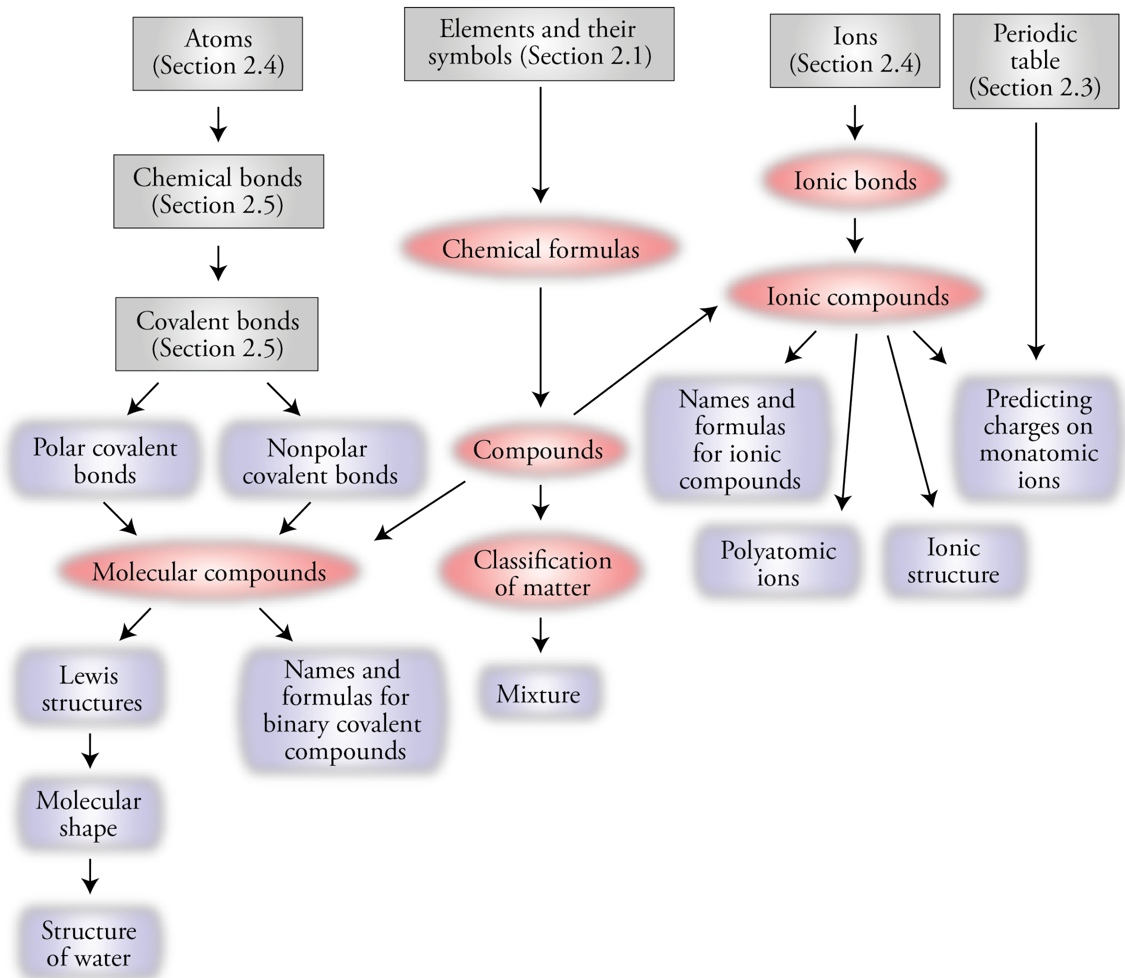
Chapter 3
Chemical Compounds

An Introduction to Chemistry

by Mark Bishop

Chapter Map



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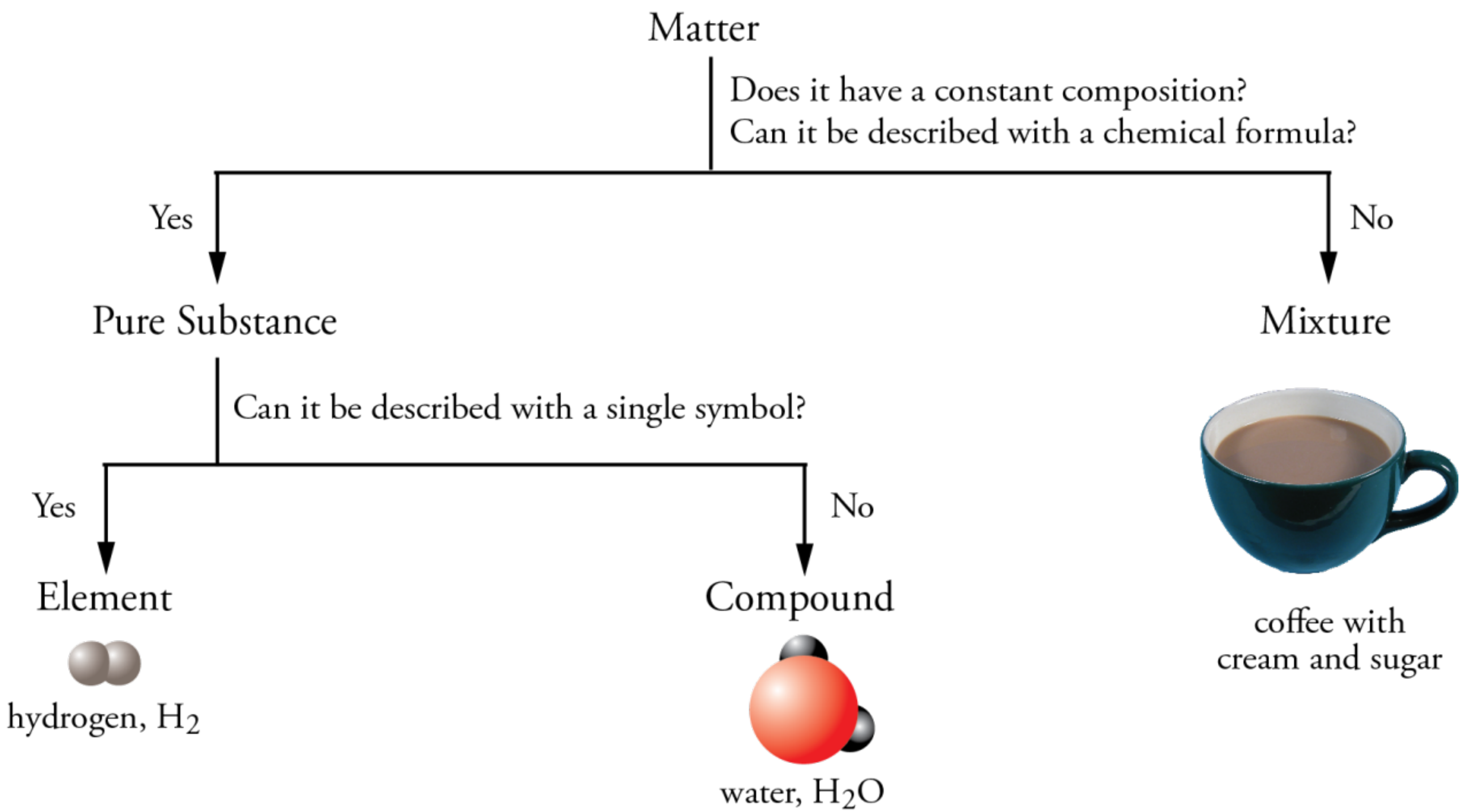
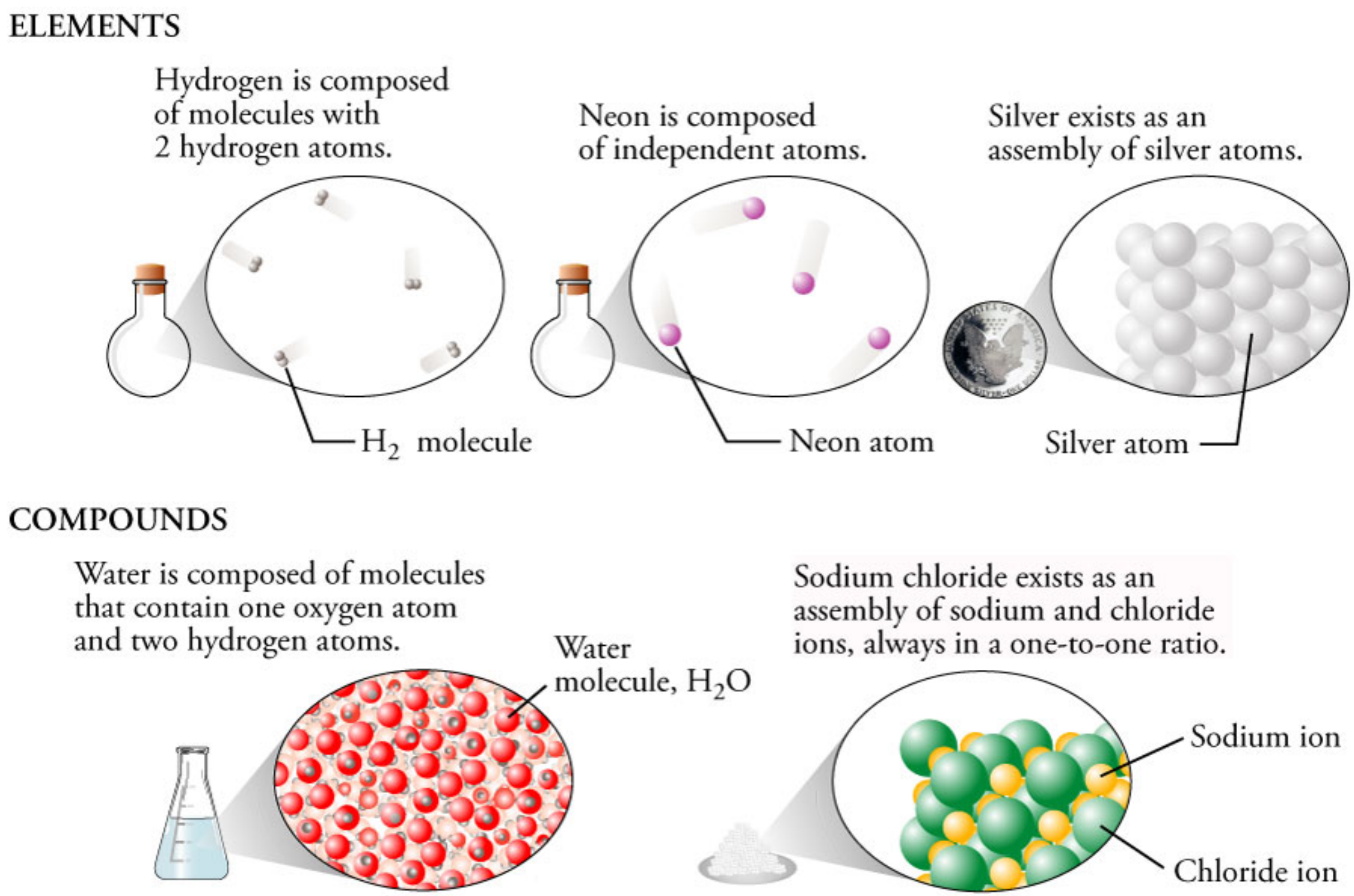
Elements, Compounds, and Mixtures

- **Element:** A substance that cannot be chemically converted into simpler substances; a substance in which all of the atoms have the same number of protons and therefore the same chemical characteristics.
- **Compound:** A substance that contains two or more elements, the atoms of these elements always combining in the same whole-number ratio.
- **Mixture:** A sample of matter that contains two or more pure substances (elements and compounds) and has variable composition.

