Chapter 2

Atoms, Molecules and Ions

Origin of the idea of atoms

Starts with the ponderings about Nature and existence in pre-Socratic Greek philosophy

(600 BC – 425 BC)

Their work was called "Natural Philosophy"

In fact, until the 19th century the term "Natural Philosophy" was the term used for "Science", or the practice of studying Nature.

Pre-Socratic Greek philosophers arrived at the concept of atoms because there was no other way to explain the existence of change!

Parmenides:
Change is not real; it's an illusion!

A→B means that A is disappearing into nothing,
and B is appearing out of nothing

A→ nothing

nothing→B

"Something" cannot turn into "Nothing", and
"Nothing" cannot turn into "Something",
⇨ Change cannot be real!

Oh, by the way, there is no such thing as "void" (empty space).

- Solid reasoning. Pretty bold. But kind of unacceptable.
- But these well-reasoned conclusions had to be proven wrong. That led to the idea of atoms.

Democritus and the "atomists":

- Parmenides is correct in stating that parts of the universe can't just disappear, or appear out of nothing.
- But we can have changes and transformations, if things are made up of tiny, invisible particles that rearrange and recombine.
- Those fundamental, permanent, indivisible particles (atoms) themselves don't change, but their rearrangements and re-combinations are the cause for observed change.
- Different atoms can come together to form a new substance
- Each substance has its characteristic particle, and the attributes of these particles determine the attributes of the substance they make up.

Atomists:
Oh, by the way, there has to be a void (empty space) for atoms to move around and do their rearranging.

Paraphrasing Democritus:
"Reality is nothing but the atoms moving around in the void"

The first mechanical view of universe
-- originally expressed much more poetically (literally in poem form)

- So, the ancient (460-400 BC) Greek concept of atom was not simply a intuitive guess or idle speculation
- It was the inescapable result of impressively disciplined thinking by a few generations of philosophers.
  - **<u>They had to</u> invent the idea of atoms to explain the existence of change**
- Usually identified with the modern idea of atom
- But it's deeper than that: it's about **<u>particles of "stuff"</u>**

Very famous physicist Richard Feynman (1918-1988)

From Feynman Lectures:

"If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words?

I believe it is the *atomic hypothesis* (or the atomic *fact*, or whatever you wish to call it) that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*. In that one sentence, you will see, there is an *enormous* amount of information about the world, **if just a little imagination and thinking are applied**. "

http://www.feynmanlectures.caltech.edu/I_01.html

Universe is made up of ~5% ordinary matter, ~27% Dark Matter and ~68% Dark Energy
We don't know what the latter two really are, but …
Whether through intuition, or by thinking along the lines of ancient Greek philosophers:

Dark Matter density varies across the universe, and …

Physicists are looking for Dark Matter "particles", even though they know nothing about Dark Matter

"Dark Energy" appears to be a constant, and …

They aren't looking for particles of Dark Energy (the mysterious "thing" that makes the universe expand faster and faster)

Now, back to chemistry and on to the (early) modern era …

Robert Boyle was the first "chemist" (1661)

- Used the "scientific method"
- Performed quantitative experiments on the pressure and volume of gases
- Developed the first experimental definition of an element:

A substance is an element unless it can be broken down into two or more simpler substances

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Three Important Laws:

Law of conservation of mass (Lavoisier):

Mass is neither created nor destroyed in a chemical reaction.

Law of definite proportion (Proust):

A given compound always contains exactly the same proportion of elements by mass.

Law of multiple proportions (Dalton):

When two elements form a series of compounds, the ratios of the masses of the second element that combine with a fixed amount of the first element will be ratios of small whole numbers.

Law of conservation of mass (Lavoisier):

Mass is neither created nor destroyed in a chemical reaction.

A plant grows from a tiny seed up to a huge tree.
Does this violate the Law of Conservation of Mass? Explain.

Law of definite proportion (Proust):

A given compound always contains exactly the same proportion of elements by mass.

Question:

According to the Law of Definite Proportions:

a) If the same two elements form two different compounds, they do so in the same ratio

b) It is not possible for the same two elements to form more than one compound

c) The ratio of the masses of the elements in a compound is always the same

d) The total mass after a chemical change is the same as before the change.

A sample of chemical X is found to contain 5.0 grams of oxygen, 10.0 grams of carbon, and 20.0 grams of nitrogen. The law of definite proportion would predict that a 70 gram sample of chemical X should contain how many grams of carbon?

a) 5.0 grams
b) 7.0 grams
c) 10. grams
d) 15 grams
e) 20 grams

Law of multiple proportions (Dalton):

When **two** elements form a **series of compounds**:

For a fixed amount of one element,

the amounts of the **other** element in those compounds

will be in **ratios of "small" whole numbers**.

1:2, 1:3, 2:3, 5:2 etc.

Law of multiple proportions (Dalton):

When **two** elements form a **series of compounds**:

For a fixed amount of one element,

the amounts of the **other** element in those compounds

will be in **ratios of "small"* whole numbers**.

1:2, 1:3, 2:3, 5:2 etc.

Compounds known at that time had at most a few atoms of any element in their formulas. Quantitative methods were not good enough to deal with larger numbers anyway. But the principle is still valid, even when the numbers are large, and our methods are accurate and precise enough to tell apart 133:100 from 4:3

Example

- Carbon and oxygen make two compounds. Their molecules are composed of:

1 carbon with 1 oxygen for "Carbon monoxide"

1 carbon with 2 oxygens for "Carbon dioxide"

Without knowing anything about the mass of carbon and oxygen atoms, we can say that *"carbon dioxide" has twice as much oxygen for a given amount of carbon as "carbon monoxide"*.

How about the amount of carbon per oxygen?

Example (cont.)

1 carbon with 1 oxygen for "Carbon monoxide"

1 carbon with 2 oxygens for "Carbon dioxide"

Now we are comparing the amount of carbon per oxygen in the two compounds. It's a bit trickier.

We can make it easier to think about by making the number of oxygens the same. So we take two carbon monoxide molecules, corresponding to 2 oxygens.

2 carbons per 2 oxygens for "Carbon monoxide"

1 carbon with 2 oxygens for "Carbon dioxide"

Carbon dioxide has half as much carbon for a given amount of oxygen as carbon monoxide

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A compound of chromium (symbol: Cr) and oxygen (symbol: O) has the formula CrO_2. Using the Law of Multiple Proportions, guess the formulas for the other compounds of Cr and O, using the data provided in the table below.

Compound	Mass of Cr (grams)	Mass of O (grams)
CrO_2	52	32
Compound A	39	12
Compound B	26	24

In CrO_2, there is 32 g of O per 52 g of Cr → $\frac{32\text{ g O}}{52\text{ g Cr}} = \frac{0.615\text{ g O}}{1\text{ g Cr}}$

In A, there is 12 g of O per 39 g of Cr → $\frac{12\text{ g O}}{39\text{ g Cr}} = \frac{0.308\text{ g O}}{1\text{ g Cr}}$

→ In A, there is 0.308 g of O per gram of Cr
Compared to 0.615 g O per gram of Cr in CrO_2 → $\frac{0.308\text{ g}}{0.615\text{ g}} \approx \frac{1}{2}$

→ In A, there is half as much O **per gram of Cr** as in CrO_2

So ....

