CHEM 103: Chemistry in Context

Unit 2.3
Solution Chemistry
(ionic solutions, acids & bases)

Colorado State University

Water as a Solvent

Mineral: a naturally occurring element or compound with (usually) a definite chemical composition, and a crystalline structure formed as a result of geological processes

Water is a polar molecule, it is adept at dissolving charged species…

Minerals/salts **do not** dissolve the same way as sugars and organic molecules do…

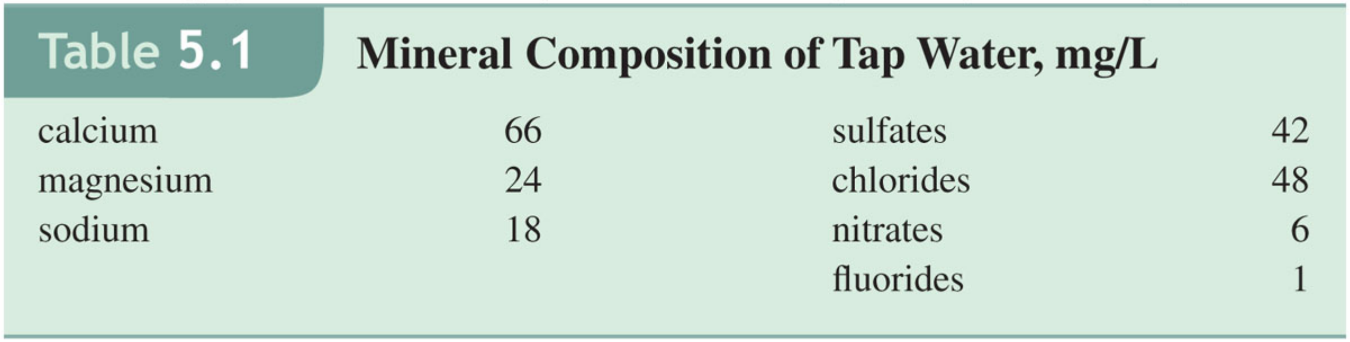


Table 5.1 Mineral Composition of Tap Water, mg/L

calcium	66	sulfates	42
magnesium	24	chlorides	48
sodium	18	nitrates	6
		fluorides	1

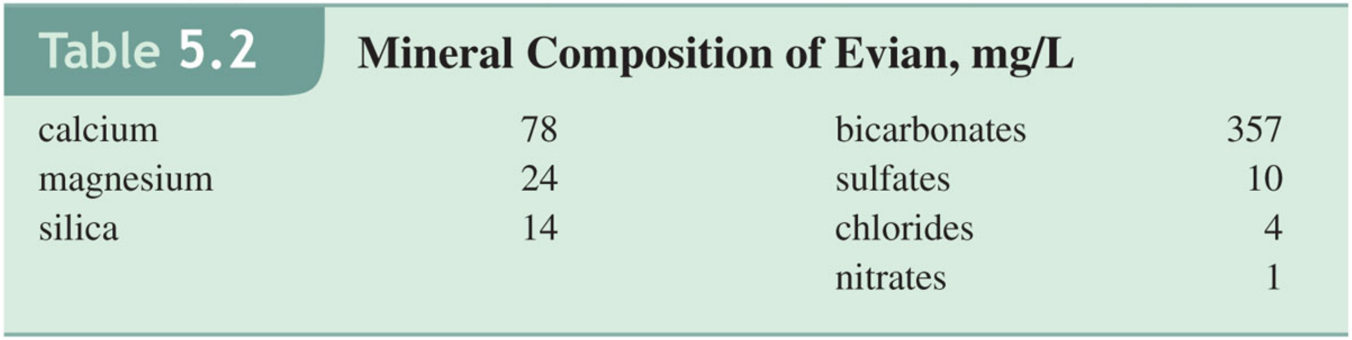


Table 5.2 Mineral Composition of Evian, mg/L

calcium	78	bicarbonates	357
magnesium	24	sulfates	10
silica	14	chlorides	4
		nitrates	1

