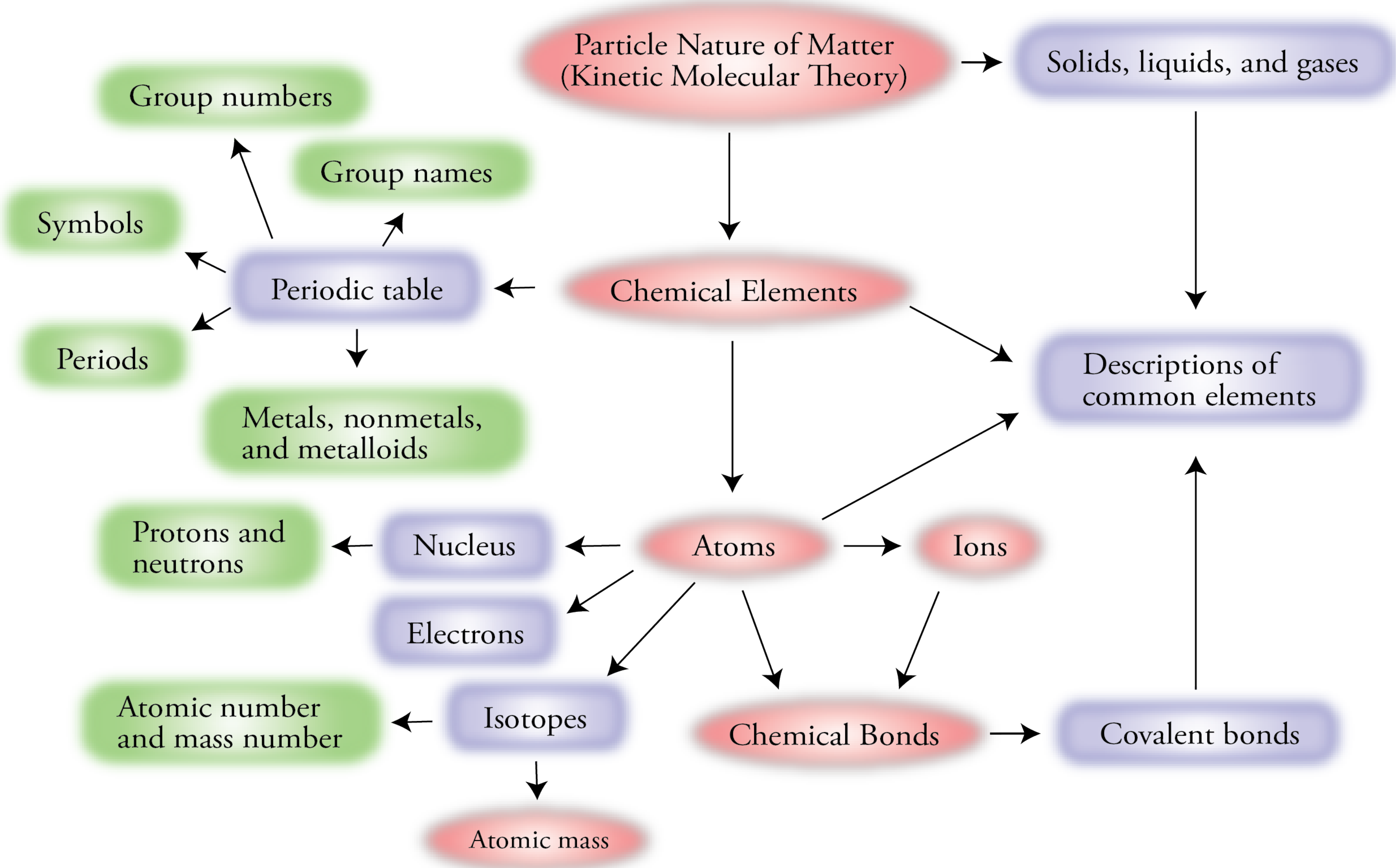
Chapter 3
The Structure of Matter and the Chemical Elements

An Introduction to Chemistry

By Mark Bishop

Chapter Map


Particle Nature of Matter
(Kinetic Molecular Theory)
Solids, liquids, and gases
Group numbers
Group names
Symbols
Periodic table
Chemical Elements
Periods
Descriptions of
common elements
Metals, nonmetals,
and metalloids
Protons and
neutrons
Nucleus
Atoms
Ions
Electrons
Atomic number
and mass number
Isotopes
Chemical Bonds
Covalent bonds
Atomic mass

Chemistry

The science that deals with the structure and behavior of matter

Scientific Models

- A ***model*** is a simplified approximation of reality.
- Scientific models are simplified but *useful* representations of something real.

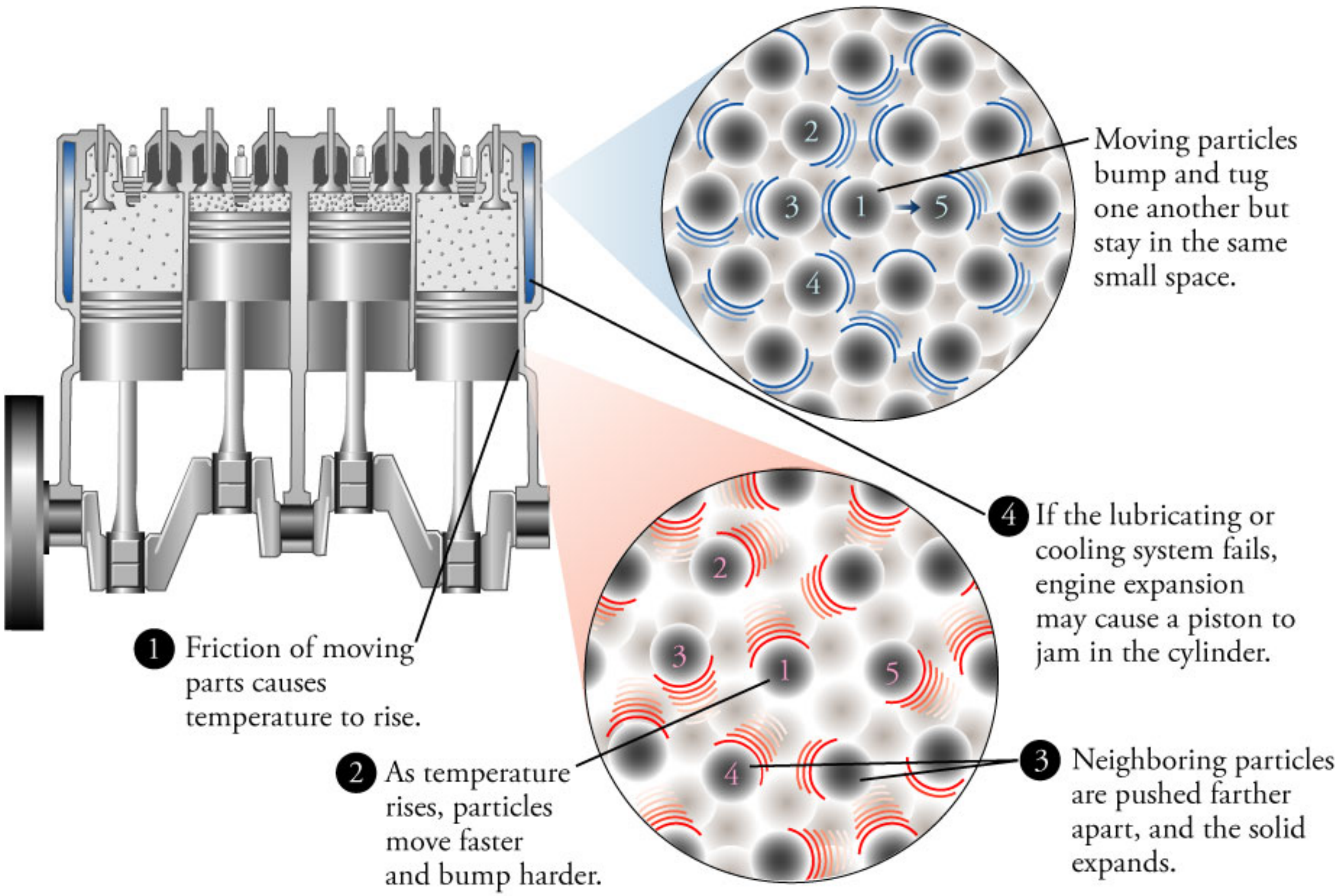
Kinetic Molecular Theory

- All matter is composed of tiny particles.
- The particles are in constant motion.
- Increased temperature reflects increased motion of particles.
- Solids, liquids and gases differ in the freedom of motion of their particles and in how strongly the particles attract each other.

Solid

- Constant shape and volume
- The particles are constantly moving, colliding with other particles, and changing their direction and velocity.
- Each particle is trapped in a small cage whose walls are formed by other particles that are strongly attracted to each other.

