2.2 THE PERIODIC LAW

Many things in life occur over and over again in a repetitive or "periodic" manner. The sun rises and sets at predictable times, ocean tides come and go on schedule, and hopefully your school bus arrives and departs on time each day! Many other phenomena such as the swinging of the pendulum of a grandfather clock, your circadian rhythm (daily waking and sleeping schedule), the seasons of the year, and the daily opening and closing of many flowers are periodic, and thus predictable. It so happens that there is periodicity and predictability among the elements as well!

An element is a substance composed of only one kind of atom: the element iron is composed of iron atoms, the element oxygen is composed of oxygen atoms, and the element gold is composed of gold atoms. There are presently 112 known elements, some naturally occurring, and some man-made. Element 112 was recently made by bombarding lead with zinc until atoms of these elements fused to form the new element. Although 83 elements are found in nature, they are not equally distributed. While the sun is primarily hydrogen (95 % hydrogen; 5% helium and other elements), the Earth's crust is primarily oxygen and silicon, the Earth's core is primarily iron, and our bodies are primarily hydrogen and oxygen: (hydrogen - 63 %, oxygen - 25.5 %, carbon - 9.5 %, nitrogen - 1.4 %, calcium - 0.31 %, phosphorous - 0.22 %, chlorine - 0.03 %, potassium - 0.06 %, sulfur - 0.05 %, sodium - 0.03 %, magnesium - 0.01 %.) How does one keep track of, and make sense of, all these elements?

In the nineteenth century, chemists did not know much about atoms and molecules, and they knew nothing about electrons and protons. However, they did realize that some groups of elements shared common properties, and they thought that these properties might be related to atomic mass. Dimitri Mendeleev (1834-1907), a Russian chemist and teacher, was writing a chemistry book and wished to include new values for the atomic masses of the elements that had been recently determined. He was hoping to use this information, and the known chemical and physical properties of the elements, to arrange them according to their properties. Mendeleev approached the task in an organized manner. On separate cards, he listed the names of each element, together with their atomic masses and known properties. He organized the cards according to various properties and then searched for trends and patterns. Mendeleev noticed that when elements were arranged in order of increasing atomic mass, similar properties appeared at regular (periodic) intervals! He also noticed that when he did this, three gaps remained -- spaces where there were no known elements with the appropriate masses and properties. Mendeleev boldly suggested that these spaces represented elements that were as of yet undiscovered, and within fifteen years of his prediction, all three were found!

The following is a simplified example of how Mendeleev came upon his discovery. Suppose we have nine elements: A_1(gas), A_2(liquid), A_3(solid), A_4(gas), A_5(liquid), A_6(solid), A_7(gas), A_8 (liquid), and A_9 (solid), with the subscript representing the atomic mass. Construct your own periodic table of these nine elements, sequencing them by atomic number, and grouping them by "families" with similar properties. Suppose someone discovers a new element that is a liquid with atomic weight between 9 and 13. Place this element in your periodic table and predict its atomic weight.

Table 1 Hypothetical "periodic table"

Your periodic table	*Group α (gas)*	*Group β (liquid)*	*Group χ (solid)*
Period α	A_1	A_2	A_3
Period β	A_4	A_5	A_6
Period χ	A_7	A_8	A_9
Period δ		$\mathbf{A_{11}}$	

Does your table resemble Table 1? Were you able to place the newly discovered element in an appropriate row (period, series) and column (group, family)? Notice that in your table, the properties (gas, liquid, solid) of elements in any period change as you move through the period. At the end of one period, another period begins in which the properties again change in a predictable manner. Also notice that, within any group, the properties are the same: all elements in Group α are gases, all elements in Group β are liquids, and all elements in Group χ are solids. Although your table is greatly simplified, it helps explain what is meant by periodicity and illustrates how properties change as one moves from left to right across a period.

The success of Mendeleev's predictions led to the acceptance of his periodic table. However, although Mendeleev's table was good, it was not perfect. For example, to get properties to match, Mendeleev placed argon (atomic mass 39.95) before potassium (atomic mass 39.10) even though this was inconsistent with his principle of arranging the elements in order of increasing mass. Although such discrepancies may seem minor, they indicated that atomic mass was not a perfect predictor or periodicity. This problem was resolved in 1911 when the English chemist Henry Moseley determined the atomic number (nuclear charge-- the number or protons in the nucleus) of elements and discovered that discrepancies disappeared when the elements were arranged by this feature rather than atomic mass. Moseley's work led the conclusion that the chemical and physical properties of the elements are periodic functions of their atomic numbers. This principle is now known as the periodic law, and is one of the major principles in chemistry.

The modern periodic table (Figure A) arranges elements by atomic number. Hydrogen (atomic number 1), because of its many unique properties, is placed at the top of the table in a cell by itself. Helium (atomic number 2) is placed at the top of the right-hand column above the other noble gases. Hydrogen and helium form the first series or period (row). The number at the top of each cell represents the atomic number of the element. The number at the bottom represents the average atomic mass. Examine the periodic table to find adjacent elements in which the mass of the first is greater than the mass of the second. These pairs represent the discrepancies that accompanied Mendeleev's table.

Table 2 lists the first 20 elements, arranged in order of increasing atomic number. The series are separated by bold lines. Can you see any patterns (periodicity) among the electrons of each series when the elements are arranged in this manner? Look carefully, because periodicity of electron configuration underlies periodicity in chemical and physical properties.

PERIODIC TABLE OF THE ELEMENTS

A

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
1	1 H Hydrogen 1.008																	2 He Helium 4.003
2	3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.179
3	11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.981	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.098	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
5	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29
6	55 Cs Cesium 132.905	56 Ba Barium 137.33	57 La Lanthanum 138.906	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
7	87 Fr Francium (223)	88 Ra Radium 226.025	89 Ac Actinium 227.028	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)						

Lanthanide Series	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)

1 — atomic number
H — symbol
Hydrogen — name
1.008 — atomic mass

Table 2 Atomic numbers, masses and electron configuration							
Element	*Symbol*	*Atomic Number*	*Atomic Mass*	*Electrons*			
				n=1	*n=2*	*n=3*	*n=4*
hydrogen	H	1	1	1			
helium	He	2	4	2			
lithium	Li	3	7	2	1		
beryllium	Be	4	9	2	2		
boron	B	5	11	2	3		
carbon	C	6	12	2	4		
nitrogen	N	7	14	2	5		
oxygen	O	8	16	2	6		
fluorine	F	9	19	2	7		
neon	Ne	10	20	2	8		
sodium	Na	11	23	2	8	1	
magnesium	Mg	12	24	2	8	2	
aluminum	Al	13	27	2	8	3	
silicon	Si	14	28	2	8	4	
phosphorous	P	15	31	2	8	5	
sulfur	S	16	32	2	8	6	
chlorine	Cl	17	35	2	8	7	
argon	Ar	18	40	2	8	8	
potassium	K	19	39	2	8	8	1
calcium	Ca	20	40	2	8	8	2

As you prepare to investigate the periodicity of the elements, keep in mind these general principles:

(1) An element has the same number of protons as electrons. The number of protons is the atomic number of the element.

