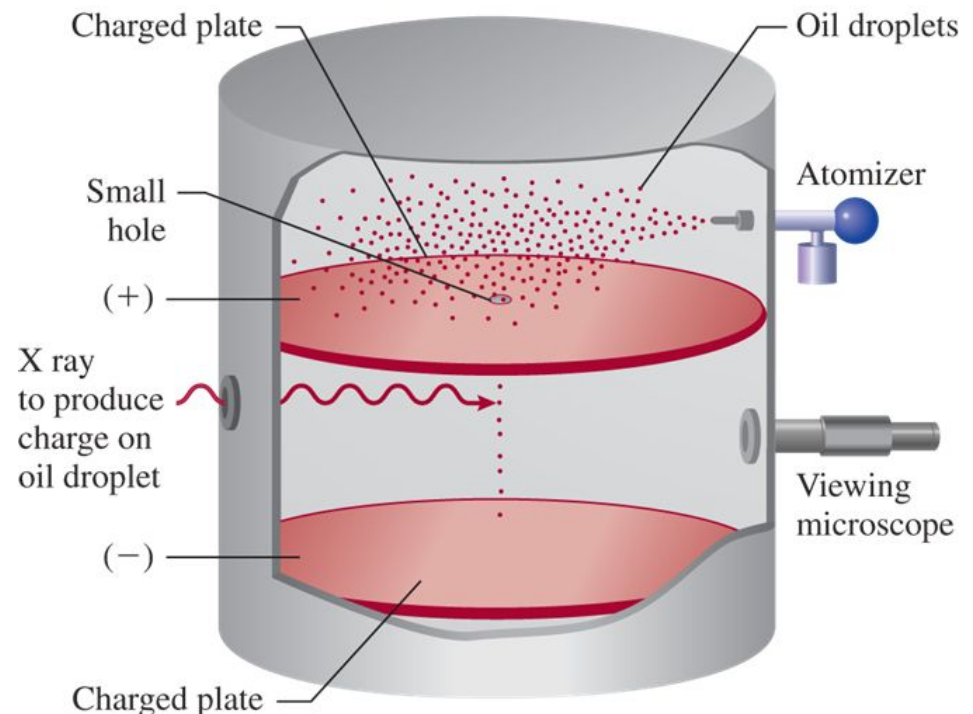
Robert Millikan

Charge on an electron:

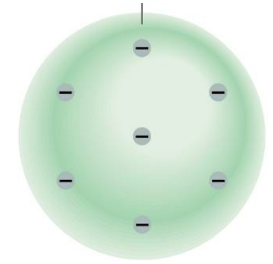
$$e = -1.602 \times 10^{-19} \text{ C}$$

Mass of an electron:

$$m_e = 9.10 \times 10^{-28} \text{ g}$$



Discovery of The Nucleus

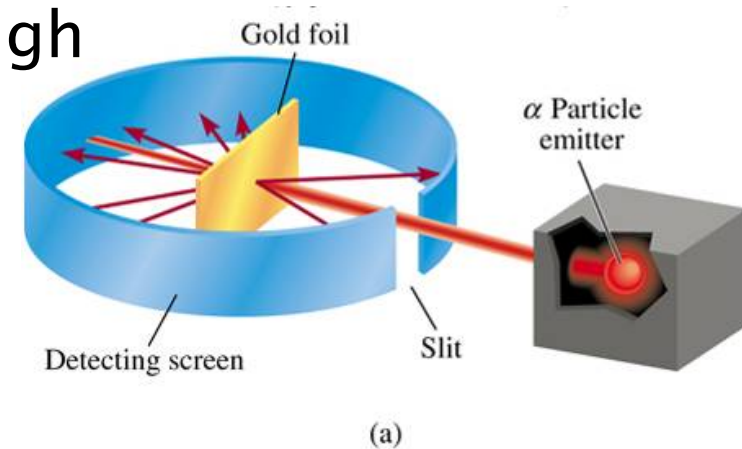


J. J. Thomson's Raisin (or Plum) Pudding Model

- Positively charged sphere with electrons imbedded inside
- Ball of Chocolate Chip Cookie Dough

Rutherford's Experiments

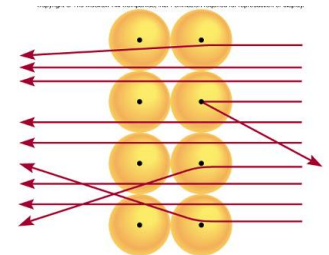
- Shot α particles through gold foil



Results:

- Most hit detector w/ no interference (empty space!)
- Some deflected from straight line: Charge interference
- A few reflected back toward emitter
 - Hit something small & positive in center

Nucleus!