Is it ok to also say "In A, there is half as much O per each atom of Cr"?

Yes. For a given amount of Cr, A has half as much O as CrO_2.

The sample size doesn't matter.

The amount of Cr we are considering doesn't change the **relative** amounts of oxygen in the two compounds.

If one compound is half as rich in oxygen as the other compound, that fact won't change with sample size.

For any given amount of Cr, compiound A has half as much O as CrO_2.

After all, we could consider the amount of O for a mass of Cr equal to the mass of 1 Cr atom. It's still "for a given amount of Cr".

So the **relative** amounts applies equally to the number of atoms contained in the two compounds.

1 O atom instead of 2 O atoms per Cr atom

So the formula for A can be: **CrO**

Now guess the formula for Compound B using the same table and the same reasoning

Compound	Mass of Cr (grams)	Mass of O (grams)
CrO_2	52	32
Compound A	39	12
Compound B	26	24

Which of the following pairs of compounds can be used to illustrate the law of multiple proportions?

A) NH_4 and NH_4Cl
B) ZnO_2 and $ZnCl_2$
C) H_2O and HCl
D) NO and NO_2

- **Law of Definite Proportions** did give a hint that matter was acting "as if" it were made of discrete particles (atoms)
  - -- at least to those who liked the idea of atoms.
  - -- Otherwise why else would two elements come together in a definite ratio of masses?
  - -- Think Lego pieces that have different masses
- On the other hand, it was reasonable to think that there might be some other explanation.
- After all, the mass ratios were nothing special. The numbers didn't look like "counts" (or rather, ratios of counts of particles.)

- **Law of Multiple Proportions** all of a sudden produced these simple ratios of **small integers** relating different compounds of the same two elements.
- That was a much stronger hint that different elements were combining using discrete particles (atoms)
- One had to be irrationally opposed to the idea of atoms to ignore the hint.
- In fact it was stated by Dalton as **one of the predictions by his atomic theory**.

Dalton's Atomic Theory (1808)

- *Each element is made up of tiny particles called atoms.*
- *The atoms of a given element are identical;* the atoms of different elements are different in some fundamental way or ways. Not quite, we now know there are "isotopes"
- *Chemical compounds are formed when atoms of different elements combine with each other.* A given compound always has the same relative numbers and types of atoms.
- *Chemical reactions involve reorganization of the atoms*—changes in the way they are bound together.
- The atoms themselves are not changed in a chemical reaction.

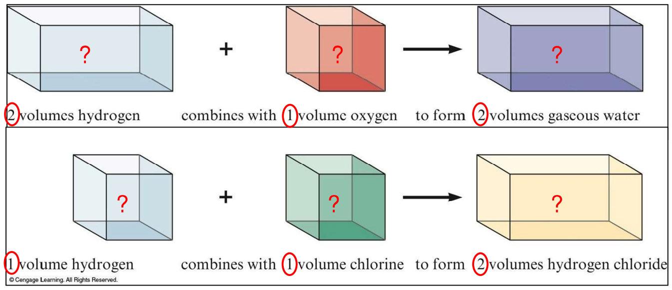
Gay-Lussac's Observations (1808)

- Measured (under same conditions of T and P) the volumes of gases that reacted with each other.
- Ratio of volumes of gases used in a reaction are simple integers.

For example:

1 liter of oxygen reacts with 2 liters of hydrogen to form water.

Gay—Lussac's Results



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Ratio of volumes of gases used in a reaction are ratios of simple integers.

- Has nothing to say about molecules or atoms
- It's just a law with no microscopic insight

Avogadro's ~~Hypothesis~~ Theory (1811)

Gay-Lussac's results got Avogadro thinking:

There is no reason for those simple ratios of reactant volumes used, unless …

At the same T and P, equal volumes of different gases contain the same number of particles.

In other words:

Volume of a gas is determined by the number, not the size or anything else of the gas particles

Explained Gay-Lussac's observations

Not accepted until 1860! 😳

Avogadro's theory was our first true connection to the atomic world

Chemists did not suspect that gases like hydrogen, oxygen, chlorine, etc. were made of diatomic molecules

- If you don't know how heavy each oxygen atom and each hydrogen atom is,
- And you see that 1 g of hydrogen combines with 8 grams of oxygen to form water,
- Assuming the simplest formula for water (HO), you conclude that oxygen atoms are 8 times as heavy as hydrogen atoms

Likewise, you would also think

H + Cl → HCl

Hydrogen + Chlorine → Hydrogen Chloride

But when you get

Hydrogen + Chlorine → Hydrogen Chloride

You figure hydrogen and chlorine must be diatomic:

$H_2 + Cl_2 \rightarrow 2\ HCl$

And when you find

Water → Hydrogen + Oxygen

instead of the following expected from HO molecules

Water → Hydrogen + Oxygen

You figure water molecules must be H_2O instead of HO

So,

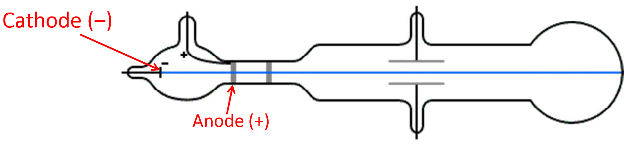
Avogadro's "hypothesis", for the first time, made a connection between macroscopic (human scale) measurements and the number of particles in a sample.

Until early 20th century (1900s), atoms were still a "working assumption", as far as physicists were concerned.

- Chemists were sure atoms actually existed
- Physicists insisted on more direct evidence
  - ➢ All they could say was that "matter behaves as if it is made of atoms"

Either way, nobody knew what they were made of, or their internal structure, if any.

J. J. Thomson (Around 1900; i.e. beginning of 20th century)



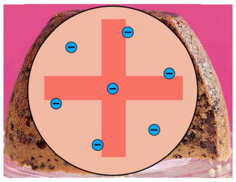
J. J. Thompson studied the "cathode rays" and determined:

- They were made of "matter"
  - ➢ not "immaterial" like light
- They were made of negatively charged particles
  - ➢ Later called "**electrons**"

- J. J. Thomson also calculated the **mass-to-charge ratio** (m/e) of the electron from the amount of deflection of the rays by electric and magnetic fields
- Those negative particles had to be coming from atoms, if all matter were made of atoms
- Being negatively charged, they could not be the entire atom
  - ➢ **Atoms must be electrically neutral** because materials are normally neutral.
- If the atom had negatively charged particles, it must have had a **positively charged part too**.

J. J. Thomson came up with the “plum pudding” model:

(–) electrons dispersed in a ball of (+) charge



Pro:
- Only has what he knew experimentally
- Assumed the simplest possible distribution for the positive charge, about which he knew that he knew nothing

Con:
Had little chance of being right and violated fairly basic physics because:
- (–) charges touching the (+) “blob” would lead to an energy of negative infinity

Plum pudding model turned out to be wrong.
Rutherford’s “gold foil” experiment gave the first hint.