(2) The electrons exist outside the nucleus of an atom in orbitals.

(3) The outer electrons of an atom, which are those involved in chemical reactions (bonding), are referred to as valence electrons.

(4) Electron configurations of elements help explain the recurrence of physical and chemical properties.

(5) An element with 8 electrons in its outer shell is stable and does not normally enter into chemical reactions. If the outer shell has less than 4 electrons the element normally gives up electrons in chemical reactions. If the outer shell has more than 4 electrons, the element normally accepts electrons in chemical reactions.

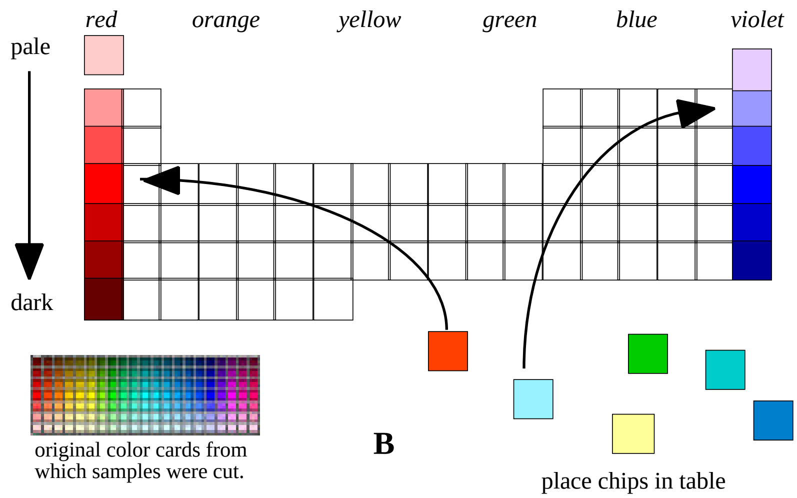
In this chapter you will investigate the periodic table, the reasons for chemical and physical periodicity, and how the periodic law can be used to predict physical and chemical properties of elements. In addition, you will have an opportunity to develop your own periodic table in the same manner as Mendeleev.

2.2.1 FINDING THE "MISSING ELEMENTS"

Concepts to Investigate: Periodicity, predicting properties, Periodic Table of the Elements, groups, families, series, periods.

Materials: Paint color samples (available at paint stores).

Principles and Procedures: Mendeleev's original periodic table arranged elements according to observed properties. You will go through the same process as you attempt to arrange paint color "chips" in a logical fashion. Your instructor will provide you with an envelope that includes paint chips of a variety of colors and intensities. The basic color of a paint chip represents its "chemical" properties. For example, all blue paint chips can be considered to have similar properties which are different from those of all red paint chips. The shade of a paint chip represents its "atomic mass". Thus, a light blue paint chip represents an element of low atomic mass while a dark blue paint chip represents an element that has similar properties but more mass. Arrange all chips with similar colors in the same column (family), and all colors with similar intensity (shade) in the same row (series). In the real Periodic Table of the Elements, properties gradually change from metallic to non-metallic as you proceed through a series from the left to the right across the table. You may illustrate this concept by arranging your columns in a logical manner such as the sequence of colors in the visible spectrum: red-orange-yellow-green-blue-violet. Place the reddest colors on the left of your table, and the most violet colors on the right (Figure B).



B

After Mendeleev arranged the known elements in a table he noted that there were holes (vacancies) and he predicted that new elements would be found to fill these. Within 15 years of his prediction, all holes were filled with elements that had properties similar to those Mendeleev predicted. Examine your "Periodic Table of Paint Chips". Are any paint chips missing? Describe the properties of those missing paint chips. When you have completed your table, ask your instructor for the envelope containing the "missing elements" for your set. Were your predictions correct? Can you see how the Periodic Table is useful in predicting properties of unknown elements?

Questions:

(1) Were you able to form a periodic table with rows (periods) and columns (groups)? Explain how you arranged your table.

(2) Were you able to predict the properties (color and shade) of the three elements not yet discovered. Where did you place these elements in your table?

(3) Explain the value of your periodic table in predicting properties of paint chips, and explain how chemists used the Periodic Table to predict the existence of unknown elements.

2.2.2 DESIGNING YOUR OWN PERIODIC TABLE

Concepts to Investigate: Periodicity, properties, atomic mass, period, group (family), family, series, predicting characteristics.

Materials: Figure C.

C

average atomic mass: **39.95**
density at 293K: 1.784 Kg/m^3
melting point: 83.78 K
boiling point: 87.29 K
thermal conductivity: 0.0177 Wm^{-1}K^{-1}
properties: non-metal, colorless, odorless gas; inert

average atomic mass: **4.00**
density at 293K: 0.1785 Kg/m^3
melting point: 0.95 K
boiling point: 4.216 K
thermal conductivity: 0.152 Wm^{-1}K^{-1}
properties: colorless, odorless gas, inert

average atomic mass: **6.94**
density at 293K: 534 Kg/m^3
melting point: 453.69 K
boiling point: 1620 K
thermal conductivity: 84.7 Wm^{-1}K^{-1}
properties: soft, white, silvery metal, reacts slowly with oxygen and water

average atomic mass: **20.20**
density at 293K: 0.900 Kg/m^3
melting point: 24.48 K
boiling point: 27.10 K
thermal conductivity: 0.0493 Wm^{-1}K^{-1}
properties: non-metal, colorless, odorless gas, chemically inert

average atomic mass: **35.45**
density at 293K: 3.24 Kg/m^3
melting point: 172.17 K
boiling point: 239.18 K
thermal conductivity: 0.0089 Wm^{-1}K^{-1}
properties: non-metal, yellow-green, dense gas

average atomic mass: **19.00**
density at 293K: 1.696 Kg/m^3
melting point: 53.53 K
boiling point: 85.01 K
thermal conductivity: 0.0248 Wm^{-1}K^{-1}
properties: non-metal, pale, yellow gas, most reactive of all elements

average atomic mass: **10.81**
density at 293K: 2340 Kg/m^3
melting point: 2573 K
boiling point: 3931 K
thermal conductivity: 27 Wm^{-1}K^{-1}
properties: metalloid, dark powder, unreactive with water and acids.