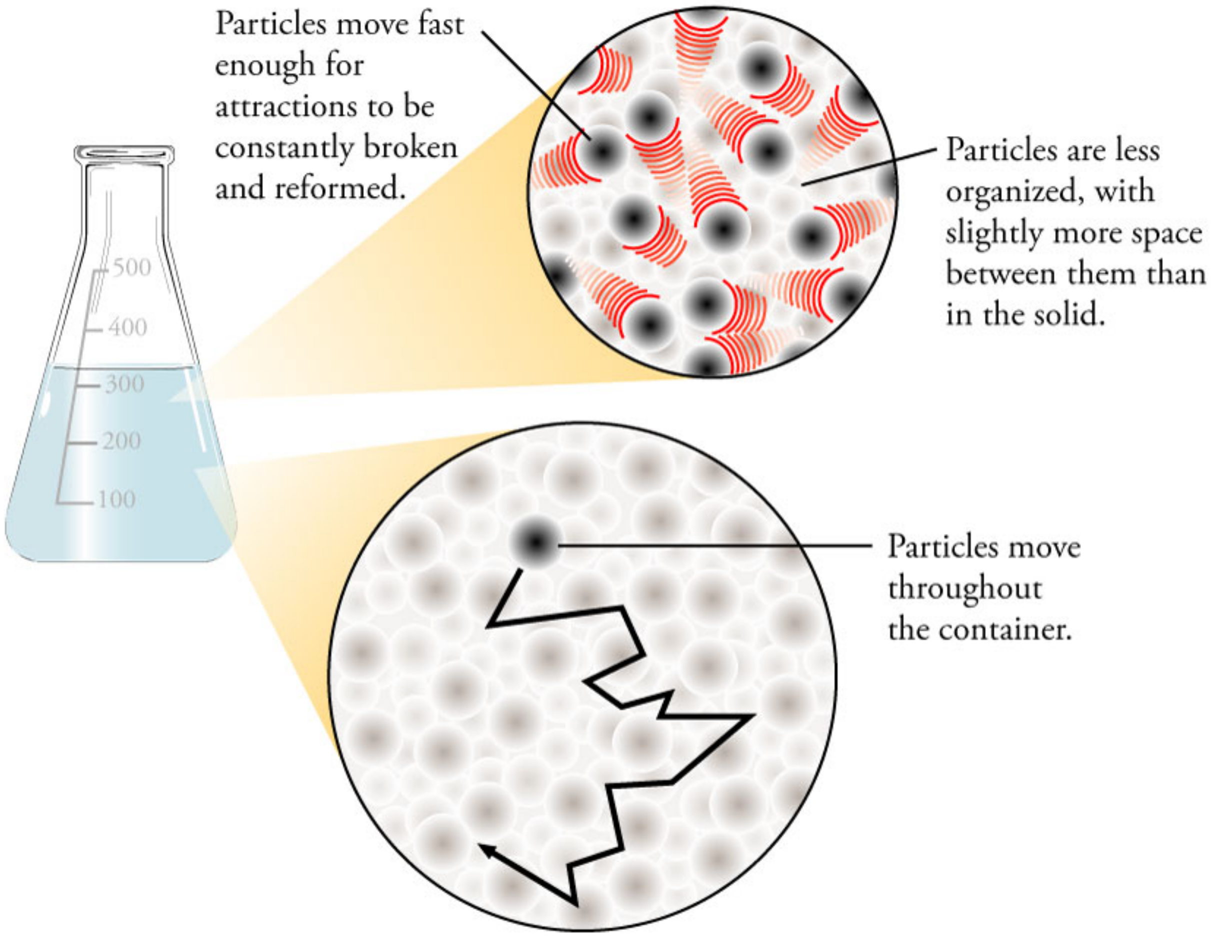
The Nature of Solids



Liquid

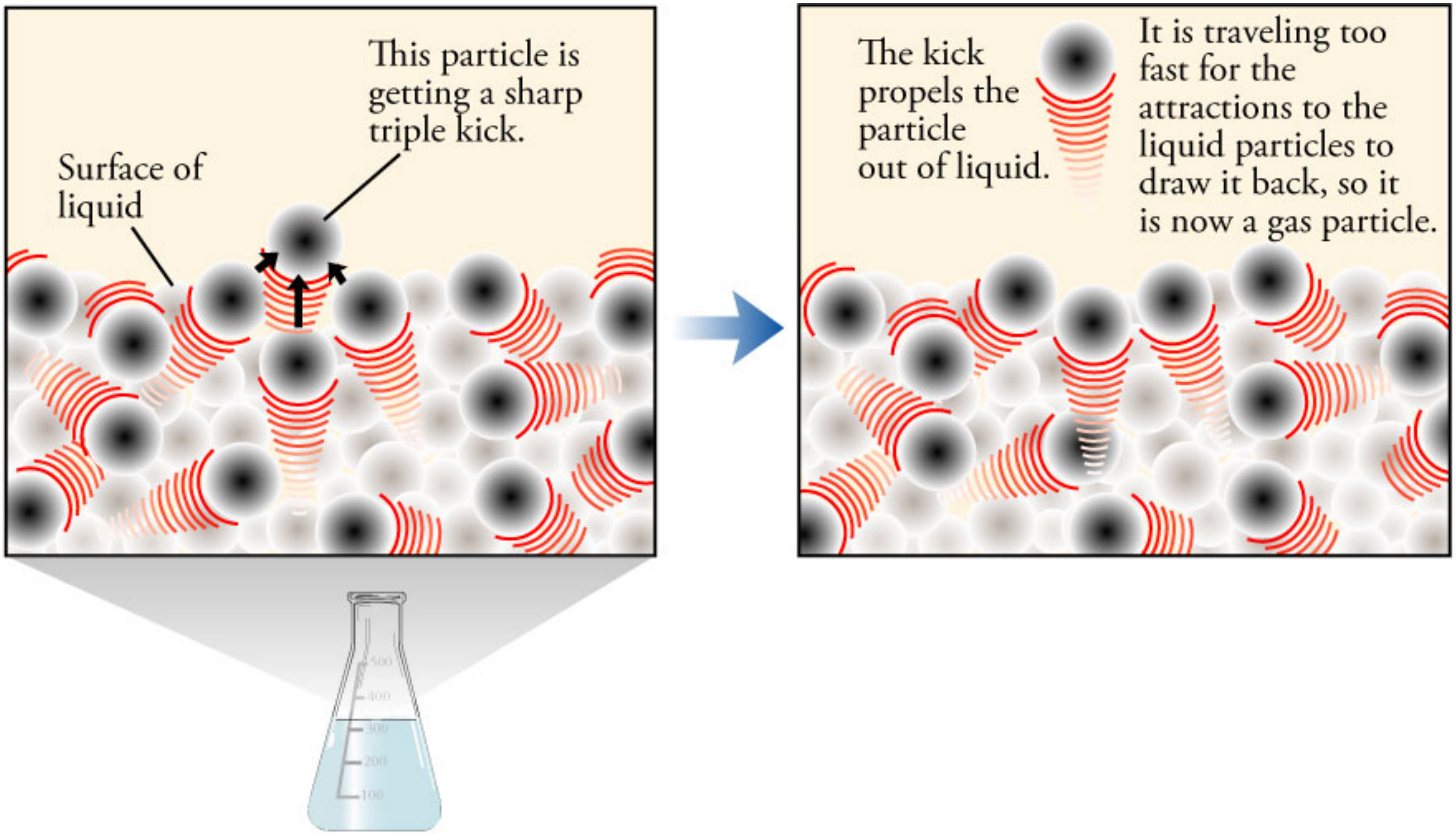
- Constant volume but variable shape
- The particles are moving fast enough to break the attractions between particles that form the walls of the cage that surround particles in the solid form.
- Thus each particle in a liquid is constantly moving from one part of the liquid to another.

Liquids



500
400
300
200
100
Particles move fast enough for attractions to be constantly broken and reformed.
Particles are less organized, with slightly more space between them than in the solid.
Particles move throughout the container.

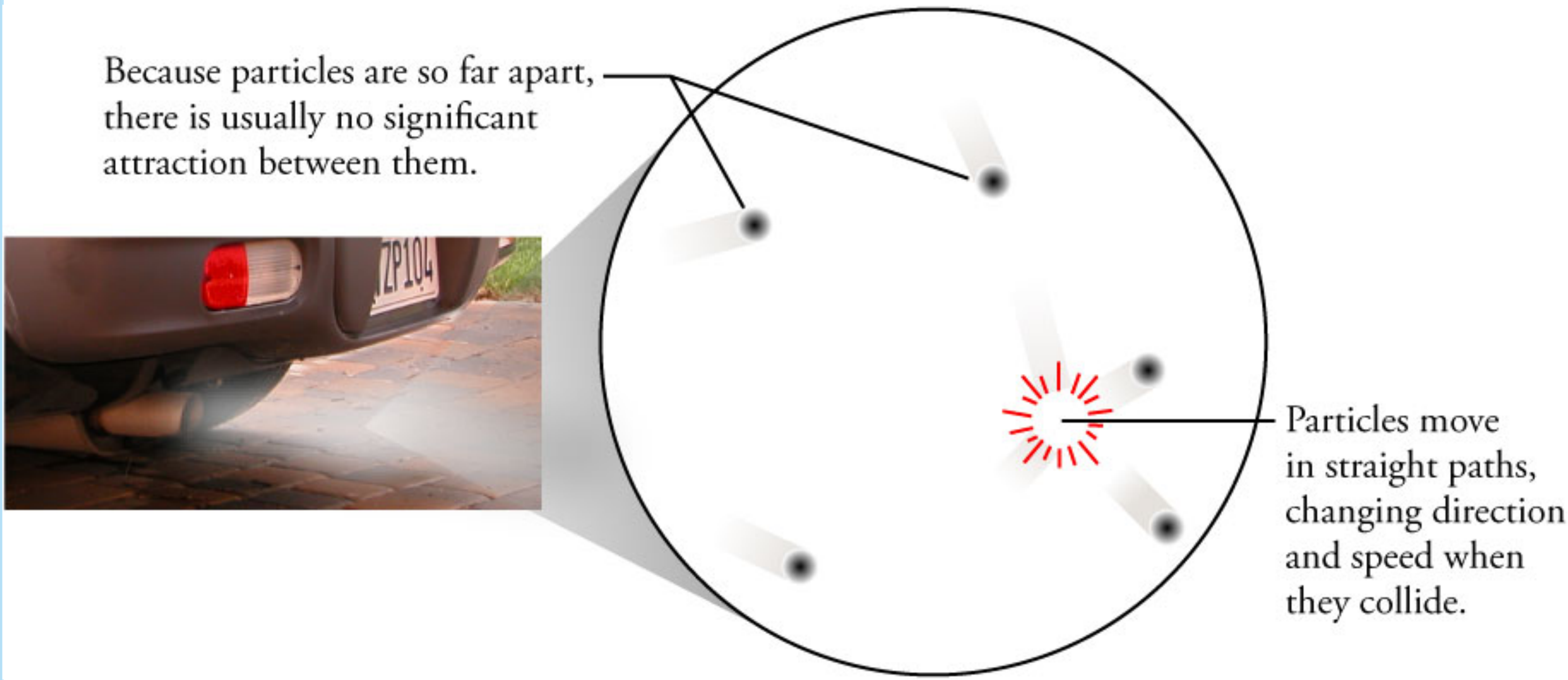
Evaporation



Gas

- Variable shape and volume
- Large average distances between particles
- Little attraction between particles
- Constant collisions between particles, leading to constant changes in direction and velocity

The Nature of Gases



Description of Solid

- Particles constantly moving.
- About 70% of volume occupied by particles…30% empty.
- Strong attractions keep particles trapped in cage.
- Constant collisions that lead to changes in direction and velocity.
- Constant volume and shape due to strong attractions and little freedom of motion.

Description of Liquid

- Particles constantly moving.
- About 70% of volume occupied by particles…30% empty
- Attractions are strong but not strong enough to keep particles from moving throughout the liquid.
- Constant collisions that lead to changes in direction and velocity.
- Constant volume, due to significant attractions between the particles that keeps the particles at a constant average distance, but not constant shape, due to the freedom of motion.

Description of Gas

- Particles constantly moving in straight-line paths
- About 0.1% of volume occupied by particles…99.9% empty.
- Average distance between particles is about 10 times their diameter.
- No significant attractions or repulsions.
- Constant collisions that lead to changes in direction and velocity.
- Variable volume and shape, due to lack of attractions and a great freedom of motion.

