EXTENSION ACTIVITY
INTRODUCTION TO COLLEGE CHEMISTRY

IONIC BONDING - KEY

Activity Directions

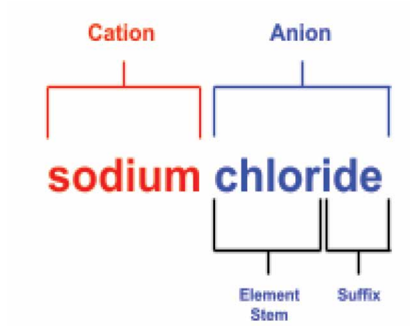
This activity will serve as practice for the topics covered in the Ionic Bonding game. This activity is best used in conjunction with not only the tutorial levels, but also supplementary learning resources such as course lectures, textbook reading, etc. Questions labeled "Lock It In" are simply opportunities for you to solidify what you have accomplished in each task and help ensure you meet each objective.

1. Log into Collisions and navigate to the Ionic Bonding Game.
2. Play the Tutorial levels, if you haven't done so already.
3. Exit the levels and enter the Ionic Bonding sandbox.
4. Follow all instructions as written below. Be sure to reference your course's textbook, lecture notes, etc. as needed.

OBJECTIVE 1

Demonstrate an understanding of ionic compound nomenclature and ionic ratios for main group elements.

Ionic bonds form as a result of electrostatic attraction between cations and anions. As a result, ionic compounds are given two-part names that acknowledge both the cation and anion. The name of the cation appears first, while the anion name appears second. Metals (cations) will simply keep their element name. However, with nonmetals (the anions) the suffix -ide is added to the element stem name. Take the compound NaCl as an example:



LOCK IT IN: Does the nomenclature used here for main group ionic compounds reflect the number of individual ions in the formula unit? Explain.

The nomenclature used here does not indicate the number of individual ions in the formula unit. The name of the compound simply tells us the different elements that are present in the substance. For example, magnesium chloride indicates that there is magnesium and chlorine in the compound, but not that there is only one magnesium ion and two chloride ions.

TASK 1: Complete the table below by creating each compound in the sandbox and by using the information provided in the text above.

Compound Name	Chemical Formula	Charge of Each Cation	Number of Individual Cations in Formula Unit	Charge of Each Anion	Number of Individual Anions in Formula Unit	Cation-Anion Ratio
potassium bromide	KBr	1+	1	1-	1	1:1
magnesium chloride	$MgCl_2$	2+	1	1-	2	1:2
aluminum oxide	Al_2O_3	3+	2	2-	3	2:3
Lithium nitride	Li_3N	1+	3	3-	1	3:1
calcium sulfide	CaS	2+	1	2-	1	1:1

OBJECTIVE 1

Demonstrate an understanding of ionic compound nomenclature and ionic ratios for main group elements.

Ionic compound nomenclature with polyatomic ions is straightforward except that the names of the polyatomic ions must be memorized or obtained from a reference source. Once again, the cation will appear first in the name, while the anion will appear second without name modification (e.g. ammonium chlorate - NH_4ClO_3). Below is a table of the polyatomic ions available in the Ionic Bonding Sandbox. Use them to complete Task 2.

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

LOCK IT IN: Does the nomenclature used here for compounds containing polyatomic ions reflect the number of individual ions in the formula unit? Explain.

The nomenclature used here does not indicate the number of individual ions in the formula unit. The name of the compound simply tells us the different elements and polyatomic ions that are present in the substance. For example, aluminum sulfate indicates that there is aluminum and sulfate in the compound, but not that there are two aluminum ions and three sulfate ions.

TASK 2: Complete the table below by creating each compound in the sandbox and by using the information provided in the text above.