average atomic mass: **16.00**
density at 293K: 1.429 Kg/m^3
melting point: 54.8 K
boiling point: 90.188 K
thermal conductivity: 8.2674 Wm^{-1}K^{-1}
properties: non-metal, colorless gas, very reactive with all elements except nobel gases

average atomic mass: **32.07**
density at 293K: 1957 Kg/m^3
melting point: 386 K
boiling point: 717.8 K
thermal conductivity: 0.269 Wm^{-1}K^{-1}
properties: non-meal, stable in water and air, but burns if heated

average atomic mass: **9.01**
density at 293K: 1847.7 Kg/m^3
melting point: 1551 K
boiling point: 3243 K
thermal conductivity: 200 Wm^{-1}K^{-1}
properties: silvery-white, relatively soft metal, does not react with water oxygen

C

average atomic mass: **1.00**
density at 293K: 0.08988 Kg/m^3
melting point: 14.01 K
boiling point: 20.28 K
thermal conductivity: 0.1815 $Wm^{-1}K^{-1}$
properties: colorless, odorless gas, burns in air

average atomic mass: **39.10**
density at 293K: 862 Kg/m^3
melting point: 336.80 K
boiling point: 1047 K
thermal conductivity: 102.4 $Wm^{-1}K^{-1}$
properties: soft, silvery metal, reacts with oxygen and vigorously with water

average atomic mass: **28.09**
density at 293K: 2329 Kg/m^3
melting point: 1683 K
boiling point: 2628 K
thermal conductivity: 148 $Wm^{-1}K^{-1}$
properties: metalloid, semi-conductor; unreactive toward oxygen and water

average atomic mass: **40.08**
density at 293K: 1550 Kg/m^3
melting point: 1112 K
boiling point: 1757 K
thermal conductivity: 200 $Wm^{-1}K^{-1}$
properties: silvery white, soft metal; reacts with oxygen and water

average atomic mass: **14.01**
density at 293K: 1.25 Kg/m^3
melting point: 63.29 K
boiling point: 77.4 K
thermal conductivity: 0.0260 $Wm^{-1}K^{-1}$
properties: colorless, odorless gas; unreactive at room temperatures

average atomic mass: **22.99**
density at 293K: 971 Kg/m^3
melting point: 370.96 K
boiling point: 1156.1 K
thermal conductivity: 141 $Wm^{-1}K^{-1}$
properties: soft, silvery metal, oxidizes rapidly, reacts vigorously with water

average atomic mass: **26.98**
density at 293K: 2698 Kg/m^3
melting point: 933.52 K
boiling point: 2740 K
thermal conductivity: 237 $Wm^{-1}K^{-1}$
properties: hard, strong, silvery-white metal, forms oxides

average atomic mass: **12.01**
density at 293K: 3513 Kg/m^3
melting point: 3820 K
boiling point: 5100 K
thermal conductivity: 990-2320 $Wm^{-1}K^{-1}$
properties: non-metal

average atomic mass: **30.97**
density at 293K: 1820-2690 Kg/m^3
melting point: 317.3 K
boiling point: 553 K
thermal conductivity: 0.235-12.1 $Wm^{-1}K^{-1}$
properties: non-metal, flammable, does not react with water

average atomic mass: **24.30**
density at 293K: 1738 Kg/m^3
melting point: 922 K
boiling point: 1363 K
thermal conductivity: 156 $Wm^{-1}K^{-1}$
properties: silvery white, lustrous, relatively soft metal, burns in air and reacts with hot water

Principles and Procedures: In the previous activity we used a rather simple idea, color and shade, to arrange elements in a logical order. Mendeleev's original Periodic Table was arranged according to chemical and physical properties. He placed the name of an element, its atomic mass, and a list of the element's properties on a card. He then arranged these cards according to atomic mass and then grouped them according to observed properties and searched for patterns and trends. In this activity you will repeat Mendeleev's procedure. Figure C lists the first 20 elements of the periodic table and gives the type of information that Mendeleev had available when he set out to organize the elements. Photocopy Figure C and cut out all 20 cards. A member of another lab team should select two of the cards to represent "undiscovered elements", and should place them in a separate location where you will not see them. Shuffle the cards, place them on a desk or table, and then organize them in a logical pattern (tabular form) as Mendeleev might have done. Remember that you will need to leave two blanks for the "undiscovered elements". What is the best way to sequence the elements? At what points do properties appear to repeat themselves?

Questions:

(1) Explain the importance of periodicity in the historical development of chemistry.

(2) Were you able to form a periodic table with rows (periods) and columns (groups)? Was the task more difficult than in the previous activity where one color represented a variety of properties?

(3) Which of the properties on the element cards is most appropriate for sequencing the elements?

(4) Which properties are periodic? Explain.

(5) Compare your table with Figure A to identify the elements. What properties are common to elements on the left side of the periodic table? The right side?