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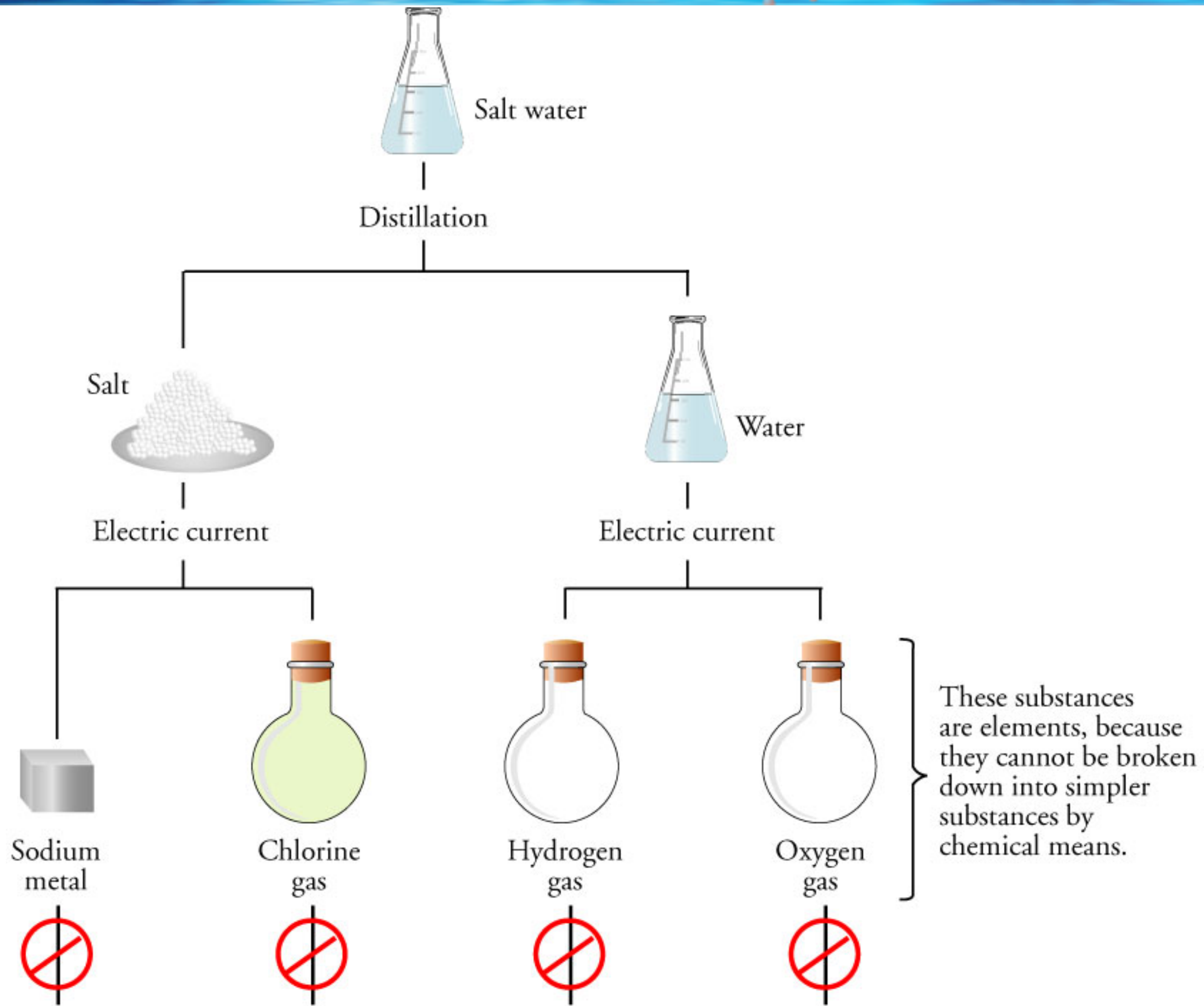
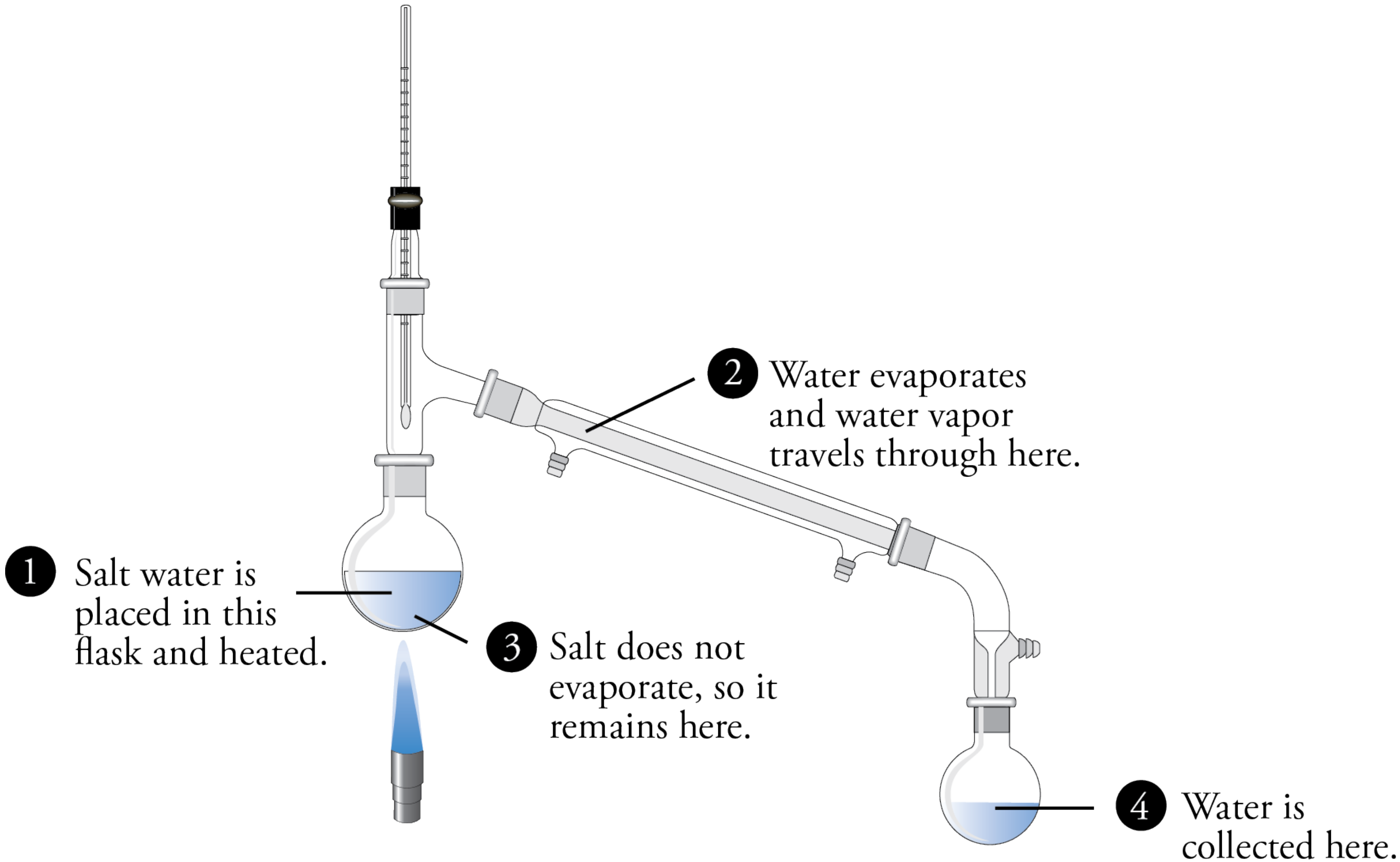
Separation of Salt Water



Distillation



118 Known Elements

- 83 are stable and found in nature.
  - Many of these a very rare.
- 7 are found in nature but are radioactive.
- 28 are not natural on the earth.
  - 2 or 3 of these might be found in stars.

Group Numbers on the Periodic Table

	1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9 8B	10 8B	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1											1 H							2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh		

6	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
7	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

Group Names

Alkali Metals

Alkaline Earth Metals

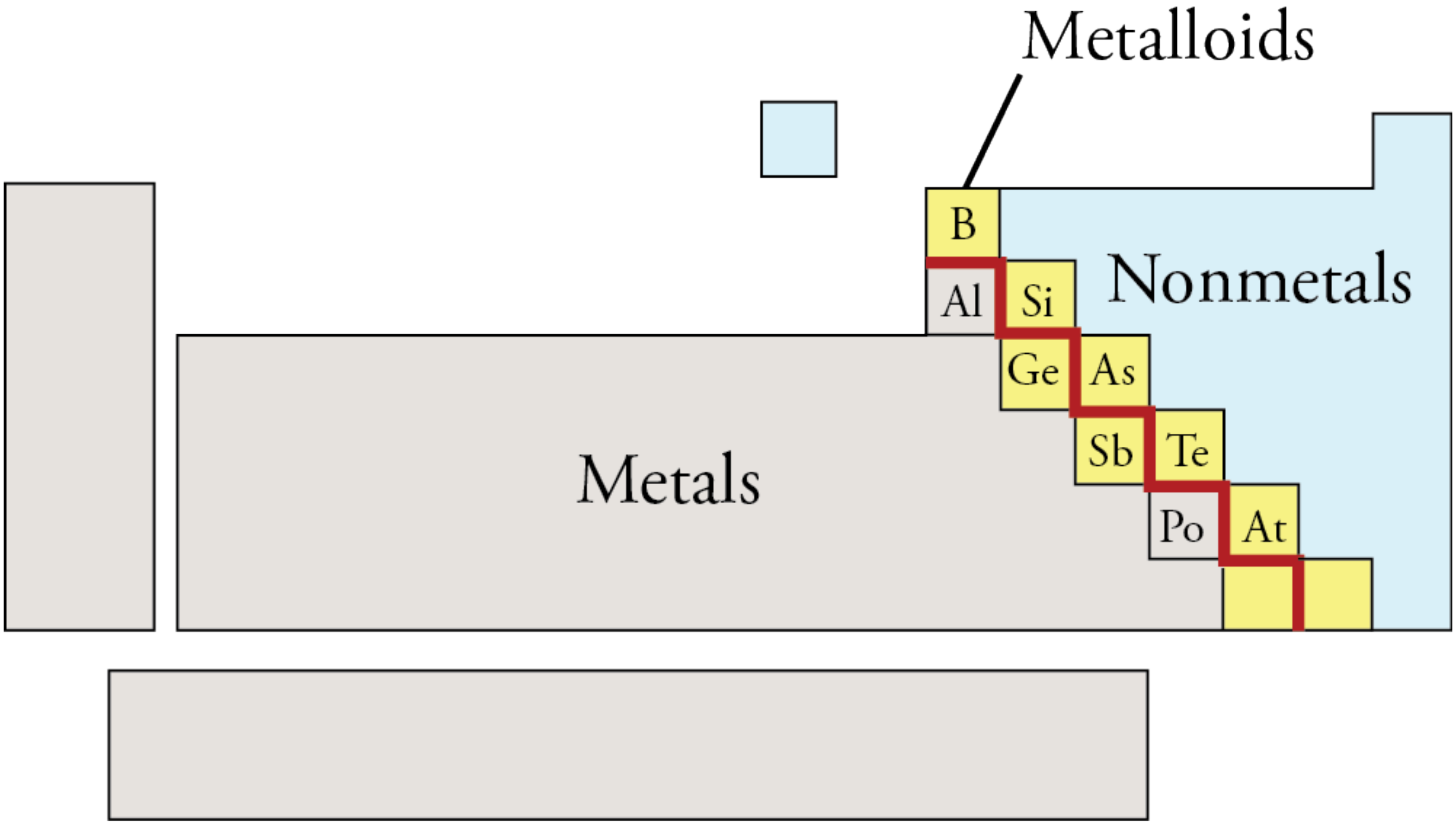
Halogens

Noble Gases

	1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9 8B	10 8B	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh		

6	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
7	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

