UNIT (2) ATOMS AND ELEMENTS

2.1 Elements

An **element** is a fundamental substance that cannot be broken down by chemical means into simpler substances.
Each element is represented by an abbreviation called the **symbol** of the element. The first letter in the symbol of the element is always capitalized, however the second letter (if present), is never capitalized.
The following table lists the names and symbols of some common elements.

You are expected to learn the name and the symbol of these elements:

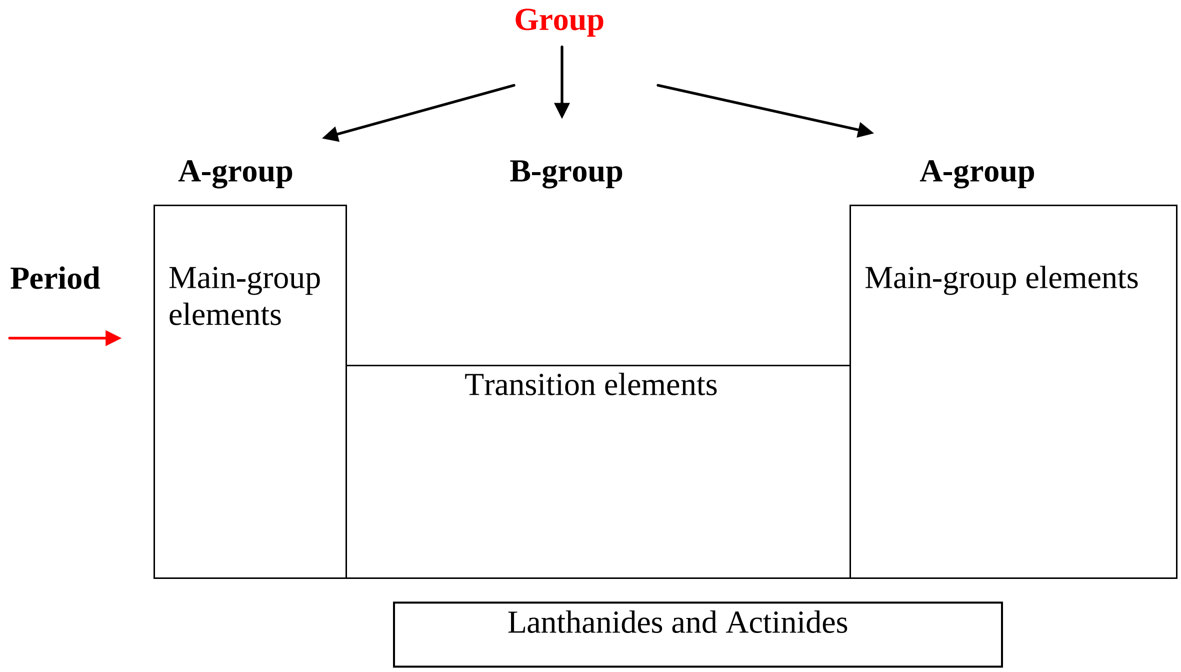
Element	Symbol	Element	Symbol	Element	Symbol
Aluminum	Al	Gold	Au	Nitrogen	N
Argon	Ar	Helium	He	Oxygen	O
Barium	Ba	Hydrogen	H	Phosphorous	P
Boron	B	Iodine	I	Potassium	K
Bromine	Br	Iron	Fe	Silicon	Si
Calcium	Ca	Lead	Pb	Silver	Ag
Carbon	C	Lithium	Li	Sodium	Na
Chlorine	Cl	Magnesium	Mg	Strontium	Sr
Chromium	Cr	Manganese	Mn	Sulfur	S
Cobalt	Co	Mercury	Hg	Tin	Sn
Copper	Cu	Neon	Ne	Xenon	Xe
Fluorine	F	Nickel	Ni	Zinc	Zn

2.2 The Periodic Law and the Periodic Table

The **periodic law** states that the properties of elements exhibit a repeating pattern when arranged according to **increasing atomic number**.