2.2.3 FAMILY CHARACTERISTICS

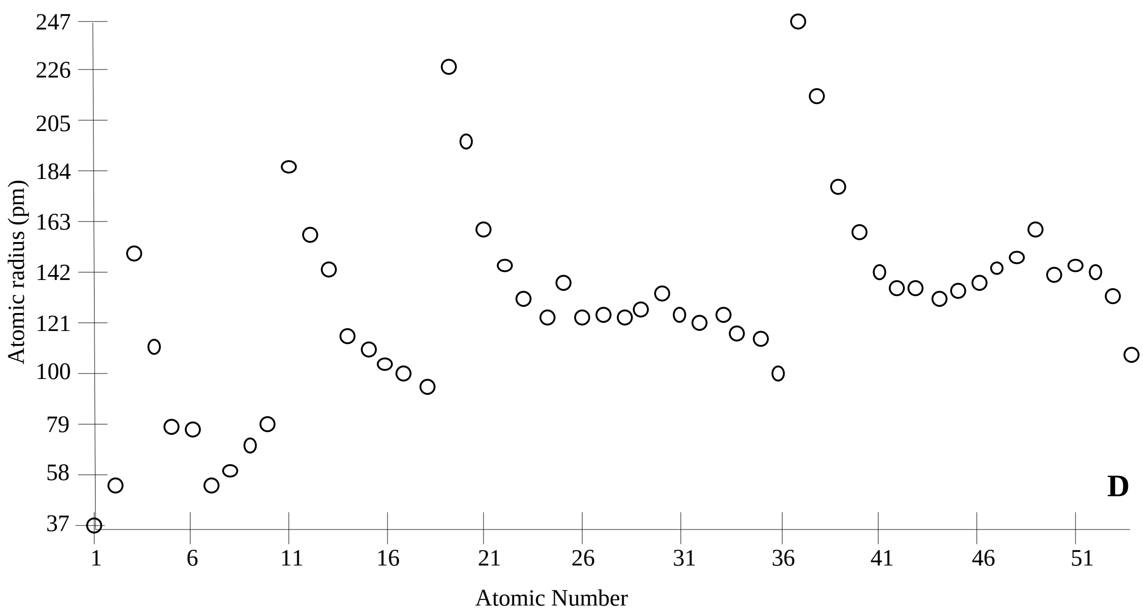
Concepts to Investigate: Atomic radius, ionization energy, electron affinity, periodic table, family characteristics.

Materials: None

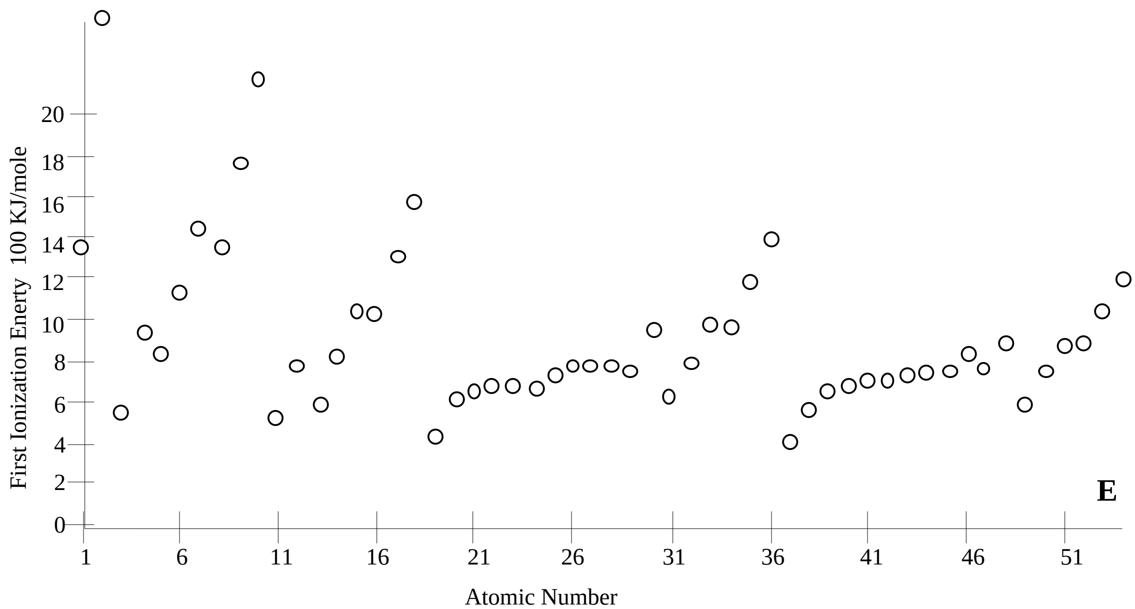
Principles and Procedures: Elements in the same family show "family characteristics" just as animals or plants in taxonomic families share many similar characteristics. All species of the pine family (Pinaceae) have needle-like leaves and produce seeds in cones. By contrast, all species in the palm family (Palmaceae) have broad fond-like leaves and produce seeds in fruits. Although pines and palms have many things in common, their family characteristics distinguish them from each other. The same is true among elements.

Part 1: Atomic radius: The atomic radius is defined as half the distance between the nuclei of two atoms of the same element that are bonded together. The atomic radius helps us predict many other characteristics about an element including how it will react with other elements. In general, it is more difficult to remove electrons from atoms with small atomic radii because those electrons are held more tightly by the nearby positive charge of the nucleus. By contrast, elements with large atomic radii are generally more prone to lose electrons because their valence (outermost) electrons are far from the attractive force of the nuclei. Although there are many other factors to consider, atomic radius is of primary importance in helping us predict properties of elements.

Is there any periodicity of atomic radii? Figure D plots atomic radii vs. atomic number for the first half of the periodic table. Connect the circles from atomic number 1 (hydrogen) to atomic number 54 (xenon) on Figure D using black pen or pencil. Use different colors to identify the circles that represent the members of the following families: group 1 (alkali metals), group 2 (calcium family), group 13 (boron family), group 14 (carbon family), group 17 (halogens), and group 18 (noble gases). For example, color all circles representing elements in the first family red, all circles representing elements of the second family orange, and so on. Now draw lines between circles with similar colors (elements in the same family). Do the lines representing the different families cross each other? Are there strong similarities between elements within the same families? Does atomic radius appear to be a periodic property?



<u>Part 2: First Ionization Energy:</u> The first ionization energy is the energy required to remove one valence electron from an atom of an element. If the first ionization energy is low, it indicates that the element will readily surrender an electron in a chemical reaction, and will often exist in the cationic (positive) form. If, however, the first ionization is very high, then we know that it is unlikely that the element will lose electrons. Connect the circles from atomic number 1 (hydrogen) to atomic number 54 (xenon) on Figure E using a black pen or pencil. Use different colors to identify the circles that represent the members of the following families: group 1 (alkali metals), group 13 (boron family), group 15 (nitrogen family), group 17 (halogens), and group 18 (noble gases). Now draw lines between circles with similar colors (elements in the same family). Do the lines representing the different families cross each other? Are there strong similarities between elements within the same families. Does first ionization energy appear to be a periodic property?



Questions:

(1) Does atomic radius appear to be a periodic property? Explain.

(2) Does first ionization energy appear to be a periodic property. Explain.

(3) Which family has the largest atomic radii within any given period?