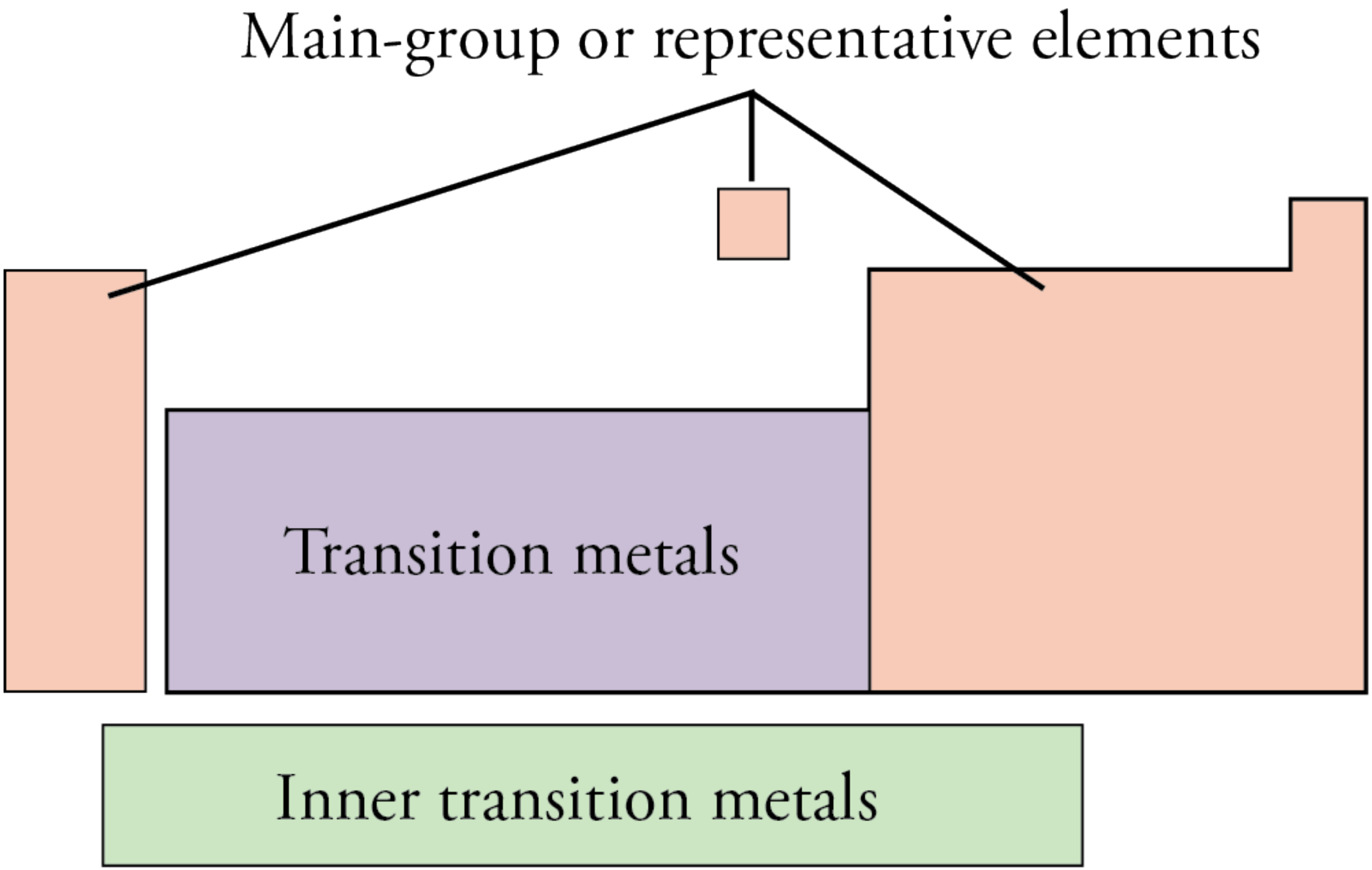
Metals, Nonmetals, and Metalloids



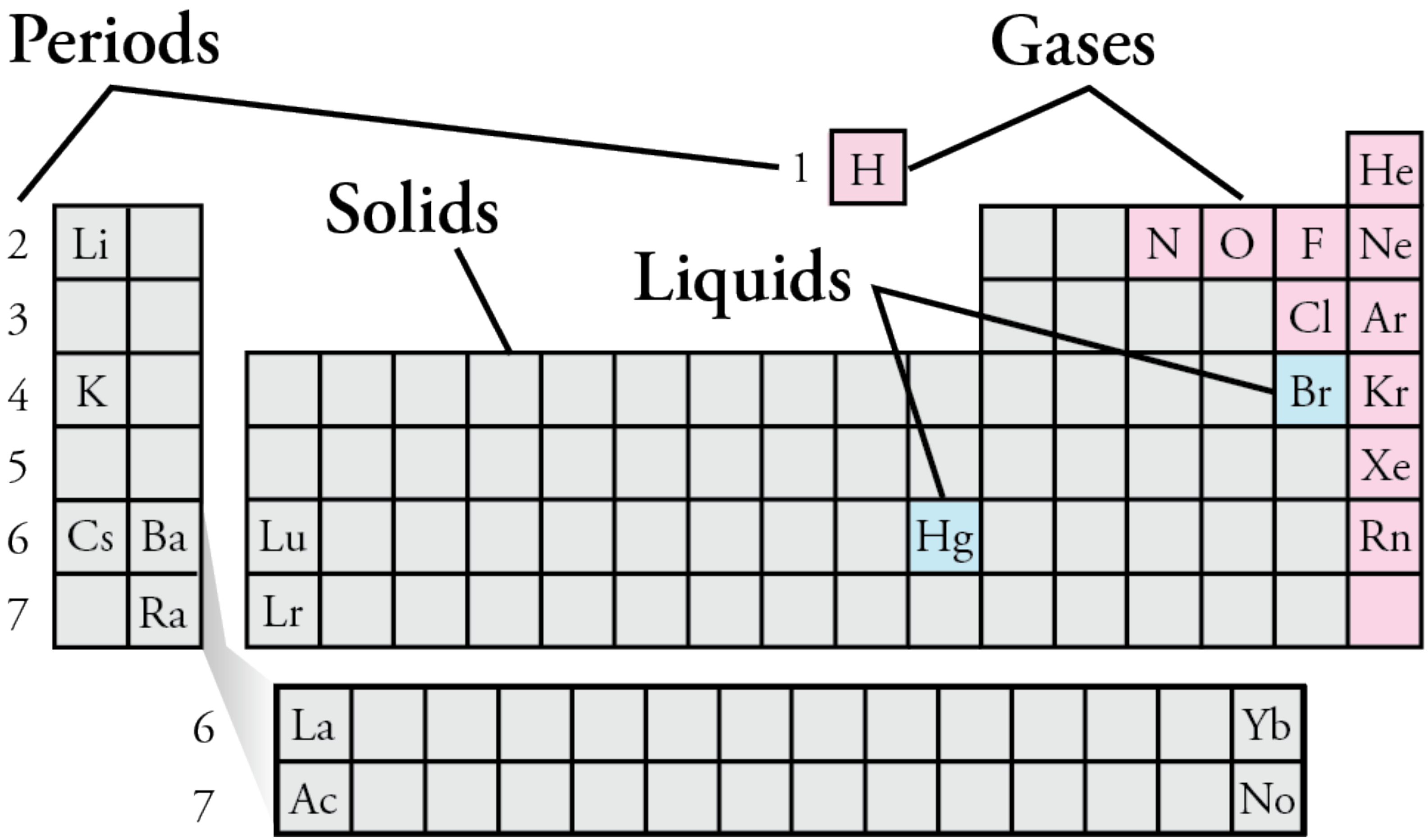
Characteristics of Metallic Elements

- Metals have a shiny metallic luster.
- Metals conduct heat well and conduct electric currents in the solid form.
- Metals are malleable.
  - For example, gold, Au, can be hammered into very thin sheets without breaking.

Classification of Elements



Solid, Liquid, and Gaseous Elements



Atoms

- Tiny…about 10^{-10} m
  - If the atoms in your body were 1 in. in diameter, you’d bump your head on the moon.
- Huge number of atoms in even a small sample of an element
  - 1/2 carat diamond has 5×10^{21} atoms…if lined up, would stretch to the sun.

Particles in the Atom

- Neutron (n)

  0 charge 1.00867 u in nucleus

- Proton (p)

  +1 charge 1.00728 u in nucleus

- Electron (e^-)

  –1 charge 0.000549 u outside nucleus

What do we know about charge?

- Only some particles have it.
- There are two types of charge, plus and minus.
- It’s the characteristic of matter that leads to electromagnetic forces due to passing photons back and forth.
- Like charges repel.
- Opposite charges attract.
- The closer the charges, the stronger the force.
- The higher the charges, the stronger the force.

The Electron

"If I seem unusually clear to you, you must have misunderstood what I said."

Alan Greenspan,

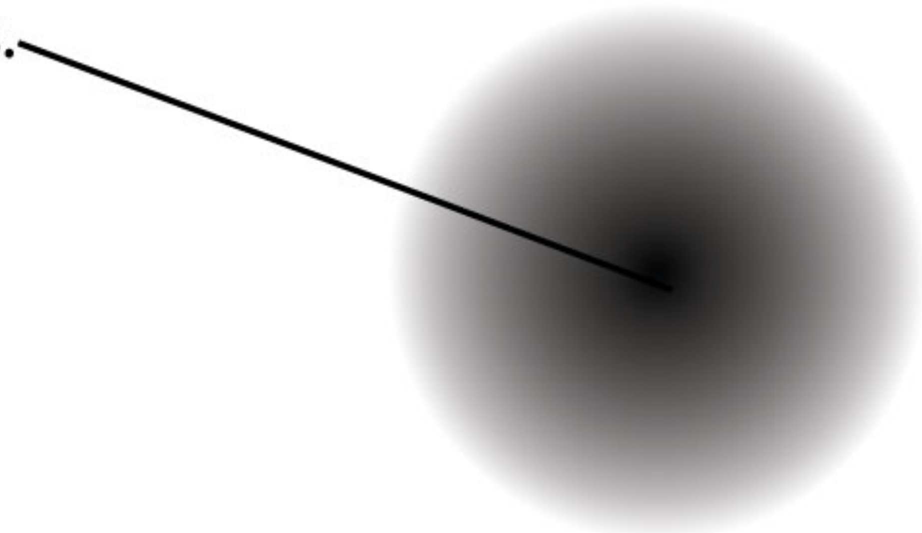
Head of the Federal Reserve Board

"It is probably as meaningless to discuss how much room an electron takes up as to discuss how much room a fear, an anxiety, or an uncertainty takes up."

Sir James Hopwood Jeans,
English mathematician, physicist and astronomer (1877-1946)

Electron Cloud for Hydrogen Atom

The negative charge is most intense at the nucleus and diminishes in intensity with increased distance from the nucleus.



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Helium Atom

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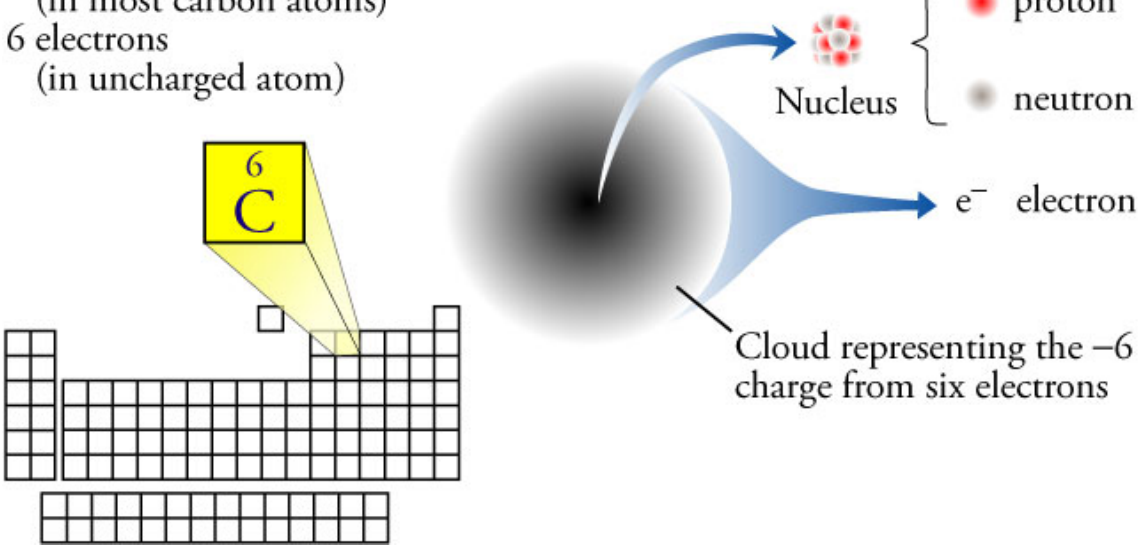
Carbon Atom

Carbon atom

6 protons
6 neutrons
(in most carbon atoms)
6 electrons
(in uncharged atom)

