Ions and the Octet Rule

1.3

The noble gases are extremely stable (inert) elements. They do not usually form compounds. One of the noble gases, helium, is less dense than air. Because of its stability and low density, helium is a good choice for filling blimps **(Figure 1)**. Helium is not the only gas to be used for lighter-than-air flight, though. An alternative is hydrogen, a very light but highly flammable gas. In 1937 a hydrogen-filled German airship, *Hindenburg*, caught fire and killed 36 people. Helium was already being used for airships in the United States. However, the U.S. government would not share the technology for isolating helium with Germany. Since that tragic event, most airships have been filled with helium.

Argon and krypton are used extensively inside incandescent light bulbs. These noble gases make the filaments in the bulbs last much longer. As well, neon is used in colourful lighting displays and in vacuum and television tubes (**Figure 2**). It is ideal for this use primarily because of its chemical inertness.

Figure 1 Modern blimps get their "lift" from inert helium.

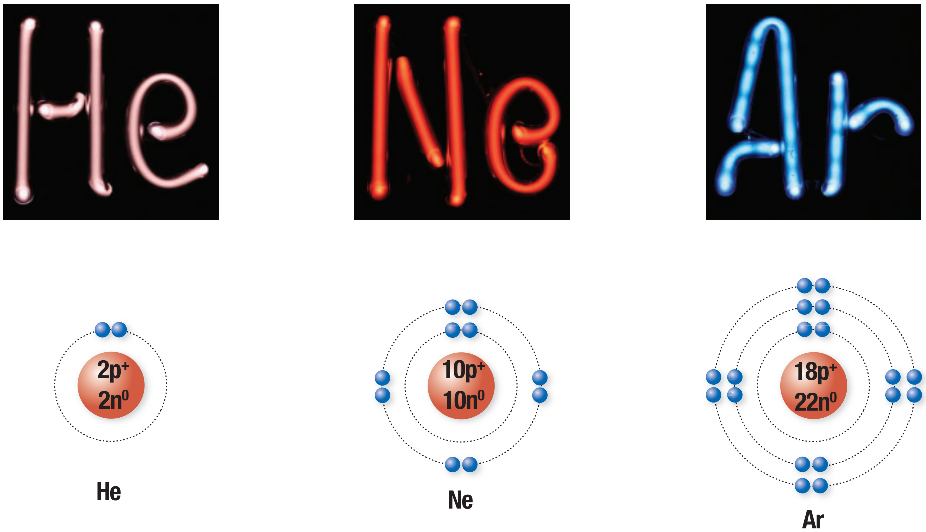

Figure 2 The Bohr–Rutherford diagrams of helium, neon, and argon show their full valence shells.

The Octet Rule

Elements with a full valence shell have a special stability. In the first 18 elements, a full valence shell (except the first shell) contains 8 electrons. Atoms of noble gases each have 8 electrons in their valence shells. This stable arrangement is known as a **full or stable octet**. The exception is helium, which is stable with 2 electrons in its valence shell.

Atoms of other elements do not have a full valence shell. Atoms, when they combine with other atoms, tend to attain this electron arrangement. This generalization is known as the **octet rule**. There are three possible ways in which an atom can achieve this stable arrangement: it can share, lose, or gain electrons. When an atom loses or gains electrons, it forms an **ion:** an entity with a positive or negative charge. (Recall that "entity" is a term that chemists use for an atom, an ion, or a molecule.) Whether an atom loses or gains electrons depends on the number of valence electrons it has.

full or stable octet an electron arrangement where the valence shell is filled with 8 valence electrons (2 for hydrogen and helium)

octet rule a generalization stating that when atoms combine, they tend to achieve 8 valence electrons

ion a charged entity formed when an atom gains or loses one or more electrons

The Formation of Ions

As you know, atoms sometimes lose or gain electrons to form ions. Some elements are more likely to lose electrons and become positive ions; others are more likely to gain electrons and become negative ions.

Positive Ions: Cations

The metals are located to the left of the zigzag staircase line on the periodic table. In the first few groups (columns) on the left side of the periodic table, the metals typically have just a few electrons in their valence shell. In general, metal atoms tend to lose valence electrons in order to achieve a stable electron arrangement.