(4) In general, what happens to atomic radius as you proceed through a period (row) from the alkali metals to the noble gases. Explain why this might be so in terms of the attractive force between the nucleus and electrons.

(5) Which family has the smallest radius? Explain

(6) Does the family with the lowest first ionization energy have relatively large or small radii? Explain this relationship.

(7) Which families have the highest first ionization energies? Is there any relationship between their ionization energies and their radii? Explain.

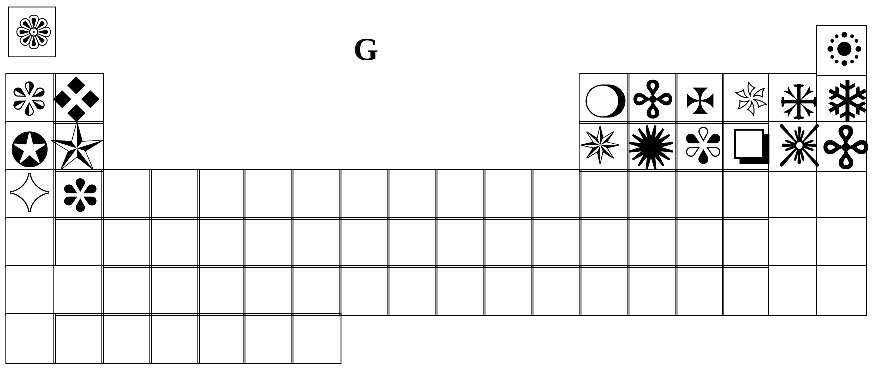
(8) Electron affinity (Figure F) represents the pull nuclei have for additional electrons. A large negative value indicates a strong attraction. Do you think that electron affinity is also a periodic property? Examine Figure E and identify as many periodic trends as you can find, providing they exist!

F

Electron Affinities (kJ/mol)

-77																	21
-58	241											-23	-123	0	-141	-322	29
-53	230											-44	-120	-74	-200	-349	35
-48	154											-36	-116	-77	-195	-325	39
-47	120											-34	-121	-101	-190	-295	41
-45	52											-50	-101	-101	-170	-270	41
-44																	

G



2.2.4 TRENDS WITHIN FAMILIES

Concepts to Investigate: Reactivity, periodicity, predicting properties, electron shielding, nuclear attraction, periodic table, electron affinity.

Materials: Part 1: lithium, sodium, potassium, Petri dish, overhead, copper (pre-1982 US penny), silver (U.S. Mercury dime), gold (ring or other jewelry), projector, phenolphthalein. Part 2: 0.2 M solutions of the following: KCl, KBr, KI; test tubes, chlorine water (or bleach and hydrochloric acid), bromine water (or potassium bromate and hydrochloric acid) , iodine water (or potassium iodate, potassium iodide and hydrochloric acid), test tube rack.

Safety: *This should be performed as a teacher demonstration only. Use protective eyeware and clothing. Lithium, sodium, and potassium react violently with water to produce hydrogen. The heat from the reaction may ignite the hydrogen causing a small explosion and splattering material. The resulting solution is strongly basic and should be handled with appropriate precautions. The halogen gases produced in part 2 are toxic, and should be handled only in a fume hood.*

Principles and Procedures:

Part 1: Reactivity trends in the first family: Although the elements in groups 1 (Li, Na, K, Rb, Cs, Fr) and 11 (Cu, Ag, Au) are metals and therefore share many properties in common, they possess many family distinctives that set them apart from each other. While elements in both groups (families) are malleable, ductile, good conductors of heat, and good conductors of electricity, they differ widely with respect to their reactivity.

It is obvious that group members do not react readily with water. A copper penny looks the same after sitting for a week in a "wishing well"; silverware looks the same after being washed in the sink; and a gold wedding band still appears gold even at a 50th wedding anniversary. By contrast elements in the first family react vigorously with water to form metal hydroxides and hydrogen gas:

$$2X + 2H_2O \longrightarrow 2X^+OH^- + H_2$$

Examine the label on a container of lithium, sodium, or potassium and note the firm warning to keep away from water. It is clear that the metals in group 1 share many "family characteristics" with each other that are distinct from those of group 11.

Although all members of the first family react with water, not all react with the same intensity. Just as there are differences within a taxonomic family (not all pine trees have the same length needles or same size cones), so not all elements in a family share exactly the same properties. Do you think that lithium (period 2) , sodium (period 3) , or potassium (period 4) will react more violently with water? Although all three of these elements have only one valence electron, the valence electron of potassium is farther away from the nucleus than is the valence electron of sodium, which itself is farther away than the valence electron of lithium. In addition to being farther away from the nucleus, the valence electron in potassium is shielded from the attractive pull of the nucleus by the repulsive force of one more shells of electrons than is the valence electron in sodium. Similarly, the valence electron in sodium is shielded from the pull of the nucleus by the repulsive force of one more shell of electrons than is the valence electron in lithium. Based upon this knowledge, which do you think will react more violently with water, lithium, sodium, or potassium? Make your prediction before your instructor continues with the demonstration.

Having considered these issues, and made your predictions, you are now ready to investigate the relative reactivity of these elements in water. Reactivity will be qualitatively assessed by the apparent rate and vigor of the reaction, and by the rapidity with which the phenolphthalein turns pink (indicating the rate of hydroxide formation). Place three beakers away from students in a location where nothing will be damaged should splattering occur. Fill the beakers half full with water and add a couple of drops of phenolphthalein. In the first beaker place a "pea"-sized chunk of lithium. When the reaction is complete, repeat the process with sodium and then potassium using different beakers. Which of these first family elements is the most reactive? Does the reactivity of alkali metals increase or decrease as you proceed from top to bottom in the periodic table?

<u>Part 2: Reactivity trends in halogens</u>: The halogens, like the alkali metals, have many distinctive family characteristics. All have seven valence electrons and a high electron affinity. In other words, all have a tendency to remove electrons from other atoms to become negative ions. The high electron affinity makes the halogens reactive, but does reactivity increase or decrease within the halogen family?

Iodine is a large atom with four inner shells of electrons that shield its valence electrons from the pull of the nucleus. Bromine is smaller than iodine, with only three inner shells, and chlorine is smaller yet with only two inner shells. Knowing this, which do you think has the greatest electron affinity. In other words, which has the greatest pull for the electrons of another element and is consequently the most reactive? To find out, perform the following activity.