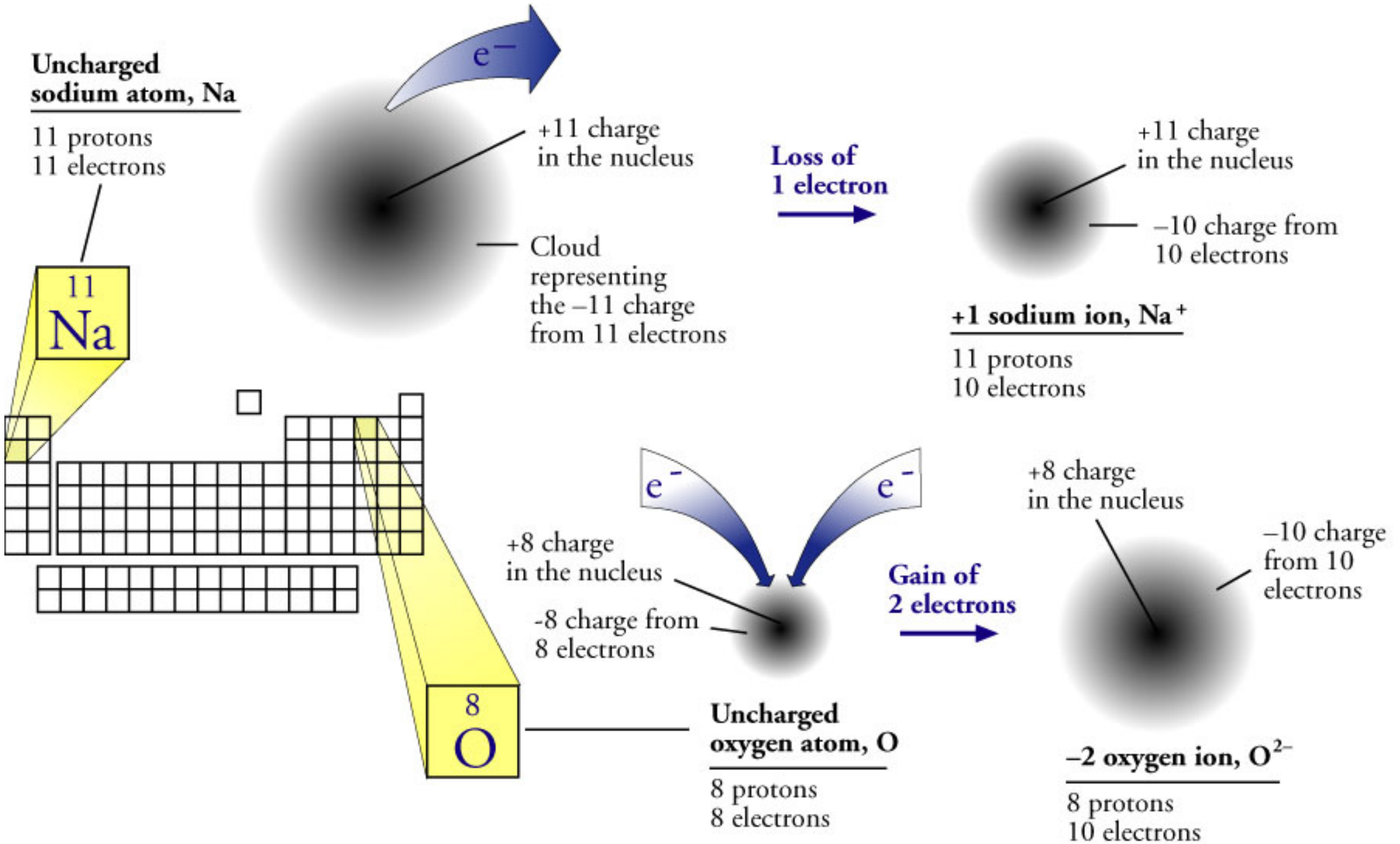


Particle	Charge	Mass
proton	+1	1.00728 u (1.6726×10^{-24} g)
neutron	0	1.00867 u (1.6750×10^{-24} g)
e^- electron	−1	0.000549 u (9.1096×10^{-28} g)

Ions

- ***Ions*** are charged particles due to a loss or gain of electrons.
- When particles lose one or more electrons, leaving them with a positive overall charge, they become ***cations***.
- When particles gain one or more electrons, leaving them with a negative overall charge, they become ***anions***.

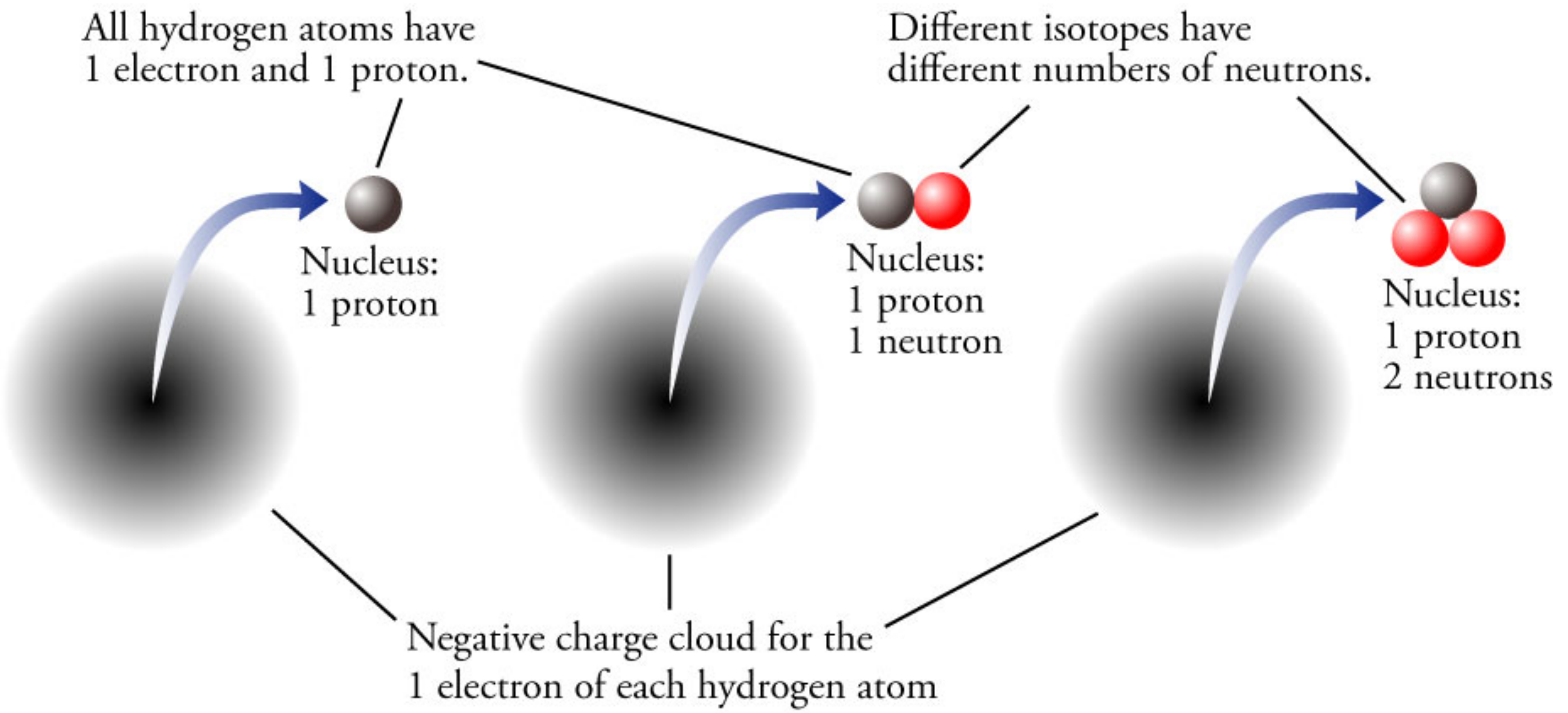
Example Ions



Isotopes

- ***Isotopes*** are atoms with the same atomic number but different mass numbers.
- ***Isotopes*** are atoms with the same number of protons and electrons in the uncharged atom but different numbers of neutrons.
- ***Isotopes*** are atoms of the same element with different masses.

Isotopes of Hydrogen



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https://preparatorychemistry.com/Hydrogen_3_Canvas.html

Possible Discovery of Elements 113 and 115

- Dubna, Russia
- Dubna's Joint Institute for Nuclear Research and Lawrence Livermore National Laboratory
- Bombarded a target enriched in americium, ^{243}Am, with calcium atoms, ^{48}Ca.
- From analysis of decay products, they concluded that four atoms of element 115 were created.

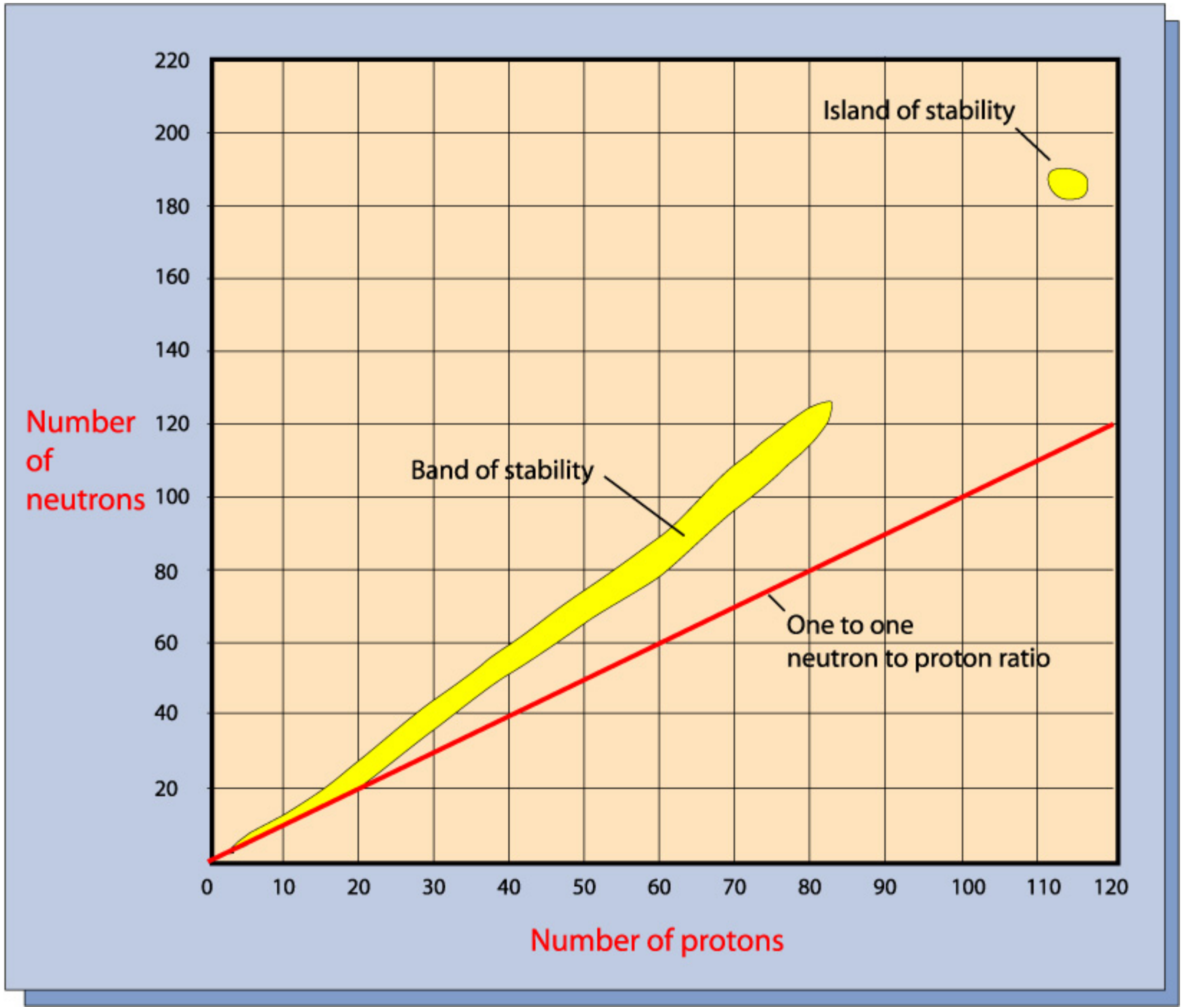
Elements 113 and 115

- Created $^{288}115$, which lasted about 100 milliseconds…a very long time for this large an isotope.
- $^{288}115$ emitted an α-particle, ^{4}He, to form $^{284}113$.
- The results need to be confirmed.

Why try to make elements that last such a short time?

- To support theories of the nature of matter.
  - The standard model of the nature of matter predicts that elements with roughly 184 neutrons and 114 protons would be fairly stable. (See next slide.)
  - $^{288}115$, which lasted a relatively long time, has 115 protons and 173 neutrons.