Compound Name	Chemical Formula	Charge of Each Cation	Number of Individual Cations in Formula Unit	Charge of Each Anion	Number of Individual Anions in Formula Unit	Cation-Anion Ratio
aluminum sulfate	$Al_2(SO_4)_3$	3+	2	2-	3	2:3
sodium nitrate	$NaNO_3$	1+	1	1-	1	1:1
ammonium carbonate	$(NH_4)_2CO_3$	1+	2	2-	1	2:1
calcium hydroxide	$Ca(OH)_2$	2+	1	1-	2	1:2
magnesium nitrate	$Mg(NO_3)_2$	2+	1	1-	2	1:2

OBJECTIVE 1

Demonstrate an understanding of ionic compound nomenclature and ionic ratios for main group elements.

Ionic compound nomenclature becomes more involved when considering the transition metals. Take a look at the iron (Fe) and copper (Cu) ions in the sandbox. You will notice that there are two possible charges for iron ions and two possible charges for copper ions. The existence of multiple ion charges is a very common characteristic of transition metals. As such, special nomenclature rules exist to keep track of them. The Stock system now provides what is considered the preferred and formal name for the transition metal ions. In this system, the metal is named and followed by the roman numeral for the charge of the ion in parentheses (e.g. the Fe^{2+} ion is iron (II) in the Stock system).

Element	Ion	Ion Stock System Name
Iron	Fe^{2+}	iron (II)
	Fe^{3+}	Iron (III)
Copper	Cu^{+}	copper (I)
	Cu^{2+}	copper (II)
Tin	Sn^{2+}	tin (II)
	Sn^{4+}	tin (IV)
Lead	Pb^{2+}	lead (II)
	Pb^{4+}	lead (IV)
Cobalt	Co^{2+}	cobalt (II)
	Co^{3+}	cobalt (III)
Chromium	Cr^{2+}	chromium (II)
	Cr^{3+}	chromium (III)

OBJECTIVE 1

Demonstrate an understanding of ionic compound nomenclature and ionic ratios for main group elements.

TASK 3: Complete the table below by creating each compound in the sandbox and by using the information provided in the text above.

Compound Name (Stock system name)	**Chemical Formula**	**Charge of Each Cation**	**Number of Individual Cations in Formula Unit**	**Charge of Each Anion**	**Number of Individual Anions in Formula Unit**	**Cation-Anion Ratio**
iron (II) sulfate	$FeSO_4$	2+	1	2-	1	1:1
copper (II) chloride	$CuCl_2$	2+	1	1-	2	1:2
copper (I) sulfate	Cu_2SO_4	1+	2	2-	1	2:1
copper (II) phosphate	$Cu_3(PO_4)_2$	2+	3	3-	2	3:2
iron(III) nitrate	$Fe(NO_3)_3$	3+	1	1-	3	1:3

OBJECTIVE 2

Demonstrate an understanding of how ionic bonding is an energetically favorable process.

It is important to remember that ionic bonding is the result of two key processes: the transfer of an electron(s) from one atom to another and the resulting electrostatic attraction between the now oppositely charged particles. As such, two key concepts immediately become important—**ionization energy** and **electron affinity**. Ionization energy describes the amount of energy required to remove an electron from an atom in the gaseous state. Electron affinity describes the amount of energy either required or released to add an electron to an atom in the gaseous state. Considering this, one would assume that the formation of ionic bonds occurs when the ionization energy of one atom is less than the amount of energy released when the atom with which it bonds accepts an electron. Let's see if this is true.

TASK 4: Complete the fifth column of the table by determining the sum of ionization energies and electron affinities of the elements in each reaction by adding the two together. Signs are important here! **The last column will remain empty until Task 5.** Also, remember that in some cases the number of electrons exchanged is more than one, so you will sometimes have to also consider second ionization energies and electron affinities.

Compound	Synthesis Reaction	Metal Ionization Energy (kJ/mol)	Nonmetal Electron Affinity (kJ/mol)	IE + EA (kJ/mol)	Endothermic or Exothermic?
lithium bromide (LiBr)	$Li(s) + ½ Br_2(g) \rightarrow LiBr(s)$	+ 520	— 325	+ 195	Endothermic
potassium fluoride (KCl)	$K(s) + ½ F_2(g) \rightarrow KF(s)$	+ 419	— 328	+ 91	Endothermic
calcium oxide (CaO)	$Ca(s) + ½ O_2(g) \rightarrow CaO(s)$	**First:** + 590 **Second:** + 1145	**First:** —142 **Second:** + 844	+2,437	Endothermic
magnesium chloride ($MgCl_2$)	$Mg(s) + Cl_2(g) \rightarrow MgCl_2(s)$	**First:** + 738 **Second:** + 1451	— 349	+1,840	Endothermic

OBJECTIVE 2

Demonstrate an understanding of how ionic bonding is an energetically favorable process.