Carry out the following activities in a fume hood. Prepare 0.2 M solutions of KCl, KBr, and KI by placing 1.5 g of KCl, 2.4 g of KBr, or 3.4 g of KI into one of three labeled containers, and adding 100 mL of distilled water to each. If you do not have chlorine water, you may prepare it by combining 60 mL of household bleach (NaClO solution) and 40 mL of 2.0 M HCl. Chlorine from the hypochlorite ion (ClO^-) and the hydrochloric acid combine to form molecular chlorine gas (Cl_2).

$$ClO^-(aq) + Cl^-(aq) + 2H^+(aq) \longrightarrow Cl_2(g) + H_2O(l)$$

Prepare bromine water by mixing 90 mL of 0.2 M KBr solution, 0.1 g of potassium bromate ($KBrO_3$), and 10 mL of 2.0 M HCl. The chlorine from hydrochloric acid replaces bromine, the bromine atoms then combine to form dissolved bromine gas (Br_2). Iodine water may be prepared by combining 80 mL water, approximately 0.1 g of potassium iodate (KIO_3), 5 mL of 0.2M potassium iodide solution, and 15 mL of 2.O M HCl. All halogen water solutions should be capped to prevent the escape of these gases. Add 10 mL of each potassium salt solution to 10 mL of each halogen solution, stopper, shake, and record the resulting colors in Table 3.

Table 3: Reactivity trends within the halogen family

	chlorine water (10 mL)	bromine water (10 mL)	iodine water (10 mL)
0.2 M KCl solution (10 mL)			
0.2 M KBr solution (10 mL)			
0.2 M KI solution (10 mL)			

The color of the final solution indicates which gas is present. Water containing molecular chlorine (Cl_2) is relatively colorless, while water with bromine (Br_2) is straw-yellow and water with iodine (I_2) is brownish. Identify which halogen gases are present after each mixing.

All of the halogens have significant electron affinity (tendency to gain and retain electrons):

$$Cl_2(aq) + 2e^- \longrightarrow 2Cl^-(aq)$$

$$Br_2(aq) + 2e^- \longrightarrow 2Br^-(aq)$$

$$I_2(aq) + 2e^- \longrightarrow 2I^-(aq)$$

This activity allows you to determine whether electron affinity increases or decreases within the halogens by pitting molecular halogens (Cl_2, Br_2, I_2) against different halogen salts (KI, KBr, KCl). The halogen with the greater electron affinity will emerge in ionic form (Cl^-, Br^-, I^-) while the halogen with lesser electron affinity will emerge as a molecular halogen gas (Cl_2, Br_2, I_2). Thus, in the "battle for electrons", the "winner" will appear in ionic form, and the "loser" will emerge as a diatomic gas. The color of the solution indicates the "loser", or the halogen with less electron affinity. If the resulting solution is colorless, then chlorine is the "loser"; if it is yellow, bromine is the "loser"; and if it is brown, iodine is the "loser". Let's begin the competition for electrons by mixing solutions according to the specifications of Table 3.

From the color changes reported in Table 3, determine which halogen has the greatest electron affinity. Does electron affinity (reactivity) increase or decrease with the increased shielding that occurs as you descend within the halogens?

Questions:

(1) What characteristics can be used to distinguish metals in the first family from those in Group 11?

(2) Phenolphthalein turns pink in the presence of base. Which elements reacted with water to produce bases? What are the names of the bases that were produced?

(3) Which element reacted most strongly with the water? Explain why this is the case. Does reactivity increase or decrease within the first family as you proceed to higher periods?

(4) Was there any evidence of a chemical reaction between the 11th family elements and water? Between the 1st family elements and water? Explain.

(5) Members of the 11th family may be found in elemental form in nature, while those in the first family are never found except in compounds. Explain

(6) Was there a color change when chlorine water was added to the solution of KCl?

(7) Was there a color change when chlorine water was added to the solution of KBr? Explain what this means about the comparative electron affinities of chlorine and bromine.

(8) Was there a color change when bromine water was added to the solution of KI? Explain what this means about the comparative electron affinities of bromine and iodine..

(9) Does electron affinity increase or decrease within the halogens. In other words, is electron affinity higher at the top or bottom of the family?

(10) Summarize trends in reactivity for the alkali metals and the halogens.

FOR THE TEACHER

Finding the "Missing elements"

Discussion: Most stores that sell house paints offer free color matching cards that contain various shades (intensities) of a given color of paint. Customers take these cards home to determine which colors and shades will look best in their own homes. Select at least 8 basic colors (to represent groups 1,2,13,14,15,16,17 and 18), excluding white or black, and cut the paint cards into pieces so that each portion has one and only one shade of a given color. It is recommended that you select chips that match up well with the periodic table. For example, you may wish to have only two very pale chips, representing the two elements in the first series, while you have 8 slightly darker chips representing the slightly heavier elements of the second series. We recommend that you use at least 18 different chips to represent the first 3 series, although you may wish to use enough paint chips to represent the entire periodic table. Remove three chips from each set (to represent "undiscovered elements") and place these in one envelope while you place the rest in a second envelope that you mark with the same code number. Repeat the process for as many lab teams as you have in your class.

Since three chips have been set aside from each set, there will be vacancies in the students' tables just as there were in Mendeleev's table. Make certain students see the value of their table in predicting the properties of these yet unknown elements (colors) and in determining where these fit in their tables. At the end of the activity, give each student the matching envelope that contains the "missing elements" to see if their predictions were correct.

You may perform a variation of this activity using nuts, bolts, and assorted fasteners. Families (groups) may be represented by the type of fastener (e.g. square-headed bolt, hex-headed bolt, wood screw, sheet metal screw, washer, hex nut, square nut, cotter pin etc.), and series (period) by relative size. For example, group 1 may be represented by square-headed bolts, with the smallest bolt at the top of the table, and the largest at the bottom. Group 2 (e.g. hex-headed bolts) should resemble group 1 (square-headed bolts), but should be distinct, just as the group 2 elements share properties in common with group 1, but also have their own distinctive characteristics. You may wish to select square nuts for group 17, and hex-nuts for group 16, to indicate that these groups have properties that are opposite and complementary to those of the first two families. Just as nuts and bolts may combine, so the members of the groups 1 (the alkali metals) and 2 (the calcium family) react with the elements of groups 16 (the oxygen family) and 17 (the halogens). You may wish to represent group 18 (the noble gases) with a fastener unlike the rest (e.g. a cotter pin) to indicate that the noble gases are distinct and relatively inert. Make certain your students understand the limitations of these analogies.