Consider sodium in Group 1, the alkali metals. Each sodium atom has one valence electron in its outer orbit. In order to achieve a more stable arrangement, a sodium atom tends to lose that one electron (**Figure 3**). When it loses its electron it becomes a positively charged ion. A positively charged ion is known as a **cation**.

cation a positively charged ion formed by the removal of one or more electrons from the valence shell of a neutral atom

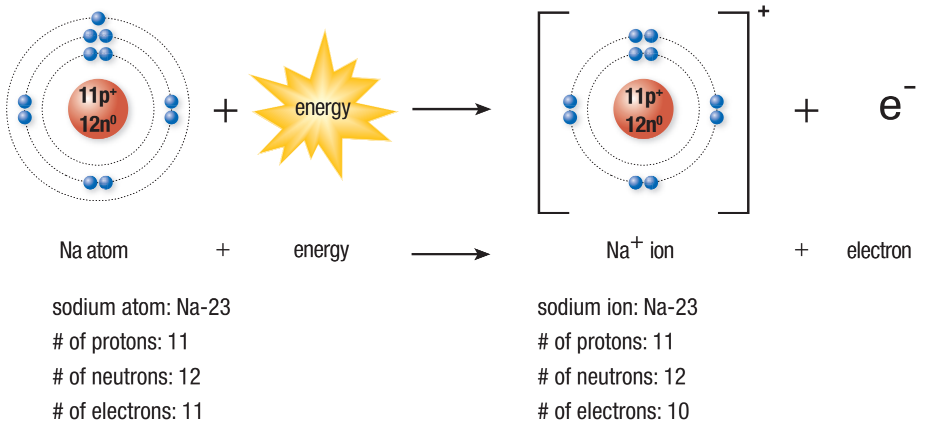

Figure 3 A sodium atom loses its one valence electron to become a sodium cation, Na^+.

A sodium ion has a positive charge of +1 because it has 11 positive charges (protons) and 10 negative charges (electrons). The charge of an ion is often called the **valence**. Hence, sodium has a valence of +1.

valence the charge of an ion; the combining capacity of an atom determined by the number of electrons that it will lose, add, or share when it reacts with other atoms

As another example, an aluminum atom has 3 valence electrons. It will therefore lose 3 electrons to become an Al^{3+} ion. Note that when we represent ions as Bohr–Rutherford diagrams, we enclose them with square brackets and write the charge as a superscript outside the brackets.

Naming cations is very simple. They have the same name as their element. Na^+ ions are simply called sodium ions and Al^{3+} ions are aluminum ions.

Negative Ions: Anions

The elements on the right side of the periodic table are mostly non-metals. They generally have almost-complete valence shells. Non-metallic atoms tend to gain electrons in order to fill their valence shells. In doing so, they become negatively charged ions. A negatively charged ion is called an **anion**. Consider chlorine, in the halogen family (**Figure 4**). A chlorine atom gains one valence electron to fill its outer shell, forming a Cl^- ion. This ion has a negative charge of –1 because it has 17 positive charges (protons) and 18 negative charges (electrons). Chlorine has a valence of –1.

anion a negatively charged ion formed by the addition of one or more electrons to a neutral atom

LEARNING TIP

Memory Aid—Cations and Anions
There are several ways to help you remember that cations are positive ions and anions are negative ions. The "t" in cation is like a plus (positive) sign. The first three letters in the word anion might stand for "are negative ions." Finally, the spelling of anion is close to that of "onion," which may have a negative effect on one's breath!

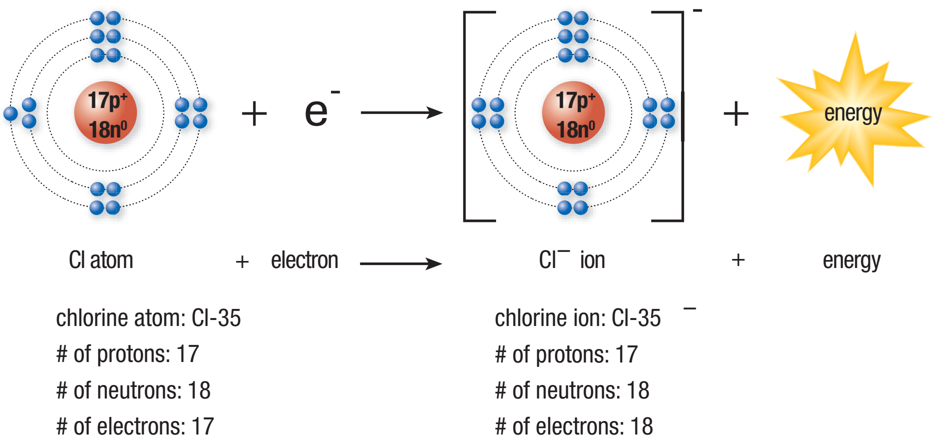

Figure 4 An atom of chlorine gains an electron to become a chloride anion, Cl^-.