Band of Stability



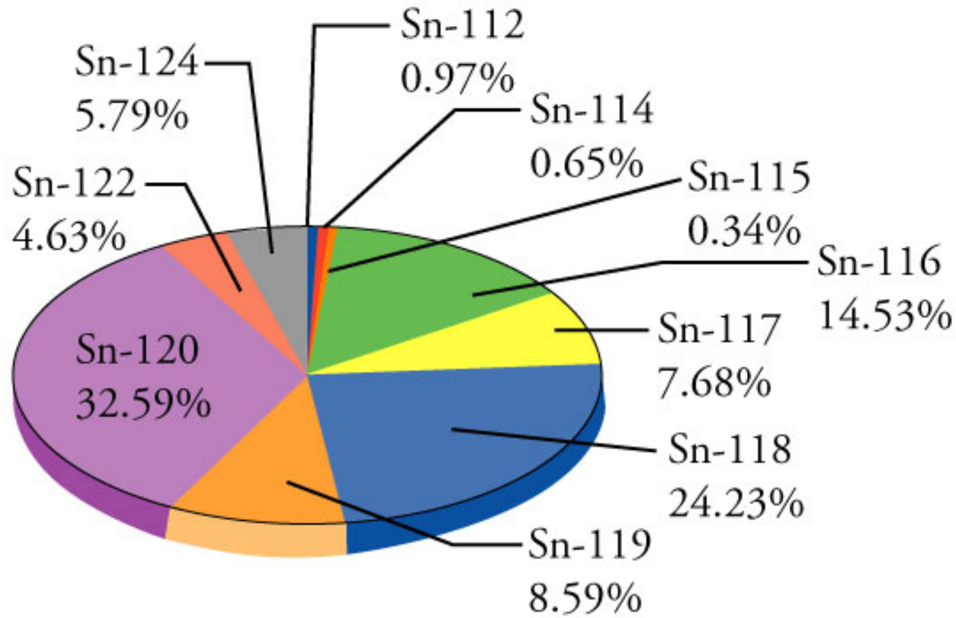
Why try to make elements that last such a short time? (cont.)

- The technology developed to make new elements is also being used for medical purposes.
  - Heavy-ion therapy as a treatment for inoperable cancers
    - Beams of carbon atoms shot at tumor.
    - Heavier particle beam is less likely to scatter.
    - Releases most of energy at end of path so easier to focus.

Effect on Chemical Changes

- Electrons
  - Can be gained, lost, or shared…actively participate in chemical changes
  - Affect other atoms through their -1 charge
- Protons
  - Affect other atoms through their +1 charge
  - Determine the number of electrons in uncharged atoms
- Neutrons
  - No charge…no effect outside the atom and no direct effect on the number of electrons.

Tin has ten natural isotopes.



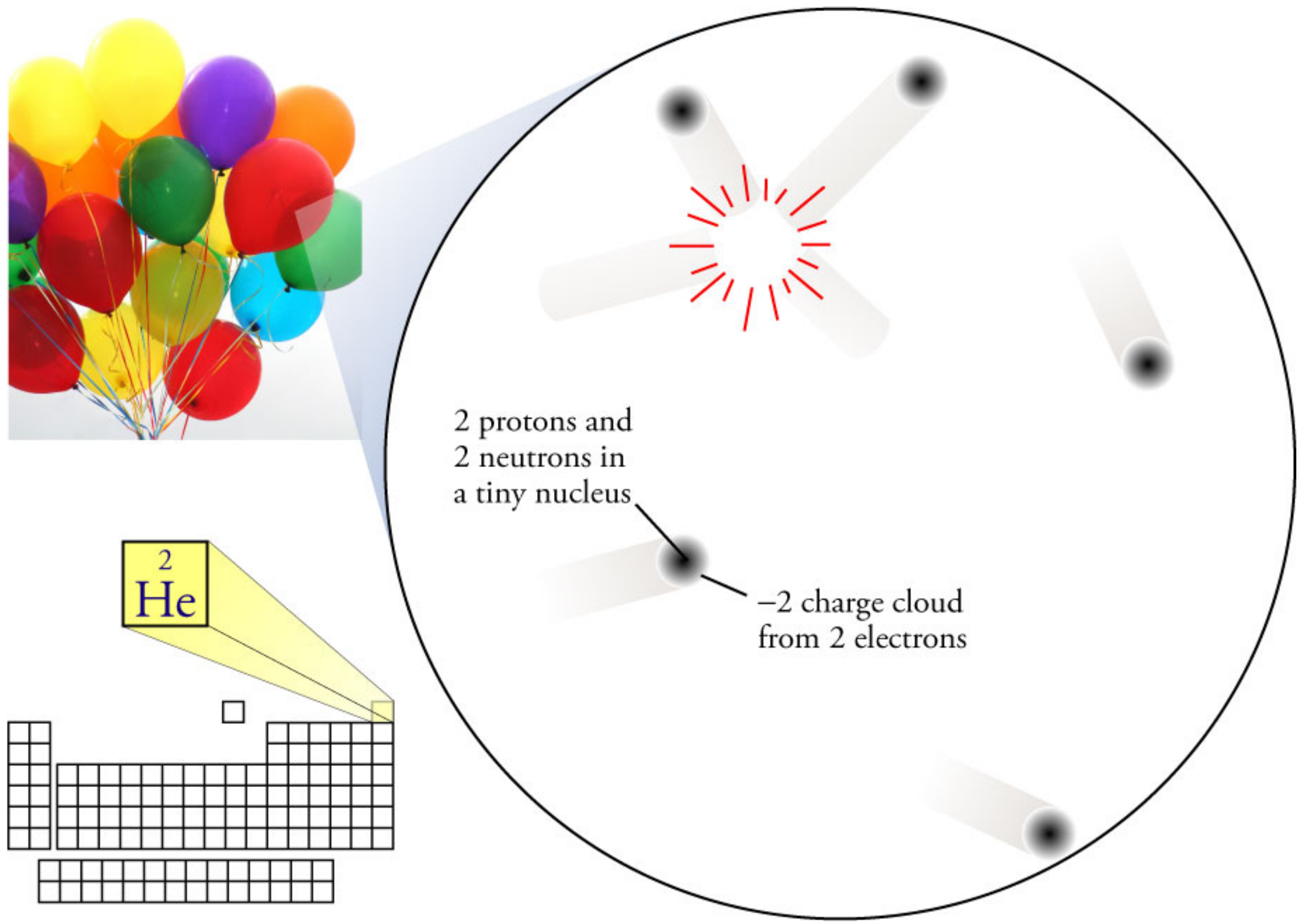
To Describe Structure of Elements

- What particles?
  - Noble gases – atoms
  - Other nonmetals - molecules
    - Diatomic elements – H_2, N_2, O_2, F_2, Cl_2, Br_2, I_2
    - S_8, Se_8, P_4
    - C(diamond) huge molecules
  - Metallic elements – cations in a sea of electrons

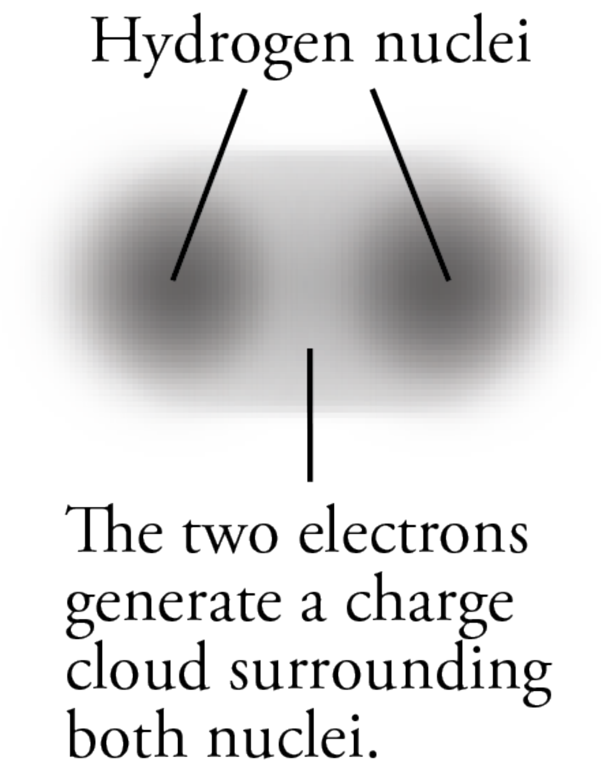
To Describe Structure of Elements (2)

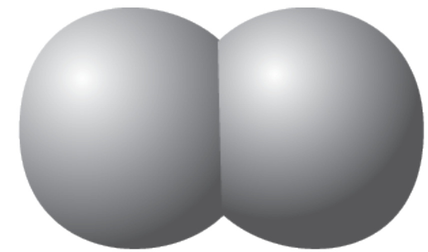
- Solid, liquid, or gas?
  - Gases - H_2, N_2, O_2, F_2, Cl_2, He, Ne, Ar, Kr, and Xe
  - Liquids – Br_2 and Hg
  - Solids – the rest
- Standard description of (1) solid, (2) liquid, (3) gas, or (4) metal.