Fort Collins Water, mg/L

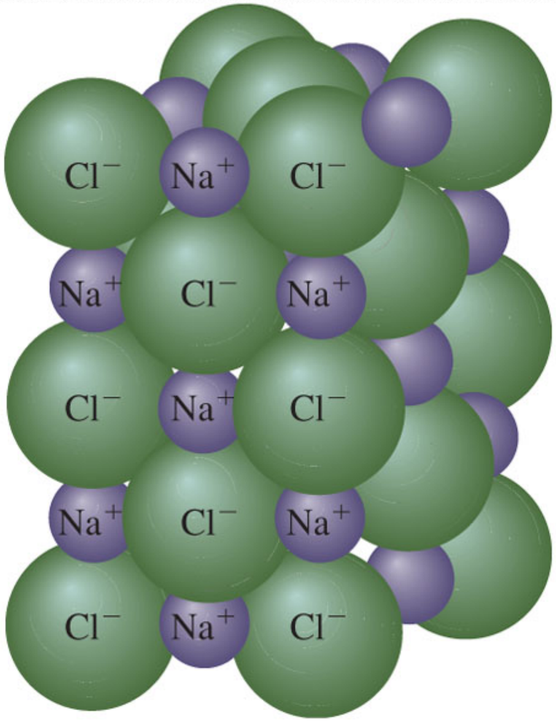
Ca^{2+}, calcium	16.6	SO_4^{2-}, sulfate	12.7 (250)
Mg^{2+}, magnesium	1.7	NO_3^-, nitrate	<0.0002 (0.001)
Na^+, sodium	2.8	F^-, fluoride	0.99 (4)
Cl^-, chloride	2.4	*(#) = max contaminant level (MCL)*	

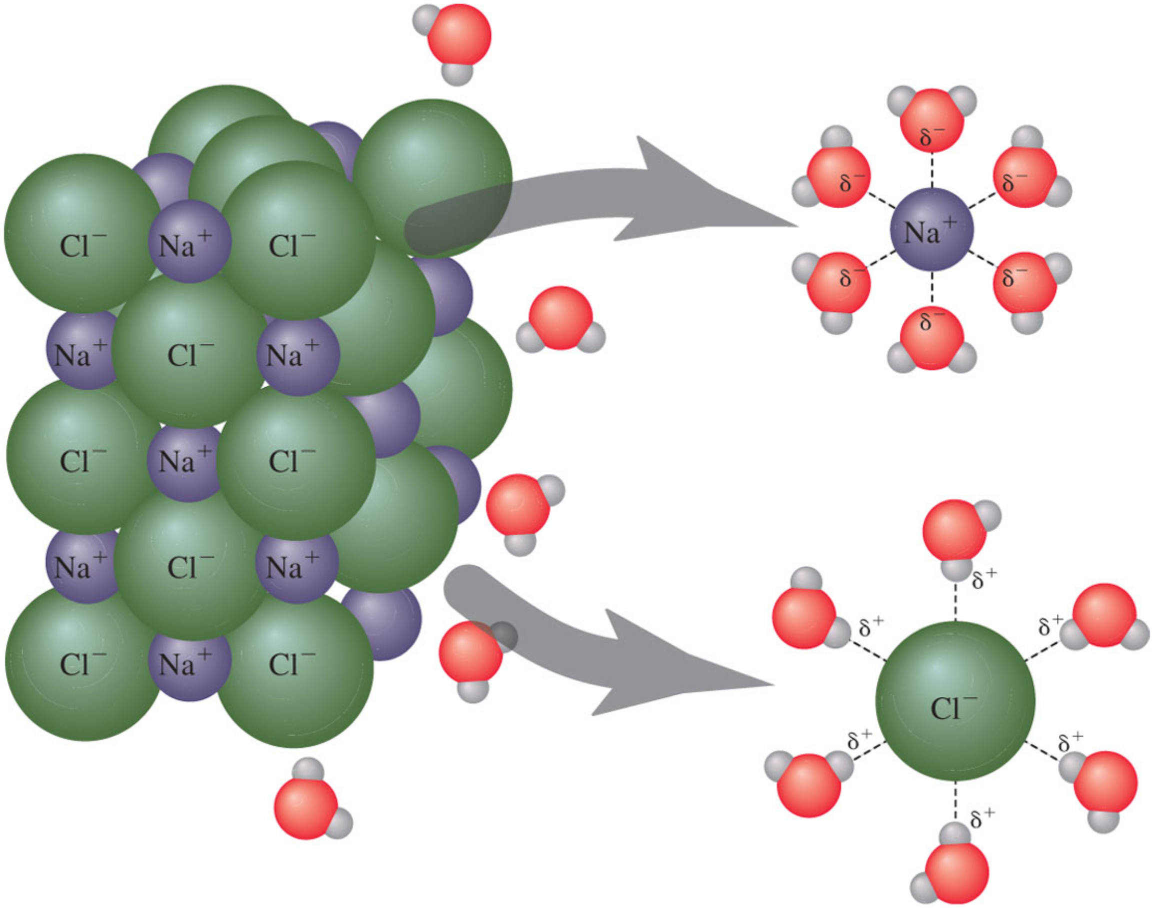
Aqueous Solutions of Ionic Compounds

Table salt, aka sodium chloride (NaCl)
alternating Na^+ and Cl^- ions form an **ionic compound**

Both “ends” of water participate in dissolving salt:

$$NaCl(s) \xrightarrow{H_2O} Na^+(aq) + Cl^-(aq)$$





Ion Formation

(Some) elements can achieve noble gas configuration by losing or gaining electrons