But before we come to Rutherford …

Robert Millikan (1909)

- Performed experiments involving charged oil drops.
  - Made microscopic oil droplets; determined their size
  - Calculated their weight from their size and density
  - Charged microscopic oil droplets with random charges
  - The electrical force needed to balance the droplets against gravity let him calculate the charges on droplets
  - Charges turned out to be multiples of a certain small number
  - That had to be the smallest possible charge: i.e. the charge of an electron
- Charge on a single electron = 1.6×10^{-19} Coulombs
- Calculated the mass of the electron (9.11×10^{-31} kg) from the charge-to-mass ratio measured by Thomson.

Don’t memorize numbers like that just because they are on the slides

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Henri Becquerel (1896)

- Discovered radioactivity by observing the spontaneous emission of radiation by uranium.
- Using a magnetic field he found that there were three kinds of radiation:
  - negatively charged
  - positively charged
  - neutral

Ernest Rutherford (1911)

Classified three types of radioactive emission based on their penetrating power (instead of charge, as Becquerel did)

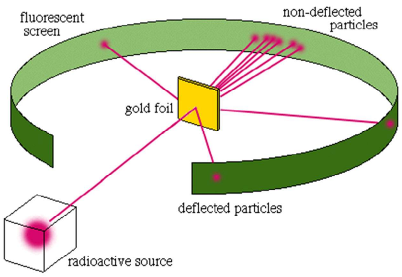
- Alpha (α)
  -- a particle with a +2 charge (least penetrating)
  -- much heavier than other types of radiation
- Beta (β)
  a high speed electron (–1 charge)
- Gamma (ϒ)
  high energy light (neutral) (most penetrating)

There are other kinds of radiation too

Ernest Rutherford (1911)

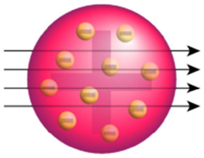
- Showed “plum pudding” model to be wrong
- Found that:
  - The atom has a very dense center with (+) charge: **nucleus**
  - Electrons travel around the nucleus, at large distances compared with the size of the nucleus
- And here is how he did that:

Rutherford’s gold foil experiment (~1911)

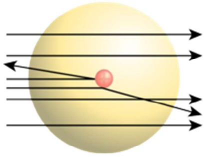


Alpha particles:
- much heavier than electrons
- positively charged

Most alpha particles went through non-deflected,
but some bounced off in all directions



Plum-pudding model: Thompson
Mass spread uniformly
⟹No (or very small) deflections
⟹Does not match the experiment!



Nuclear model: Rutherford
Mass is concentrated at center
Very light electrons fill the volume
⟹Mostly no deflection
⟹Occasional big deflection
⟹Matches the gold-foil experiment

Neutrons

- hypothesized by Rutherford in 1920
- discovered experimentally in 1932 by James Chadwick
- have no electric charge (neutral)
- mass and size similar to proton; very slightly heavier

- Act as glue holding the positively charged protons together
- There is a special nuclear force, the “strong nuclear force” between neutrons and protons that can overcome the electrostatic repulsion between positively charged protons.
- Without neutrons the repulsion between the (+) charged protons would break the nucleus apart

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So, the atom contains:

Electrons:
- outside the nucleus
- negatively charged
- much lighter than protons and neutrons
- spread over a much larger volume than the nucleus

Protons:
- in the nucleus
- positive charge equal in magnitude to the electron’s negative charge.
- tiny but heavy (dense)

Neutrons:
- in the nucleus
- no charge
- density similar to proton; very slightly heavier

The nucleus is:
- **Small** compared with the overall size of the atom.
- Extremely **dense**; accounts for almost all of the atom’s mass

Each proton or neutron is ~1850 times heavier than an electron

-- we normally ignore the mass of electrons
-- proton and neutron masses are slightly different
-- and their mass changes slightly depending on nucleus they are in

Very strong nuclear forces ⇨ Very large nuclear energies ⇨ Large variations in very large nuclear energies ⇨ $E = mc^2$ noticeable variation in particle mass

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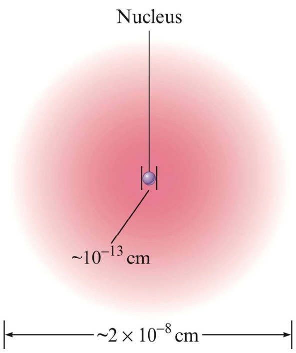
Nuclear Atom Viewed in Cross Section



Actually this picture exaggerates the size of the nucleus.

The nucleus would be invisible in this picture of an atom!

$$\frac{2 \times 10^{-8}\text{ cm}}{10^{-13}\text{ cm}} = 200,000$$

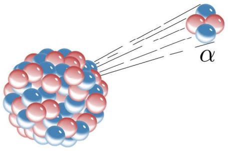
The atom is 200,000 times larger than the nucleus.
200,000 pixel-wide screen needed for the nucleus to occupy 1 pixel.

Now that we learned about nuclei and particles …

Let's make sure we know what an alpha particle is

- **Nucleus of a Helium atom** ; has **+2 charge**
- Heaviest of the common radiation types
- Has **2 protons** and **2 neutrons**

  -- **Atomic number of the atom left behind changes**
  (because it has 2 less protons)



Isotopes

- Atoms with the same number of protons
  ⇨ same element
  - but different numbers of neutrons.
- Isotopes show virtually identical chemical properties because chemistry is done by the electrons.

  (the isotopes of the lightest elements like H or Li have measurable chemical differences, but the reasons for that is beyond the scope of the course)
- In nature most elements are mixtures of isotopes.
  The relative abundances of isotopes on Earth are fairly well fixed

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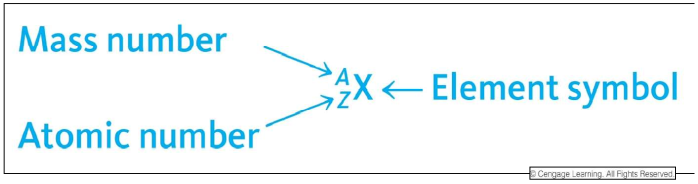
Isotopes are identified by:

Atomic Number (Z) = number of protons (p)

Mass Number (A) = number of protons (p) + number of neutrons (n)

Z = p   A = p + n



Example -- Isotopes of Magnesium:

		Natural abundance
${}^{24}_{12}\mathrm{Mg}$	12 protons, 12 neutrons	79%
${}^{25}_{12}\mathrm{Mg}$	12 protons, 13 neutrons	10%
${}^{26}_{12}\mathrm{Mg}$	12 protons, 14 neutrons	11%

Isotope symbol: ${}^{24}_{12}\mathrm{Mg}$

Showing the Z value is redundant, since its value is fixed for the isotopes of a given element.

If it's a magnesium isotope, Z is always 12

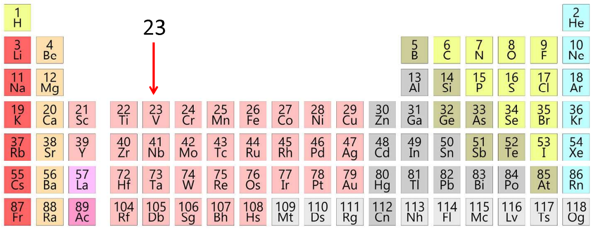
Isotope name: {element name}– {mass number}

${}^{24}_{12}\mathrm{Mg}$ is magnesium – 24

A certain isotope X contains 23 protons and 28 neutrons.