Periodic table: A chart of the elements arranged in order of increasing atomic number. The elements are arranged in rows (periods) that create vertical columns of elements (group) that exhibit similar chemical properties.
A box differentiates each element and contains its atomic number, atomic symbol, and atomic mass. For example, locate nitrogen on the periodic table. You will find it in the second horizontal row and fifth vertical column; it is therefore a second period, group VA element. The symbol for nitrogen is (N), the atomic number is 7 and the atomic mass is 14.01 amu. (We will see more on atomic number and atomic mass shortly).

The Periodic Table



Periods and Groups

A **period** is a horizontal row of elements and a **group** is a vertical column of elements. The eight A-groups (two on the left and six on the right) contain the main group elements. The ten B-groups, located between the two A-groups, contain the transition elements.

Certain groups have common names that you should learn:

- Group IA are the alkali metals (except for hydrogen).
- Group IIA are the alkaline earth metals.
- Group VIIA are the halogens.
- Group VIIIA are known as noble gases (or inert gases).

Metals, Nonmetals, and Metalloids

Metals occupy the left side of the table and they have similar properties. They are good conductors of heat and electricity and most of the elements are metals.
Nonmetals occupy the upper right side of the table and have more varied properties.
Metalloids are sometimes called semiconductors because of their intermediate electrical conductivity, which can be controlled and changed.
Metalloids lie along the stepwise diagonal line beginning at boron (B) and extending downward through polonium/astatine (Po/At). This line separates the metals to the left and nonmetals to the right.

The following seven elements exist as diatomic molecules:
H_2 N_2 O_2 F_2 Cl_2 Br_2 I_2

Practice 2-1

Write the **name** and the **symbol** of the element that fits each of the following descriptions:

a) the alkaline earth metal in the sixth period.
b) the metalloid in the third period.
c) the nonmetal in group IVA.
d) the halogen that is liquid at room temperature.
e) the group-VIIIB transition metal with properties similar to Ru.
f) the third-period element that exists as diatomic molecule.

Answer

2.3 Composition of the Atom

Atom: The smallest unit of an element that retains the properties of that element. Atoms are composed of three subatomic particles: protons, neutrons, and electrons. Protons and neutrons are located in the center of the atom and form a compact core termed the **nucleus**. The electrons are located in the considerably larger space outside the nucleus.

Table 2.1 Properties and Location of Subatomic Particles

Subatomic Particle	Charge	Mass (g)	Mass (amu)*	Location
Proton	+1	1.67×10^{-24}	1.01	nucleus
Neutron	0	1.67×10^{-24}	1.01	nucleus
Electron	-1	9.11×10^{-28}	0.000548	outside nucleus

* Atomic mass unit (abbreviated **amu**) is convenient for representing the mass of very small particles.

$$1 \text{ amu} = 1.67 \times 10^{-24} \text{ g}$$

Each nucleus is characterized by 2 quantities: the atomic number and the mass number. The **atomic number** is the number of protons contained in the nucleus of an atom. The **mass number** is the total number of protons and neutrons in the nucleus of an atom. Atoms are electrically neutral; therefore the number of electrons (negative charges) is equal to the number of protons (positive charges). Given this fact, the atomic number also gives the number of electrons for neutral atoms.

Consider the element sodium with atomic number of 11 and the mass number of 23. The mass number is written in the upper-left corner (as a superscript) of the symbol for the element, and the atomic number in the lower-left corner (as a subscript).

mass number ^{23}
Na
atomic number $_{11}$

Worked Example 2-1

State the number of protons, neutrons, and electrons in an atom of each of the following:

$^{7}_{3}Li$	$^{14}_{7}N$	$^{24}_{12}Mg$	$^{25}_{12}Mg$	$^{26}_{12}Mg$

Solution

The subscript value refers to the atomic number (p^+), and the superscript value refers to the mass number (p^+ and n^0).

Thus, $^{7}_{3}Li$ has 3 p^+ and 4 n^0 (7 – 3 = 4)
In a neutral atom, the number of protons in the nucleus is exactly equal to the number of electrons outside the nucleus.