The Atom and Sub-Atomic Particles

✚ Protons ✚

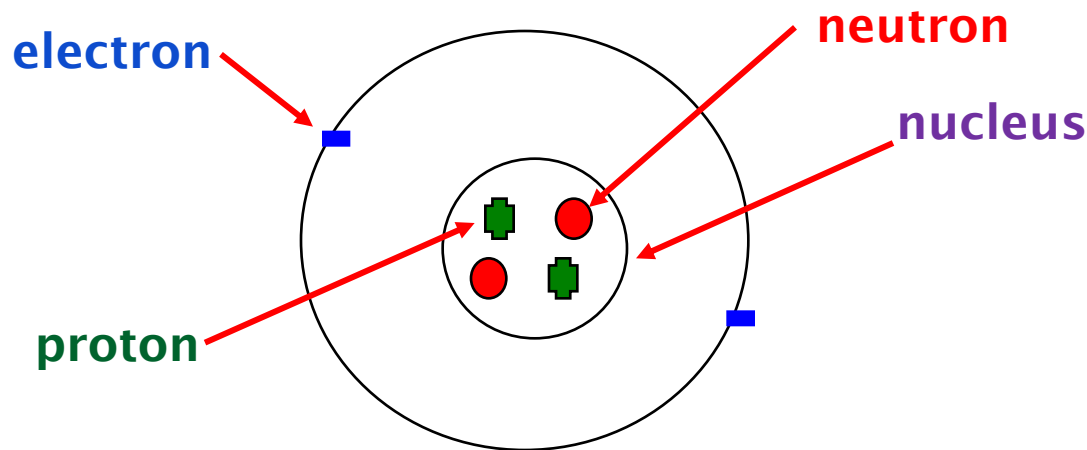
large, positively charged particles in small central nucleus

- Electrons -

tiny, negatively charged particles in cloud around nucleus

● Neutrons ●

large, neutral particles in nucleus

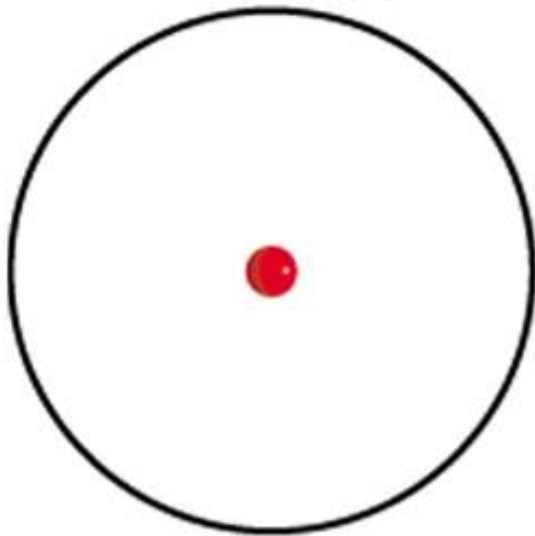


- Elements are not electrically charged
- Must have equal numbers of protons & electrons