Helium Gas, He

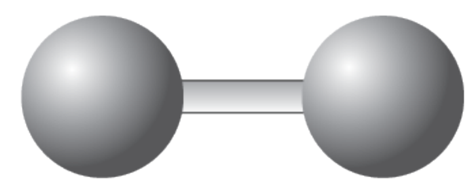


Hydrogen, H_2, Molecule



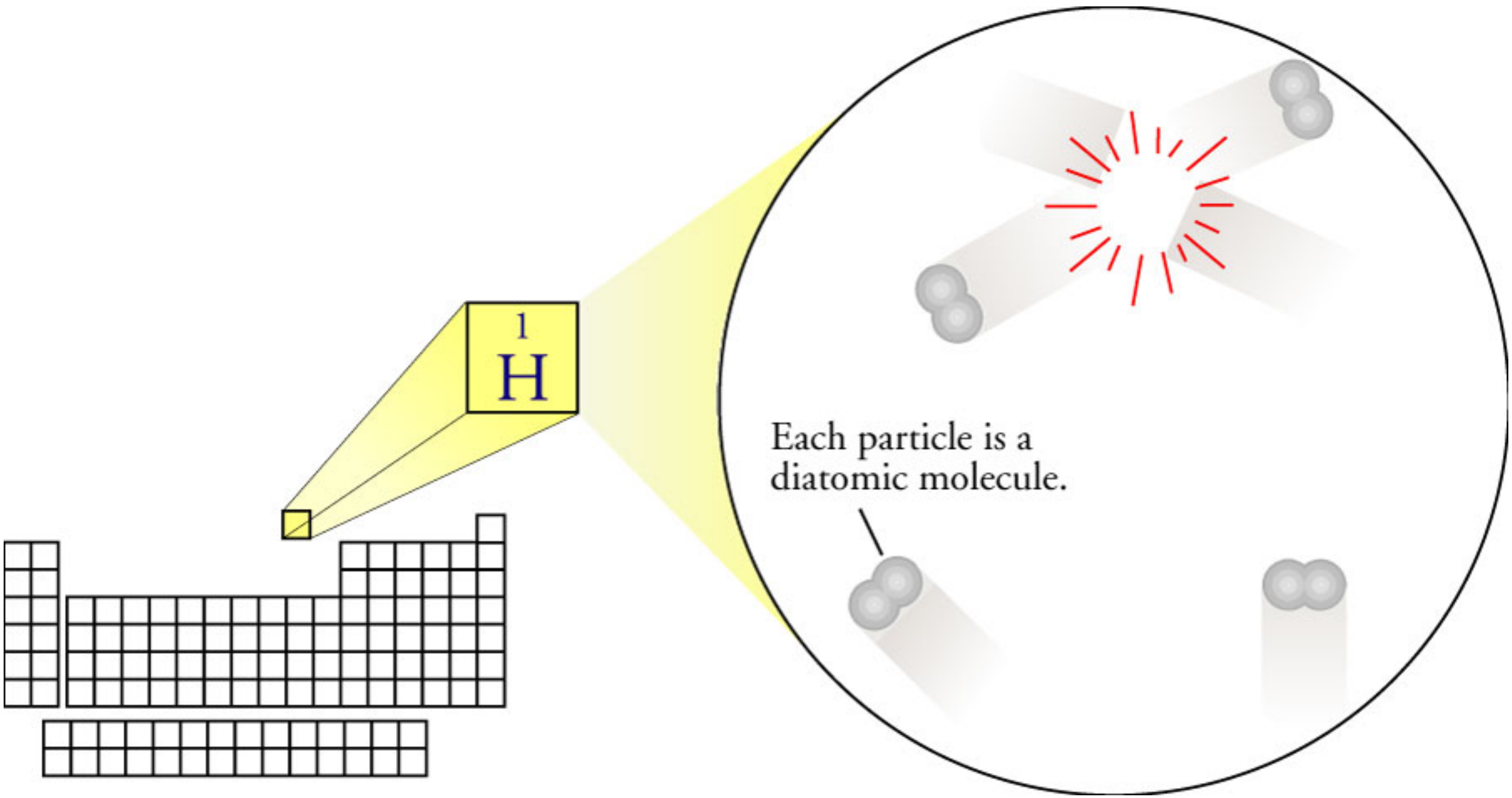


Space-filling model
Emphasizes individual atoms

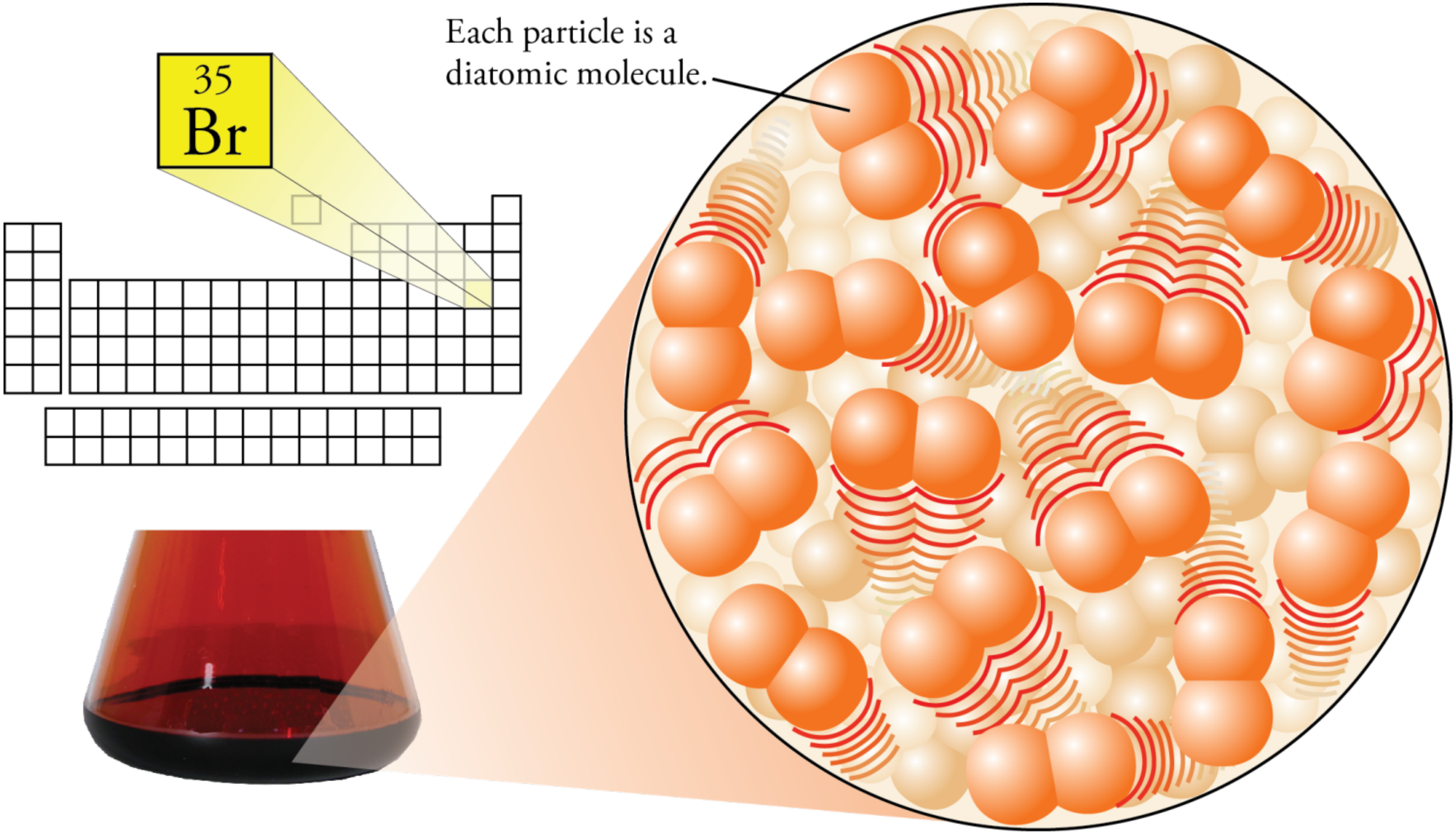


Ball-and-stick model
Emphasizes bond

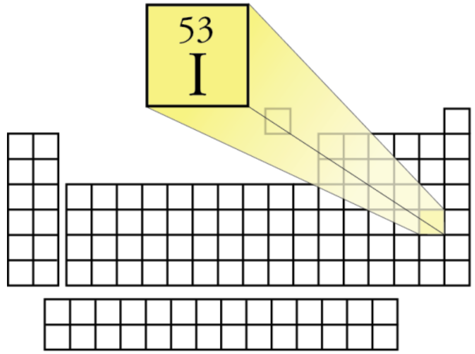
Hydrogen Gas, H_2

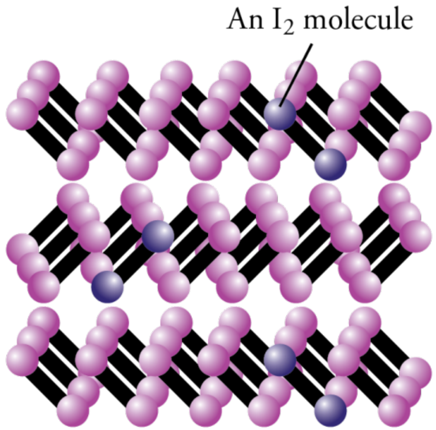


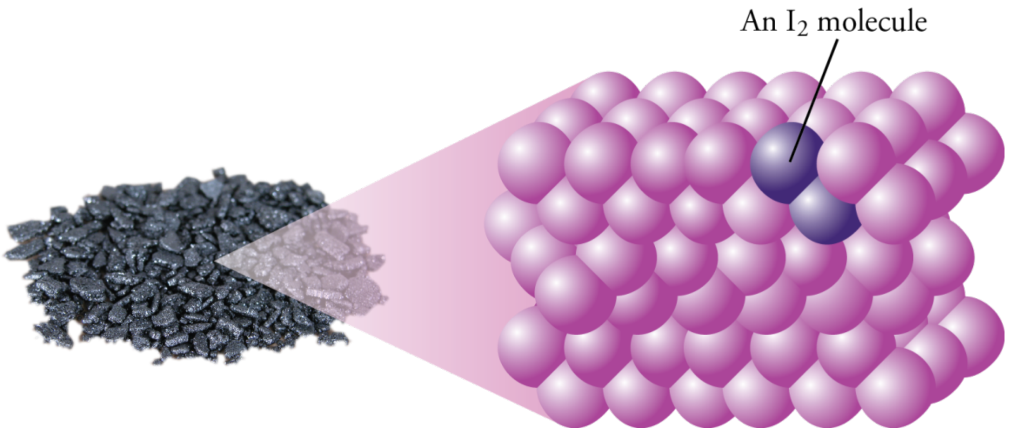
Bromine Liquid, Br_2



Iodine Solid







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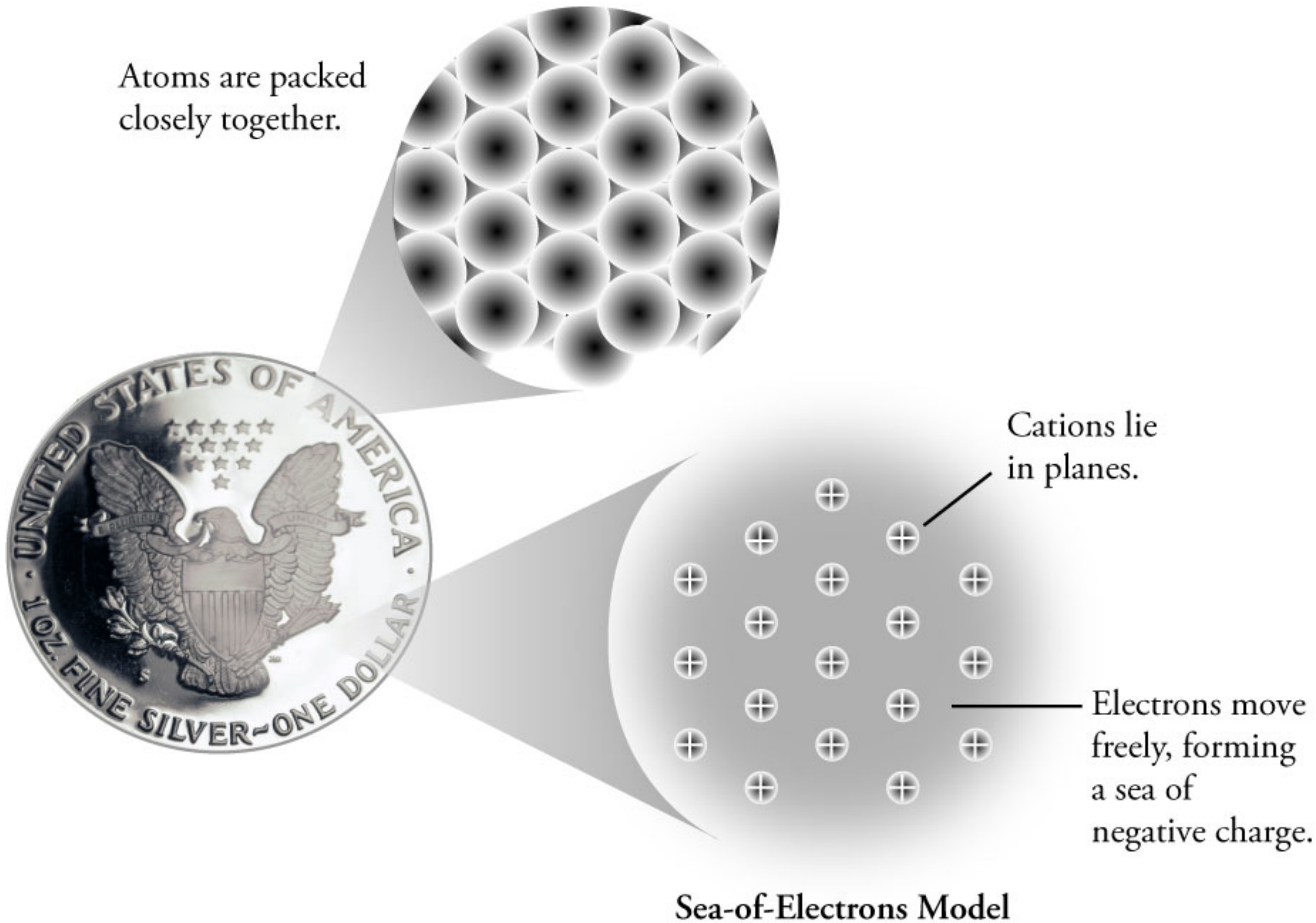
Typical Metallic Solid and Its "Sea of Electrons"



Making Phosphoric Acid

- Furnace Process for making H_3PO_4 to be used to make fertilizers, detergents, and pharmaceuticals.
  - React phosphate rock with sand and coke at 2000 ºC.