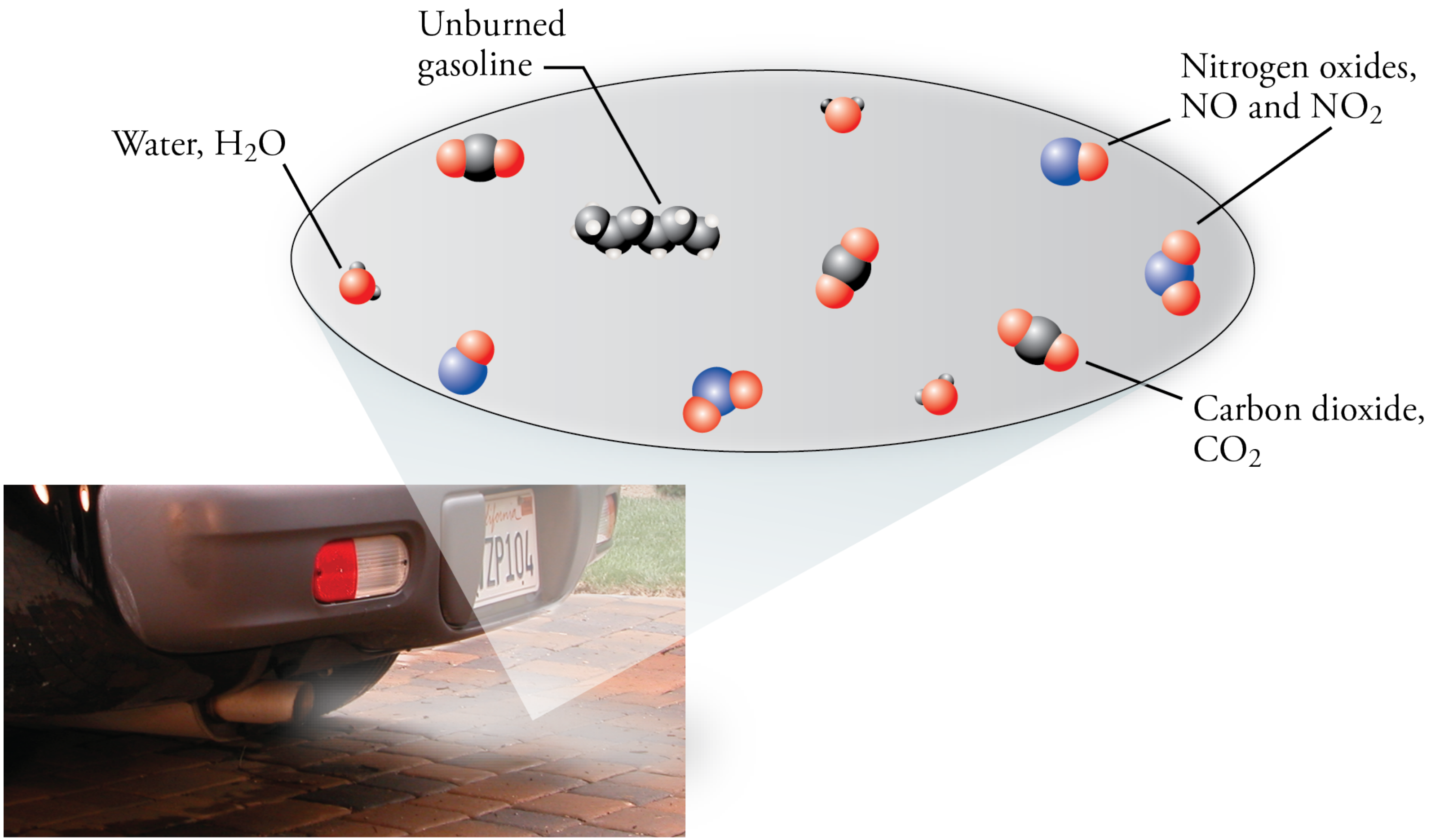
Classification of Matter



Elements and Compounds



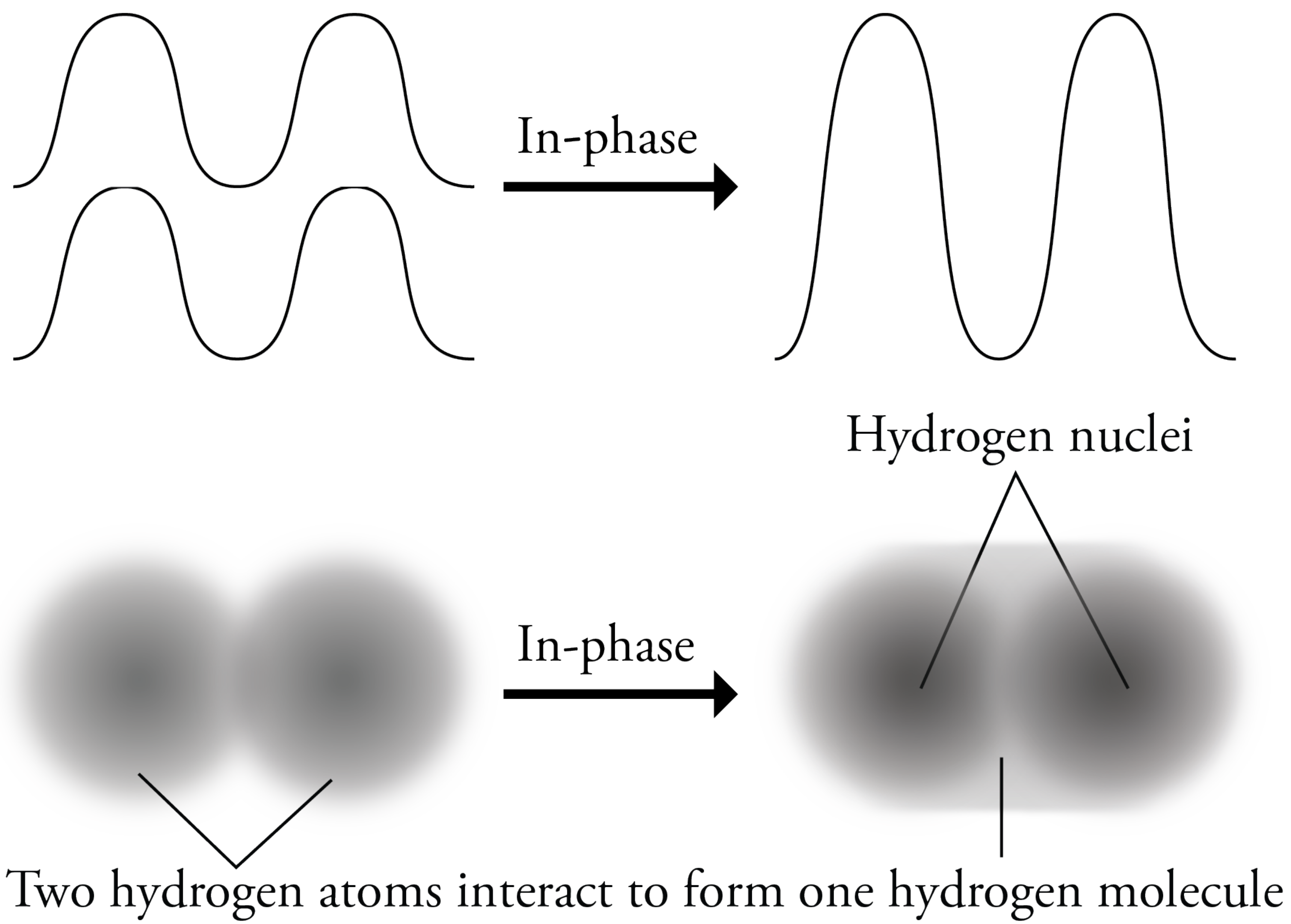
Exhaust – a Mixture



Particle and Wave Nature

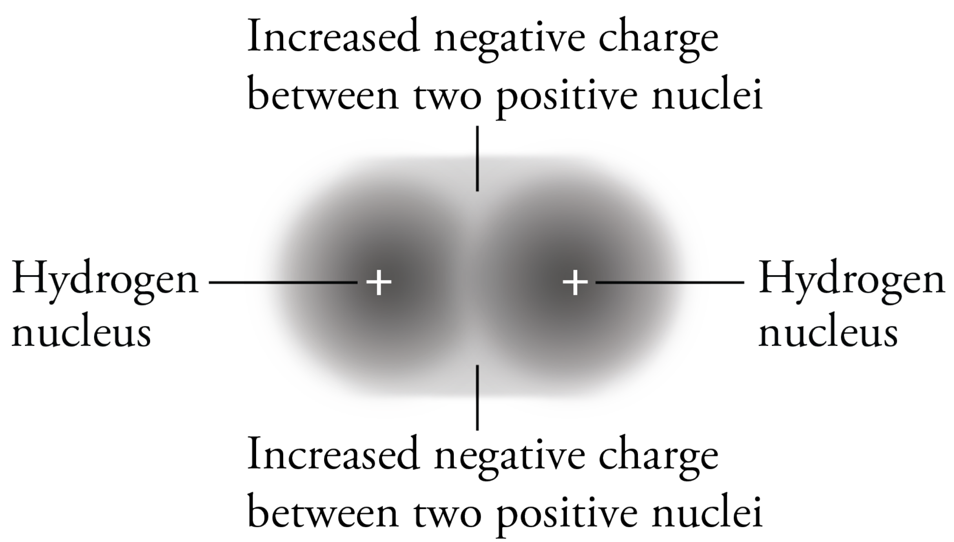
- All matter has both particle and wave character.
- The less massive the particle, the more important its wave character.
- The electron has a very low mass, low enough to have significant wave character.

Covalent Bond Formation



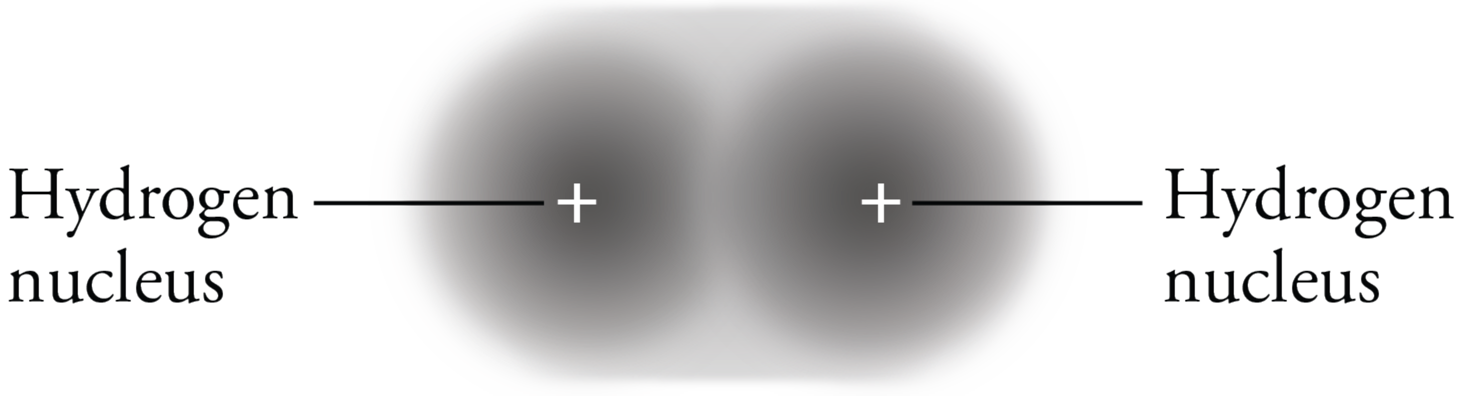
Covalent Bond Formation

- Increased negative charge between the two positive nuclei leads to increased +/- attraction and holds the atoms together.
- **Covalent bond** = a link between atoms due to the sharing of two electrons



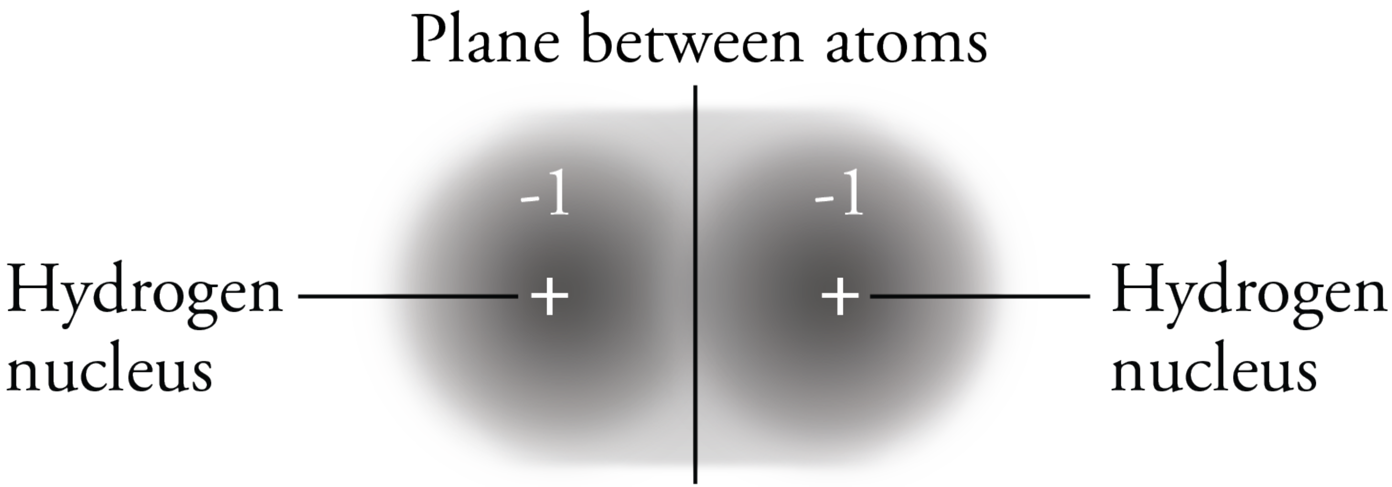
Molecule

- **Molecule** = an uncharged collection of atoms held together by covalent bonds.
- Two hydrogen atoms combine to form a hydrogen molecule, which is described with the formula H_2.