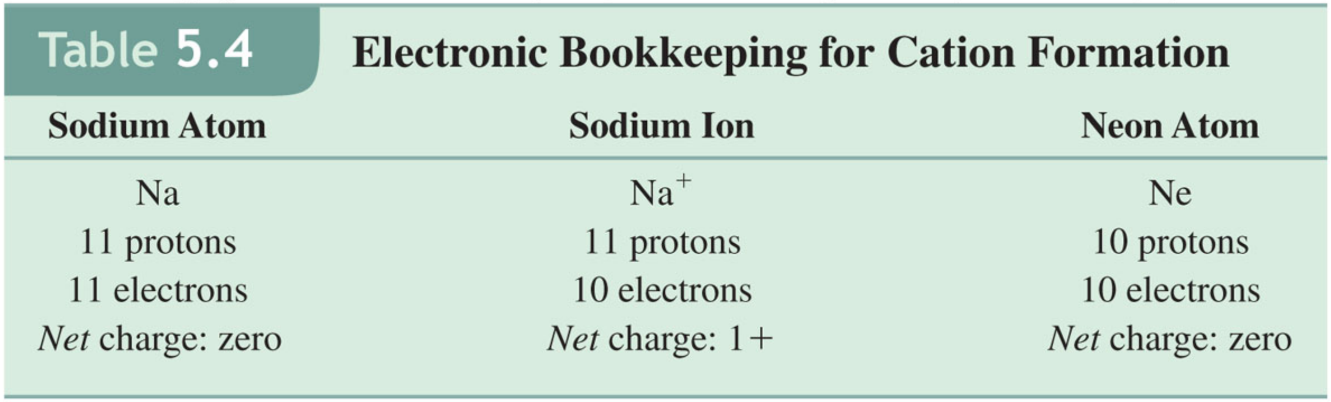


Table 5.4 Electronic Bookkeeping for Cation Formation

Sodium Atom	Sodium Ion	Neon Atom
Na 11 protons 11 electrons *Net* charge: zero	Na^+ 11 protons 10 electrons *Net* charge: 1+	Ne 10 protons 10 electrons *Net* charge: zero