Thus, $^{7}_{3}Li$ has 3 electrons.

	# protons	# neutrons	# electrons
$^{7}_{3}Li$	3	4	3
$^{14}_{7}N$	7	7	7
$^{24}_{12}Mg$	12	12	12
$^{25}_{12}Mg$	12	13	12
$^{26}_{12}Mg$	12	14	12

Worked Example 2-2

The nucleus of an atom contains 15 protons and 16 neutrons. Write the symbol for the atom.

Solution

The atomic number equals the number of protons (15) and the mass number equals the sum of the protons and neutrons (15 + 16 = 31).
The element with an atomic number of 15 is phosphorous (see the periodic table).
Therefore the symbol of the atom is

$$\text{mass number } {}^{31}_{15}\text{P} \text{ atomic number}$$

Practice 2-2

The nucleus of an atom contains 27 protons and 33 neutrons. Write the symbol for the atom.

Answer

2.4 Isotopes and Atomic Masses

A magnesium atom will always have 12 protons; however, the number of neutrons can vary. Some magnesium atoms found in nature have 12 neutrons, some have 13, and some have 14.
Atoms with the *same number of protons* but *different numbers of neutrons* are called **isotopes**. Isotopes are the same element with different atomic masses.
Most elements found in nature exist in isotopic forms. We often refer to an isotope by stating the elements name followed by its mass number, for example, magnesium-24. All naturally occurring magnesium atoms contain 78.99% magnesium-24, 10.00% magnesium-25, and 11.01% magnesium-26. The atomic mass of an element reported on the periodic table is the weighted average mass of all naturally occurring isotopes of the elements.

Natural abundance and atomic masses of several isotopes are listed in the following table:

Isotope	Atomic mass (amu)	Percent abundance in nature
${}^{1}_{1}H$	1.0078	99.985
${}^{2}_{1}H$	2.0140	0.015
${}^{24}_{12}Mg$	23.9850	78.99
${}^{25}_{12}Mg$	24.9858	10.00
${}^{26}_{12}Mg$	25.9826	11.01
${}^{58}_{28}Ni$	57.9353	68.27
${}^{60}_{28}Ni$	58.9302	26.10
${}^{61}_{28}Ni$	60.9310	1.13
${}^{62}_{28}Ni$	61.9283	3.59
${}^{64}_{28}Ni$	63.9280	0.91

The following worked example illustrates the calculation of atomic mass from isotopic mass and abundance data.

Worked Example 2-3

Calculate the atomic mass of magnesium using the three naturally occurring isotopes below:

$^{24}_{12}Mg$ (atomic mass 23.9850 amu, abundance 78.99%)

$^{25}_{12}Mg$ (atomic mass 24.9858 amu, abundance 10.00%)

$^{26}_{12}Mg$ (atomic mass 25.9826 amu, abundance 11.01%)

Solution:

The atomic mass of magnesium is called a weighted average of the atomic masses of these three isotopes. To calculate the atomic mass, simply multiply the atomic mass by the percent abundance in decimal form (the percent divided by 100), then add the results.

$$\text{Fraction Mg-24} = \frac{78.99}{100} = 0.7899$$

$$\text{Fraction Mg-25} = \frac{10.00}{100} = 0.1000$$

$$\text{Fraction Mg-26} = \frac{11.01}{100} = 0.1101$$

$$(23.9850 \text{ amu} \times 0.7899) + (24.9858 \text{ amu} \times 0.1000) + (25.9826 \text{ amu} \times 0.1101) = 24.31 \text{ amu}$$

The “average” mass of a magnesium atom is 24.31 amu, although you should note that no magnesium atom actually exists with a mass of 24.31 amu. In nature, magnesium atoms weigh 23.9850 amu or 24.9858 amu or 25.9826 amu. A mass of 24.31 amu represents the mass of a hypothetical average magnesium atom. Mathematics tells that an average of data points is a more reliable representation of the data than any individual value; we remain consistent with that principle here. The mass reported on the periodic table for magnesium is 24.31 amu.
See the periodic table.