Answers:

(1) Yes. The rows represent elements with similar atomic mass as identified by similar color shades (intensities). The columns represent elements with similar chemical properties as identified by similar basic colors.

(2) Student answers will vary.

(3) When the paint chips were arranged it was clear that certain shades of certain colors were missing. In a similar manner, chemists noticed that certain elements were missing when the elements were arranged by atomic mass or number (shades) in groups with similar properties (colors). These "missing" elements were simply ones not yet discovered.

2.2.2 DESIGN YOUR OWN PERIODIC TABLE

Discussion: In this activity the student is faced with a task similar to Mendeleev's. Although the number of elements is less than what confronted Mendeleev, the outcome and concomitant understanding is the same. Figure G shows how the cards should be arranged to correspond to the periodic table.

Answers:

(1) The periodicity of the elements enabled chemists to predict the existence of yet unknown elements, and more importantly stimulated research to understand the physical reasons for the periodicity that is observed.

(2) Student answer.

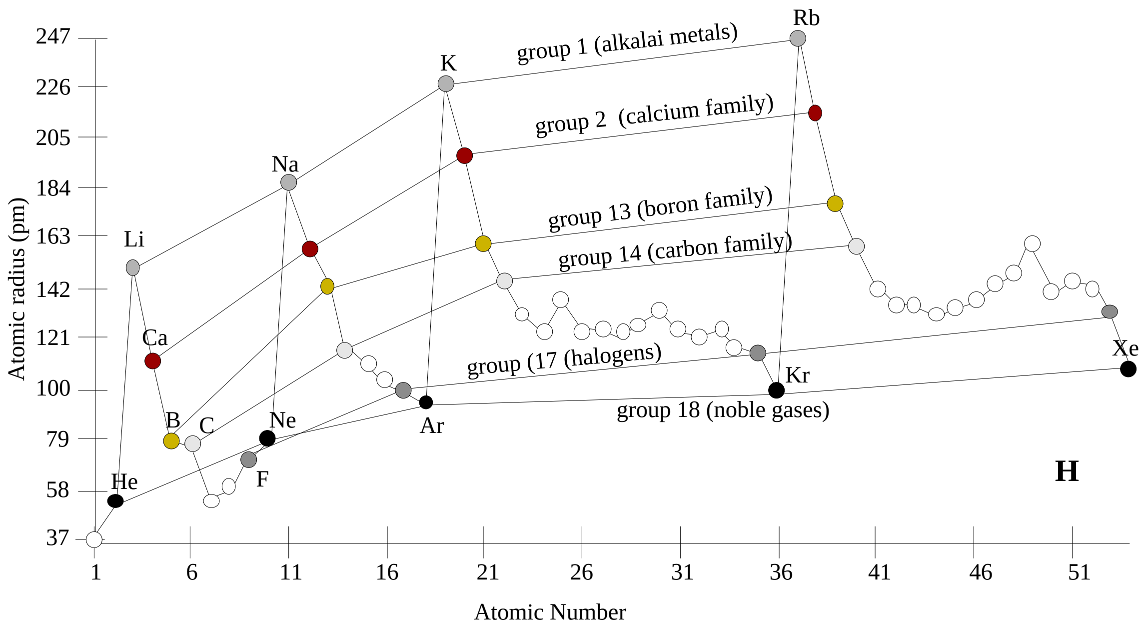
(3) Atomic mass. Atomic number would be better, but Mendeleev did not have this information.

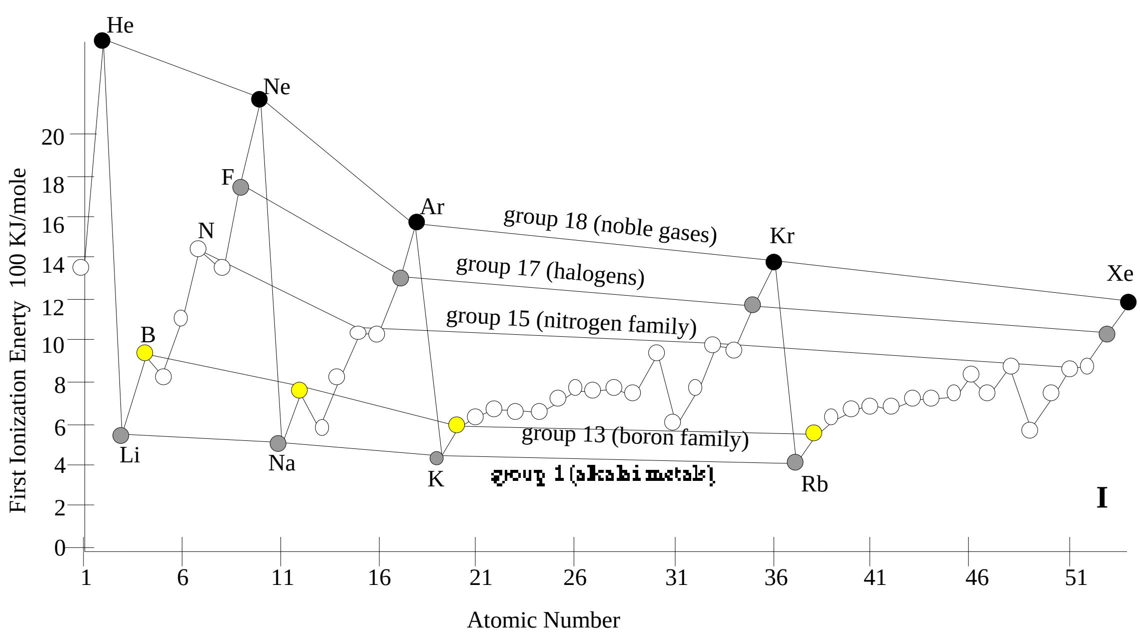
(4) All of the properties listed are periodic except atomic mass.

(5) The left side of the periodic table is characterized by elements that are metallic, often silvery, and good conductors of heat (high thermal conductivity). They have high melting and boiling points and exist as solids at room temperature. The elements on the right side tend to have properties that are opposite of these.