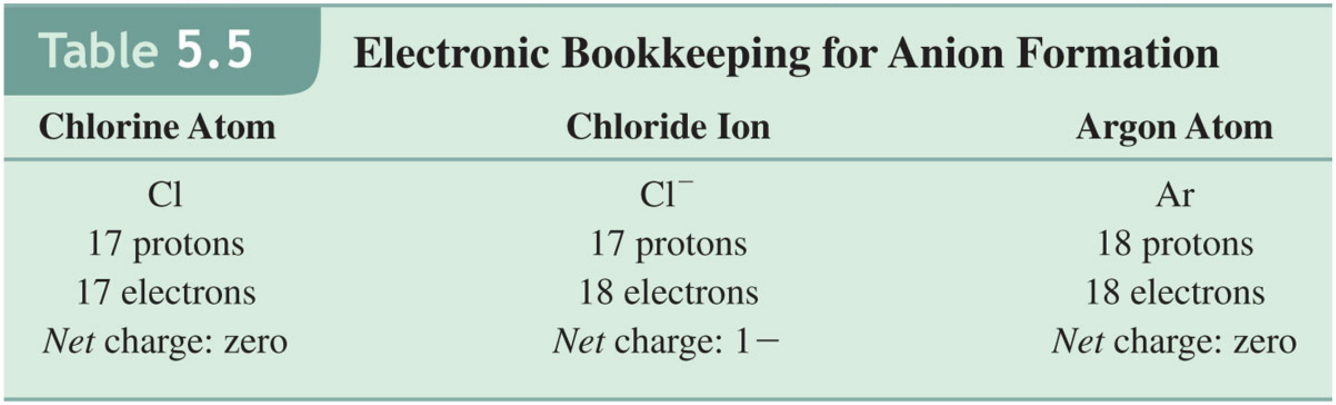
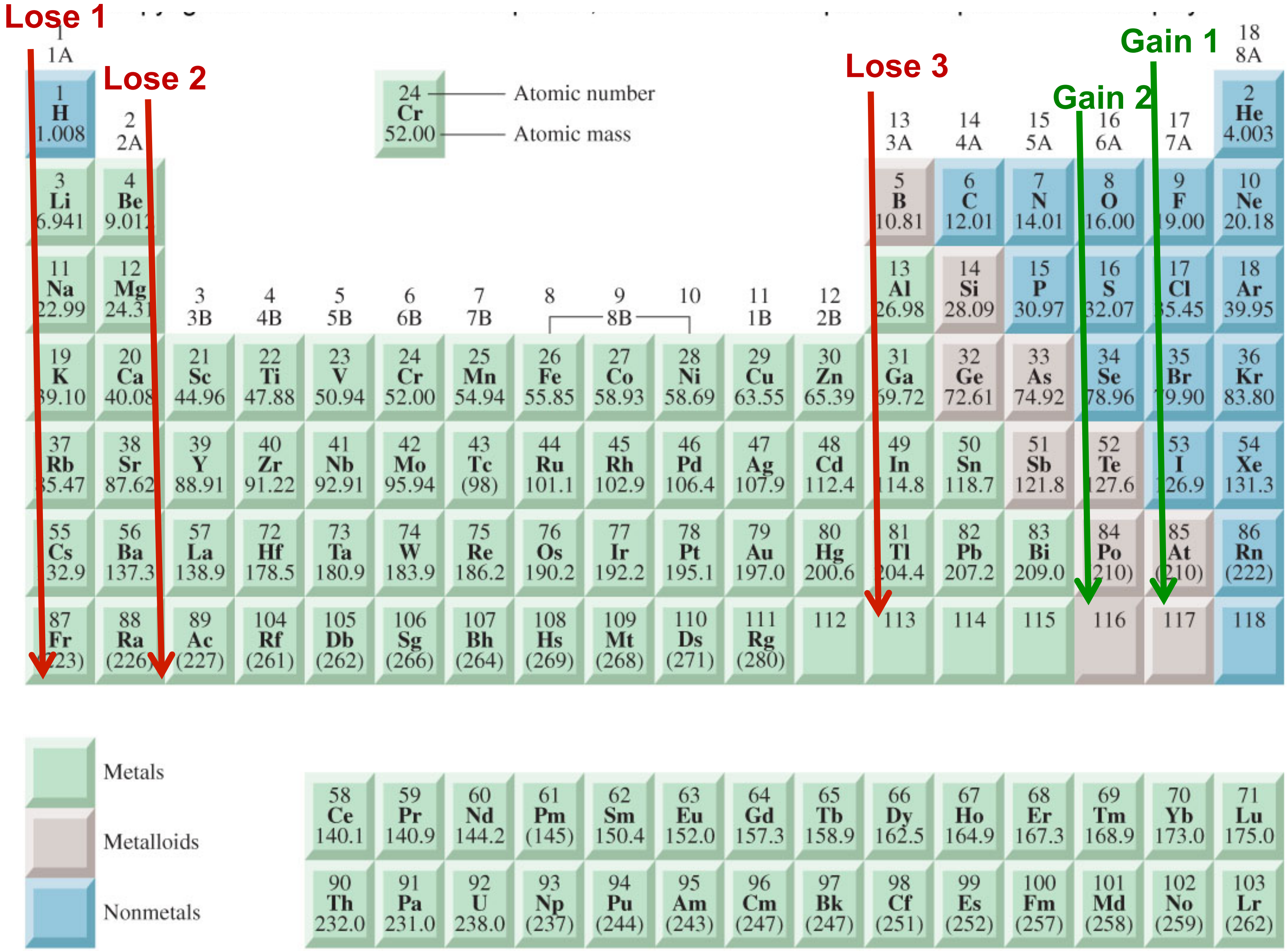


Table 5.5 Electronic Bookkeeping for Anion Formation

Chlorine Atom	Chloride Ion	Argon Atom
Cl 17 protons 17 electrons *Net* charge: zero	Cl^- 17 protons 18 electrons *Net* charge: 1−	Ar 18 protons 18 electrons *Net* charge: zero

Periodicity of Ion Formation



1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 H 1.008																	2 He 4.003
3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (269)	109 Mt (268)	110 Ds (271)	111 Rg (280)	112	113	114	115	116	117	118

58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

24 — Atomic number
Cr
52.00 — Atomic mass

🟩 Metals
▨ Metalloids
🟦 Nonmetals

Common Polyatomic Anions

Some ions made up of several atoms:

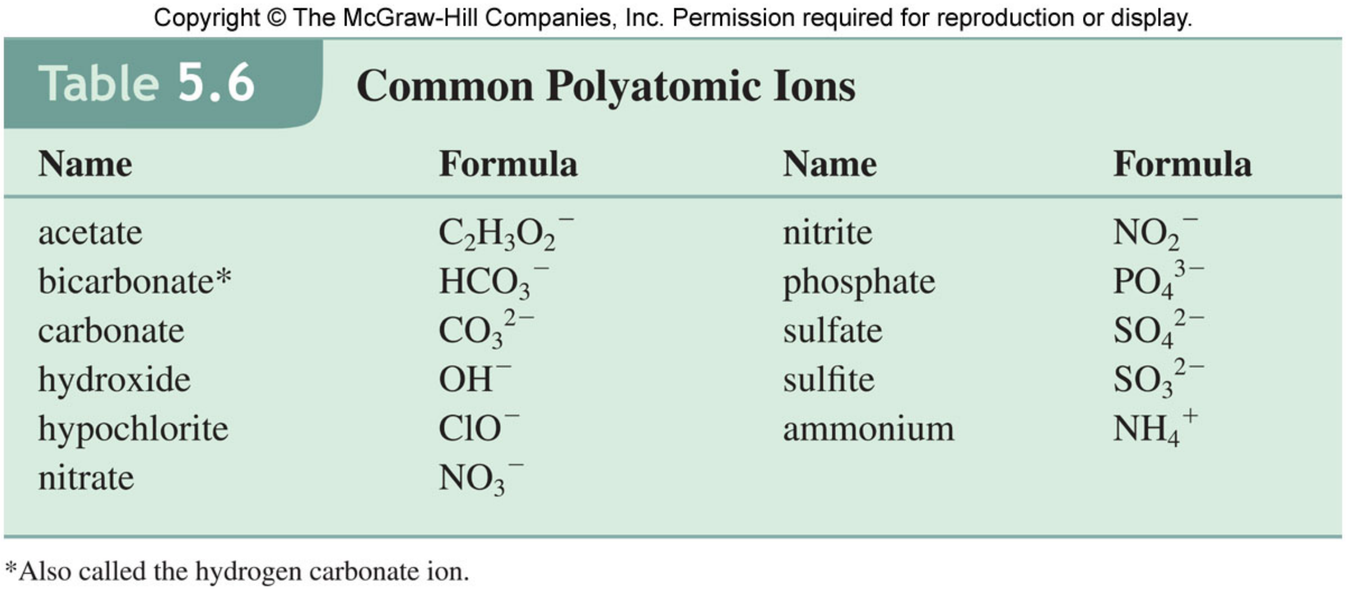


Table 5.6 Common Polyatomic Ions

Name	Formula	Name	Formula
acetate	$C_2H_3O_2^-$	nitrite	NO_2^-
bicarbonate*	HCO_3^-	phosphate	PO_4^{3-}
carbonate	CO_3^{2-}	sulfate	SO_4^{2-}
hydroxide	OH^-	sulfite	SO_3^{2-}
hypochlorite	ClO^-	ammonium	NH_4^+
nitrate	NO_3^-		

*Also called the hydrogen carbonate ion.

Formulas for ionic compounds balance charge (add up to zero):

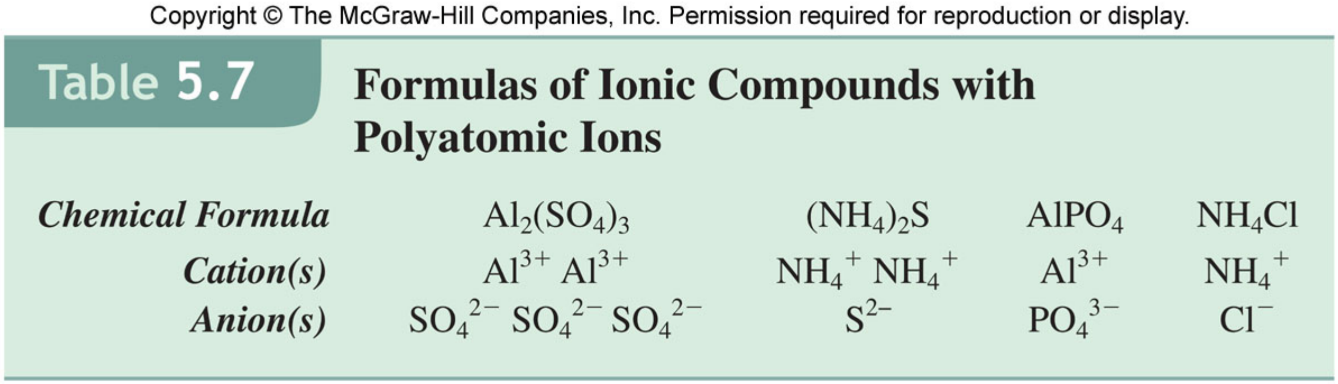


Table 5.7 Formulas of Ionic Compounds with Polyatomic Ions

Chemical Formula	$Al_2(SO_4)_3$	$(NH_4)_2S$	$AlPO_4$	NH_4Cl
Cation(s)	Al^{3+} Al^{3+}	NH_4^+ NH_4^+	Al^{3+}	NH_4^+
Anion(s)	SO_4^{2-} SO_4^{2-} SO_4^{2-}	S^{2-}	PO_4^{3-}	Cl^-

Understanding Charge in Ionic Compounds

- Elements/groups with low EN tend to form cations; elements/groups with high EN tend to form anions
- For ionic compounds, remember that the overall compound has to be neutral—i.e. the total charges have to balance
- Examples
  - Table salt: $NaCl = Na^{+} + Cl^{-}$
  - Calcium sulfate: $CaSO_4 = Ca^{2+} + (SO_4)^{2-}$
  - Iron(III) oxide (aka rust): $Fe_2O_3 = 2Fe^{3+} + 3O^{2-}$