Practice 2-3

Calculate the atomic mass of chlorine given the two naturally occurring isotopes below.

$^{35}_{17}Cl$ (atomic mass 34.969 amu, abundance 75.77%)

$^{37}_{17}Cl$ (atomic mass 36.966 amu, abundance 24.23%)

Answer

2.5 Electron Arrangement

Energy Levels

Atoms have electrons in several different **energy levels**. These energy levels are symbolized by n; n can equal 1, 2, 3, 4, … Level 1 corresponds to n = 1, level 2 corresponds to n = 2, and so on. The energy of the level increases as the value of n increases.

The maximum number of electrons per energy level = $2n^2$.

For example, the third energy level (n = 3) holds a maximum of 18 electrons ($2 \times 3^2 = 18$).

Sublevels (Subshells)

Each energy level is divided into **sublevels**, symbolized as s, p, d, and f.

Energy level 1 consists of one sublevel, labeled 1s.

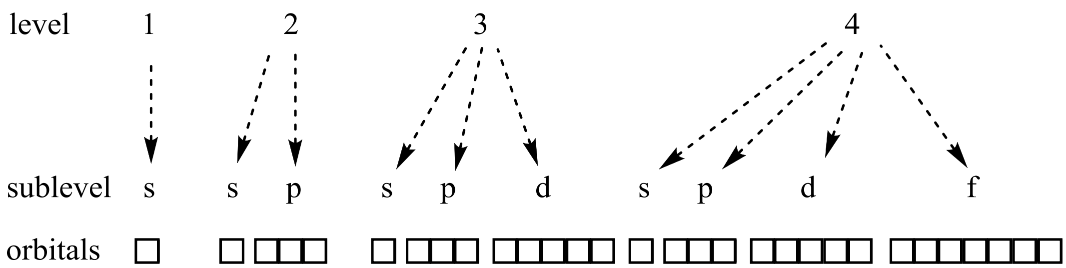
Energy level 2 consists of two sublevels, labeled 2s and 2p.

Energy level 3 consists of three sublevels, labeled 3s, 3p, and 3d.

Energy level 4 consists of four sublevels, labeled 4s, 4p, 4d, and 4f.

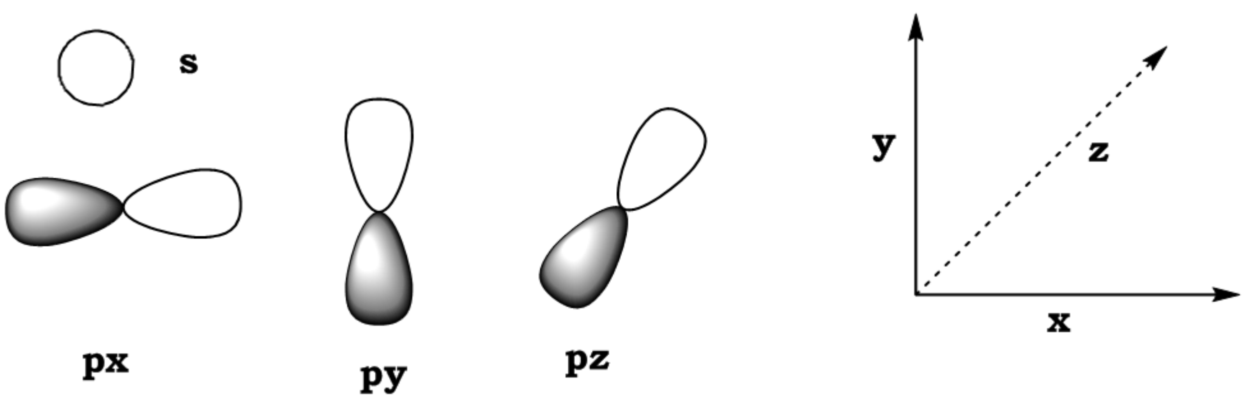
Orbitals

An atomic orbital is a specific region of a sublevel containing a maximum of two electrons.
The orbital on sublevel s is called s orbital. There is only one possible s orbital.
The orbitals on sublevel p are called p orbitals. There are three possible p orbitals.
The orbitals on sublevel d are called d orbitals. There are five possible d orbitals.
The orbitals on sublevel f are called f orbitals. There are seven possible f orbitals.