- What is the mass number of this isotope?
- Identify the element.

- The identity of an atom is determined by its number of **protons**
- It's Vanadium (V) because of the number of protons (23), **not** the mass number (51)



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											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 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

The element rhenium (Re) exists as 2 stable isotopes and 18 unstable isotopes. The nucleus of rhenium-185 contains:

a) 75 protons and 75 neutrons
b) 75 protons and 130 neutrons
c) 130 protons and 75 neutrons
d) 75 protons and 110 neutrons

Which of the following statements are true?

I. The number of protons is the same for all neutral atoms of an element.
II. The number of electrons is the same for all neutral atoms of an element.
III. The number of neutrons is the same for all neutral atoms of an element.

a) I, II, and III are true
b) Only I and II are true
c) Only II and III are true
d) Only I and III are true
e) I, II, and III are false.

Ions

Cations

- Formed when an atom loses one or more electrons

$Li \rightarrow Li^{+} + e^{-}$

$Ba \rightarrow Ba^{2+} + 2e^{-}$

Anions

- Formed when an atom gains one or more electrons

$F + e^{-} \rightarrow F^{-}$

$N + 3e^{-} \rightarrow N^{3-}$

Note that we put the size of the charge before the sign:
2+ instead of +2
3– instead of –3

Ions

Unless the atom is undergoing a nuclear reaction (which is not chemistry), ions are formed only by **gaining or losing electrons**

Ions are denoted by a superscript on the right side of the entity, indicating the charge.

Examples:

Cl^{-} Ca^{2+} S^{2-}

How is an ion formed in a chemical process, starting with a neutral atom?

a) By adding or removing protons
b) By adding or removing electrons
c) By adding or removing neutrons
d) All of these are true
e) Two of these are true.

A certain isotope X^+ contains 54 electrons and 78 neutrons.

What is the mass number of this isotope?

Which of the following statements regarding Dalton's atomic theory are still considered true?

I. Elements are made of tiny particles called atoms.
II. All atoms of a given element are identical.
III. A given compound always has the same relative numbers and types of atoms.
IV. Atoms are indestructible.

By the way:
This is the part where the "**Law** of Definite Proportions" is **explained** (if we read his whole theory), in Dalton's Atomic **Theory**.

The Periodic Table

Periods

- **horizontal** rows of elements
- properties change in a similar way in each period
- with each new period, the trend repeats (or more like "rhymes")

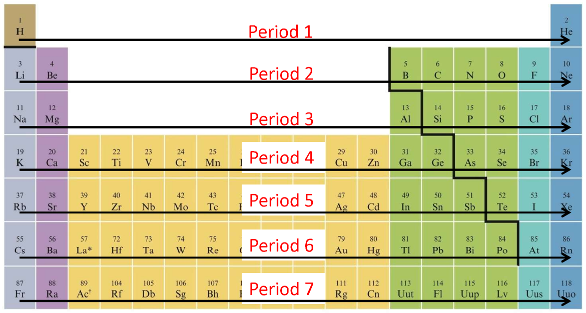
Groups or Families

- elements in the same **vertical** columns
- have similar chemical properties

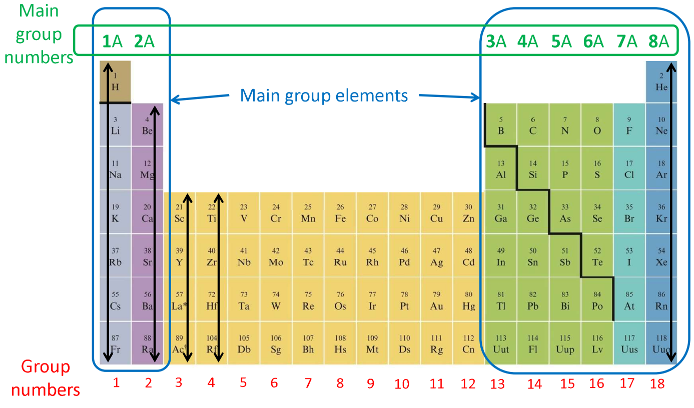
Most elements are metals

Nonmetals are huddled towards the top-right corner

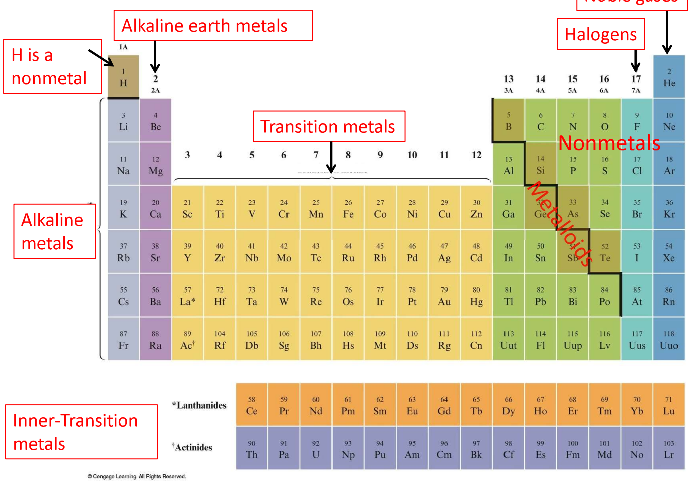
Periods are horizontal

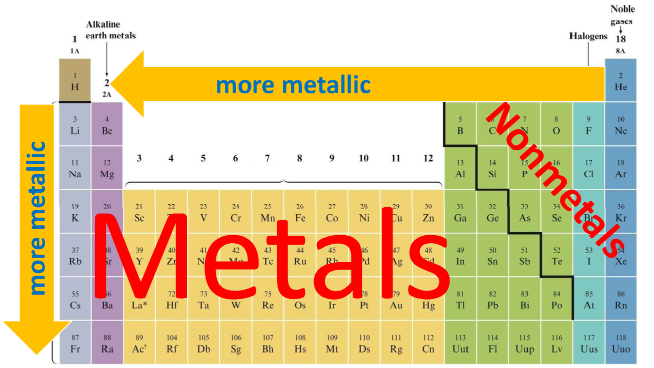


Groups are vertical



The Periodic Table





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Groups or “Families” of elements and their ions

- Metals form cations by losing electrons
- Main group metals lose as many electrons as their main group number

cation charge = main group #

- Nonmetals form anions by gaining electrons
- Nonmetal anion charge size is the difference between main group number and 8 (main group number of noble gases at the very right)

anion charge = {main group #} - 8

Chemical Bonds

Strong attraction holding two atoms together

Ionic Bonds

- Due to attraction between oppositely charged **ions**.
- Form an extensive lattice of ions (**ionic crystals**), **not molecules**.