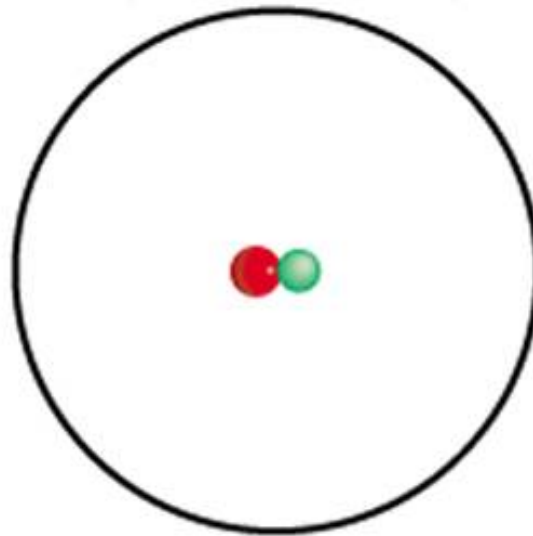
Neutrons

Subatomic particle with same mass as proton

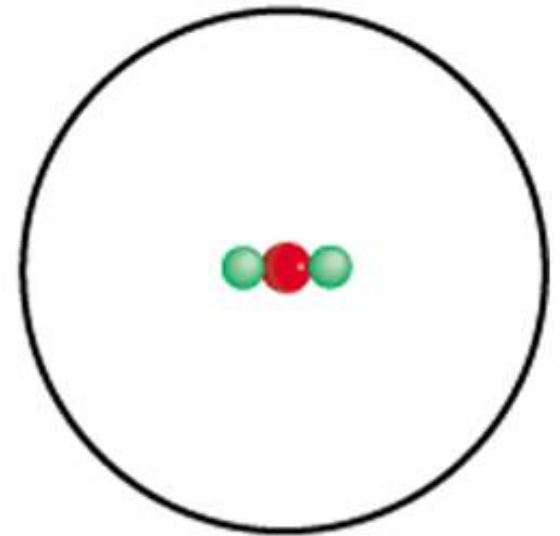
- Discovered by James Chadwick
- Located in nucleus
- No charge - accounts for extra mass of isotopes
- Change in mass, no change in chemical properties



Hydrogen

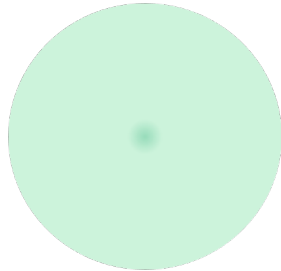


Deuterium



Tritium

Modern View of the Atom

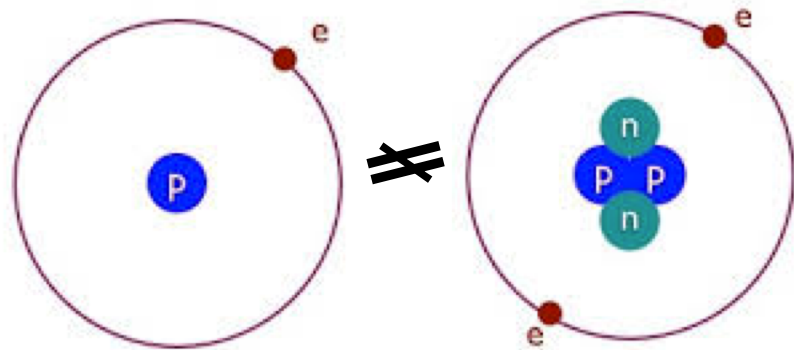


$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \Psi + [V_1(x) + iV_2(x)] \Psi$$

- Protons (p⁺) & Neutrons (n⁰) in nucleus
- Electrons (e⁻) in “cloud” around nucleus
 - Exist in mathematically defined energy levels
 - Highest energy level – electrons can travel furthest away from nucleus
 - Electrons in highest energy level are called valence electrons
 - Chemical reactions and bonding most often involve valence electrons.
 - Max number of valence electrons is 8 (an octet)
 - 8 valence electrons is stable (don't want to react)

Atomic Number, Mass Number, & Isotopes

Differences between atoms



astro.psu.edu

Atomic Symbols

Atomic Number (Z)

protons in a nucleus

Determines element identity

Located lower left on symbol

- can also be used to
determine # electrons in
uncharged atom

Mass Number (A)

protons + # neutrons

Determines isotope identity

Located upper left on symbol

- use to determine # neutrons!

General Form



Actual Element

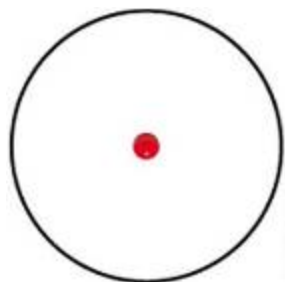


Isotopes

Elements with the same number of protons and electrons, but differing number of neutrons

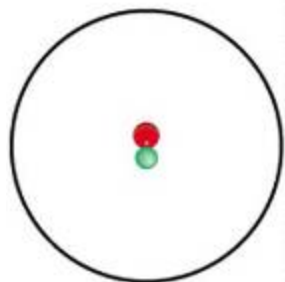
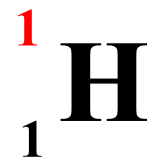
Used in chemistry for structure identification or to follow a particular molecule through a reaction