Orbital types	**number of orbitals**	**max number of electrons**
s	1	2
p	3	6
d	5	10
f	7	14

Shape of orbitals:



Practice 2-4

How many orbitals exist in the third energy level? What are they?

Answer

Electron Configuration

The distribution of electrons in atomic orbitals is called the atom **electron configuration**. Orbitals fill in the order of increasing energy from lowest to highest. See Figure 2.1.

Orbital energies: 1s < 2s < 2p < 3s < 3p< 4s< 3d < 4p < 5s < 4d < 5p < 6s……

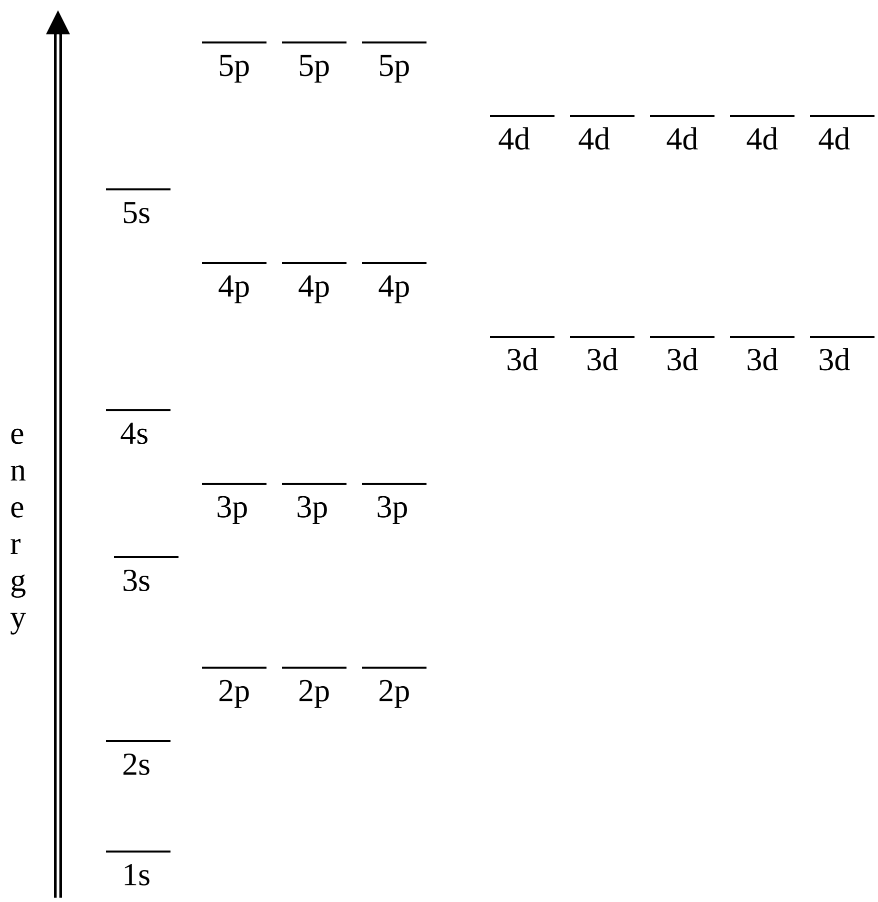


Figure 2.1
Approximate relative energies of atomic orbitals. Electrons fill orbitals in the order of increasing energy.

Writing Electron Configurations (Orbital Notations)

We describe an electron configuration by listing the symbols for the occupied sublevels one after another, adding a superscript to each symbol to show the number of electrons in the sublevel. For example, nitrogen in its lowest energy state has two electrons in its 1s sublevel, two electrons in its 2s sublevel, and three electrons in its 2p sublevel.
The notation for this configuration is: $1s^2 2s^2 2p^3$.

number of electrons

energy level

$$\mathbf{2p^3}$$

energy sublevel

Worked Example 2-4

Write the electron configuration for an atom of bromine (Br).