Covalent Bonds

- Formed by sharing electrons.
- The nuclei of the bonded atoms are attracted to the electrons in between.
- **Molecules** are formed by covalent bonds

  But covalent bonds can lead to other structures too, like covalent crystals

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Groups or “Families” of elements and their ions

Group or Family	Charge of ion	
Alkali Metals (1A)	1+	
Alkaline Earth Metals (2A)	2+	
Aluminum *(not a group)* (3A)	3+	
Group 5 nonmetals (5A)	3–	5–8 = –3
Chalcogens (6A)	2–	6–8 = –2
Halogens (7A)	1–	7–8 = –1
Noble Gases (8A)	0	(they don’t ionize)

Main Group #

Main Group #

Main Group # of noble gases

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By the way:

These charges are taken on **only when they are stabilized by nearby charges of the opposite sign.**

-- such as in an ionic compound

-- or when that ionic compound is dissolved in a solvent with “polar” molecules, like water

Some parts are electron-rich (–), some parts are electron poor (+)

If you ignore this point, you might think those elements always exist as ions!

A common misconception!

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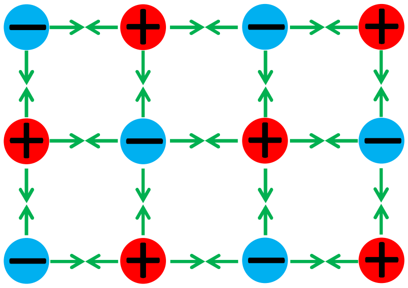
Ionic bonding

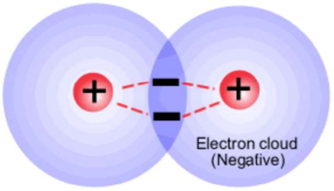
Due to the electrostatic attraction between positive and negative ions

The ions form an extended lattice instead of a molecule



Covalent bonding

Two electrons (normally one from each atom) spend most of their time between the two nuclei, attracted and stabilized by both, instead of just one.



The two nuclei in turn are attracted to the accumulated electrons between them.

This attraction holds the two atoms together.

Picture from http://myibchemistry.blogspot.com/2013/11/topic-42-covalent-bonding.html

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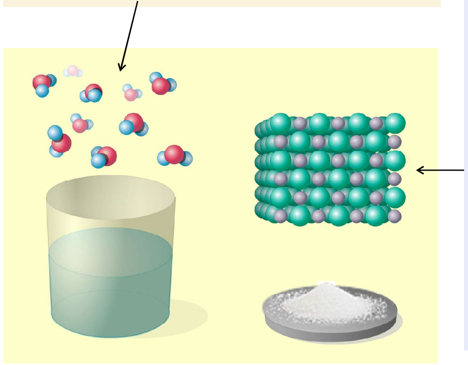
Molecular vs Ionic Compounds

Atoms covalently bonded in a molecule always travel together

It’s clear which atoms belong together



Ions in an ionic compound form a lattice but don’t travel together.

When dissolved or melted, they go their separate ways

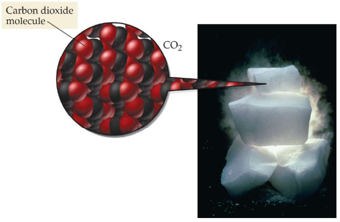
No specific cations and anions “belong” together

Molecular vs Ionic Compounds

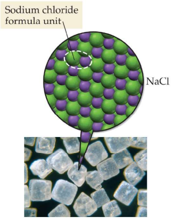
- **Covalent compounds** are formed from two or more nonmetals (usually), and <u>**only** have covalent bonds.</u>
  - Often “Molecular” is used to mean “Covalent”
  - Molecular compounds are covalent
  - But <u>not all</u> covalent compounds are molecular
  - Some covalent compounds exist as covalent crystals
- **Ionic compounds** have at least one ionic bond per formula
  - one or more cations with one or more anions

Molecular vs Ionic Compounds

The basic units that compose dry ice, a molecular compound, are CO_2 **molecules.**



The basic units that compose table salt, an ionic compound, are NaCl **<u>formula units</u>.**



Ionic Compounds

- We will focus on **binary** ionic compounds
- “Binary” indicates “two elements”
- Cation is formed by a metal
- Anion is formed by a nonmetal
- We will treat metal-nonmetal binary compounds as **ionic** (even though some are covalent)
- The basic unit of ionic compounds is the **<u>formula unit</u>.**
- Formula unit is the “pretend molecule”
- It has the smallest overall-neutral group of cations and anions of the ionic compound

---

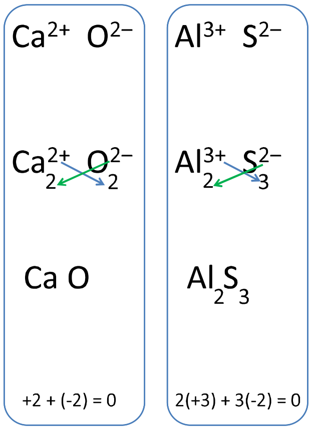
Ionic Compounds

- Ionic compounds always contain positive and negative ions.
- In the chemical formula of an ionic compound, the sum of the charges of the positive ions (cations) must always equal the sum of the charges of the negative ions (anions).
  - ➢Compounds are neutral

Writing Formulas for Ionic Compounds

Ionic Compounds

1. Write the symbol for the metal and its charge followed by the symbol of the nonmetal and its charge.
2. Make the magnitude of the charge on each ion (without the sign) become the subscript for the other ion.
3. If possible, reduce the subscripts to give a ratio with the smallest whole numbers.
   - Don't write a subscript of 1
4. Make sure charges add up to zero.



Ca^{2+} O^{2-}

Ca^{2+}_{2} O^{2-}_{2}

Ca O

+2 + (-2) = 0

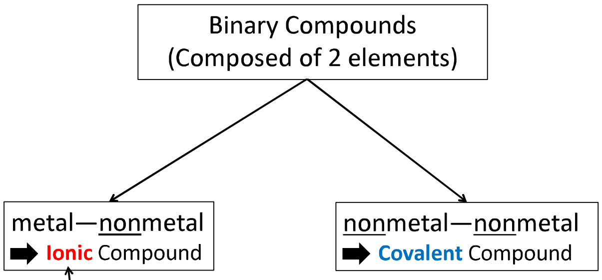
Al^{3+} S^{2-}

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

Al_2S_3

2(+3) + 3(-2) = 0

Naming Binary Compounds (Nomenclature)



Binary Compounds
(Composed of 2 elements)

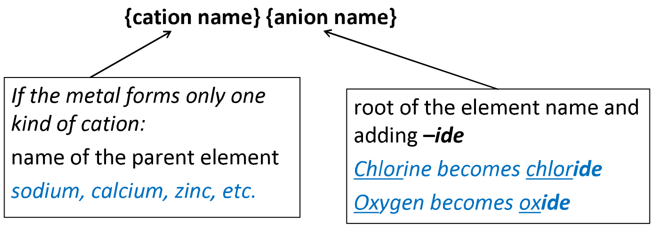
metal—<u>nonmetal</u>
➡ **Ionic** Compound

<u>nonmetal</u>—<u>nonmetal</u>
➡ **Covalent** Compound

Assumed ionic, and named accordingly.
Sometimes it's not really ionic, but even then it is named as if it were ionic.