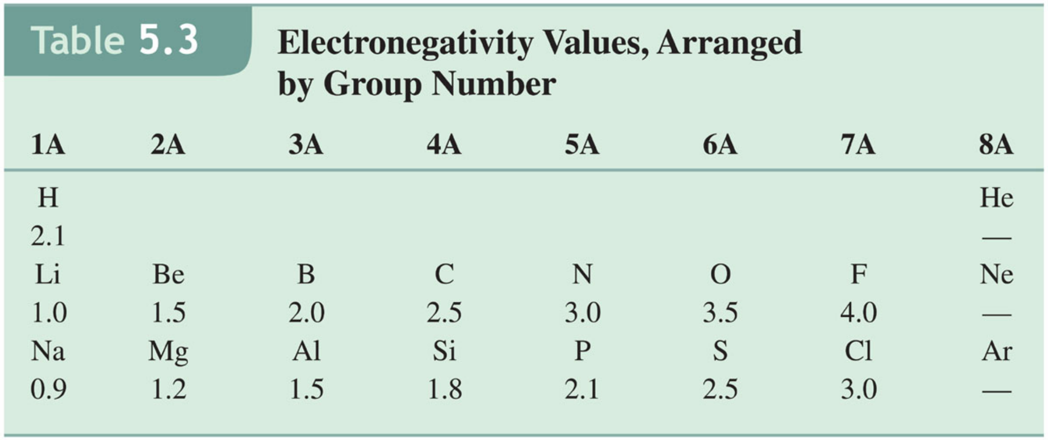


Table 5.3 Electronegativity Values, Arranged by Group Number

1A	2A	3A	4A	5A	6A	7A	8A
H							He
2.1							—
Li	Be	B	C	N	O	F	Ne
1.0	1.5	2.0	2.5	3.0	3.5	4.0	—
Na	Mg	Al	Si	P	S	Cl	Ar
0.9	1.2	1.5	1.8	2.1	2.5	3.0	—

(Aqueous) Solutions: Concentration Units

Important concentration units:

% (parts per hundred)

ppm: $$1\ \text{ppm} = \frac{1\ \text{g solute}}{1\text{x}10^{6}\ \text{g water}} \times \frac{1000\ \text{mg solute}}{1\ \text{g solute}} \times \frac{1000\ \text{g water}}{1\ \text{L water}} = \frac{1\ \text{mg solute}}{1\ \text{L water}}$$

ppb: $$1\ \text{ppb} = \frac{1\ \text{g solute}}{1\text{x}10^{9}\ \text{g water}} \times \frac{1\text{x}10^{6}\ \mu\text{g solute}}{1\ \text{g solute}} \times \frac{1000\ \text{g water}}{1\ \text{L water}} = \frac{1\ \mu\text{g solute}}{1\ \text{L water}}$$

Molarity (M): $$\text{Molarity} = \frac{\text{moles of solute}}{\text{L of solution}}$$

Mass / Mole

How many atoms are in 12 grams of C-12?
Need to use *unit conversion* (*factor-label method*) to get the answer:

$1 \text{ amu} = 1.66\text{x}10^{-24} \text{ g}$ → $\frac{1 \text{ amu}}{1.66\text{x}10^{-24}\text{g}}$ or $\frac{1.66\text{x}10^{-24}\text{g}}{1 \text{ amu}}$

$1 \text{ atom C-12} = 12 \text{ amu}$ → $\frac{1 \text{ atom C-12}}{12 \text{ amu}}$ or $\frac{12 \text{ amu}}{1 \text{ atom C-12}}$

ratios

$$12 \text{ g C-12} \times \frac{1 \text{ amu}}{1.66\text{x}10^{-24}\text{g}} \times \frac{1 \text{ atom C-12}}{12 \text{ amu}} = 6.02\text{x}10^{23} \text{ atoms C-12}$$