Solution

The correct filling order of atomic orbitals from Fig 2.1 is

1s, 2s, 2p, 3s, 3p, 4s, 3d, 4p, 5s, 4d, 5p …………

An s orbital can hold 2 electrons, p orbitals 6, d orbitals 10, and f orbitals 14 electrons.
Bromine is element 35 and therefore contains 35 electrons. The electron configuration is

$$\mathbf{1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2 3d^{10} 4p^5}$$

Practice 2-5

Give the electron configuration for each of the following: Mg, P, Cl, and Ca.

Answer

Orbital Diagrams

We can represent the electrons in orbitals by means of **orbital diagrams**.
We use a box to show an orbital, an arrow, pointing upward, to represent a single electron, and a pair of arrows pointing in opposite directions to represent two electrons. See worked example 2-5.

When drawing orbital diagrams, use the following rules:

- Orbitals fill in the order of increasing energy. See Figure 2.1.
- Each orbital can hold a maximum of two electrons.
- When there is a set of orbitals of equal energy, each orbital is occupied by a single electron before a second electron enters. For example, all three p orbitals must be half-filled (contain one electron) before the second electron enters.

Worked Example 2-5

Write the electron configuration and draw orbital diagrams for the first eight elements in the periodic table.

Solution

atom	electron configuration	orbital diagram 1s	2s	2p
H	$1s^1$	↑		
He	$1s^2$	↑↓		
Li	$1s^2 2s^1$	↑↓	↑	
Be	$1s^2 2s^2$	↑↓	↑↓	
B	$1s^2 2s^2 2p^1$	↑↓	↑↓	[↑][ ][ ]
C	$1s^2 2s^2 2p^2$	↑↓	↑↓	[↑][↑][ ]
N	$1s^2 2s^2 2p^3$	↑↓	↑↓	[↑][↑][↑]
O	$1s^2 2s^2 2p^4$	↑↓	↑↓	[↑↓][↑][↑]

Practice 2-6

For the element sulfur:

a) write the electron configuration,

b) draw the orbital diagrams,

c) how many unpaired electrons are in the sulfur atom?

Answer

Shorthand Electron Configurations

An electron configuration can also be written in an abbreviated (shorthand) configuration. In this method the electron configuration of the preceding noble gas is replaced by writing its symbol inside brackets.

B: [He] $2s^2 2p^1$

Si: [Ne] $3s^2 3p^2$

Ca: [Ar] $4s^2$

Cs: [Xe] $6s^1$

2.6 Valence Electrons and Lewis Structures

The electrons in the highest energy level of an atom are called **valence electrons**. For example, phosphorous, which has the electron configuration: $1s^2 2s^2 2p^6 3s^2 3p^3$, has electrons in the first, second, and the third energy level. The third energy level, the highest energy level, has a total of five electrons ($3s^2 3p^3$), so phosphorous has five valence electrons.

For all group A elements, the number of valence electrons is equal to the group number. For example, the elements in Group IIA such as Be, Mg, Ca, Sr, and Ba, all have two electrons in the highest energy level.

Be: $1s^2 \mathbf{2s^2}$

Mg: $1s^2 2s^2 2p^6 \mathbf{3s^2}$

Ca: $1s^2 2s^2 2p^6 3s^2 3p^6 \mathbf{4s^2}$

Sr: $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 \mathbf{5s^2}$

Ba: $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6 5s^2 4d^{10} 5p^6 \mathbf{6s^2}$

Periodic table group	**Example**	**Electron configuration**	**Valence electrons**	**Group number**
Group IA	Na	$1s^22s^22p^6\mathbf{3s^1}$	1	1
Group IIA	Mg	$1s^22s^22p^6\mathbf{3s^2}$	2	2
Group IIIA	Al	$1s^22s^22p^6\mathbf{3s^23p^1}$	3	3
Group IVA	Si	$1s^22s^22p^6\mathbf{3s^23p^2}$	4	4
Group VA	P	$1s^22s^22p^6\mathbf{3s^23p^3}$	5	5
Group VIA	S	$1s^22s^22p^6\mathbf{3s^23p^4}$	6	6
Group VIIA	Cl	$1s^22s^22p^6\mathbf{3s^23p^5}$	7	7
Group VIIIA	Ar	$1s^22s^22p^6\mathbf{3s^23p^6}$	8	8

Worked Example 2-6

Give the number of valence electrons for each the following: K, Ba, O, Br, and P.