Naming <u>Binary</u> (two elements) <u>Ionic</u> Compounds

- <u>If the first element in the formula is a metal, it is an ionic compound</u>
- The metal is the cation.
- Cation name first, anion name second.



{cation name} {anion name}

If the metal forms only one kind of cation:
name of the parent element
sodium, calcium, zinc, etc.

root of the element name and adding ***–ide***
*<u>Chlorine</u> becomes <u>chlor</u>**ide***
*<u>Oxygen</u> becomes <u>ox</u>**ide***

What if the metal can form cations with different charges?
See next page

Naming <u>Binary</u> <u>Ionic</u> Compounds (continued)

What if the metals in compound can form cations with <u>more than one</u> charge?

Similar to the simple, "one charge" case, except:

- Charge on the metal ion must be specified with a <u>Roman numeral</u> in parentheses
- **Transition metal cations** (except for Ag, Zn, Cd) **<u>usually</u> require a Roman numeral**.
- **Lead** (Pb) and **Tin** (Sn) require a Roman numeral
- Metals that form only one cation <u>should not</u> be identified by a roman numeral

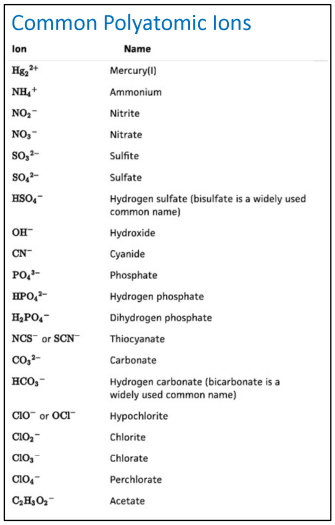
Examples:		
	CuBr	Copper(I) bromide
	FeS	Iron(II) sulfide
	PbO_2	Lead(IV) oxide

Polyatomic Ions

- Ions containing more than one atom ("poly"=many)
- like molecules, except that they carry a charge.
- each has a definite, characteristic charge.
- Almost all (here) are anions, except NH_4^+ and Hg_2^{2+}
- Naming ionic compounds of polyatomic ions are just like binary ionic compounds.
  - -- The polyatomic anion name follows the cation name (which may itself be polyatomic)
- Polyatomic ion names must be memorized
  - -- But there are some rules that help deriving some of them
  - -- Table 2.5 in textbook (page 65 for 9th ed., page 58 for 10th ed.)
  - -- Use "Procedure" for the Inorganic Nomenclature Lab Exercise
- If you do enough practice and homework, those ions become your "knowledge" rather than things to "memorize"

The more you work on practice questions that use those ions, the more you will naturally learn the formulas, and the less you must memorize.

It's exactly like gaining fluency in a language.



Common Polyatomic Ions

Ion	Name
Hg_2^{2+}	Mercury(I)
NH_4^+	Ammonium
NO_2^-	Nitrite
NO_3^-	Nitrate
SO_3^{2-}	Sulfite
SO_4^{2-}	Sulfate
HSO_4^-	Hydrogen sulfate (bisulfate is a widely used common name)
OH^-	Hydroxide
CN^-	Cyanide
PO_4^{3-}	Phosphate
HPO_4^{2-}	Hydrogen phosphate
$H_2PO_4^-$	Dihydrogen phosphate
NCS^- or SCN^-	Thiocyanate
CO_3^{2-}	Carbonate
HCO_3^-	Hydrogen carbonate (bicarbonate is a widely used common name)
ClO^- or OCl^-	Hypochlorite
ClO_2^-	Chlorite
ClO_3^-	Chlorate
ClO_4^-	Perchlorate
$C_2H_3O_2^-$	Acetate

We can figure out polyatomic ion charges:

odd number of odd-group atoms gives odd charge

Goes with odd atomic number

If the charge is odd:

- Almost always −1 for anions (except −3 for phosphate)
- +1 for ammonium)

If the charge is not odd (i.e. even)

- −2 for anions
- +2 for the Hg_2^{2+} cation

Even/Odd part of the charge is "always" correct

For ions not encountered in General Chemistry, the charge magnitude can be (far) beyond −3 or +3

---

odd number of odd-group atoms gives odd charge

In the examples below, following elements have odd atomic numbers

H: atomic no.=1	**N**: atomic no.=7	**Cl**: atomic no.=17	**Mn**: atom no.=25
(Group **1**)	(Group **15**; or **5**A)	(Group **17**; or **7**A)	(Group **7**)

ClO_3^-	**one** atom with odd atomic number	➡	charge should be **odd**	➡	−1
CO_3^{2-}	**zero** atoms with odd atomic number	➡	charge should be **even**	➡	−2
NO_3^-	**one** atom with odd atomic number	➡	charge should be **odd**	➡	−1
SO_4^{2-}	**zero** atoms with odd atomic number	➡	charge should be **even**	➡	−2
HPO_4^{2-}	**two** atoms with odd atomic number	➡	charge should be **even**	➡	−2
HCO_3^-	**one** atom with odd atomic number	➡	charge should be **odd**	➡	−1
$Cr_2O_7^{2-}$	**zero** atoms with odd atomic number	➡	charge should be **even**	➡	−2
MnO_4^-	**one** atom with odd atomic number	➡	charge should be **odd**	➡	−1
$C_2O_4^{2-}$	**zero** atoms with odd atomic number	➡	charge should be **even**	➡	−2
$C_2H_3O_2^-$	**three** atoms with odd atomic number	➡	charge should be **odd**	➡	−1

Can you predict the charges on the following anions not on your usual list of polyatomic ions?

Only hint: the magnitude of the charge will not exceed 2

$CF_3SO_3^x$

$C_4O_4^x$

Naming of Oxyanions

- Almost all of the anions we deal with here are "oxyanions"
  - — They contain oxygen in addition to a non-oxygen "central" element
- If there is only one kind of common oxyanion of an element (it combines with only a certain number of oxygen atoms to form its one oxyanion):

  {root of element name} ate
- If the element can form two kinds of oxyanions (each with a different number of oxygens), then:
  - — the **low-oxygen** one ends with –ite

    {root of element name} ite
  - — the **high-oxygen** one again ends with –ate

    {root of element name} ate

Naming of Oxyanions

NO_2^-	Nitrite	Low oxygen content
NO_3^-	Nitrate	High oxygen content

SO_3^{2-}	Sulfite	Low oxygen content
SO_4^{2-}	Sulfate	High oxygen content

- Unfortunately there is no fixed number of oxygens corresponding to –ite and –ate
- We only know that –ite goes with less oxygen, and –ate goes with more oxygen, when there are two choices
  - ➢ 2 and 3 for oxyanions of nitrogen, but …
  - ➢ 3 and 4 for oxyanions of sulfur, etc.