Example: hydrogen and deuterium



Water, H₂O

H has 1 proton and 0 neutrons
Most abundant



Heavy water, D₂O

D (deuterium) has 1 proton & 1 neutron
Occurs 1/6700 molecules



Los Alamos National Laboratory Chemistry Division

Periodic Table of the Elements

1A	2A	3A	4A	5A	6A	7A	8A
1 H hydrogen 1.008	2 He helium 4.003						
3 Li lithium 6.94	4 Be beryllium 9.012	5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31	13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.06	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85
27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.64	33 As arsenic 74.92	34 Se selenium 78.96
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.96	43 Tc technetium (98)	44 Ru ruthenium 101.1
45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6
53 I iodine 126.9	54 Xe xenon 131.3	55 Cs cesium 132.9	56 Ba barium 137.3	*	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9
75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 192.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.6	81 Tl thallium 204.4	82 Pb lead 207.2
83 Bi bismuth 209.0	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)	87 Fr francium (223)	88 Ra radium (226)	89 Ac actinium (227)	90 Th thorium (232)
91 Pa protactinium 231	92 U uranium 238	93 Np neptunium (237)	94 Pu plutonium (244)	95 Am americium (243)	96 Cm curium (247)	97 Bk berkelium (247)	98 Cf californium (251)
99 Es einsteinium (252)	100 Fm fermium (257)	101 Md mendelevium (258)	102 No nobelium (259)	103 Lr lawrencium (262)	104 Rf rutherfordium (261)	105 Db dubnium (268)	106 Sg seaborgium (271)
107 Boh bohrium (270)	108 Hs hassium (277)	109 Mt meitnerium (276)	110 Ds darmstadtium (281)	111 Rg roentgenium (280)	112 Cn copernicium (285)	113 Nh nihonium (284)	114 Fl flerovium (289)
115 Mc moscovium (288)	116 Lv livermorium (293)	117 Ts tennessine (294)	118 Uuo ununoctium (294)				

The Periodic Table

Organizing the Elements

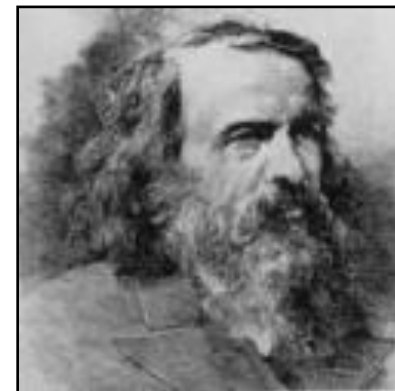
Lanthanide Series*

57 La lanthanum 138.9	58 Ce cerium 140.1	59 Pr praseodymium 140.9	60 Nd neodymium 144.2	61 Pm promethium (145)	62 Sm samarium 150.4	63 Eu europium 152.0	64 Gd gadolinium 157.2	65 Tb terbium 158.9	66 Dy dysprosium 162.5	67 Ho holmium 164.9	68 Er erbium 167.3	69 Tm thulium 168.9	70 Yb ytterbium 173.0	71 Lu lutetium 175.0
89 Ac actinium (227)	90 Th thorium 232	91 Pa protactinium 231	92 U uranium 238	93 Np neptunium (237)	94 Pu plutonium (244)	95 Am americium (243)	96 Cm curium (247)	97 Bk berkelium (247)	98 Cf californium (251)	99 Es einsteinium (252)	100 Fm fermium (257)	101 Md mendelevium (258)	102 No nobelium (259)	103 Lr lawrencium (262)

Mendeleev's Periodic Table 1869

Known elements arranged in order of increasing **atomic mass** from left to right and from top to bottom in groups.

Elements with similar properties are placed in same column.



	H 1						
He 4	Li 7	Be 9	B 11	C 12	N 14	O 16	F 19
Ne 20	Na 23	Mg 24	Al 27	Si 28	P 31	S 32	Cl 35
Ar 40	K 39	Ca 40		Ge 72	As 75	Se 79	Br 80
Kr 84	Rb 85	Sr 88	In 115	Sn 119	Sb 122	Te 128	I 127
Xe 131	Cs 133	Ba 137	Tl 204	Pb 207	Bi 209		
Rn (222)							

Used table to predict properties of undiscovered elements!