Solution

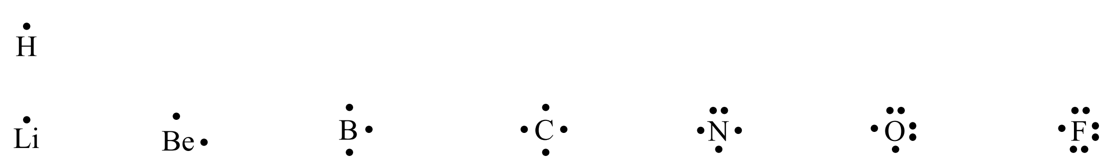
For group A elements, you can predict the number of valence electrons by noting the group number of each element from the periodic table.

K is in group IA …... K has 1 valence electron.
Ba is in group IIA …. Ba has 2 valence electrons.
O is in group VIA …. O has 6 valence electrons.
Br is in group VIIA… Br has 7 valence electrons.
P is in group VA …... P has 5 valence electrons.

Lewis Structures (Electron-dot Formulas)

To keep track of valence electrons we use a notation called electron-dot formula. In this notation, the outer electrons are shown as dots on the sides of the symbol for the element. Each dot corresponds to an outer-shell electron. Although dot placement isn't critical, one method is to begin at the top of the symbol and move clockwise around it placing dots on each side of the symbol one at a time. You must not pair any electrons until all four sides have one dot.

IA	IIA	IIIA	IVA	VA	VIA	VIIA



Electron Configuration and the Periodic Table

The periodic table can be divided into four blocks (s block, p block, d block, and f block).

s block: the first two columns on the left side
p block: the six columns on the right side
d block: the transition elements
f block: the lanthanides and actinides