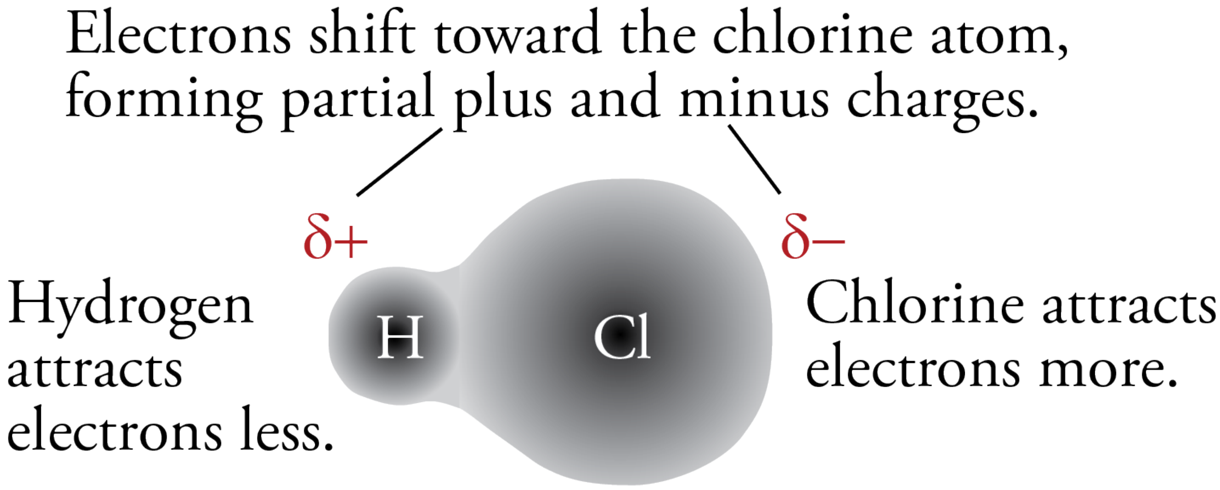
Nonpolar Covalent Bond

- If the electrons are shared equally, there is a even distribution of the negative charge for the electrons in the bond, so there is no partial charges on the atoms. The bond is called a ***nonpolar covalent bond***.



Polar Covalent Bond

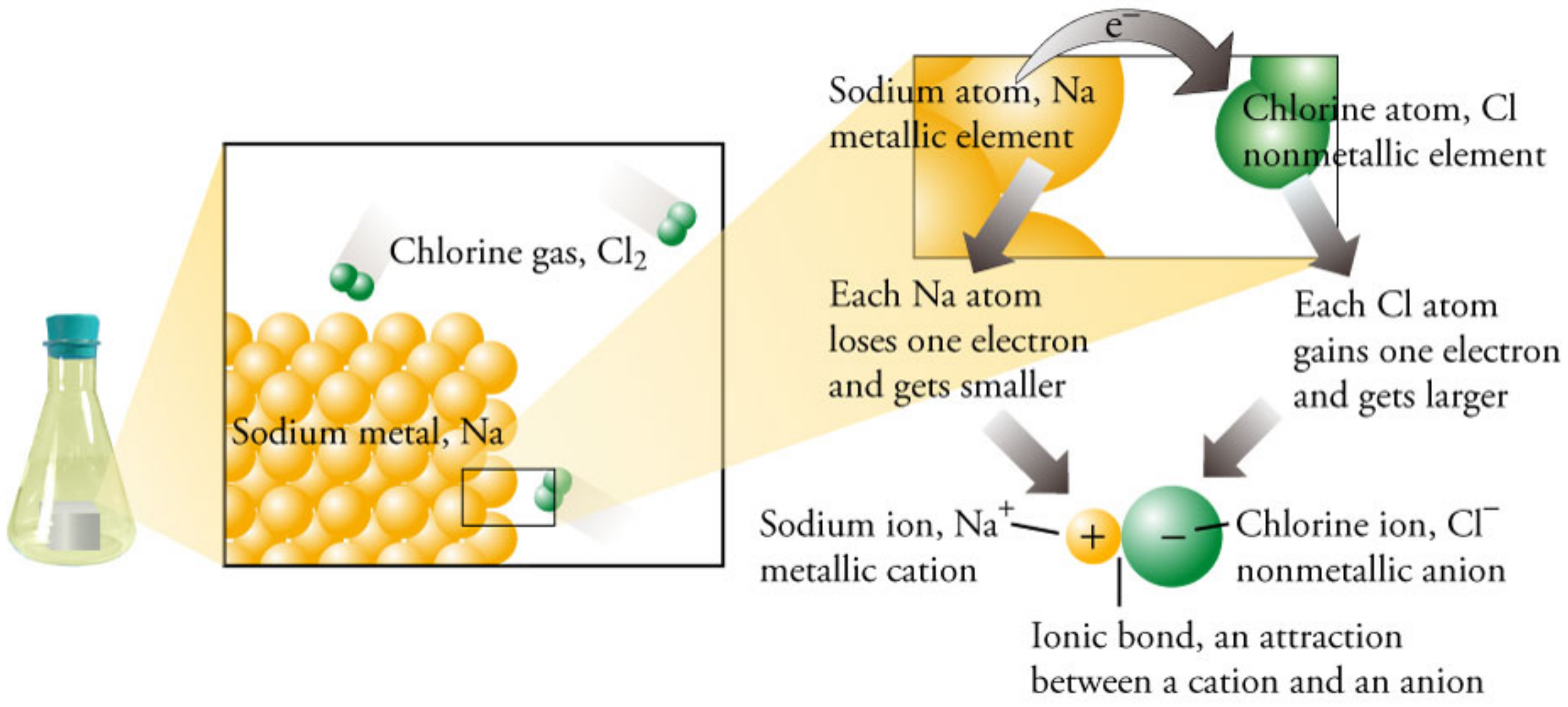
- If one atom in the bond attracts electrons more than the other atom, the electron negative charge shifts to that atom giving it a partial negative charge. The other atom loses negative charge giving it a partial positive charge. The bond is called a ***polar covalent bond***.



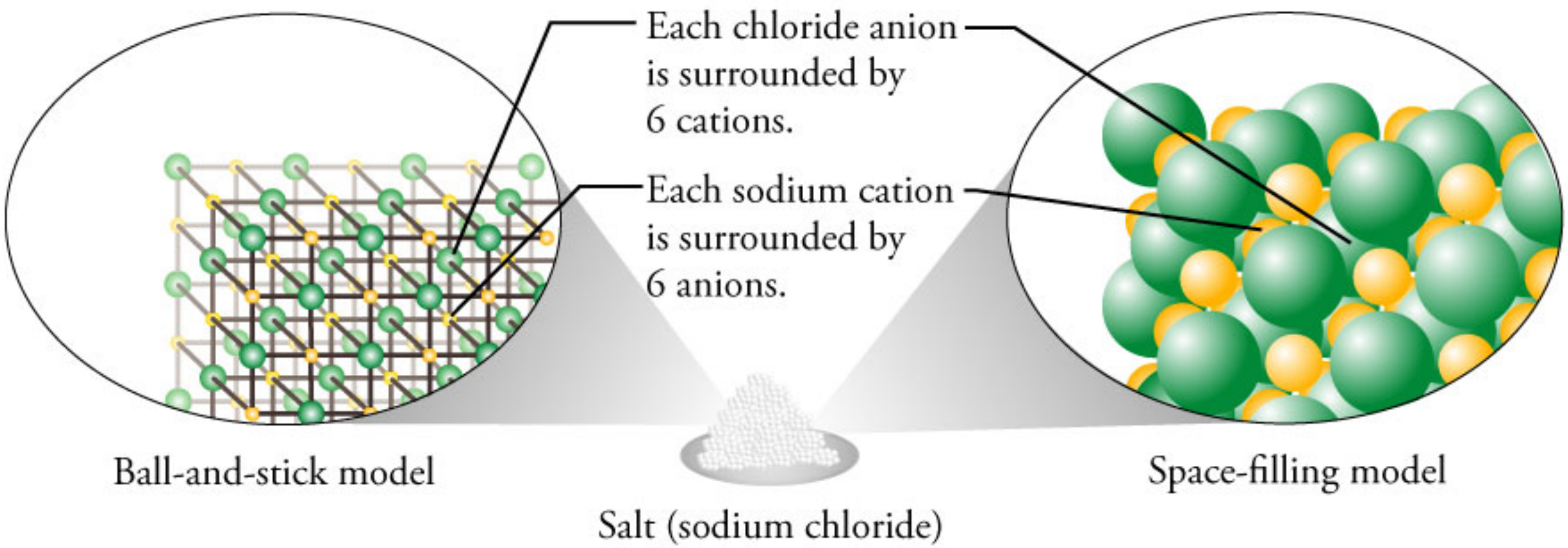
Ionic Bond

- The attraction between cation and anion.
- Atoms of nonmetallic elements often attract electrons so much more strongly than atoms of metallic elements that one or more electrons are transferred from the metallic atom (forming a positively charged particle or ***cation***), to the nonmetallic atom (forming a negatively charged particle or ***anion***).
- For example, an uncharged chlorine atom can pull one electron from an uncharged sodium atom, yielding Cl^- and Na^+.