$$2Ca_3(PO_4)_2 + 6SiO_2 + 10C \rightarrow 4P + 10CO + 6CaSiO_3$$

  - React phosphorus with oxygen to get tetraphosphorus decoxide.

$$4P + 5O_2 \rightarrow P_4O_{10}$$

  - React tetraphosphorus decoxide with water to make phosphoric acid.

$$P_4O_{10} + 6H_2O \rightarrow 4H_3PO_4$$

Sample Calculations (1)

- What is the maximum mass of P_4O_{10} that can be formed from 1.09×10^4 kg P?
- Beginning of unit analysis setup.

$$? \text{ kg } P_4O_{10} = 1.09 \times 10^4 \text{ kg P} \left(\frac{\qquad}{1 \text{ kg}} \right)$$

- The formula for P_4O_{10} provides us with a conversion factor that converts from units of P to units of P_4O_{10}.

$$\frac{1 \text{ molecule } P_4O_{10}}{4 \text{ atoms P}}$$

Goal: To develop conversion factors that will convert between a measurable property (mass) and number of particles

$$? \text{ kg } P_4O_{10} = 1.09 \times 10^4 \cancel{\text{kg}} \text{ P} \left(\frac{\quad}{1 \cancel{\text{kg}}} \right)$$

Measurable Property 1	Mass 1
↓	↓
Number of Particles 1	Number of Particles 1
↓	↓
Number of Particles 2	Number of Particles 2
↓	↓
Measurable Property 2	Mass 2

Counting by Weighing for Nails

- **Step 1:** Choose an easily measurable property.
  - Mass for nails
- **Step 2:** Choose a convenient unit for measurement.
  - Pounds for nails

Counting by Weighing for Nails (cont)

- **Step 3:** If the measurable property is mass, determine the mass of the individual objects being measured.
  - Weigh 100 nails: 82 are 3.80 g, 14 are 3.70 g, and 4 are 3.60 g
- **Step 4:** If the objects do not all have the same mass, determine the weighted average mass of the objects.

$$0.82(3.80\text{ g}) + 0.14(3.70\text{ g}) + 0.04(3.60\text{ g}) = 3.78\text{ g}$$

Counting by Weighing for Nails (cont)

- **Step 5:** Use the conversion factor from the weighted average to make conversions between mass and number of objects.

$$? \text{ nails} = 218 \cancel{\text{lb}} \cancel{\text{nails}} \left(\frac{453.6 \cancel{\text{g}}}{1 \cancel{\text{lb}}}\right)\left(\frac{1 \text{ nail}}{3.78 \cancel{\text{g}} \cancel{\text{nails}}}\right) = 2.62 \times 10^4 \text{ nails}$$

Counting by Weighing for Nails (cont)

- **Step 6**: Describe the number of objects in terms of a collective unit, such as a dozen, a gross, or a ream.

$$\frac{?\ \text{g nails}}{1\ \text{gross nails}} = \left(\frac{3.78\ \text{g nails}}{1\ \cancel{\text{nail}}}\right)\left(\frac{144\ \cancel{\text{nails}}}{1\ \text{gross nails}}\right) = \frac{544\ \text{g nails}}{1\ \text{gross nails}}$$

$$?\ \text{gross nails} = 218\ \cancel{\text{lb}}\ \cancel{\text{nails}}\left(\frac{453.6\ \cancel{\text{g}}}{1\ \cancel{\text{lb}}}\right)\left(\frac{1\ \text{gross nails}}{544\ \cancel{\text{g}}\ \cancel{\text{nails}}}\right) = 182\ \text{gross nails}$$

Counting by Weighing for Carbon Atoms

- **Step 1:** Choose an easily measurable property.
  - Mass for carbon atoms
- **Step 2:** Choose a convenient unit for measurement.
  - Atomic mass units (u) for carbon atoms
  - Atomic mass unit (u) = 1/12 the mass of a carbon-12 atom (with 6 p, 6 n, and 6 e^-)

Counting by Weighing for Carbon Atoms (cont.)

- **Step 3:** If the measurable property is mass, determine the mass of the individual objects being measured.
  - For carbon: 98.90% are 12 u and 1.10% are 13.003355 u.
- **Step 4:** If the objects do not all have the same mass, determine the weighted average mass of the objects.

$$0.9890(12\ u) + 0.0110(13.003355\ u) = 12.011\ u$$

Counting by Weighing for Carbon Atoms (cont.)

- For two reasons, we will skip step 5 where we would have used the weighted average mass, 12.011 u per atom, as a conversion factor.
  - The first reason is that we don’t measure mass in unified mass units.
  - The second reason is that if we used 12.011 u per atom as a conversion factor, we would get the actual number of atoms, which for any sample of carbon would be a huge and inconvenient number.

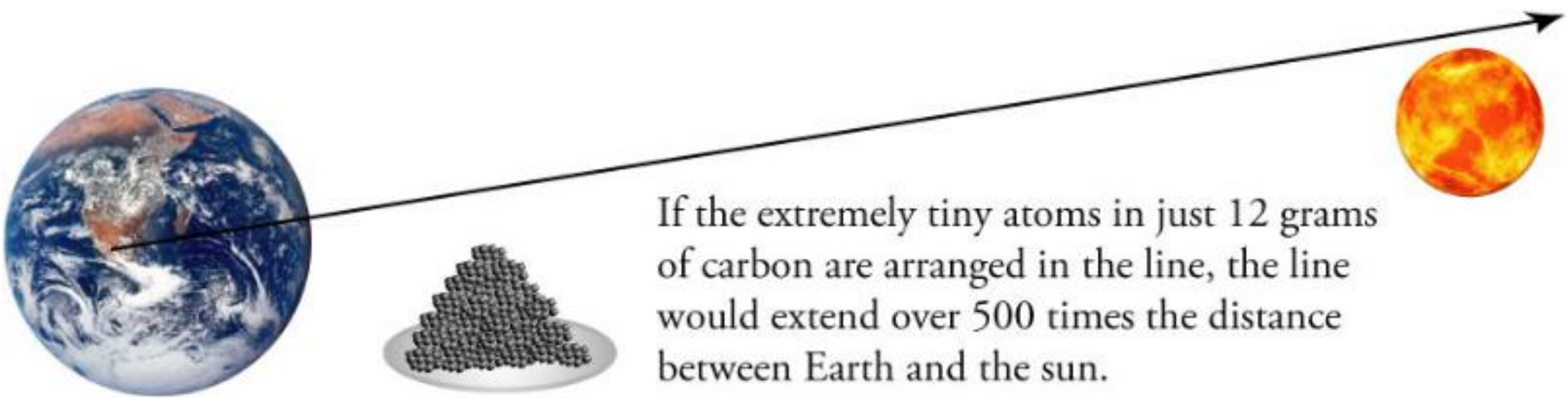
Counting by Weighing for Carbon Atoms (cont.)

- We would rather have a conversion factor that has a more common mass unit, such as grams, and we would rather describe the number of atoms in terms of a collective unit, such as a dozen, a gross, or a ream.
- That collective unit is a mole.

Mole

- A ***mole*** (mol) is an amount of substance that contains the same number of particles as there are atoms in 12 g of carbon-12.
- To four significant figures, there are 6.022×10^{23} atoms in 12 g of carbon-12.
- Thus a mole of natural carbon is the amount of carbon that contains 6.022×10^{23} carbon atoms.
- The number 6.022×10^{23} is often called ***Avogadro's number***.

Avogadro's Number



Molar Mass Development

From the definition of mole $\frac{12\ \text{g C-12}}{1\ \text{mol C-12}}$

From relative atomic masses

$$\frac{12.011\ \text{g C}}{1\ \text{mol C}} \qquad \frac{24.3050\ \text{g Mg}}{1\ \text{mol Mg}}$$

$$\frac{15.9994\ \text{g O}}{1\ \text{mol O}} \qquad \frac{1.00794\ \text{g H}}{1\ \text{mol H}}$$

Molar Mass of Elements

- The atomic masses found on the periodic table can be used to get molar masses, which can be used to convert between grams and moles of any element.

$$\left(\frac{\text{(atomic mass) g element}}{\text{1 mol element}}\right)$$

Example Calculations

- The masses of diamonds and other gemstones are measured in carats. There are exactly 5 carats per gram. How many moles of carbon atoms are in a 0.55 carat diamond? (Assume that the diamond is pure carbon.)

$$? \text{ mol C} = 0.55 \text{ } \cancel{\text{carat C}} \left(\frac{1 \cancel{\text{g}}}{5 \cancel{\text{carat}}}\right)\left(\frac{1 \text{ mol C}}{12.011 \cancel{\text{g C}}}\right)$$

$$= 9.2\times10^{-3} \text{ mol C} \left(\frac{6.022\times10^{23} \text{ C atoms}}{1 \text{ mol C}}\right)$$

$$= 5.5\times10^{21} \text{ C atoms}$$

Our Calculation

- What is the maximum mass of P_4O_{10} that can be formed from 1.09×10^4 kg P?

Mass 1	Mass 1
↓	↓
Number of Particles 1	Moles 1
↓	↓
Number of Particles 2	Moles 2
↓	↓
Mass 2	Mass 2

Our Calculation

- What is the maximum mass of P_4O_{10} that can be formed from 1.09×10^4 kg P?
- Here are the general steps for our calculation. We'll see how to do the first two steps in this lesson, and I'll tell you how to do the last step in another lesson.

Mass P $\longrightarrow$ moles P $\longrightarrow$ moles P_4O_{10} $\rightarrow$ mass P_4O_{10}

Our Calculation – Step 1

- What is the maximum mass of P_4O_{10} that can be formed from 1.09×10^4 kg P?

Mass P → moles P → moles P_4O_{10} → mass P_4O_{10}

- We can convert grams of P to moles of P using the molar mass of P, which comes from its atomic mass that is found on the periodic table.

$$\frac{30.9738 \text{ g P}}{1 \text{ mol P}} \quad \text{or} \quad \frac{1 \text{ mol P}}{30.9738 \text{ g P}}$$

Our Calculation – Step 1

- What is the maximum mass of P_4O_{10} that can be formed from 1.09×10^4 kg P?

$$\text{Mass P} \longrightarrow \text{moles P} \longrightarrow \text{moles } P_4O_{10} \rightarrow \text{mass } P_4O_{10}$$

- Before we can convert grams P to moles P, we need to convert kg to g.

Converts given mass unit into grams.

$$? \text{ kg } P_4O_{10} = 1.09 \times 10^4 \cancel{\text{kg P}} \left(\frac{10^3 \cancel{\text{g}}}{1 \cancel{\text{kg}}}\right)\left(\frac{1 \text{ mol P}}{30.9738 \cancel{\text{g P}}}\right)$$

Converts grams of element into moles.

Our Calculation

- The chemical formula provides a conversion factor for converting from moles of phosphorus atoms to moles of tetraphosphorus decoxide molecules in the second step of our calculation.

If $\frac{1 \text{ molecule } P_4O_{10}}{4 \text{ atoms P}}$ then $\frac{1 \text{ mol } P_4O_{10}}{4 \text{ mol P}}$

Our Calculation – Steps 1 and 2

- What is the maximum mass of P_4O_{10} that can be formed from 1.09×10^4 kg P?
- Here are the first two steps in our calculation.
- We'll see how to do the last step in another section.

Converts given mass unit into grams.

Converts moles of element into moles of compound.

$$? \text{ kg } P_4O_{10} = 1.09 \times 10^4 \cancel{\text{kg P}} \left(\frac{10^3 \cancel{\text{g}}}{1 \cancel{\text{kg}}}\right)\left(\frac{1 \cancel{\text{mol P}}}{30.9738 \cancel{\text{g P}}}\right)\left(\frac{1 \text{ mol } P_4O_{10}}{4 \cancel{\text{mol P}}}\right)$$

Converts grams of element into moles.