↑

Avogadro's number

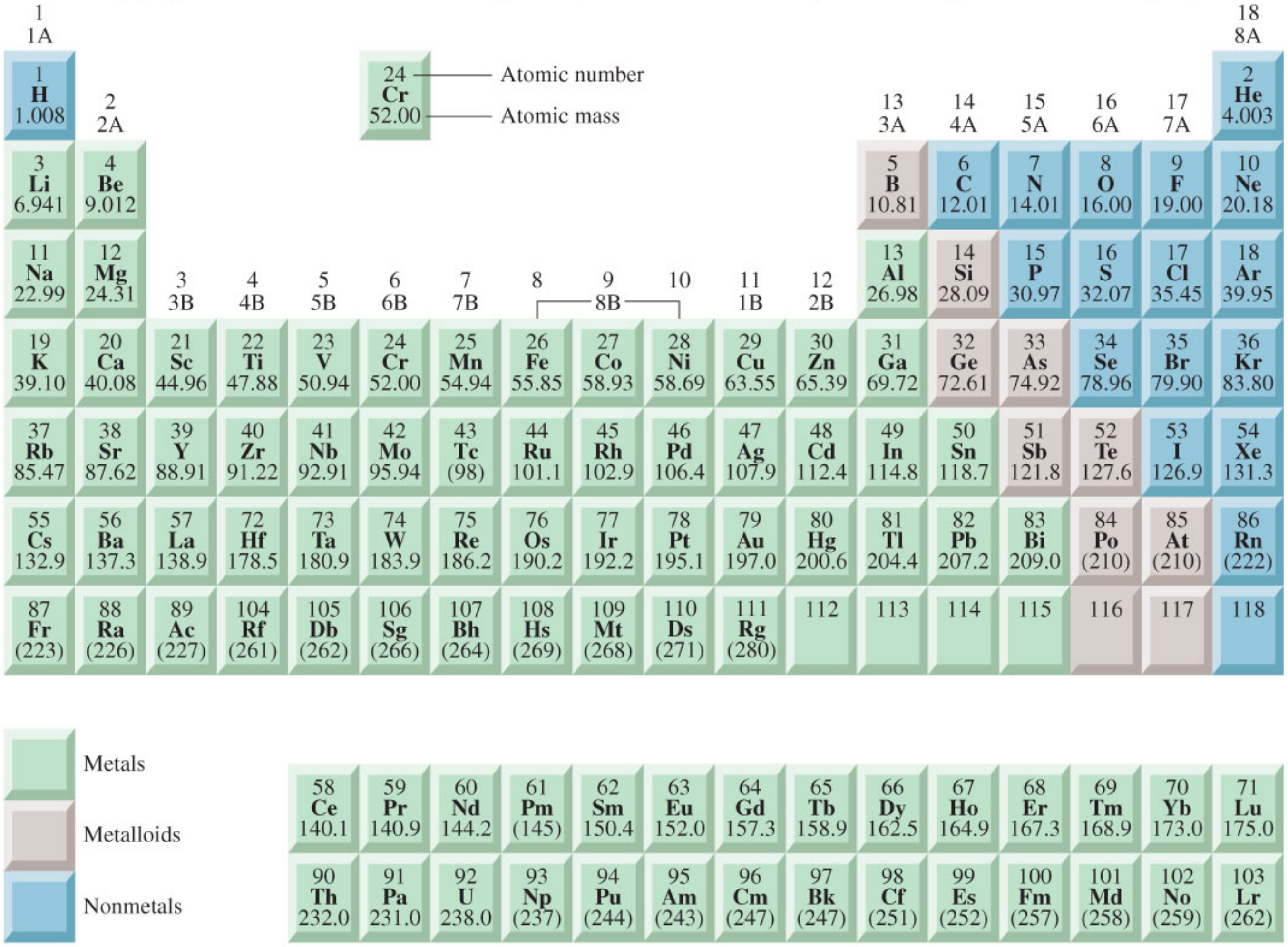
12 eggs = 1 dozen eggs

$6.02\text{x}10^{23}$ eggs = 1 **mole** eggs

The Periodic Table (mass numbers)

Elements are arranged in order of atomic number (# of protons) & in columns (groups) based on chemical properties

Note: the #s below the chemical symbols are **atomic masses**



24 — Atomic number
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52.00 — Atomic mass

1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 **H** 1.008																	2 **He** 4.003
3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.31											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.88	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.61	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
55 **Cs** 132.9	56 **Ba** 137.3	57 **La** 138.9	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.9	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** (210)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89 **Ac** (227)	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (269)	109 **Mt** (268)	110 **Ds** (271)	111 **Rg** (280)	112	113	114	115	116	117	118

🟩 Metals
▨ Metalloids
🟦 Nonmetals

58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** (145)	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.3	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 168.9	70 **Yb** 173.0	71 **Lu** 175.0
90 **Th** 232.0	91 **Pa** 231.0	92 **U** 238.0	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

The 1–18 group designation has been recommended by the International Union of Pure and Applied Chemistry (IUPAC) but is not yet in wide use. In this text we use the standard U.S. notation for group numbers (1A–8A and 1B–8B). No name has been assigned for element 112. Elements 113–118 have not yet been synthesized.

$C + O_2 \rightarrow CO_2$

The following statements are consistent with the chemical equation above:

1 atom Carbon reacts with 1 molecule Oxygen to form 1 molecule carbon dioxide

12 atoms Carbon react with 12 molecules Oxygen to form 12 molecules carbon dioxide

1 dozen Carbon atoms react with 1 dozen Oxygen molecules to form 1 dozen carbon dioxide molecules

$6.02x10^{23}$ Carbon atoms react with $6.02x10^{23}$ Oxygen molecules to form $6.02x10^{23}$ carbon dioxide molecules

1 mole Carbon atoms react with 1 mole Oxygen molecules to form 1 mole carbon dioxide molecules

How many grams of CO_2 are formed from 10 g of Carbon?