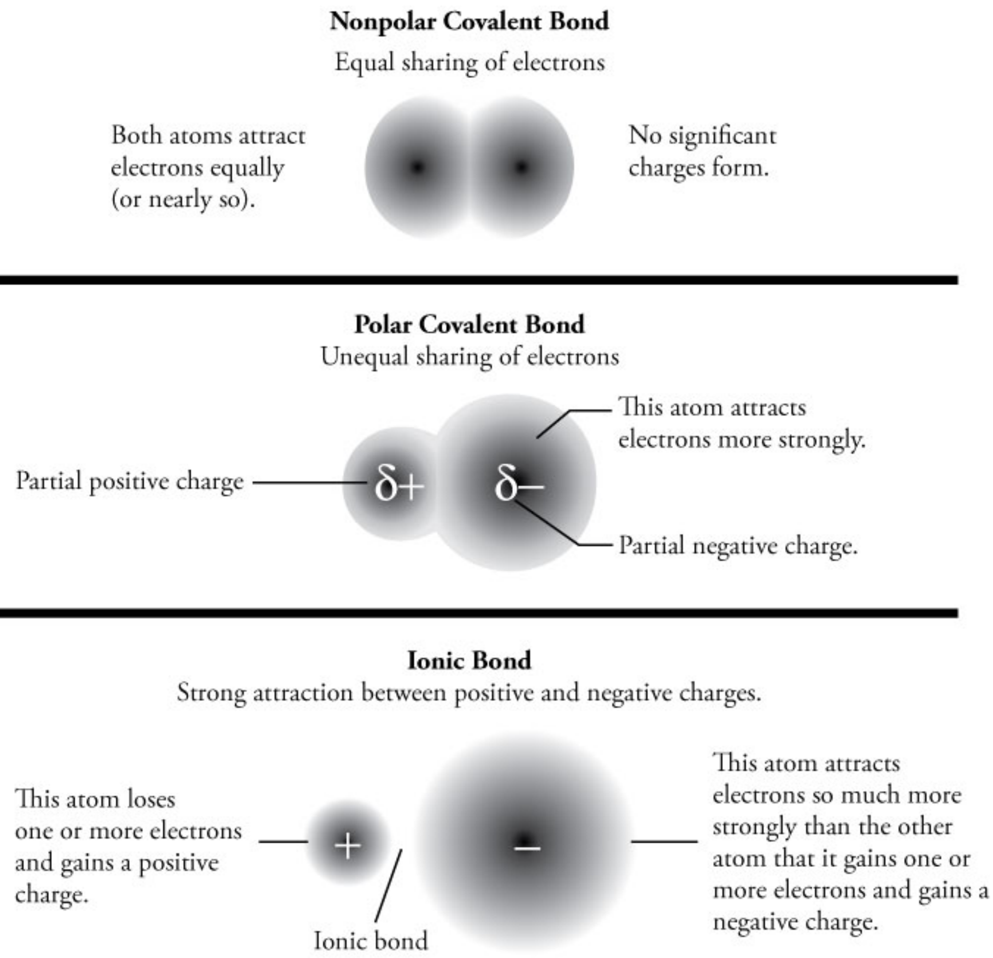
Ionic Bond Formation



Sodium Chloride, NaCl, Structure



Bond Types

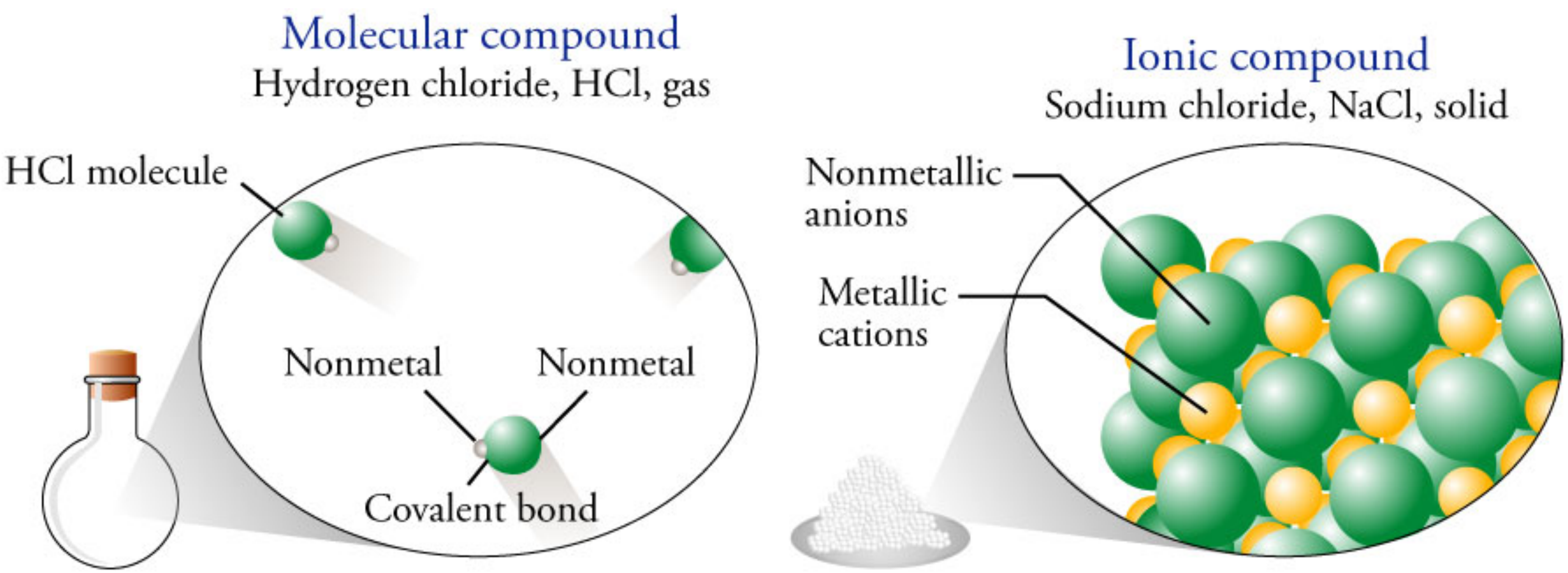


Nonpolar Covalent Bond
Equal sharing of electrons
Both atoms attract electrons equally (or nearly so).
No significant charges form.
Polar Covalent Bond
Unequal sharing of electrons
This atom attracts electrons more strongly.
Partial positive charge
δ+
δ–
Partial negative charge.
Ionic Bond
Strong attraction between positive and negative charges.
This atom loses one or more electrons and gains a positive charge.
+
–
Ionic bond
This atom attracts electrons so much more strongly than the other atom that it gains one or more electrons and gains a negative charge.

Types of Compounds

- All nonmetallic atoms usually leads to all covalent bonds, which from molecules. These compounds are called ***molecular compounds***.
- Metal-nonmetal combinations usually lead to ionic bonds and ***ionic compounds***.

Classification of Compounds



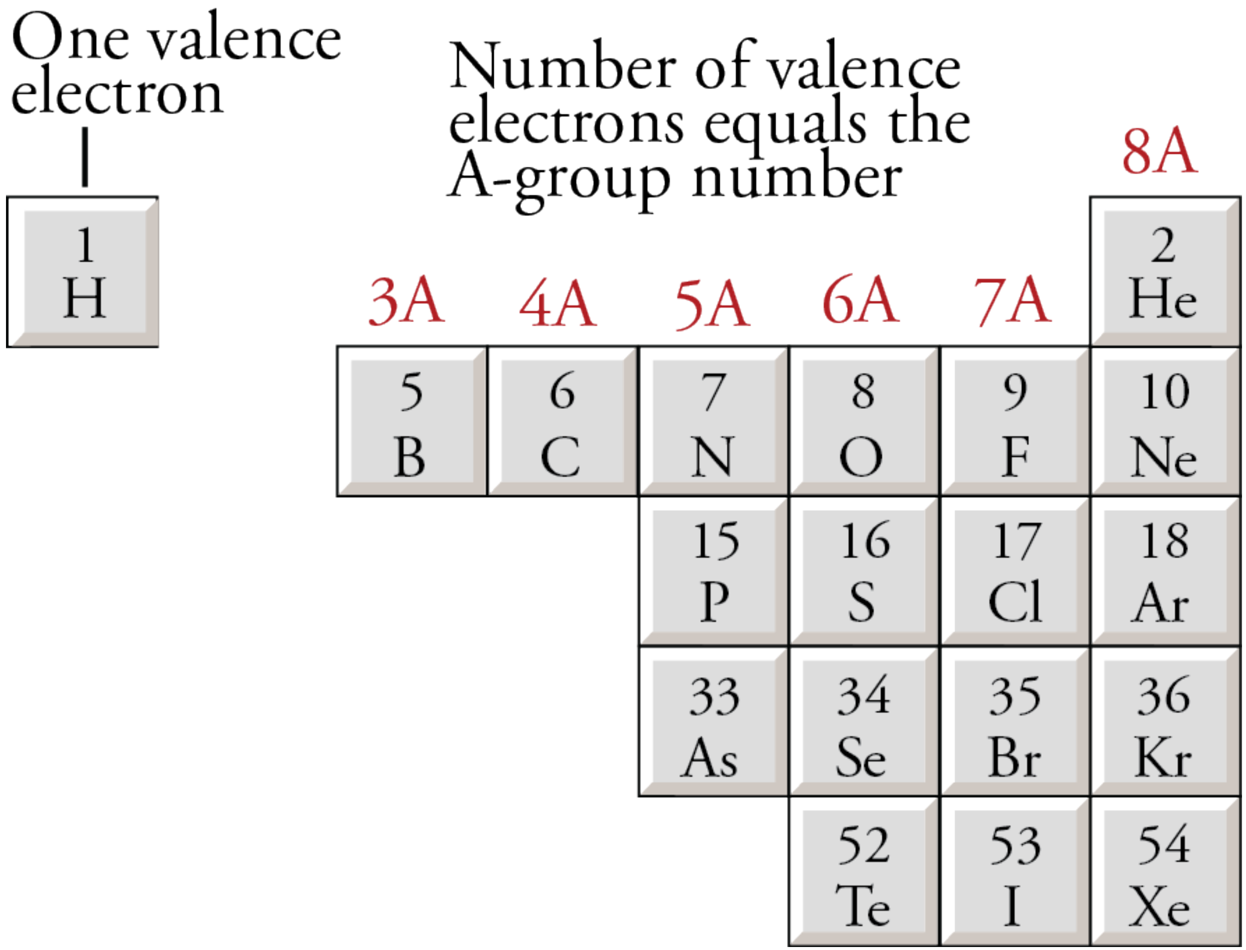
Summary

- **Nonmetal-nonmetal** combinations (e.g. HCl)
  - Covalent bonds
  - Molecules
  - Molecular Compound
- **Metal-nonmetal** combinations (e.g. NaCl)
  - Probably ionic bonds
  - Alternating cations and anions in crystal structure
  - Ionic compound

Valence Electrons

- The valence electrons for each atom are the most important electrons in the formation of chemical bonds.
- The number of valence electrons for the atoms of each element is equal to the element’s A-group number on the periodic table.
- Covalent bonds often form to pair unpaired electrons and give the atoms of the elements other than hydrogen and boron eight valence electrons (an octet of valence electrons).

Valence Electrons and A-Group Numbers



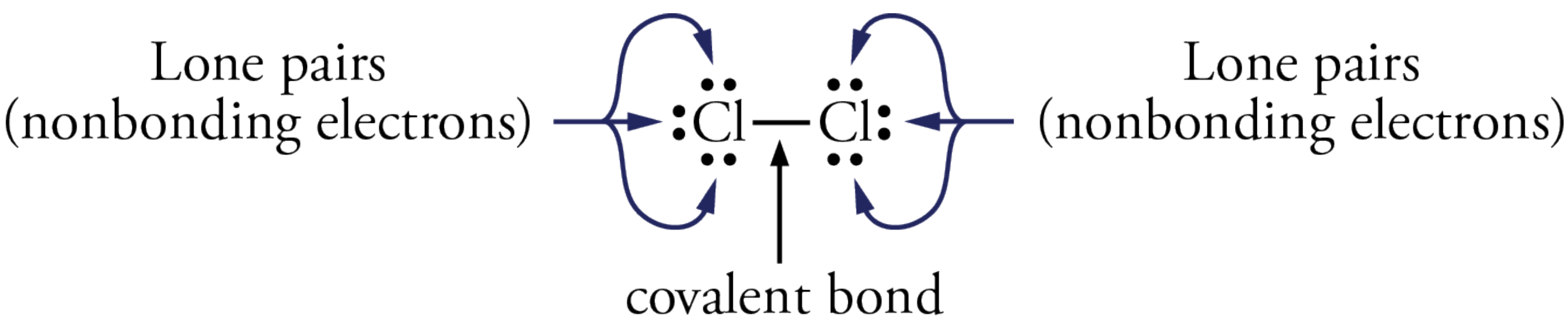
Electron-Dot Symbols and Lewis Structures

- **Electron-dot symbols** show valence electrons.

- Nonbonding pairs of valence electrons are called ***lone pairs***.

Lewis Structures

- ***Lewis structures*** represent molecules using element symbols, lines for bonds, and dots for lone pairs.



Most Common Bonding Patterns for Nonmetals

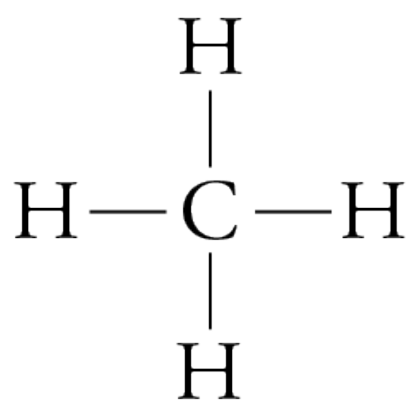
Element	# Bonds	# lone pairs
H	1	0
C	4	0
N, P	3	1
O, S, Se	2	2
F, Cl, Br, I	1	3

Drawing Lewis Structures

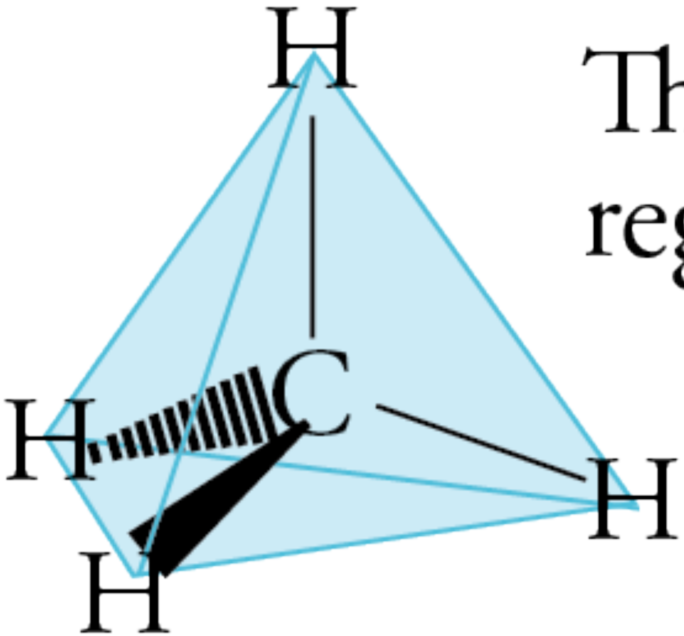
- Chapter 12 describes procedure that allows you to draw Lewis structures for many different molecules.
- Many Lewis structures can be drawn by attempting to give each atom in a molecule its most common bonding pattern.

Lewis Structure for Methane, CH_4

- Carbon atoms usually have 4 bonds and no lone pairs.
- Hydrogen atoms have 1 bond and no lone pairs.

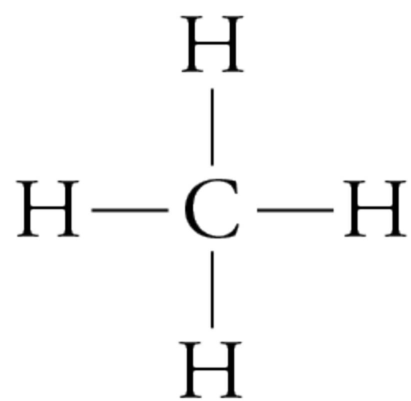


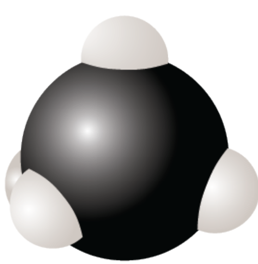
Tetrahedral Geometry



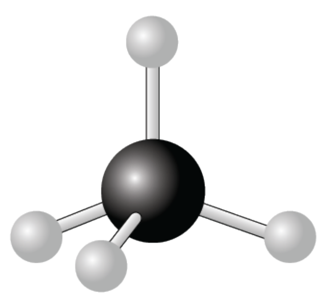
The shaded shape is a regular tetrahedron.