2.2.3 Family Characteristics

Discussion: This "paper and pencil" exercise is designed to encourage analysis of empirical data. By examining such data, students can discover numerous examples of periodicity. We believe that students will understand the concepts better and remember them longer if they can discover them on their own. These activities help build inductive reasoning as students look for trends in specific data and try to develop reasons for the generalizations they discover. Figures H and I illustrate the results students should have produced. You may wish to introduce data to show the periodicity of other phenomena such as ionic radii and electronegativity.





<u>Answers:</u>

(1) Yes. Although the graph of atomic radius drops within a period, it increases with each increasing shell. With each repeating period (return to the alkali metals) the graph of atomic

radius jumps up again. This repetitious behavior within each new period is known as periodicity.

(2) Yes. As with radius, the graph of first ionization energy goes through cycles. The first family (alkali metals) has very small ionization energies, while the noble gases have very high ionization energies.

(3) The alkali metals have the greatest radius within any period.

(4) The atomic radius decreases across a period. The alkali metals have a single electron in their outermost (valence) shell. With each successive element in this shell, there is an additional electron and an additional proton. The attractive force of the nucleus therefore increases as you proceed through a series, and this collapses the orbitals so that they are closer to the nucleus.

(5) The noble gases. The noble gases have completed outer shells, the smallest radii, and consequently exhibit the greatest pull for valence electrons.

(6) Large. In large atoms, the valence electrons are quite distant from the attractive forces of the nucleus. As a result, valence electrons in large atoms are lost more easily.

(7) The noble gases have the highest ionization energies. Noble gases have the smallest radii, and therefore their electrons are closest to the attractive forces of the nuclei and consequently are most difficult to remove.

(8) Yes. Students should note that the halogens have the strongest electron affinity and the second family has the weakest. They may also see other more subtle trends.

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2.2.4 Trends within families

Discussion: The results from part 2 should appear as follows:

	chlorine water (10 mL)	bromine water (10 mL)	iodine water (10 mL)
0.2 M KCl solution (10 mL)	colorless Cl_2	straw yellow Br_2	brown I_2
0.2 M KBr solution (10 mL)	straw yellow Br_2	straw yellow Br_2	brown I_2
0.2 M KI solution (10 mL)	brown I_2	brown I_2	brown I_2

The reactivity series for the halogens is nicely demonstrated in these reactions showing that reactivity (electron affinity) decreases with increasing atomic number. Although each halogen has seven valence electrons, shielding occurs as shells are added. Hence, molecular chlorine replaces the bromide ion and molecular bromine replaces the iodide ion. The reactions are as follows:

$$Cl_2 + 2KBr \longrightarrow 2KCl + Br_2 \quad \text{[straw yellow]}$$

$$Br_2 + 2KI \longrightarrow 2KBr + I_2 \quad \text{[brown]}$$

Notice that we did not include fluorine in this activity. Molecular fluorine can replace chloride, bromide, and iodide ions in solution. However, molecular fluorine is so reactive that it even reacts with water. Consequently, the reactions we have described for chlorine, bromine, and iodine in aqueous solutions cannot occur with fluorine. The halogens as a group are the most reactive of the nonmetallic elements and are strong oxidizing agents.

The colors of halogen gases in water are different than they are in air. In air, chlorine is yellow-green, but in water it is nearly colorless. As a gas, bromine is reddish brown, but in water it is straw yellow. As a gas, iodine is violet, but in water it is brown. You may wish to tell your students this to avoid confusion if they have previously studied the nature of these halogen gases.

<u>Answers</u>:

(1) Elements in the first family react readily with water to form metal hydroxides, while those in the 11th family do not.

(2) The elements in the first family react with water to form hydroxides according to the following equation.

$$2X + 2H_2O \longrightarrow 2X^+OH^- + H_2$$

Lithium hydroxide, sodium hydroxide and potassium hydroxide will be formed depending upon which alkali metal is added to the water.

(3) Potassium reacts the most violently with water because its valence electron is at the highest energy level (the 4th shell), and is shielded by three inner shells. This electron is more easily lost than the valence electron of sodium, which is lost more easily than the valence electron of lithium. Reactivity increases with increasing period number within elements of the first family.

(4) There is no visible reaction between the 11th family metals and water. Chemical reactions between first family elements and water are evidenced by the production of light, heat, and the color change of the base indicator, phenolphthalein.

(5) The 11th family metals are relatively unreactive, and so it is possible that they may exist in elemental form. The alkali metals react vigorously with water and other materials to form various compounds, and as a result, are never found in elemental form.

(6) No. Chlorine water is colorless, and so there is no color change.

(7) Yes. Chlorine has a greater affinity for electrons than bromine and thus molecular bromine forms, turning the solution straw yellow.

(8) Yes. Bromine has a greater affinity for electrons than iodine and thus molecular iodine forms, turning the solution brown.
(9) Decrease. Electron affinity is greatest at the top of the halogen family, and decreases with increasing size.
(10) As atomic number increases, the reactivity of alkali metals increases (ionization energy becomes lower), while the reactivity of halogens decreases (electron affinity becomes lower).

APPLICATIONS TO EVERYDAY LIFE

Predicting the properties of unknown elements: Just as Mendeleev predicted the properties of unknown elements on the basis of their positions in the periodic table, so chemists today have predicted the properties of elements that have yet to be discovered or synthesized.

Selecting materials: The periodic table can be helpful when selecting materials for use in various products. For example, we know that gold is malleable, conductive, and unreactive and therefore useful in coinage and electrical circuits. When looking for less expensive substitutes, one only needs to look for other members of the same family that are found in greater abundance, namely copper and silver. When looking for semi-conducting materials for use in transistors, chemists looked for elements similar to silicon, a known semiconductor. Germanium, the element directly below silicon in the 14th group, was examined and found to meet the criteria, and is now used extensively in computer chips and similar applications.

Hazards: Elements that are in the same family tend to share similar properties. Many chemistry students have witnessed the dramatic reaction between sodium and water and may correctly infer from the periodic table that other members of the 1st family, namely lithium, sodium, potassium, rubidium, cesium and francium, share similar properties and must be handled with caution.

Periodicity in nature: The periodicity within the periodic table is but one example of the periodicity in the natural world. Electrons spin about their axes and orbit around nuclei in known orbitals, quartz crystals vibrate at predictable frequencies, the Moon orbits the Earth in predictable periods, the planets orbit the sun with known frequencies, etc. Ask your students to list as many natural phenomenon as they can think of that exhibit an element of periodicity.