Naming of Oxyanions of Halogens

Naming of Oxyanions

- **Halogens** can form **four kinds** of oxyanions
  - With 1, 2, 3, 4 oxygens (pretty simple to remember)
- Middle two are the "regular" low-oxygen and high-oxygen ions
- The ion with even less oxygen than the "low-oxygen" ion end with the same –ite ending, but takes a prefix of **"hypo"**
- The ion with even more oxygen than the "high-oxygen" ion end with the same –ate ending, but takes a prefix of **"per"**

Higher than "high"

ClO_4^-	Perchlorate	Highest oxygen content (4)
ClO_3^-	Chlorate	High oxygen content (3)
ClO_2^-	Chlorite	Low oxygen content (2)
ClO^- or OCl^-	Hypochlorite	Lowest oxygen content (1)

Lower than "low"

Chlorine, Bromine, and Iodine form analogous oxyanions:

BrO_3^-	Bromate
IO_4^-	Periodate
IO^-	Hypoiodite
BrO_2^-	Bromite
FO^-	Hypofluorite The only oxyanion of fluorine!

Examples of ionic compounds with polyatomic ions:

$NaOH$	Sodium hydroxide
$Mg\underset{\uparrow}{(}NO_3\underset{\uparrow}{)}_{\textcircled{2}}$	Magnesium nitrate
$\underset{\uparrow}{(}NH_4\underset{\uparrow}{)}_{\textcircled{2}}SO_4$	Ammonium sulfate

If multiple polyatomic ions are needed in the formula, they are enclosed in parentheses before putting their count as subscript

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An element's most stable ion forms an ionic compound with chlorine having the formula XCl_2. If the ion has 36 electrons, what is the element that produces the ion?

a) Kr
b) Se
c) Sr
d) Rb
e) None of these

______ form ions with a 2+ charge when they react with nonmetals.

a) Alkali metals
b) Alkaline earth metals
c) Halogens
d) Noble gases
e) None of these

Which is *not* the correct chemical formula for the compound named?

a) potassium phosphate, K_3PO_4
b) iron(II) oxide, FeO
c) calcium carbonate, $CaCO_3$
d) sodium sulfide, NaS
e) lithium nitrate, $LiNO_3$

Naming Binary Covalent Compounds

Formed between two nonmetals.

- Naming scheme modeled after ionic compounds
- But we need to indicate the number of atoms of each element because they can't be predicted

1. The first element in the formula is named first, using the full element name (just like for the cations)
2. The second element is named as if it were an anion, with an *–ide* added to the root name of the element

up to this point, same as for ionic compounds, but …

3. Prefixes are used to denote the numbers of atoms present.
4. The prefix *mono-* is never used for naming the first element.

Prefixes Used to Indicate Number in Chemical Names

Prefix	Number
mono-	1
di-	2
tri-	3
tetra-	4
penta-	5
hexa-	6
hepta-	7
octa-	8
nona-	9
deca-	10

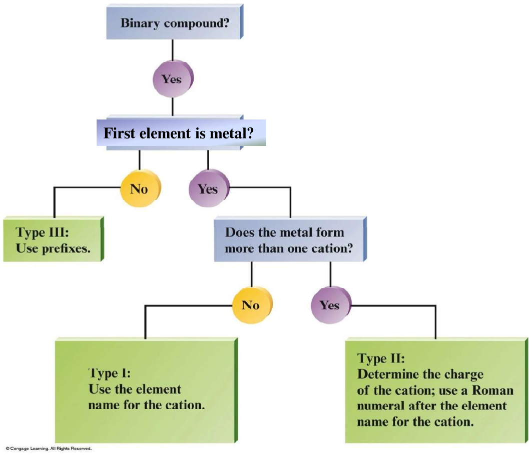
Binary Covalent Compounds Examples:

CO	Carbon monoxide
CO_2	Carbon dioxide
SF_6	Sulfur hexafluoride
N_2O_4	Dinitrogen tetroxide

"a" or "o" at the end of the prefix is dropped if followed by "o":
monooxide → monoxide
pentaoxide → pentoxide

This is basically relevant only for prefixing oxygen

Simplified Flowchart for Naming Binary Compounds



Which of the following is named incorrectly?

a. Li_2O, lithium oxide
b. $FePO_4$, iron(III) phosphate
c. HF, hydrogen fluoride
d. $BaCl_2$, barium dichloride
e. Mg_3N_2, magnesium nitride

Why didn't we consider "hydrogen fluoride" wrong?

Why didn't we say it should be "hydrogen monofluoride"?

Covalent compounds whose formula starts with hydrogen (H) are "acidic", and when they are named as an ordinary compound rather than as an acid, the prefixes are not used.

Acidic molecules "lose" the acidic hydrogens as H^+ cations.

What remains is an anion whose charge is known.

There is one anion, and the number of H atoms in the formula is equal to the charge of the anion produced.

The number of atoms of each element is known and fixed.

So:
We skip prefixes when naming acidic molecules as "compounds" (acid names are a whole different thing that we will look at later)

Which is the correct formula for copper(I) sulfide?

a) CuS
b) Cu_2S
c) CuS_2
d) Cu_2S_2
e) None of these

Which of the following is the correct chemical formula for iron(III) oxide?

a) FeO
b) Fe_3O
c) FeO_3
d) Fe_2O_3
e) Fe_3O_2

What is the correct name for the compound with the formula $Mg_3(PO_4)_2$?

a) Trimagnesium diphosphate
b) Magnesium(II) phosphate
c) Magnesium phosphate
d) Magnesium(II) diphosphate
e) Magnesium(III) diphosphate

Acids

- Acids can be recognized by:
  the **hydrogen that appears __first__** in the formula.
  For example, HCl or $HC_2H_3O_2$
- Molecule with one or more ionizable H atoms
- When the molecule acts as an acid, the acidic, ionizable H becomes an H^+, leaving behind an anion.
  - The acid **molecule** is producing ions, but it is not an ionic compound; it is a **molecular** compound.

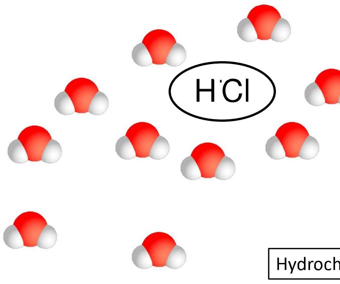
$$HA \longrightarrow H^+ + A^-$$

acidic hydrogen

anion produced by the acid

A relevant historical note

- Lavoisier (**__incorrectly__**) thought oxygen was what made a substance acidic.
  - "Oxygen" means "acid generator"
- When faced with acids that refused to reveal any oxygen in them (such as HCl), chemists of the time thought that the original substance somehow got oxygenated by water when dissolved, and __then__ became acidic.
- Therefore, acids with no oxygen were regarded and named as "acid" only in aqueous solution.
- **That naming tradition survives to this day**.



Hydrogen Chloride (g)

Molecular
H-Cl *bond is covalent*
not ionic

Hydrochloric acid (aq)

HCl *in water:*
in the form of ions H^+ *and* Cl^-
No chemical bond between H^+ *and* Cl^-

Of course what "hydrogen chloride" does in water has nothing to do with oxygen. But the tradition of naming acids without oxygen as "acids" only when in aqueous solution survives.