Methane, CH_4

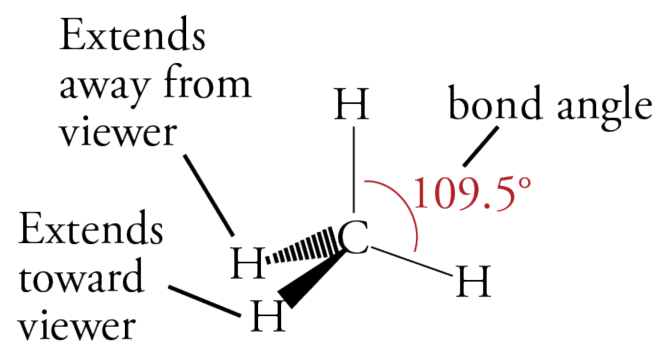




Space-filling model



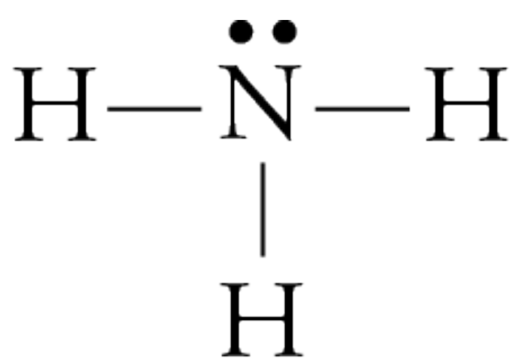
Ball-and-stick model



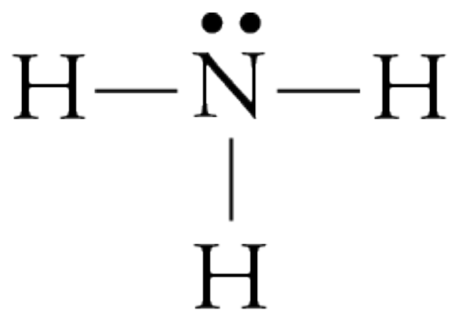
Geometric Sketch

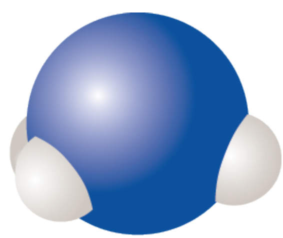
Lewis Structure for Ammonia, NH_3

- Nitrogen atoms usually have 3 bonds and 1 lone pair.
- Hydrogen atoms have 1 bond and no lone pairs.

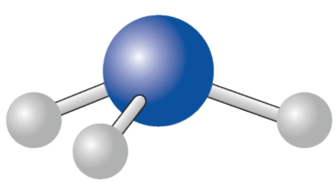


Ammonia, NH_3

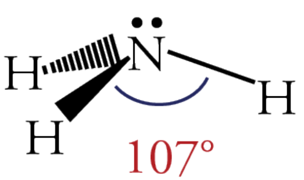




Space-filling model



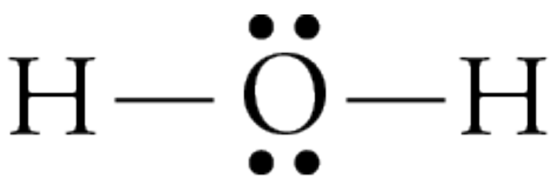
Ball-and-stick model



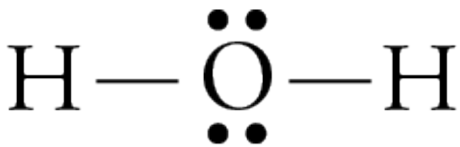
Geometric sketch

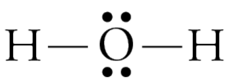
Lewis Structure for Water, H_2O

- Oxygen atoms usually have 2 bonds and 2 lone pairs.
- Hydrogen atoms have 1 bond and no lone pairs.

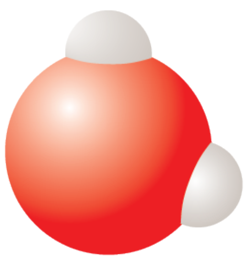


Water, H_2O

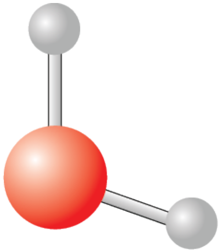




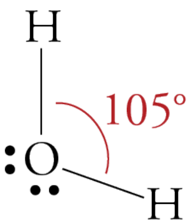
Lewis structure



Space-filling model

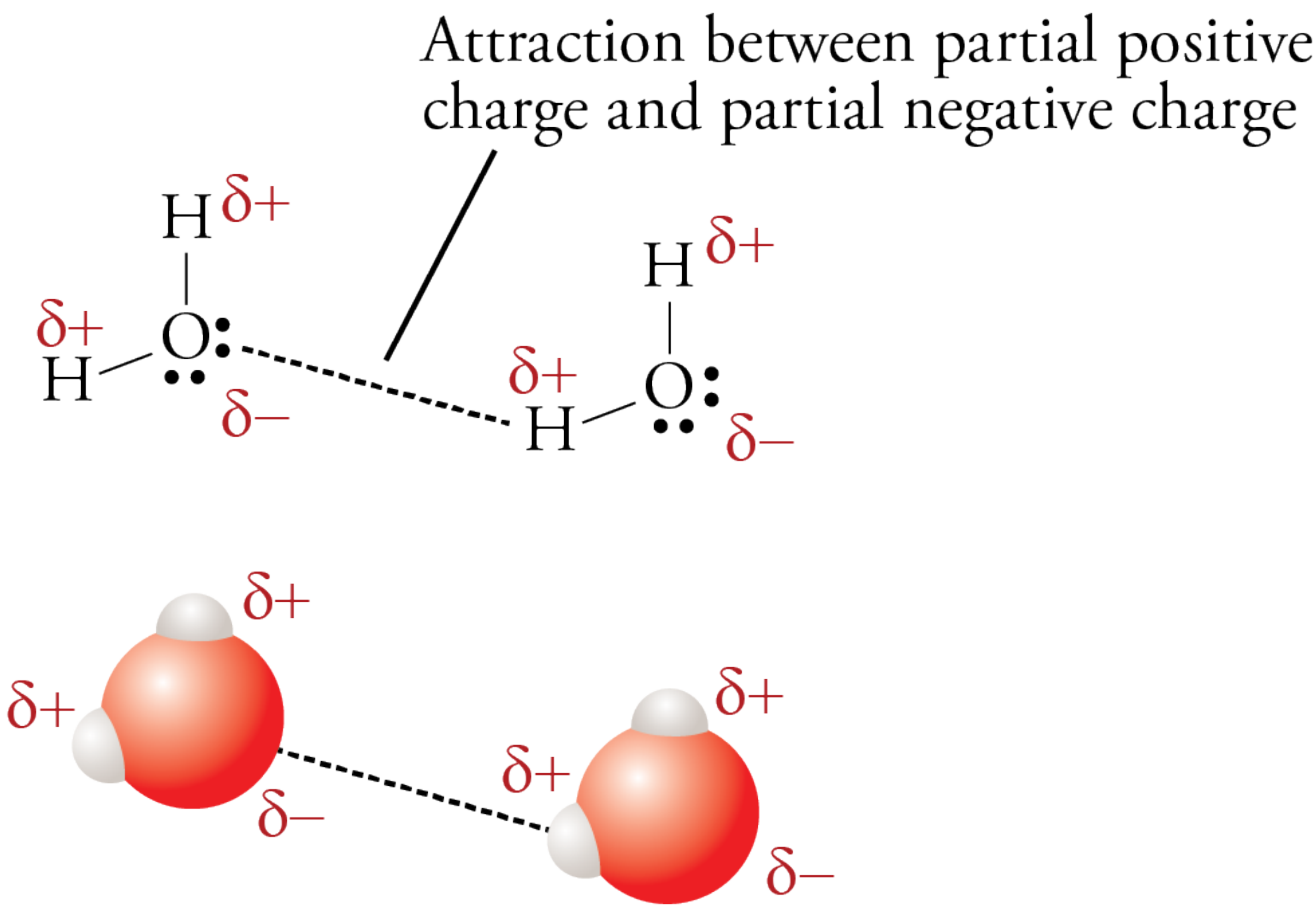


Ball-and-stick model

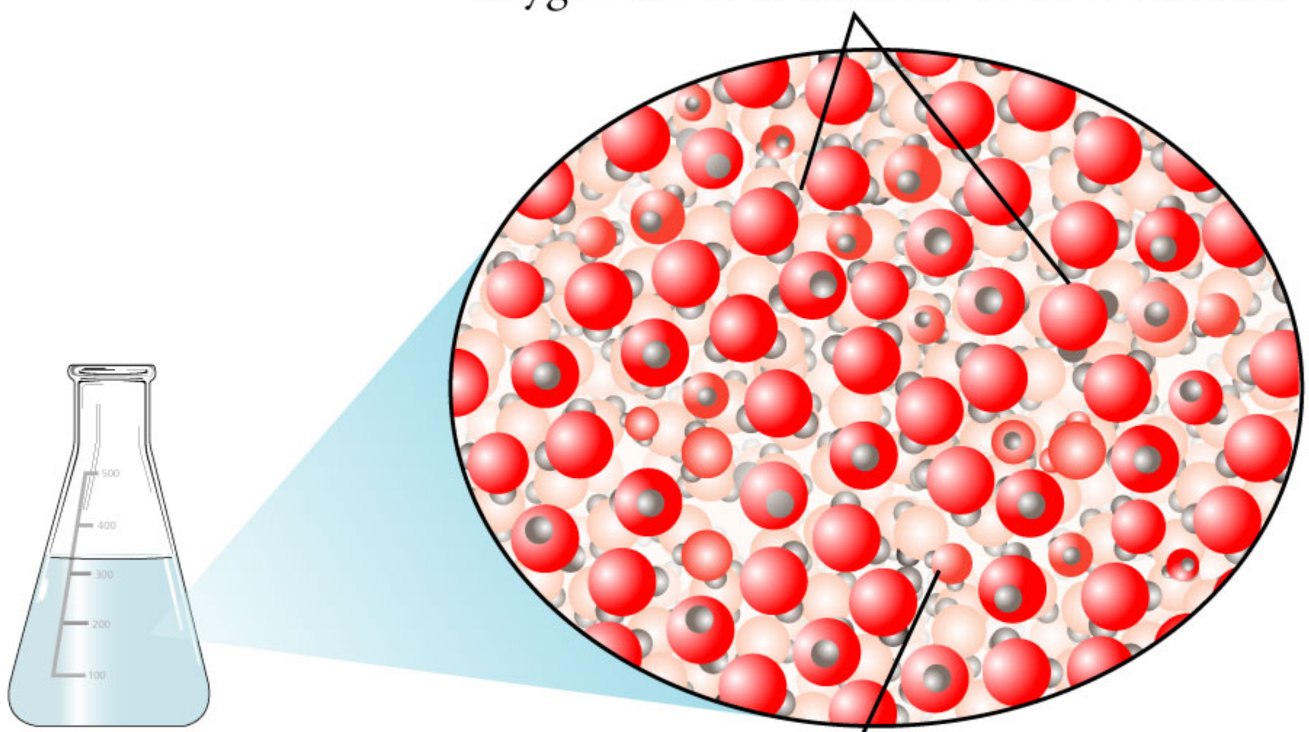


Geometric Sketch

Water Attractions



Liquid Water



Binary Covalent

Nonmetallic elements

Binary covalent compound —— A_aB_b

Subscripts (may be absent)

Common Names

- H_2O, water
- NH_3, ammonia
- CH_4, methane
- C_2H_6, ethane
- C_3H_8, propane
- C_4H_{10}, butane
- C_5H_{12}, pentane
- C_6H_{14}, hexane

Naming Binary Covalent Compounds

- If the subscript for the first element is greater than one, indicate the subscript with a prefix.
  - We do not write mono- on the first name.
  - Leave the "a" off the end of the prefixes that end in "a" and the “o” off of mono- if they are placed in front of an element that begins with a vowel (oxygen or iodine).