TASK 5: In the case that a reaction releases energy, it is considered **exothermic**. If the reactions you saw in Task 4 were exothermic, then the sum of their ionization energies and electron affinities would be negative, indicating that energy is released by the reaction. In the case that a reaction requires an input of energy, it is considered **endothermic**. If the reactions you saw in Task 4 were endothermic, then the sum of their ionization energies and electron affinities would be positive, indicating that energy input is required to complete the reaction. Use this information to complete the last column of the table in Task 4 and determine which type of reaction is predicted by ionization energies and electron affinities alone.

LOCK IT IN:
It turns out that the formation of ionic compounds in general, including the ones in Task 4, are very **exothermic** reactions. Considering this information, do the concepts of ionization energy and electron affinity alone explain the formation of ionic bonds? Explain your answer.

No, ionization energy and electron affinity alone do not explain the formation of ionic bonds. If these two factors were the only relevant ones, then the reactions would have to be endothermic. The fact that they are exothermic tells us that there is at least one other factor involved.

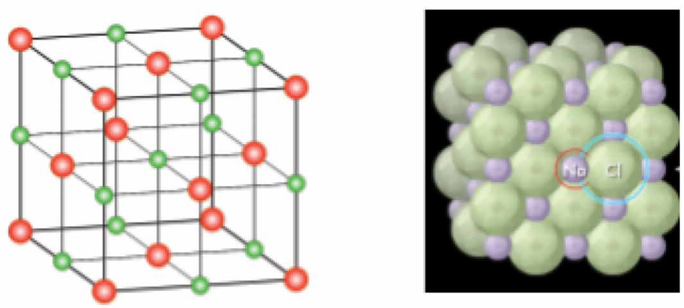
OBJECTIVE 2

Demonstrate an understanding of how ionic bonding is an energetically favorable process.

TASK 6: Leave the sandbox and go to level 3 in the ionic bonding game. Click the menu button and choose "Restart level". Build the first compound from the table in Task 4 — lithium bromide. Drag the formula unit into the correct section of the bottom panel of the game screen. In the space below, describe what appears immediately **after** the game checks and confirms the compound you created.

Immediately after the game checks and confirms the compound, the formula unit that is created appears inside a tightly packed network of alternating cations and anions.

That structure that is shown is known as a **crystal lattice**. This arrangement of ions is crucial to understanding how a process that would be endothermic based on electron transfer alone is actually exothermic. As you saw with lithium bromide in the game, ions created as a result of electron transfer coalesce to form a network of alternating cations and anions. As these oppositely charged ions approach each other, their potential energy decreases and is released as heat. This released energy is known as the **lattice energy** and is so large that it outweighs the endothermicity of the electron transfer and makes the entire process of ionic bond formation exothermic.



Left: This generic crystal lattice shows alternating cations and anions. Formation of structures like this one releases energy.

Right: Sodium chloride (NaCl) crystal lattice as depicted in the Ionic Bonding game.

Ion Lattice by Prolineserver, CC BY-SA 3.0

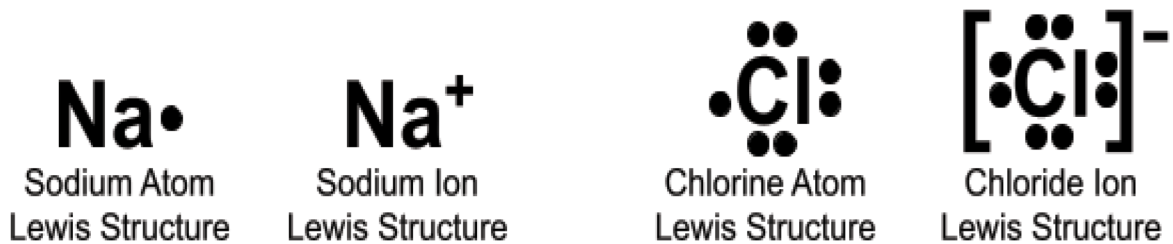
LOCK IT IN:
In your own words, use the terms endothermic and exothermic to explain why ionic bond formation releases energy.