Look at the position of sulfur on the periodic table. Each sulfur atom has 6 valence electrons and will therefore gain 2 electrons. In the process it gains a charge of –2 and becomes an S^{2-} ion.

Anions are named a little differently than cations. Non-metal ions are named by replacing the end of the element's name with the suffix *–ide*. For example, the Cl^- ion would be called a chloride ion and the S^{2-} ion would be a sulfide ion.

In general, metals lose electrons to become cations with the electron arrangement of the nearest noble gas with a smaller atomic number. Non-metals gain electrons to become anions with the electron arrangement of the nearest noble gas with a larger atomic number. **Figure 5** shows the most common valences for some of the elements on the periodic table that form ions.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 1+ 1– **H** hydrogen																	2 **He** helium
2	3 1+ **Li** lithium	4 2+ **Be** beryllium											5 **B** boron	6 **C** carbon	7 3– **N** nitrogen	8 2– **O** oxygen	9 1– **F** fluorine	10 **Ne** neon
3	11 1+ **Na** sodium	12 2+ **Mg** magnesium											13 3+ **Al** aluminum	14 **Si** silicon	15 3– **P** phosphorus	16 2– **S** sulfur	17 1– **Cl** chlorine	18 **Ar** argon
4	19 1+ **K** potassium	20 2+ **Ca** calcium	21 **Sc** scandium	22 **Ti** titanium	23 **V** vanadium	24 2+ **3+** **Cr** chromium	25 **Mn** manganese	26 2+ **3+** **Fe** iron	27 **Co** cobalt	28 **Ni** nickel	29 1+ **2+** **Cu** copper	30 2+ **Zn** zinc	31 **Ga** gallium	32 **Ge** germanium	33 **As** arsenic	34 **Se** selenium	35 1– **Br** bromine	36 **Kr** krypton
5	37 1+ **Rb** rubidium	38 2+ **Sr** strontium	39 **Y** yttrium	40 **Zr** zirconium	41 **Nb** niobium	42 **Mo** molybdenum	43 **Tc** technetium	44 **Ru** ruthenium	45 **Rh** rhodium	46 **Pd** palladium	47 1+ **Ag** silver	48 **Cd** cadmium	49 **In** indium	50 2+ **4+** **Sn** tin	51 **Sb** antimony	52 **Te** tellurium	53 1– **I** iodine	54 **Xe** xenon
6	55 1+ **Cs** cesium	56 2+ **Ba** barium	57 **La** lanthanum	72 **Hf** hafnium	73 **Ta** tantalum	74 **W** tungsten	75 **Re** rhenium	76 **Os** osmium	77 **Ir** iridium	78 **Pt** platinum	79 **Au** gold	80 **Hg** mercury	81 **Tl** thallium	82 **2+** 4+ **Pb** lead	83 **Bi** bismuth	84 **Po** polonium	85 1– **At** astatine	86 **Rn** radon
7	87 1+ **Fr** francium	88 2+ **Ra** radium	89 **Ac** actinium	104 **Rf** rutherfordium	105 **Db** dubnium	106 **Sg** seaborgium	107 **Bh** bohrium	108 **Hs** hassium	109 **Mt** meitnerium	110 **Ds** darmstadtium	111 **Rg** roentgenium	112 **Cn** copernicium	113 **Uut** ununtrium	114 **Uuq** ununquadium	115 **Uup** ununpentium	116 **Uuh** ununhexium	117 **Uus** ununseptium	118 **Uuo** ununoctium

Figure 5 This periodic table shows the common valences for various elements on the periodic table. Look in the top right corner of each cell. Where an element has more than one valence, the most common valence is indicated in bold type. Do you notice any patterns?