Prefixes

mon(o)

di

tri

tetr(a)

pent(a)

hex(a)

hept(a)

oct(a)

non(a)

dec(a)

Nitrogen Oxide Names

- N_2O_3 – name starts with *di*
- N_2O_5 – name starts with *di*
- NO_2 – no initial prefix
- NO – no initial prefix

Naming Binary Covalent Compounds

- Follow the prefix with the name of the first element in the formula.
  - N_2O_3 – *dinitrogen*
  - N_2O_3 – *dinitrogen*
  - NO_2 – *nitrogen*
  - NO – *nitrogen*

Naming Binary Covalent Compounds

- Write a prefix to indicate the subscript for the second element. (Remember to leave the "o" off of mono- and the "a" off of the prefixes that end in "a" when they are placed in front of a name that begins with a vowel.)
  - N_2O_3 – *dinitrogen tri*
  - N_2O_5 – *dinitrogen pent*
  - NO_2 – *nitrogen di*
  - NO – *nitrogen mon*

Naming Binary Covalent Compounds

- Write the root of the name of the second symbol in the formula. (See the next slide.)
  - N_2O_3 – *dinitrogen triox*
  - N_2O_5 – *dinitrogen pentox*
  - NO_2 – *nitrogen diox*
  - NO – *nitrogen monox*

Roots of Nonmetals

H hydr-	F fluor-
C carb-	Cl chlor-
N nitr-	Br brom-
P phosph-	I iod-
O ox-	
S sulf-	
Se selen-	

Naming Binary Covalent Compounds

- Add -ide to the end of the name.
  - N_2O_3 – *dinitrogen trioxide*
  - N_2O_5 – *dinitrogen pentoxide*
  - NO_2 – *nitrogen dioxide*
  - NO – *nitrogen monoxide*

Name of Br_2O_7

- Br and O both represent nonmetallic elements, so this formula represents a binary covalent compound.
- di
- dibromine
- dibromine hept
- dibromine heptox
- dibromine heptoxide

Name of PCl_3

- P and Cl both represent nonmetallic elements, so this formula represents a binary covalent compound.
- No prefix at the beginning
- phosphorus
- phosphorus tri
- phosphorus trichlor
- phosphorus trichloride

Name of CO

- C and O both represent nonmetallic elements, so this formula represents a binary covalent compound.
- No prefix at the beginning
- carbon
- carbon mon
- carbon monox
- carbon monoxide

Name of H_2S

- H and S both represent nonmetallic elements, so this formula represents a binary covalent compound.
- di
- dihydrogen
- dihydrogen mono
- dihydrogen monosulf
- dihydrogen monosulfide
- dihydrogen sulfide or hydrogen sulfide

Binary Covalent Compounds Without Prefixes

- The following binary covalent compounds are often named without prefixes
  - HF – hydrogen fluoride
  - HCl – hydrogen chloride
  - HBr – hydrogen bromide
  - HI – hydrogen iodide
  - H_2S – hydrogen sulfide

Name NH_3

- N and H both represent nonmetallic elements, so this formula represents a binary covalent compound.
- Memorized name - ammonia

Forms of Binary Covalent Names

- prefix(name of nonmetal) prefix(root of name of nonmetal)ide

  (for example, dinitrogen pentoxide)
- or (name of nonmetal) prefix(root of name of nonmetal)ide

  (for example, carbon dioxide)
- or (name of nonmetal) (root of nonmetal)ide

  (for example, hydrogen fluoride)

Writing Binary Covalent Formulas

- If the name is a memorized name that is not a systematic name, just write the memorized formula.
- Write the symbols for the elements in the order mentioned in the name.
- Write subscripts indicated by the prefixes. If the first part of the name has no prefix, assume it is mono-.

Converting from Names to Formulas

- dinitrogen tetroxide
  - N_2O_4
- phosphorus tribromide
  - PBr_3
- hydrogen iodide
  - HI
- Methane
  - CH_4

Converting between Binary Covalent Formulas and Names

- There is a tool on the textbook’s website that will allow you to practice this task.

https://preparatorychemistry.com/binary_covalent_nomenclature_Canvas.html

Cations and Anions

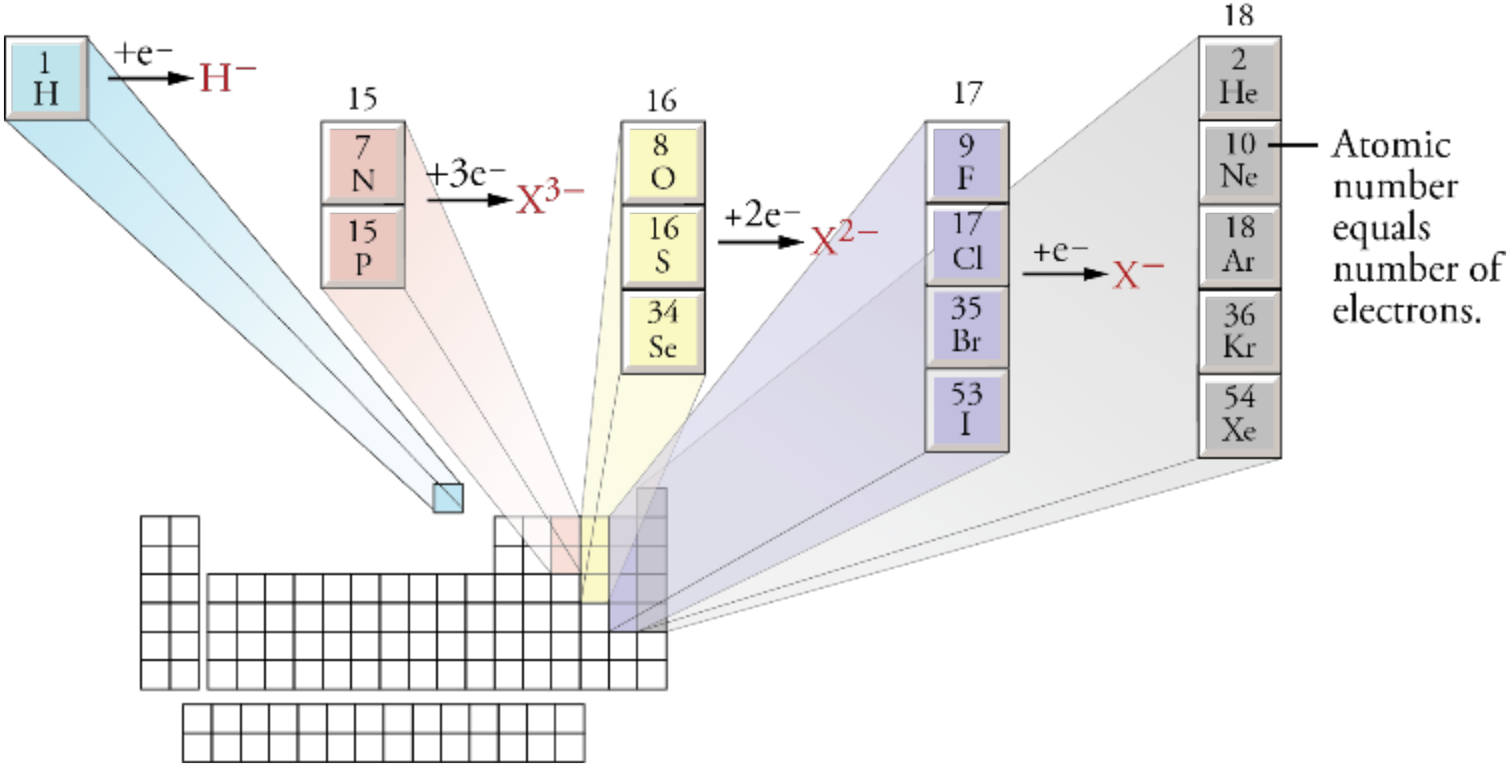
- Atoms of the metallic elements have relatively weak attractions for their electrons, so they tend to lose electrons and form monatomic cations (cations composed of one atom, such as Na^+).
- Atoms of the nonmetallic elements have relatively strong attractions for electrons, so they tend to gain electrons and form monatomic anions (anions composed of one atom, such as Cl^-).
- Therefore, when metallic and nonmetallic atoms combine, they usually form ions and ionic bonds.

Predicting Ion Charges

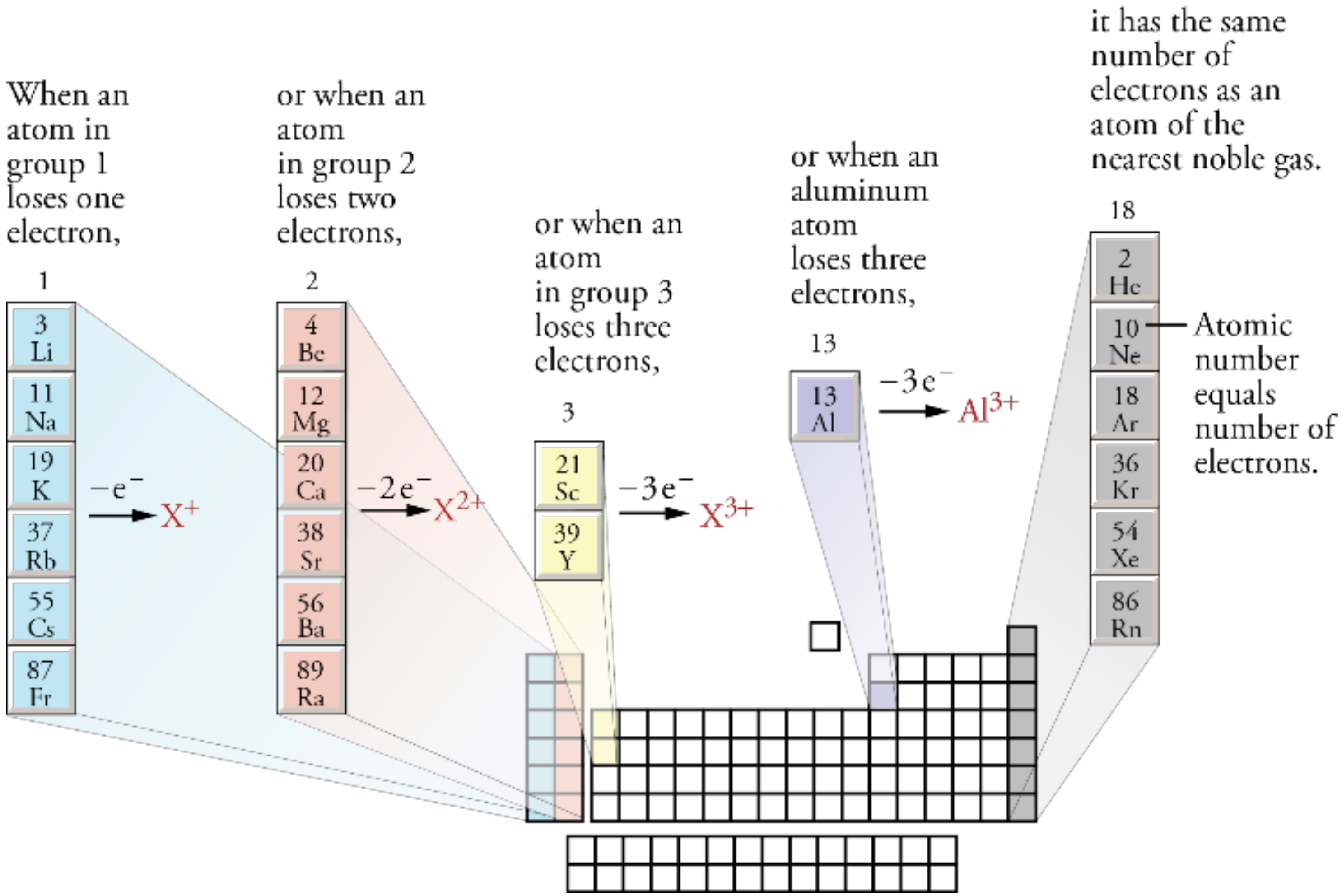
- Noble gas atoms are very stable, so when the nonmetallic atoms form anions, they gain enough electrons to get the same number of electrons as the nearest larger noble gas atom.
- When the aluminum and the metallic atoms in Groups 1, 2, and 3 form cations, they lose enough electrons to get the same number of electrons as the nearest smaller noble gas atom.

The Making of an Anion

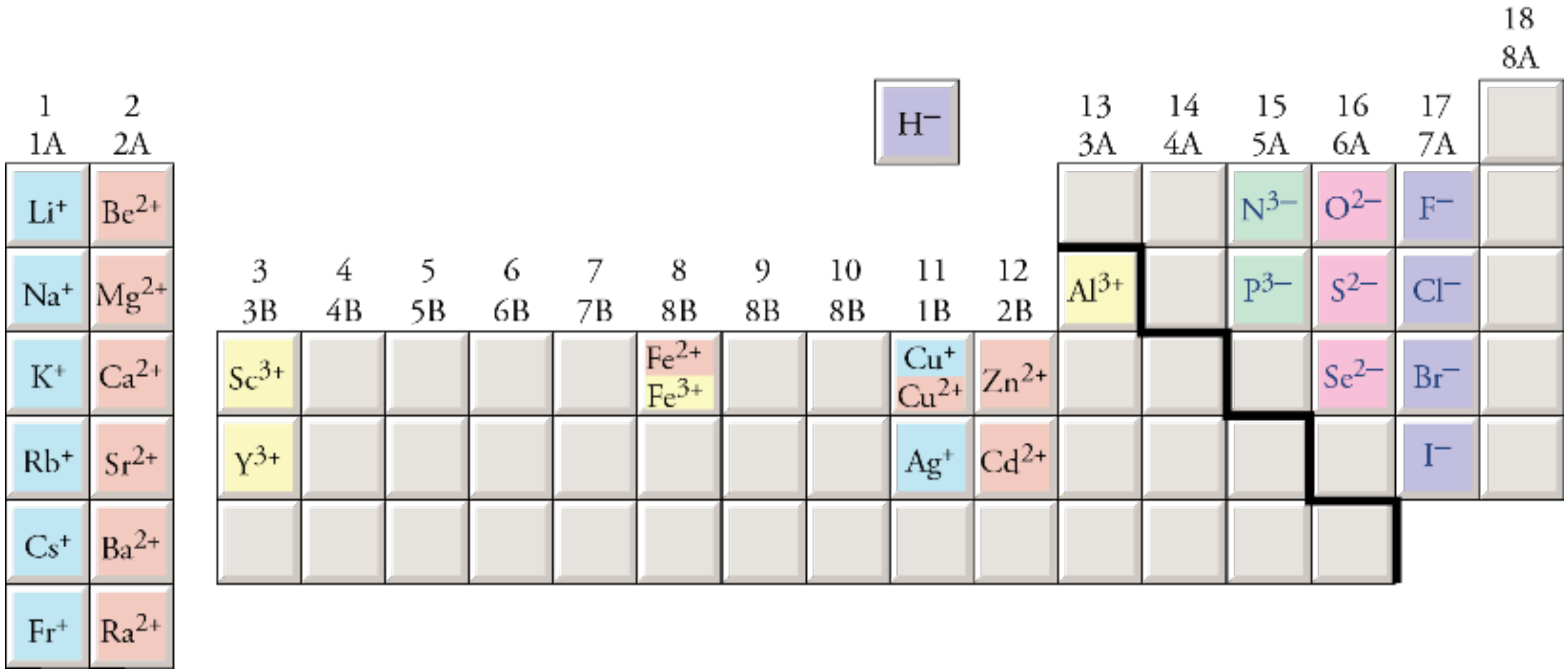
When a hydrogen atom gains one electron, or when an atom in group 15 gains three electrons, or when an atom in group 16 gains two electrons, or when an atom in group 17 gains one electron, it has the same number of electrons as an atom of the nearest noble gas.