Despite the difference between the ionization energies and electron affinities of the elements in an ionic compound indicating that the reaction that forms them should be endothermic, considering ionization energy and electron affinity alone does not account for the lattice energy. This lattice energy is the energy that is released when individual formula units converge to form a crystal lattice structure. This released energy is large enough to compensate and exceed the endothermicity of the electron transfer process.

OBJECTIVE 3

Demonstrate an understanding of how Lewis structures can represent the formation of ionic compounds.

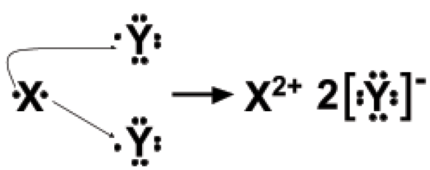
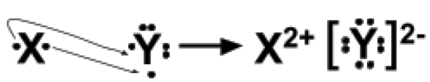
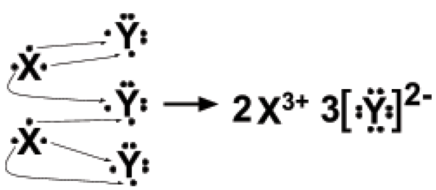
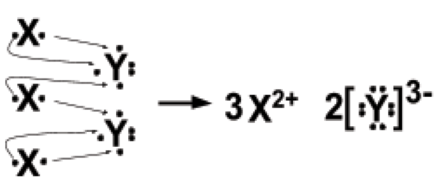
Lewis structures are a useful tool commonly used in chemistry to simply depict the valence electrons found around atoms and ions. As such, Lewis structures can also be used to show how atoms interact with one another in order to fulfill the **octet rule** that states that atoms generally prefer to have a full set of valence electrons. Such a state would be represented on a Lewis structure either by showing either 4 pairs of dots surrounding the atom or no dots surrounding the atom. Arrows can also be used to show how valence electrons move between atoms. Lewis structures are particularly useful for depicting the covalent bonds of molecules, but are also used for ionic compounds.



OBJECTIVE 3

Demonstrate an understanding of how Lewis structures can represent the formation of ionic compounds.

TASK 7: Use the sandbox to create a compound that matches the Lewis structures in the first column of the table. Record the details about that compound in the remaining columns of the table. Note: Multiple correct answers are possible for each reaction.

Lewis Structure Synthesis Reaction	Total # of Electrons Transferred	Resulting Cation-Anion Ratio	Resulting Compound Name	Resulting Chemical Formula
	1	1:1	Example: Potassium Bromide	Example: KBr
	2	1:2	Example: Calcium Fluoride	Example: CaF_2
	2	1:1	Example: Magnesium Oxide	Example: MgO
	6	2:3	Example: Aluminum Oxide	Example: Al_2O_3
	6	3:2	Example: Calcium Nitride	Example: Ca_3N_2

OBJECTIVE 4

Demonstrate an understanding of the role of electronegativity in ionic bond characterization.

Another key concept in chemical bonding is **electronegativity**. Electronegativity describes the tendency of an atom to attract shared electrons towards itself. The difference in electronegativity between two bonded elements can help reveal whether the bond is ionic or covalent (covalent bonds are covered in their own game). Metals tend to have very low electronegativities while nonmetals tend to have higher ones. Ionic bonds, which form between metals and nonmetals, are thus characterized by large differences in electronegativities between the bonding elements. The exact electronegativity difference that characterizes each bond type varies depending on source, demonstrating how bonds are never purely ionic. However, the values used here are broadly representative of the variation. Also note that there are exceptions to the general electronegativity difference patterns. Some compounds with relatively low electronegativity differences between elements are classified as ionic, while others with relatively large differences are classified as covalent. As with many areas in chemistry, gray areas do exist.