Eka-Silicon → Germanium

MM: 72

Density: 5.5g/mL

Color: dirty gray

MM: 72.6

Density: 5.47g/mL

Color: grayish white

The Modern Periodic Table

Arranged by Atomic Number

Arranged by Atomic Number																		18 8A
1 1A H	2 2A He											13 3A B	14 4A C	15 5A N	16 6A O	17 7A F	18 8A Ne	
3 Li	4 Be											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
11 Na	12 Mg	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9 8B	10 8B	11 1B	12 2B	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112	(113)	114	(115)	116	(117)	(118)	

	Metals
	Metalloids
	Nonmetals

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Green Metals Ductile, malleable, conductive, positive ionic charge
 Blue Nonmetals Brittle solids, often gases or liquids, negative charge
 Pink Metalloids Properties of both metals and nonmetals

Some Groups in the Periodic Table

Alkali Metals

- Group 1A
- +1 charge
- Highly reactive



Alkali Earth Metals

- Group 2A
- +2 charge
- Reactive



Halogens

- Group 7A
- -1 charge
- Highly reactive if single atoms
- Diatomic molecules



Metalloids

- Some characteristics of metals, some of nonmetals
- semiconductors



Silicon (Si)

Periodic Table of the Elements

Legend:

- Alkali metals
- Alkaline earth metals
- Lanthanides
- Actinides
- Transition metals
- Post-transition metals
- Metalloids
- Other nonmetals
- Halogens
- Noble gases
- Unknown properties

SOURCES: National Institute of Standards and Technology, International Union of Pure and Applied Chemistry

Transition metals

- Center of table
- Varying (+) charge
- Use Roman numerals

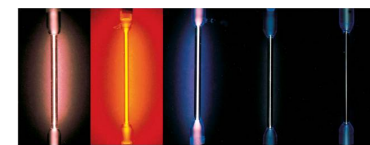


Lanthanides & Actinides

- Bottom of table
- Very reactive
- + charge
- Often radioactive

Noble Gases

- Group 8A
- + charge (if charged)
- Inert (least reactive)



Elements you should be familiar with by the end of this course:

(Name & Symbol)

First 4 rows of periodic table

Including 1st row of transition metals

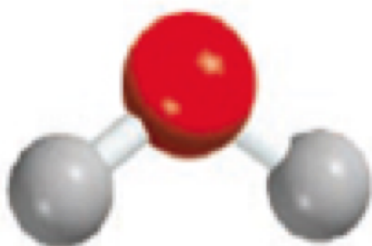
Additional elements

Ag: Silver Pb: Lead

I: Iodine Hg: Mercury

(A Periodic Table with both names & symbols will be provided in this class, but you may be expected to know these in future chemistry courses.)

Chemical Formulas & Names



Sodium chloride

Types of Compounds

Ionic:

- Cation + Anion
- Form from transfer of electrons
- Often metal + nonmetal
 - Elements that are very “different”
 - Opposite sides of Periodic Table
- Ex. NaCl (sodium chloride)
- Contain specific ratios of ions but no specific number of ions

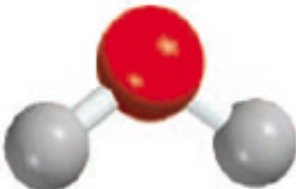
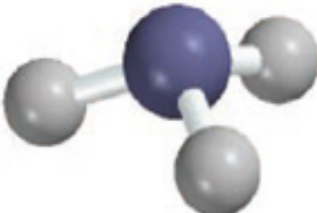
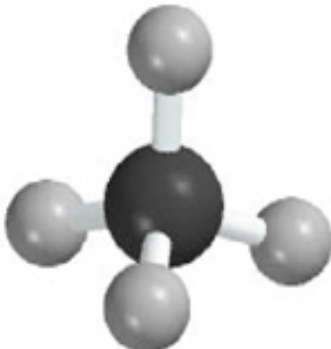
Covalent:

- Form by sharing electrons
- Contain atoms, not ions
- Often nonmetal + nonmetal
 - Elements that are “similar”
 - Same side of Periodic Table
 - Hydrogen is a nonmetal
- Ex. CO₂ (carbon dioxide)
- Molecules contain specific numbers of atoms.