The Making of a Cation



Monatomic Ions



Monatomic Ion Names

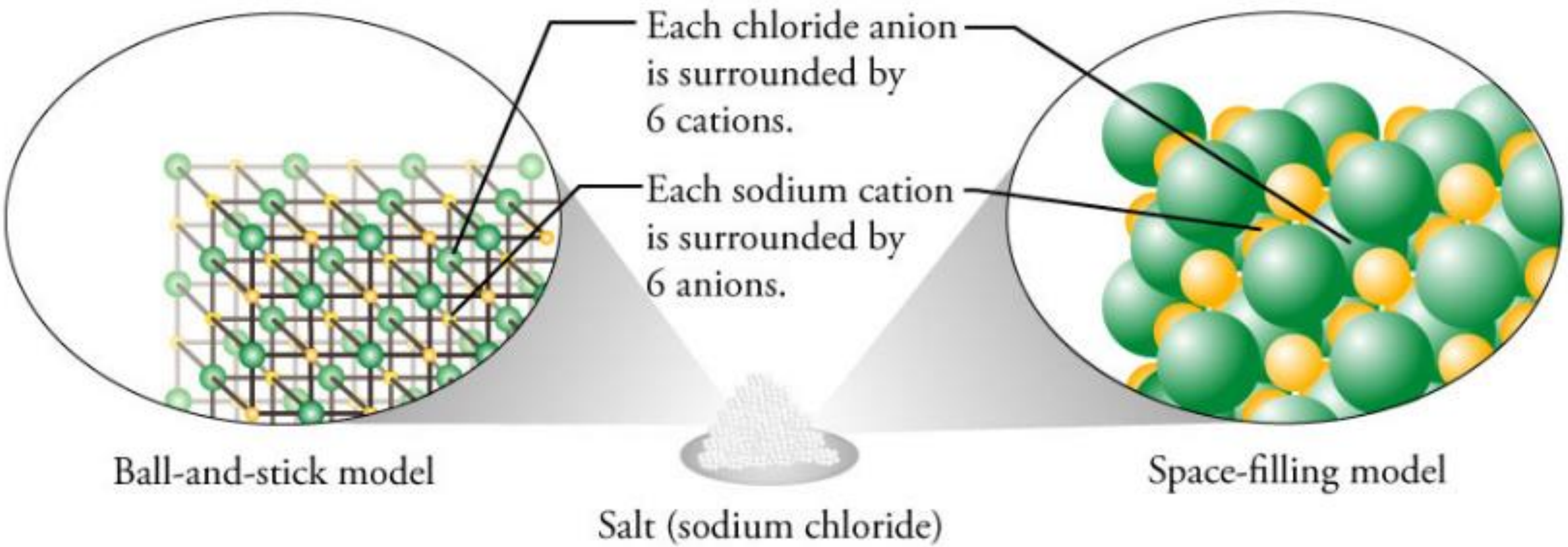
- Monatomic Cations
  - (name of metal)
    - Groups 1, 2, and 3 metals
    - Al^{3+}, Zn^{2+}, Cd^{2+}, Ag^{+}
  - (name of metal)(Roman numeral)
    - All metallic cations not mentioned above
- Monatomic Anions
  - (root of nonmetal name)ide

Monatomic Anions

hydride, H^-
nitride, N^{3-}
phosphide, P^{3-}
oxide, O^{2-}
sulfide, S^{2-}
selenide, Se^{2-}

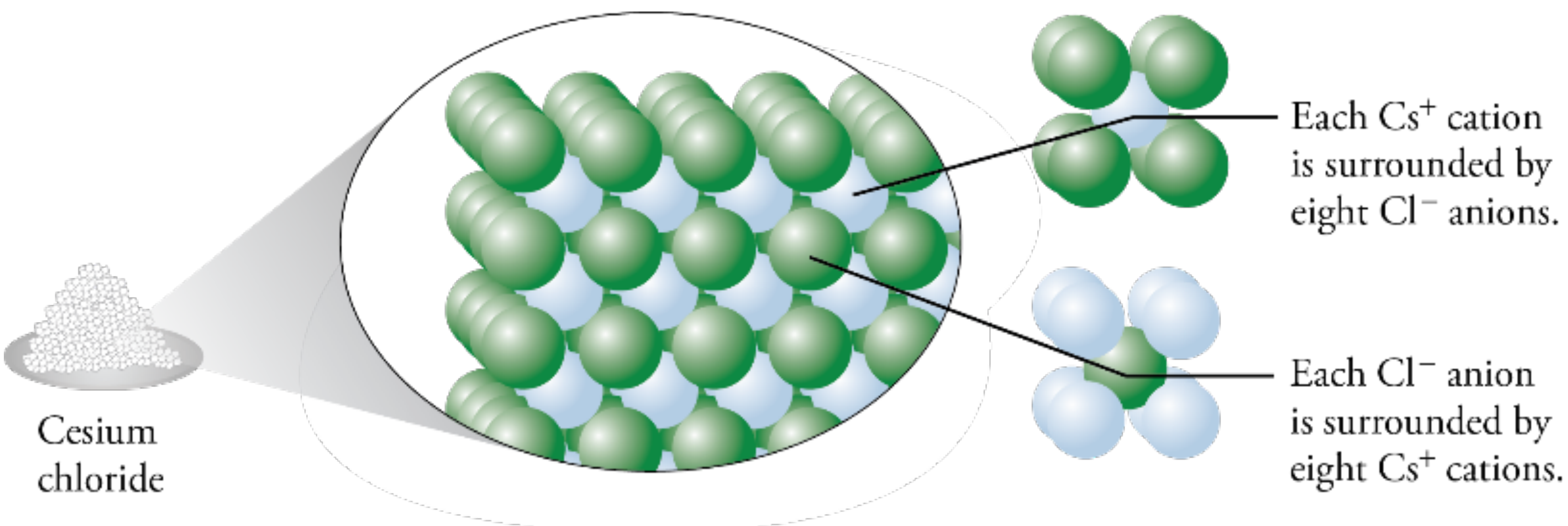
fluoride, F^-
chloride, Cl^-
bromide, Br^-
iodide, I^-

Sodium Chloride, NaCl, Structure



Cesium chloride, CsCl, Structure

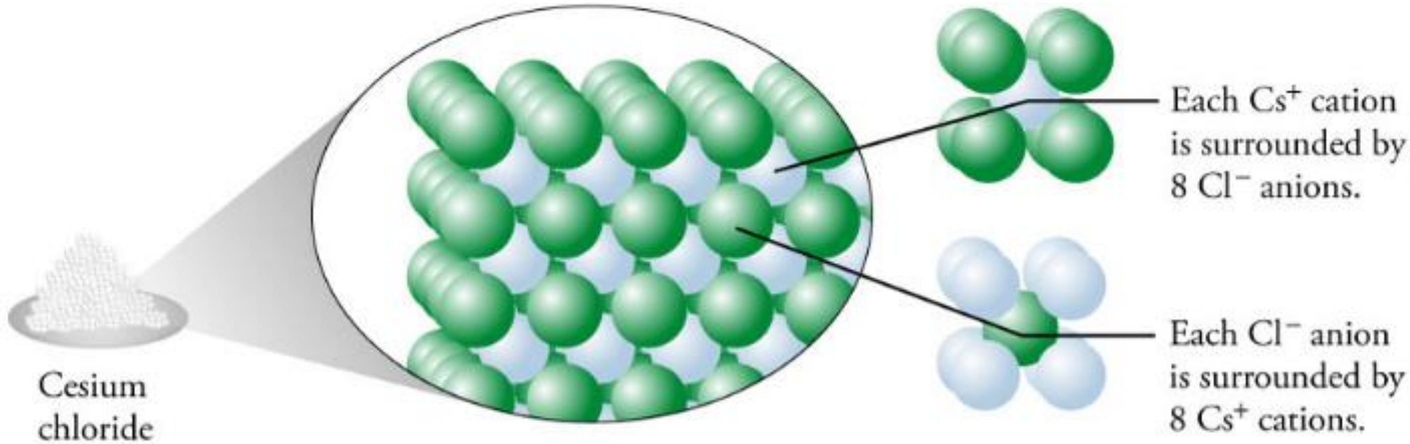
- Because the cesium ions are larger than sodium ions, there is room for eight chloride ions around each cesium ion and eight cesium ions around each chloride ion.

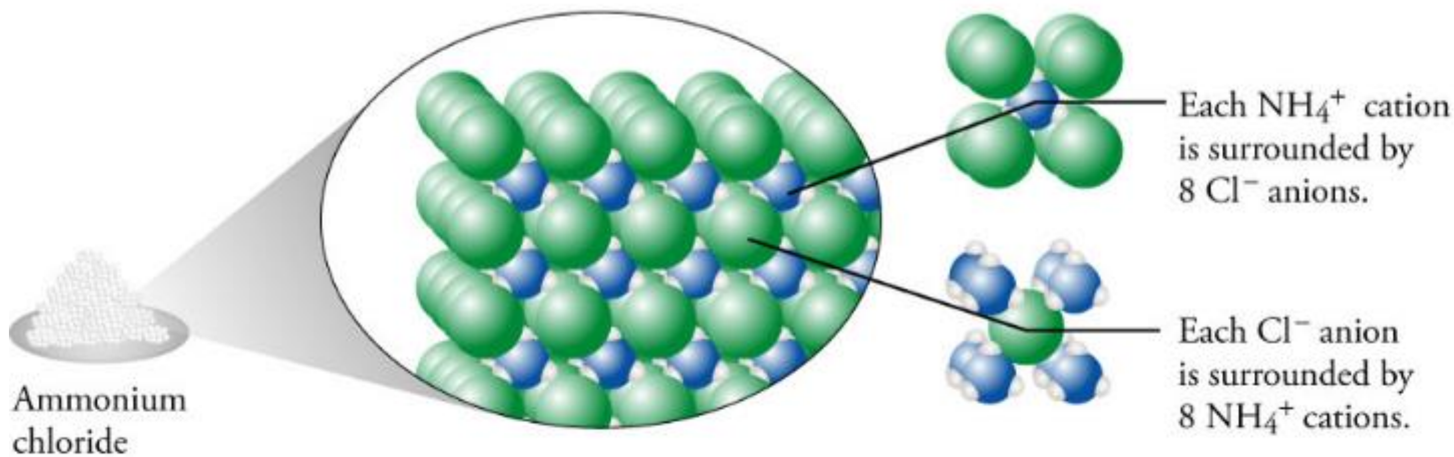


Polyatomic Ions

- Some anions and cations contain more than one atom.
- **Polyatomic ion** = a charge collection of atoms held together by covalent bonds
- For example, it is possible for a nitrogen atom to form covalent bonds to four hydrogen atoms, but to make this possible the nitrogen atom has to lose an electron, giving the collection of atoms a plus one charge. This will be explained in more detail in a later lesson. This collection of atoms with the formula NH_4^+ is called the ammonium ion.