Pauling Electronegativities of the Elements

Group (vertical) / Period (horizontal)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H 2.20																	He
2	Li 0.98	Be 1.57											B 2.04	C 2.55	N 3.04	O 3.44	F 3.98	Ne
3	Na 0.93	Mg 1.31											Al 1.61	Si 1.90	P 2.19	S 2.58	Cl 3.16	Ar
4	K 0.82	Ca 1.00	Sc 1.36	Ti 1.54	V 1.63	Cr 1.66	Mn 1.55	Fe 1.83	Co 1.88	Ni 1.91	Cu 1.90	Zn 1.65	Ga 1.81	Ge 2.01	As 2.18	Se 2.55	Br 2.96	Kr 3.00
5	Rb 0.82	Sr 0.95	Y 1.22	Zr 1.33	Nb 1.6	Mo 2.16	Tc 1.9	Ru 2.2	Rh 2.28	Pd 2.20	Ag 1.93	Cd 1.69	In 1.78	Sn 1.96	Sb 2.05	Te 2.1	I 2.66	Xe 2.60
6	Cs 0.79	Ba 0.89	*	Hf 1.3	Ta 1.5	W 2.36	Re 1.9	Os 2.2	Ir 2.20	Pt 2.28	Au 2.54	Hg 2.00	Tl 1.62	Pb 2.33	Bi 2.02	Po 2.0	At 2.2	Rn 2.2
7	Fr 0.7	Ra 0.9	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo
Lanthanides	*	La 1.1	Ce 1.12	Pr 1.13	Nd 1.14	Pm 1.13	Sm 1.17	Eu 1.2	Gd 1.2	Tb 1.1	Dy 1.22	Ho 1.23	Er 1.24	Tm 1.25	Yb 1.1	Lu 1.27		
Actinides	**	Ac 1.1	Th 1.3	Pa 1.5	U 1.38	Np 1.36	Pu 1.28	Am 1.13	Cm 1.28	Bk 1.3	Cf 1.3	Es 1.3	Fm 1.3	Md 1.3	No 1.3	Lr 1.291		

Electronegativity Values, CC BY-SA 3.0

OBJECTIVE 4

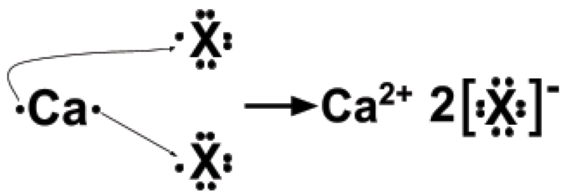
Demonstrate an understanding of the role of electronegativity in ionic bond characterization.

Electronegativity Difference	Bond Type
0 to 1.7	Covalent
> 1.7	Ionic unless between two nonmetals

TASK 8: Use the electronegativity values and bond type table provided above to identify each substance in the table below as either ionically or covalently bonded. Make any ionically bonded substance in the sandbox to practice.

Chemical Formula of Substance	Electronegativity of First Element	Electronegativity of Second Element	Electronegativity Difference	Ionic or Covalent?
Cs_2S	0.79	2.58	1.79	Ionic
KF	0.82	3.98	3.16	Ionic
CO	2.55	3.44	0.89	Covalent
NO	3.04	3.44	0.40	Covalent
MgO	1.31	3.44	2.13	Ionic

CLOSURE: Below is a Lewis structure for a substance with an anion of unknown identity. Use the sandbox to identify two ion candidates for the missing anion "X". Once you have done this, write the name and chemical formula for each compound before calculating the electronegativity difference between the elements in the two compounds you identify.



Possible Identity of X (name and chemical formula)	Compound Name	Compound Chemical Formula	Electronegativity Difference
Example: Chloride	Calcium Chloride	$CaCl_2$	2.16
Example: Bromide	Calcium Bromide	$CaBr_2$	1.96