Chemical Formulas

Represent chemical composition (atomic ratios)

- **Empirical:** Ratio of atoms (NH_2 instead of N_2H_4)
 - Can use for ionic or covalent compounds
- **Molecular:** Actual # of atoms (N_2H_4)
 - Only use for covalent compounds. Molecule = covalent
- **Structural:** Shows how atoms are connected in molecules

	Hydrogen	Water	Ammonia	Methane
Molecular formula	H_2	H_2O	NH_3	CH_4
Structural formula	$\text{H}-\text{H}$	$\text{H}-\text{O}-\text{H}$	$\begin{array}{c} \text{H}-\text{N}-\text{H} \\ \\ \text{H} \end{array}$	$\begin{array}{c} \text{H} \\ \\ \text{H}-\text{C}-\text{H} \\ \\ \text{H} \end{array}$
Ball-and-stick model				

Names of Binary Molecules (2 Elements, Covalent)

Names and formulas have 2 parts, 1 for each element:

Dinitrogen tetroxide ----- N_2O_4

1st word is 1st element name ----- N = Nitrogen

2nd word is 2nd element name

→ **change ending to “-ide”** ----- O = Oxygen → Oxide

Formula: Subscripts = # of atoms ----- N_2O_4

Name: Prefix = # of atoms ----- Dinitrogen tetroxide

Do not include a prefix for the first element if there is only one atom

Ex: CO_2 = Carbon dioxide (not monocarbon dioxide)

CO = Carbon monoxide

Memorize prefixes up to 10

# atoms	prefix	# atoms	prefix
1	mono	6	hexa
2	di	7	hepta
3	tri	8	octa
4	tetra	9	nona
5	penta	10	deca

Note that the o or a at the end of the prefix is often dropped when the element begins with a vowel.

- Monoxide, not monoxide
- Tetroxide, not tetroxide

Names & Formulas of Binary Molecules

1.) N_2O

2.) SCl_3

3.) P_2O_5

4.) nitrogen dioxide

5.) dinitrogen tetrasulfide

Ionic Compounds (salts)

During a reaction atoms may gain or lose electrons

Both atoms become charged and are called **ions**

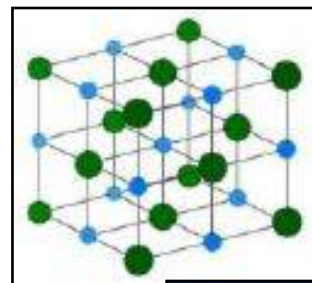
Anion: atom gaining the electron is negatively charged

Cation: atom losing the electron is positively charged

Will bind together to form crystals

The net charge on the compound is 0

- Cations & anions balance out
- Get charges from periodic table



No distinct molecular units

- Positive charge of cation attracts all nearby anions
- Negative charge of anion attracts all nearby cations

Using the Periodic Table to Predict Ionic Charge (Main Group Elements Only)

1 1A			
1 H	2 2A		
3 Li	4 Be		

						18 8A
13 3A	14 4A	15 5A	16 6A	17 7A	2 He	
5 B	6 C	7 N	8 O	9 F	10 Ne	



Goal: Get 8 valence electrons (“full”)

- electrons in “outermost” energy level
- “A” column number tells number of valence electrons
- Noble gases (column 8A/18) already have 8 – generally no charge
- Can gain or lose electrons to get 8 – generally do what is easier
- Electrons are negative → gain electrons = negative charge!

The correct charge is usually the smallest number

Left Side (metals):

Li^{1+} or Li^{-7} Mg^{2+} or Mg^{6-} **Cations!**

Right Side (nonmetals):

O^{6+} or O^{2-} F^{7+} , or F^{1-} **Anions!**

30

Sn & Pb are the “others” that you will see most often

- Become cations
- Charge is unpredictable
- Often have more than one charge (also possible for some main group elements)
 - Designated with a Roman Numeral
 - Iron (III) = Fe^{3+} ; Iron (II) = Fe^{2+}
 - Roman numerals required in names of ionic compounds if cation can have more than one charge
 - Iron (III) oxide
 - Copper (II) chloride

Polyatomic Ions

- Charged molecules
- Lose or gain electrons as a group
- Charge is spread over 2 or more atoms

Memorize the following polyatomic ions!

Ammonium	NH_4^+	Hydronium	H_3O^+
Phosphate	PO_4^{3-}	Acetate	CH_3COO^-
Hydroxide	OH^-	Nitrate	NO_3^-
Cyanide	CN^-	Sulfate	SO_4^{2-}
Permanganate	MnO_4^-	Chlorate	ClO_3^-
Carbonate	CO_3^{2-}	Perchlorate	ClO_4^-

Formula of an Ionic Compound
must give an overall charge of zero!