CsCl and NH_4Cl structure





Polyatomic Ions

Ion	Name	Ion	Name
NH_4^+	ammonium	NO_3^-	nitrate
OH^-	hydroxide	SO_4^{2-}	sulfate
CO_3^{2-}	carbonate	$C_2H_3O_2^-$	acetate
PO_4^{3-}	phosphate		

Polyatomic Ions with Hydrogen

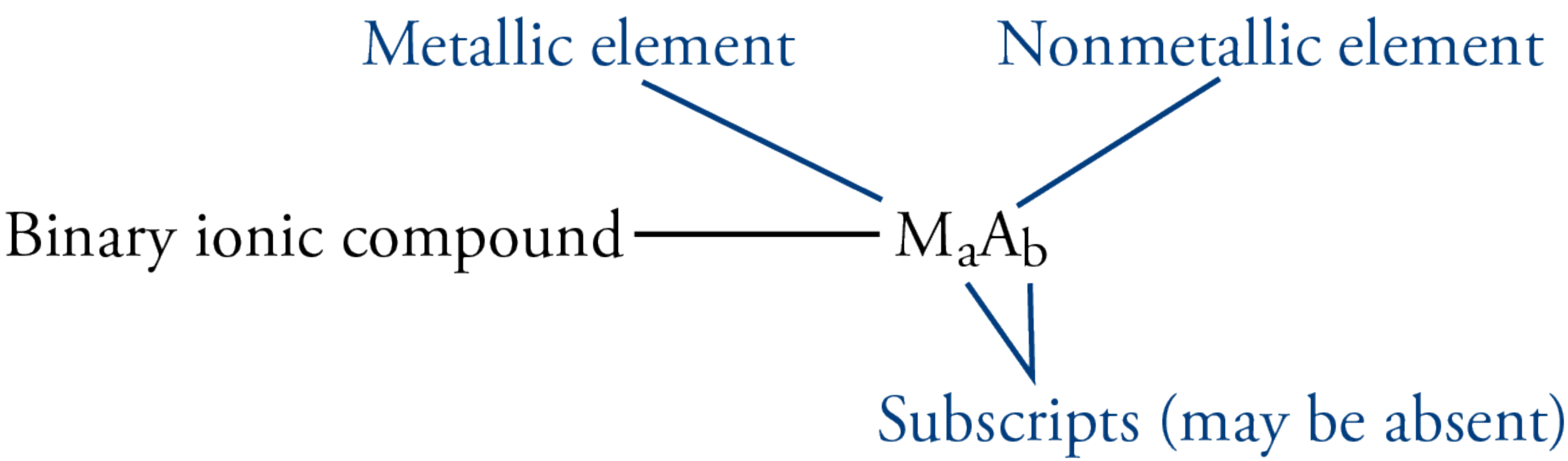
- HCO_3^- hydrogen carbonate (bicarbonate)
- HSO_4^- hydrogen sulfate
- HS^- hydrogen sulfide
- HPO_4^{2-} hydrogen phosphate
- $H_2PO_4^-$ dihydrogen phosphate

Recognizing Ionic Formulas and Names

- Different types of compounds have different guidelines for writing their names or formulas.
- Therefore, the first step in converting between names and formulas for chemical compounds is classifying them with respect to type.
- The simplest way to identify a formula as representing an ionic compound is to see a symbol for a metal or NH_4 at the beginning of the formula.
- The simplest way to identify a name as representing an ionic compound is to see the name of a metal or ammonium at the beginning of the name.

Recognizing Binary Ionic Compounds

- Binary means two, and in the case of binary ionic compounds, the word binary means two elements, a metallic element and a nonmetallic element.
- If a formula has a symbol for a metal and a symbol for a nonmetal, it's a binary ionic compound composed of a monatomic cation and a monatomic anion.



Converting Ionic Names to Formulas

- Ionic compound names include the name of the cation followed by the name of the anion.
- The following table summarizes cation names.

Metals with one possible charge (Al, Zn, Cd, (Ag), and Groups 1, 2, 3)	name of metal
Metals with more than one possible charge (the rest)	name(Roman numeral)
polyatomic cations (e.g. ammonium)	name of polyatomic ion

Anion Names

- The following table summarizes anion names.

monatomic anion	(root of nonmetal name)ide
polyatomic anion	name of polyatomic ion

Converting Ionic Formulas to Names

- What's the name of MgO?
  - Magnesium is in Group 2, so it is always +2.
  - The name for Mg^{2+} is magnesium.
  - The anion is O^{2-}, which is a monatomic anion.
  - Monatomic anions are named by combining the root of the name of the nonmetal and –ide.
  - The anion name is oxide.
  - The names of ionic compounds combine the name of the cation and the name of the anion.
  - MgO is magnesium oxide.

Converting Ionic Formulas to Names

- What's the name of $CoCl_2$?
  - Co represents cobalt, and cobalt is not on the list of elements that have only one charge, so we need a Roman numeral indicating its charge in the cobalt ion name.
  - We can determine the cobalt ion charge from recognizing that the chloride is -1, two of them would be -2, so the cobalt ion must be +2.
  - The name for Co^{2+} is cobalt(II).
  - The anion is Cl^-, so its name is chloride.
  - The name of $CoCl_2$ is cobalt(II) chloride.

Converting Ionic Formulas to Names

- What's the name of NH_4NO_3?
  - Although this formula contains symbols for all nonmetallic elements, we recognize that this formula represents an ionic compound because we see NH_4 in the formula.
  - You need to memorize formulas and names of polyatomic ions.
  - NH_4^+ is named ammonium.
  - NO_3^- is nitrate.
  - The name of NH_4NO_3 is ammonium nitrate.

Identifying Names as Ionic Compounds

- The following general names tell you that the name represents an ionic compound.
  - (name of metal) (root of nonmetal)ide
    - e.g. calcium oxide
  - (name of metal)(Roman #) (root of nonmetal)ide
    - e.g. iron(II) oxide
  - ammonium (root of nonmetal)ide
    - e.g. ammonium oxide
  - ammonium (name of polyatomic anion)
    - e.g. ammonium sulfate

Writing Ionic Formulas

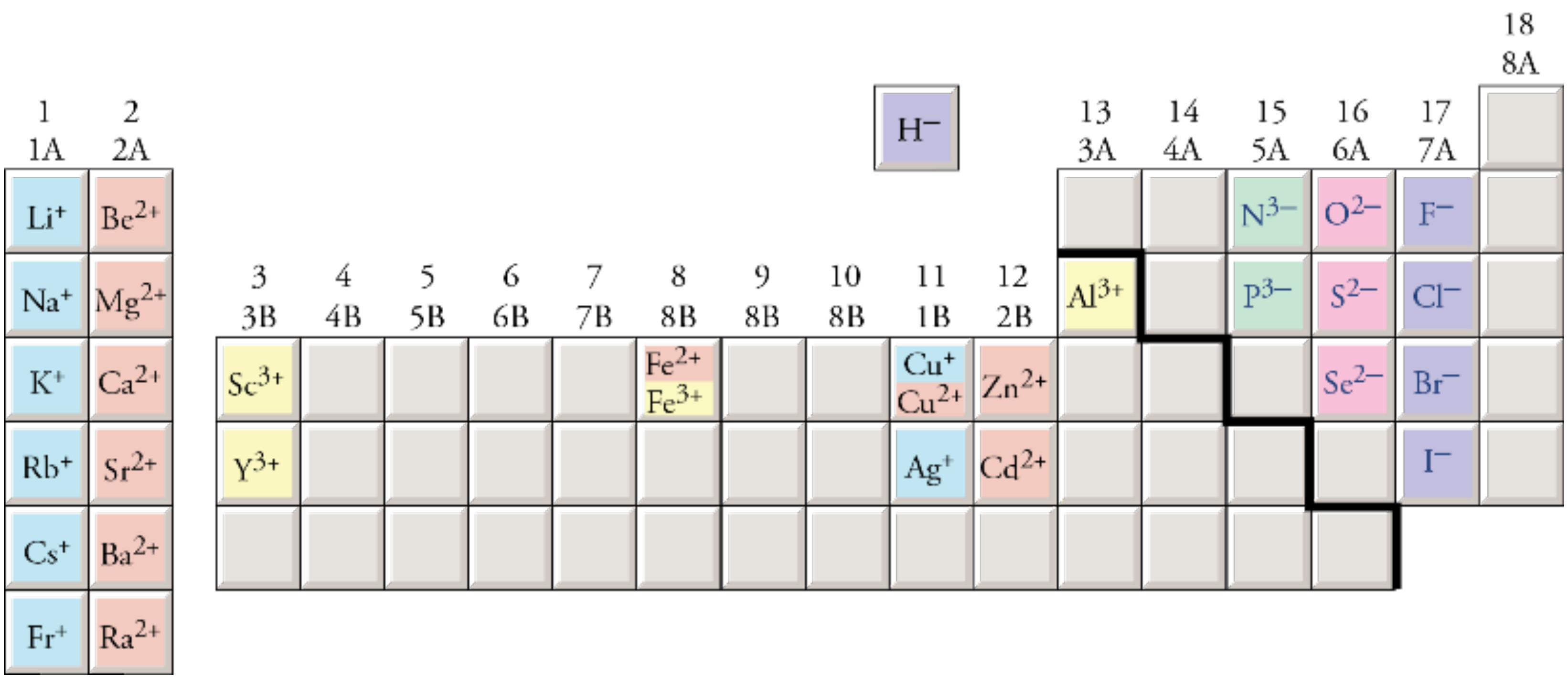
- Two steps for writing formulas for ionic compounds.
  - Determine the formula, including charge, for the cation and anion.
  - Determine the ratio of the ions that yields zero overall charge.

Formulas and Charges of Ions

- We can predict the formulas including charge for some of the ions by
  - memorizing names and symbols for some of the elements,
  - using the periodic table to predict the charges for some elements,
  - and memorizing formulas and charges for other ions.
- You can find a web-based tool that will allow you to practice converting between names and symbols at

https://preparatorychemistry.com/element_names_symbols_Canvas.html

Monatomic Ions



Polyatomic Ions

Ion	Name	Ion	Name
NH_4^+	ammonium	NO_3^-	nitrate
OH^-	hydroxide	SO_4^{2-}	sulfate
CO_3^{2-}	carbonate	$C_2H_3O_2^-$	acetate
PO_4^{3-}	phosphate		

Polyatomic Ions with Hydrogen

- HCO_3^- hydrogen carbonate
- HSO_4^- hydrogen sulfate
- HS^- hydrogen sulfide
- HPO_4^{2-} hydrogen phosphate
- $H_2PO_4^-$ dihydrogen phosphate

Ionic Formulas

Ionic charges	General formula	Example ions	Example formula
X^+ and Y^-	XY	Na^+ and Cl^-	$NaCl$
X^+ and Y^{2-}	X_2Y	NH_4^+ and SO_4^{2-}	$(NH_4)_2SO_4$
X^+ and Y^{3-}	X_3Y	Li^+ and PO_4^{3-}	Li_3PO_4
X^{2+} and Y^-	XY_2	Mg^{2+} and NO_3^-	$Mg(NO_3)_2$
X^{2+} and Y^{2-}	XY	Ca^{2+} and CO_3^{2-}	$CaCO_3$
X^{2+} and Y^{3-}	X_3Y_2	Ba^{2+} and N^{3-}	Ba_3N_2
X^{3+} and Y^-	XY_3	Al^{3+} and F^-	AlF_3
X^{3+} and Y^{2-}	X_2Y_3	Sc^{3+} and S^{2-}	Sc_2S_3
X^{3+} and Y^{3-}	XY	Fe^{3+} and PO_4^{3-}	$FePO_4$

Converting Ionic Names to Formulas

- What's the formula for aluminum chloride?
  - This name has the following form, so it is ionic.

    (name of metal) (root of nonmetal)ide
  - The symbol for aluminum is Al. Aluminum atoms have 3 more electrons than neon, so we expect it to lose 3 electron and form Al^{3+} ions.
  - The symbol for chlorine is Cl, which is found in group 17, so chloride is Cl^{-}.
  - The formula for aluminum chloride is **$AlCl_3$**.

Converting Ionic Formulas to Names

- What's the formula for chromium(III) oxide?
  - This name has the following form, so it is ionic.

    (name of metal)(Roman #) (root of nonmetal)ide
  - The symbol for chromium is Cr. The (III) in the name tells us that the cation formula, including charge, is Cr^{3+}.
  - The symbol for oxygen is O, which is found in group 16, so oxide is O^{2-}.
  - The formula for chromium(III) oxide is **Cr_2O_3**.

Converting Ionic Formulas to Names

- What's the formula for calcium nitrate?
  - There are two ways to recognize this name as representing an ionic compound.
    - The –ate on the end of the name tells us that the compound contains a polyatomic ion.
    - The symbol for the element calcium is Ca, which is a metallic element, and metals in the combined form yield ionic compounds.
  - The symbol Ca is in group 2 on the periodic table, so the charge on calcium ions is +2 – Ca^{2+}.
  - The formula for nitrate is NO_3^-.
  - The formula for calcium nitrate is **$Ca(NO_3)_2$**.

Converting Ionic Formulas to Names

- What's the formula for ammonium sulfide?
  - This name has the following form, so it is ionic.

    Ammonium (root of nonmetal)ide
  - The formula for ammonium is NH_4^+.
  - The –ide on the end of the name sulfide, tells us that it is a monatomic anion.
  - The symbol for sulfur is S, which is found in group 16, so sulfide is S^{2-}.
  - The formula for ammonium sulfide is **$(NH_4)_2S$**.
  - Note that the formula for the polyatomic ion is in parentheses.

Converting Ionic Formulas to Names

- There are three tools on the textbook's website that will allow you to practice this task.
  - Conversion between cation names and formulas.

https://preparatorychemistry.com/cation_names_formulas_Canvas.html

  - Conversion between anion names and formulas.

https://preparatorychemistry.com/anion_names_formulas_Canvas.html

  - Conversion between ionic compound names and formulas.

https://preparatorychemistry.com/ionic_nomenclature_Canvas.html