Elements with Multiple Ionic Charges

In Figure 5, above, you may notice that some elements can form more than one possible ion. These substances are said to be multivalent. A **multivalent** element is one that can form two or more different stable ions. In fact, most of the transition metals—those in the middle part of the periodic table—can form more than one type of ion. For example, chemists have observed that copper can form both Cu^+ and Cu^{2+} ions. Many of the multivalent elements are transition metals, so these elements are often called multivalent metals.

multivalent the property of having more than one possible valence

Chemists need a naming system to distinguish between the different ions formed by the same element. A traditional naming system used the Latin name of the element and a suffix of either *–ous* to represent the lower valence or *–ic* for the higher valence. Note that this naming system is useful only for multivalent elements with two different possible valences. This classical system is still widely used, but is gradually being replaced by a system approved by IUPAC. In the IUPAC system, a Roman numeral in the ion's name indicates the charge of the ion. **Table 1** shows some examples of multivalent metals and their classical and IUPAC names.

Table 1 Examples of Multivalent Metals

Metal	Ions	Classical names	IUPAC names
copper, Cu	Cu^+ Cu^{2+}	cuprous cupric	copper(I) copper(II)
iron, Fe	Fe^{2+} Fe^{3+}	ferrous ferric	iron(II) iron(III)
tin, Sn	Sn^{2+} Sn^{4+}	stannous stannic	tin(II) tin(IV)
lead, Pb	Pb^{2+} Pb^{4+}	plumbous plumbic	lead(II) lead(IV)
manganese, Mn	Mn^{2+} Mn^{3+} Mn^{4+} Mn^{6+} Mn^{7+}	n/a	manganese(II) manganese(III) manganese(IV) manganese(VI) manganese(VII)

Mini Investigation

Using Flame Tests

Skills: Predicting, Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A1, B4

Chemists use flame tests and a reference key to identify unknown metallic ions in solution. In this investigation, your task is to observe and create a key for the flame test results when you test different metallic compounds (**Figure 6**). You will then use this key to identify an unknown metallic compound.

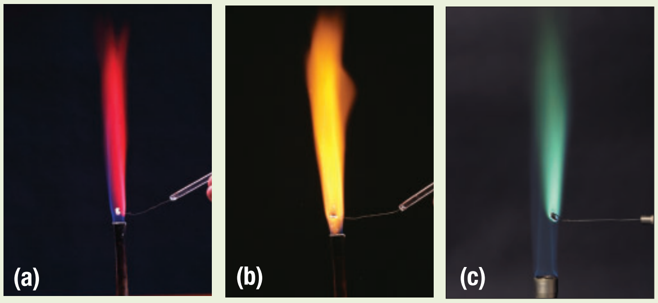

Figure 6 Flame test for (a) lithium, (b) sodium, and (c) a mystery metal compound

Equipment and Materials: chemical safety goggles; lab apron; Bunsen burner clamped to a retort stand; spark lighter; nichrome test wire; small labelled beaker containing 50 mL of dilute hydrochloric acid; small labelled beakers containing dilute 5 mL samples of the following solutions: sodium chloride, calcium chloride, strontium chloride, lithium chloride, potassium chloride, and copper(II) chloride (0.1 mol/L)

This investigation involves the use of open flames. Tie back long hair and secure loose clothing and jewellery.

The hydrochloric acid and sodium hydroxide solution used in this activity are irritants. Wash any spills on skin or clothing immediately with plenty of cool water. Report any spills to your teacher.

1. Put on your chemical safety goggles and lab apron.
2. Light the Bunsen burner with your spark lighter and adjust it so that the flame is blue.
3. Clean the nichrome test wire by dipping it in the acid and then placing it in the flame for 10 s.
4. Dip the clean nichrome wire into one of the solutions. Hold the end of the wire in the flame until a uniquely coloured flame appears. Record your observations.
5. Repeat Steps 3 and 4 to clean the wire and perform the test on the remaining substances.

A. Which, if any, of your samples gave identical results? T/I

B. Suggest an explanation for this observation. T/I

C. Suggest the identity of the mystery substance being tested in Figure 6(c). T/I

D. Suggest a real-life application in which flame tests would be used to identify ions. A

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Polyatomic Ions

polyatomic ion an ion, made up of more than one atom, that acts as a single entity

You may have noticed advertisements for phosphate-free dishwashing detergents, or nitrate-free or nitrite-free meat products (**Figure 7**). Phosphate ions (PO_4^{3-}), nitrate ions (NO_3^-), and nitrite ions (NO_2^-) are ions that consist of more than one atom. An ion that has more than one atom is called a **polyatomic ion**.