Al & O

Ca & Br

Na & CO₃

Ca & NO₃

Pb⁴⁺ & O

Names of Ions and Ionic Compounds

Naming Ions:

For cations: add the word **ION** after element name

Na = sodium

- In col 1A, so loses 1 e⁻
- Na⁺ = sodium ion

Al = aluminum

- In col 3A, so loses 3 e⁻
- Al³⁺ = aluminum ion

For anions: change the element name **ending to -ide** first

Cl = chlorine

- In col 7A, so gains 1 e⁻
- Cl⁻ = chloride ion

O = oxygen

- In col 6A, so gains 2 e⁻
- O²⁻ = oxide ion

Naming Ionic Compounds (ie salts):

- Write the name of the cation followed by the name of the anion.
- If the cation can have more than one charge, include a Roman Numeral representing the charge after the name of the cation.

Na & Cl

Net Charge: $(+1) + (-1) = 0$

Chemical Formula is NaCl

Na = sodium

Cl = chloride

Name = Sodium chloride

Al & O

Net Charge: $2(+3) + 3(-2) = 0$

Chemical Formula is Al_2O_3

Al = aluminum

O = oxide

Name = Aluminum oxide

Fe & S

Fe = iron $\rightarrow$ 2 possible charges, +2 & +3

S = Sulfide $\rightarrow$ charge is -2

If Iron is +2

Net Charge: $(+2) + (-2) = 0$

Chemical Formula is FeS

Name = Iron (II) sulfide

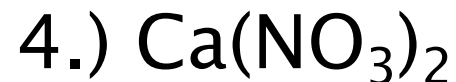
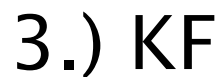
If Iron is +3

Net Charge: $2(+3) + 3(-2) = 0$

Chemical Formula is Fe_2S_3

Name = Iron (III) sulfide

Naming Ionic Compounds



If the formula contains a cation that can have more than one charge, you need to determine the charge based on the anion & include it as a Roman Numeral.



Acids and Bases

Acid

- Arrhenius: Compound ionizes in H_2O to form H^+ & anions
 - Name by changing anion -ide ending to **-ic acid**
 - Add hydro to acids with HX formula (X=halogen; col.17)
ex: $\text{HCl} = \text{Hydrochloric acid}$
- Bronsted acids: H^+ grabs H_2O to form H_3O^+ in water

Base

- Arrhenius: Compound ionizes in H_2O to form OH^- & cations
 - Name as salts: All hydroxide salts are considered bases
- Bronsted base: Pulls H^+ from H_2O so NH_3 is a base:

$$\text{H}_2\text{O} + \text{NH}_3 \rightleftharpoons \text{OH}^- + \text{NH}_4^+ \rightleftharpoons \text{NH}_4\text{OH}$$

Neutralization

- Reaction between acid & base – form water & a salt

$$\text{H}^+ + \text{OH}^- \rightleftharpoons \text{H}_2\text{O} \quad \text{and} \quad \text{cation} + \text{anion} \rightleftharpoons \text{salt}$$

$$\text{HCl} + \text{NaOH} \rightleftharpoons \text{H}_2\text{O} + \text{NaCl (aq)}$$

Common acids and bases

Be able to recognize & associate formula with name

Acids

Hydrochloric Acid:	HCl	Carbonic Acid:	H ₂ CO ₃
Sulfuric Acid:	H ₂ SO ₄	Nitric Acid:	HNO ₃
Chloric Acid:	HClO ₃	Phosphoric Acid:	H ₃ PO ₄
Perchloric acid:	HClO ₄	Acetic Acid:	CH ₃ COOH

Bases

Sodium hydroxide: NaOH
Potassium hydroxide: KOH
Ammonium hydroxide: NH₄OH (actually ammonia, NH₃ in H₂O)
Lithium hydroxide: LiOH

Hydrates

Compounds associated w/fixed number of water molecules

Presence of water alters properties such as color

Copper(II)sulfate
 CuSO_4



Copper(II)sulfate pentahydrate
 $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$



Naming Hydrates

- Use numerical prefixes for # of water molecules
 - ❖ mono, di, tri, etc.
- Add “hydrate” to the prefix & include at end of name
- A dot shows associated H_2O in formula

Water molecules must be included when calculating mass

Naming Oxoacids and their Anions: Reference Only