More on the presence and absence of oxygen in acids …

- Monatomic (single atom) anion names all end with ***–ide***
  - — Sulfide, chloride, etc. (non-oxygen, obviously)
  - — Oxide (obviously has oxygen), combined with H^+ forms water, which is not named as an acid; so not relevant
- Cyanide CN^- also ends with ***–ide***, even though it is not monatomic
  - — It acts like the anion of a halogen in many ways, so early chemists could have lumped it with the halides and named similarly
- Anions with names ending with ***–ide*** indeed don't have oxygen
- But there are some anions without oxygen whose names don't end in ***–ide***

More on the presence and absence of oxygen in acids …

- Some anions without oxygen have names that don't end with ***–ide***

  e.g. thiocyan**ate**, SCN^-

- Acid naming scheme ultimately cares about the anion **name ending**, not the presence of oxygen in the molecule
  - — Many textbooks and sources focus on the oxygen
  - — Understandable, and almost right; but not quite right

In short …

Acid naming scheme only cares about the anion name ending.

Three possibilities for anion name ending:

-ide

-ate

-ite

Naming Acids
If the anion name ends with *–ide*

Its acid is named with the prefix ***hydro–*** and the suffix ***–ic***.

{Hydro} {root} {ic} acid

root name of the anion formed by the acid

For acids whose anions end with *–ide* **only:**

Named as acid only if they are in aqueous solution

Chloride	(Cl^-)	➡	HCl(aq)	Hydrochloric acid
Cyanide	(CN^-)	➡	HCN(aq)	Hydrocyanic acid
Sulfide	(S^{2-})	➡	H_2S(aq)	Hydrosulfuric acid

means "water";
related to naming these compounds as acid only in water

Naming Acids
If the anion name ends with *–ide*

The pure compound is named as a binary covalent compound
(or *as if it were*, if the anion has more than one atom like CN^-)

HCl(g)	Hydrogen chloride
HCN(g)	Hydrogen cyanide

Again, **only when the anion name ends with** ***-ide***

Naming Acids
If the anion name ends with *–ate*

The suffix ***–ic*** is added to the root name

{root}{ic} {acid}

Examples:

Nitr**ate**	(NO_3^-)	➡	HNO_3	Nitric acid
Acet**ate**	($C_2H_3O_2^-$)	➡	$HC_2H_3O_2$	Acetic acid
Sulf**ate**	(SO_4^{2-})	➡	H_2SO_4	Sulfuric acid

Always named as an acid, aqueous solution or not.

No "hydrogen nitrate" or "hydrogen acetate"!

Naming Acids

If the anion name ends with *–ite*

The suffix ***–ous*** is added to the root name

{root}{ous} {acid}

Examples:

Nitrite (NO_2^-) → HNO_2 Nitrous acid

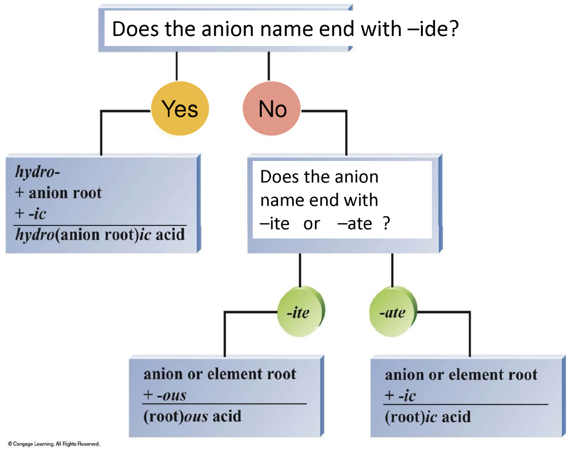
Chlorite (ClO_2^-) → $HClO_2$ Chlorous acid

Sulfite (SO_3^{2-}) → H_2SO_3 Sulfurous acid

Always named as an acid, aqueous solution or not.

No “hydrogen nitrite” or “hydrogen chlorite”!

Flowchart for Naming Acids



Does the anion name end with –ide?

Yes

No

hydro-
+ anion root
+ *-ic*
hydro(anion root)*ic* acid

Does the anion name end with –ite or –ate ?

-ite

-ate

anion or element root
+ *-ous*
(root)*ous* acid

anion or element root
+ *-ic*
(root)*ic* acid

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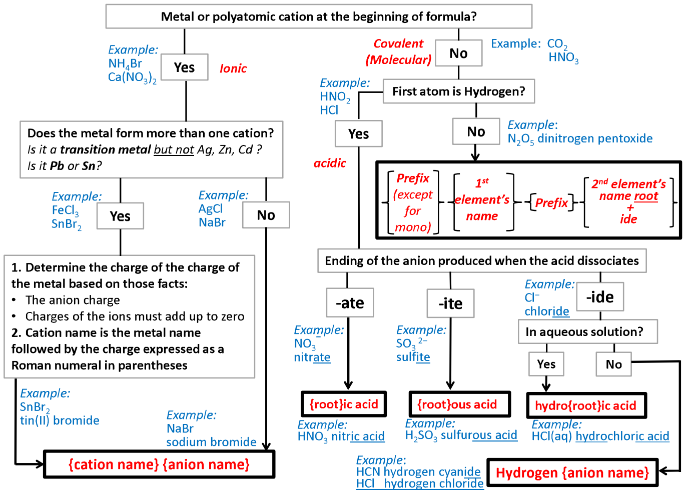
Complete Flowchart for Naming Simple Inorganic Compounds (may include polyatomic ions)



Metal or polyatomic cation at the beginning of formula?

Example: NH_4Br $Ca(NO_3)_2$

Yes

Ionic

Covalent (Molecular)

No

Example: CO_2 HNO_3

Does the metal form more than one cation?
*Is it a **transition metal** but not Ag, Zn, Cd ?*
*Is it **Pb** or **Sn**?*

Example: $FeCl_3$ $SnBr_2$

Yes

Example: AgCl NaBr

No

1. Determine the charge of the charge of the metal based on those facts:
- The anion charge
- Charges of the ions must add up to zero

2. Cation name is the metal name followed by the charge expressed as a Roman numeral in parentheses

Example: $SnBr_2$ tin(II) bromide

Example: NaBr sodium bromide

{cation name} {anion name}

First atom is Hydrogen?

Example: HNO_2 HCl

Yes

acidic

No

Example: N_2O_5 dinitrogen pentoxide

Prefix (except for mono) – *1st element’s name* – *Prefix* – *2nd element’s name root + ide*

Ending of the anion produced when the acid dissociates

-ate

Example: NO_3^- nitrate

{root}ic acid

Example: HNO_3 nitric acid

-ite

Example: SO_3^{2-} sulfite

{root}ous acid

Example: H_2SO_3 sulfurous acid

-ide

Example: Cl^- chloride

In aqueous solution?

Yes

hydro{root}ic acid

Example: HCl(aq) hydrochloric acid

No

Hydrogen {anion name}

Example: HCN hydrogen cyanide, HCl hydrogen chloride

What is the correct name for the acid with the formula HFO?

a) Fluoric Acid
b) Hydrofluoric Acid
c) Hydrofluorous Acid
d) Hypofluorous Acid
e) Perfluoric Acid

Which of the following compounds is named incorrectly?

a) KNO_3	potassium nitrate
b) TiO_2	titanium(II) oxide
c) $Sn(OH)_4$	tin(IV) hydroxide
d) PBr_5	phosphorus pentabromide
e) $CaCrO_4$	calcium chromate