People sometimes think that substances containing polyatomic ions are dangerous. The compounds have long, complicated-sounding names. If you look at the list of ingredients on food packaging, the polyatomic compounds appear to be "chemicals"—by which we often mean "synthetic compounds" rather than natural substances (**Figure 8**). This is a misconception. Polyatomic ions occur in nature and are essential to our health. For example, calcium phosphate is a major constituent of bones and teeth, and hydrogen carbonate ions help to regulate blood pH.

Figure 7 Some polyatomic ions have negative effects on the environment or human health.

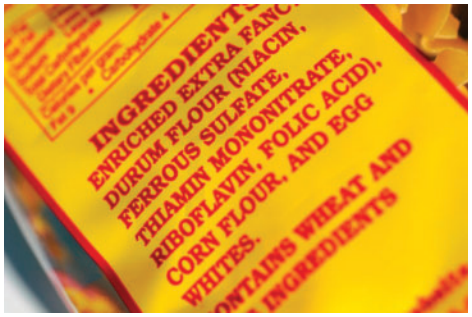


Figure 8 Many compounds containing polyatomic ions are essential for good health.

Polyatomic ions are useful in many industries. For example, sodium nitrate is used in fertilizers. Meat processors add nitrates to their products. These nitrates convert to nitrites due to natural processes within the meat. A manufacturer can claim that no nitrites are added, yet nitrites may still be present.

Polyatomic ions have some negative effects. If phosphates make their way into lakes or ponds, they act as fertilizer and cause blooms of algae. As well, nitrites form cancer-causing agents when they react with substances in the digestive system. For these reasons, the use of phosphates in cleaning products is heavily regulated and we are advised not to consume processed meats too often.

Most polyatomic ions are composed of oxygen, nitrogen, phosphorus, sulfur, chlorine, and carbon. Also, most polyatomic ions are anions (**Table 2**). Each ion gains one or more extra electrons so that each of its atoms reaches a stable arrangement of electrons. The phosphate ion, PO_4^{3-}, has gained 3 extra electrons to reach a stable configuration. A polyatomic ion behaves just like an ion made of only one atom.

Table 2 IUPAC Names and Formulas for Some Common Polyatomic Ions

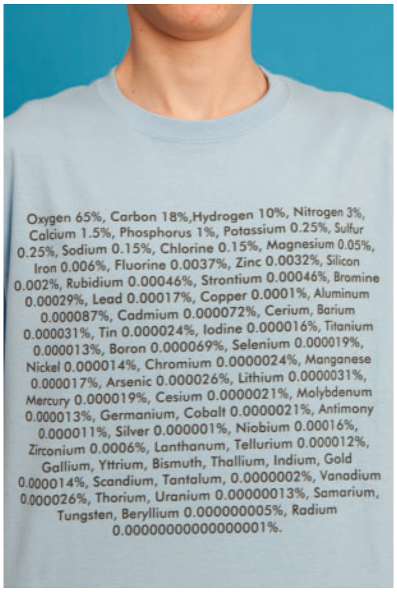
Name	Formula
acetate	$C_2H_3O_2^-$
bromate	BrO_3^-
carbonate	CO_3^{2-}
hydrogen carbonate	HCO_3^-
hypochlorite	ClO^-
chlorite	ClO_2^-
chlorate	ClO_3^-
perchlorate	ClO_4^-
chromate	CrO_4^{2-}
dichromate	$Cr_2O_7^{2-}$
cyanide	CN^-
hydroxide	OH^-
iodate	IO_3^-
permanganate	MnO_4^-
nitrite	NO_2^-
nitrate	NO_3^-
phosphate	PO_4^{3-}
hydrogen phosphite	HPO_3^{2-}
hydrogen phosphate	HPO_4^{2-}
dihydrogen phosphite	$H_2PO_3^-$
dihydrogen phosphate	$H_2PO_4^-$
sulfite	SO_3^{2-}
sulfate	SO_4^{2-}
hydrogen sulfide	HS^-
hydrogen sulfite	HSO_3^-
hydrogen sulfate	HSO_4^-
thiosulfate	$S_2O_3^{2-}$
ammonium	NH_4^+

Ions in the Human Body

About 99 % of your body is made up of only 6 elements. In order of abundance by mass, these elements are oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorus. You also contain much smaller quantities of sulfur, chlorine, sodium, magnesium, iodine, and iron. Many of these elements exist as ions dissolved in water. As you are probably aware, these ions play key roles in our bodies (**Table 3**).