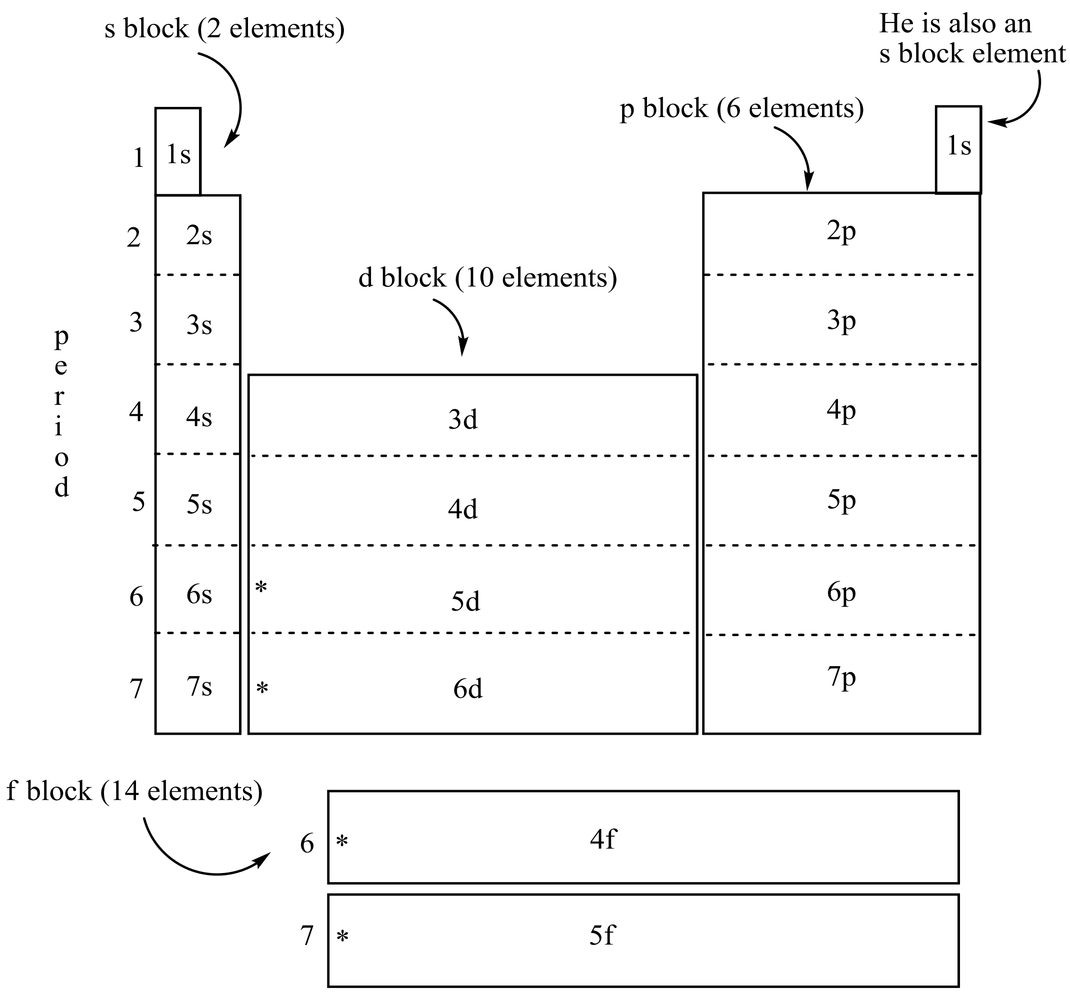


Table 2.2 The blocks of elements in the periodic table.

We can use the general pattern of the periodic table to obtain the electron configuration for an atom.

Beginning at the top left and going across successive rows of the periodic table provides a simple way of remembering the order of orbital filling:

1s → 2s → 2p → 3s → 3p → 4s → 3d → 4p → 5s → 4d →5p → 6s → 4f → 5d → 6p

This is identical to that shown in Fig 2.1.

Worked Example 2-7

Use the periodic table to write the electron configuration for arsenic, As.

Solution

Arsenic is element 33 in Period 4, Group VA, three places after the transition elements. It must contain three electrons in the 4p orbitals.

Its electron configuration is:

As: $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^3$

Practice 2-7

Use the periodic table to write both the electron configuration and the shorthand notation for iodine.

Answer

Homework Problems

2.1 For elements (Br, Ca, Fe, Na, S, Si, and Xe) which of the following term(s) apply?
a. metal
b. nonmetal
c. metalloid
d. noble gas
e. halogen
f. alkali metal
g. alkaline earth metal
h. transition metal
i. main group element
j. gas at room temperature

2.2 Identify the following atoms using their symbols:
a. contains 20 protons.
b. contains 12 electrons.
c. has atomic number = 30.
d. the fifth-period transition metal with properties similar to copper.
e. the group VA metalloid in the fifth period.
f. the lightest metallic element in group IVA.
g. the fourth-period element with properties similar to oxygen.
h. the metalloid in the second period.
i. the element with the fewest number of electrons in the sixth period.
j. the third-period element with the largest number of electrons.

2.3 In nature, gallium (Ga) is found as two isotopes. Calculate the atomic mass of this element.

$^{69}_{31}Ga$ (atomic mass 68.926 amu, abundance 60.11%)

$^{71}_{31}Ga$ (atomic mass 70.925 amu, abundance 39.89%)

2.4 Write the complete electron configuration for the following:
a. sulfur
b. potassium
c. nickel
d. xenon

2.5 Use orbital diagrams to show the distribution of electrons in the orbitals of:
a. the 5p sublevel of iodine
b. the 3d sublevel of iron
c. the 4s sublevel of potassium
d. the 3s and 3p sublevel of silicon

2.6 Write the shorthand electron configurations for each of the following:
a. iodine
b. zinc
c. phosphorous
d. barium