Table 3 Some Important Ions in the Human Body

Ion	Role	Source
Na^+	important for body fluid control	salt cheese preservatives
K^+	important for body fluid control and cell functions	bananas milk potatoes
Ca^{2+}	a key component of bone and teeth	milk cheese spinach
Fe^{3+}	important in muscle function; an essential part of hemoglobin in blood	kidney beans asparagus pine nuts
Mg^{2+}	crucial for muscle and nerve functions	green plants nuts grains
Cl^-	important for body fluid control	salt
I^-	helps regulate the body's metabolic rate	fish dairy products iodized salt



The human body requires a delicate balance of many ions for good health. Sodium ions, for example, play a critical role in the normal functioning of the human body. Sodium ions help with nerve impulse transmission, muscle contraction, and water balance. If sodium ion levels fall too low, death can result. Our Western diet usually contains plenty of sodium. In fact, many of us consume more than the recommended daily intake of sodium. Excessive sodium intake can, in some people, lead to hypertension and an increased risk of heart disease. There is a great deal of concern in many countries about the high level of sodium in today's foods—especially processed foods and meals from fast-food restaurants.

CAREER LINK

Nutritionists advise people on the best foods to eat—or avoid—for optimal health. If this is a career you would like to know more about,

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Research This

Tattoo Ink—Decorative Body Art or Toxic Mixture?

Skills: Researching, Analyzing, Defining the Issue, Communicating, Defending a Decision SKILLS HANDBOOK **A5.1, A5.2**

Tattoos have long been a form of personal expression. They are created by depositing a pigment into the skin (**Figure 9**). Colours are determined by the chemical composition of the pigment. For example, black is made from carbon and iron(II) oxide, blue is made from copper phthalocyanine, and violet gets its colour from a mixture of aluminum salts.

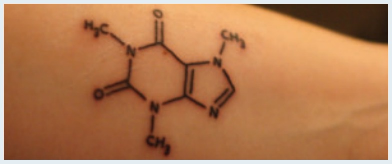

Figure 9 Are tattoos safe?

1. Research the health concerns related to getting a tattoo. Find resources that consider the concerns in an objective fashion and that cite supporting evidence. Investigate the following questions:
   - Is it safe to get a tattoo?
   - What regulations currently apply to tattoo parlours in Ontario?
   - Should the tattoo industry be more strictly controlled?
   - Canadian Blood Services will not let people donate blood if they have recently received tattoos. Why?

A. Analyze the evidence on the issue of whether or not it is safe to get a tattoo. Formulate arguments for and against the safety of tattoos. T/I A

B. Debate the safety of getting a tattoo. C A

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1.3 Summary

- The octet rule states that atoms tend to gain or lose electrons to achieve a stable octet: the electron arrangement of the nearest noble gas.
- Ions are atoms that have gained or lost electrons.
- Metals tend to lose electrons to form cations. Cations are positively charged ions that have fewer electrons than protons.
- Non-metals tend to gain electrons to form anions. Anions are negatively charged ions that have more electrons than protons.
- Multivalent elements can form two or more different ions.
- Polyatomic ions are ions composed of more than one atom.
- Many ions are necessary for good health.

1.3 Questions

1. Draw a Bohr–Rutherford diagram for each of the following ions. Represent the ions correctly with square brackets and charge. T/I C
   (a) K^+ (b) F^- (c) N^{3-} (d) Mg^{2+}
2. For each of the ions in Question 1, name the noble gas with the same electron arrangement. T/I
3. State the octet rule. K/U
4. Write the IUPAC name for each of the following ions: K/U
   (a) O^{2-} (d) SO_4^{2-}
   (b) Cu^+ (e) OH^-
   (c) Sn^{4+} (f) NH_4^+
5. Manganese atoms can form a wide variety of ions, including Mn^{2+}, Mn^{3+} and Mn^{4+}. Propose how we can communicate which ion is present in a compound. K/U
6. Write the formula and charge for each of the following polyatomic ions. K/U
   (a) nitrate (c) acetate
   (b) carbonate (d) permanganate
7. Calcium carbonate, $CaCO_3$, is a critical component of the shells of various aquatic species. Identify the cation and anion in calcium carbonate. T/I
8. Which 4 atoms or ions from the following list have the same electron arrangement? O^{2-} S^{2-} Na^+ Al^{3+} Ne F K/U
9. Give two experimental techniques that might help to identify the presence of metal ions. T/I
10. Anemia is a health condition caused by an iron deficiency. Research common symptoms of anemia and suggest foods that could be added to a diet to provide more iron. T/I A

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