1 mole (mol) Carbon = 12.01 g

1 mol Oxygen (O_2) = 2 mol Oxygen atoms

1 mol Oxygen (O_2) = 2x16.00 g = 32.00 g

1 mol CO_2 = 1 mol C + 2 mol O

$$= \left(1 \text{ mol C} \times \frac{12.01 \text{ g C}}{1 \text{ mol C}}\right) + \left(2 \text{ mol O} \times \frac{16.00 \text{ g O}}{1 \text{ mol O}}\right)$$

$$= 12.01 \text{ g C} + 32.0 \text{ g O}$$

$$1 \text{ mol } CO_2 = 44.01 \text{ g } CO_2$$

12 g Carbon reacts with 32 g Oxygen to form 44 g carbon dioxide

The C-to-CO_2 ratio in CO_2 is $\frac{12.01 \text{ g C}}{44.01 \text{ g } CO_2}$

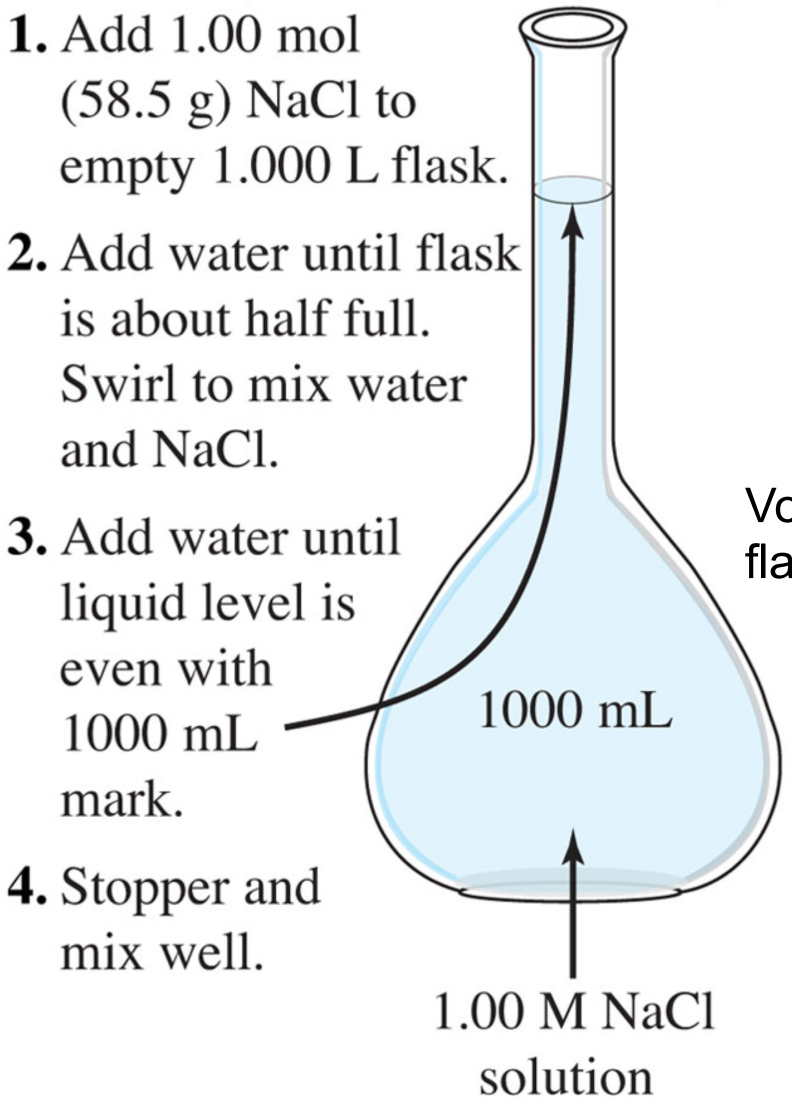
$$100.0 \text{ g } CO_2 \times \frac{12.01 \text{ g C}}{44.01 \text{ g } CO_2} = 27.29 \text{ g C}$$

the mass % of C in CO_2 is 27.29%

$$10 \text{ g Carbon} \times \frac{1 \text{ mole Carbon}}{12.01 \text{ g Carbon}} \times \frac{1 \text{ mole } CO_2}{1 \text{ mole Carbon}} \times \frac{44.01 \text{ g } CO_2}{1 \text{ mole } CO_2} = 37 \text{ g } CO_2$$

Molarity (M)

$$\text{Molarity} = \frac{\text{moles of solute}}{\text{L of solution}}$$



1. Add 1.00 mol (58.5 g) NaCl to empty 1.000 L flask.

2. Add water until flask is about half full. Swirl to mix water and NaCl.

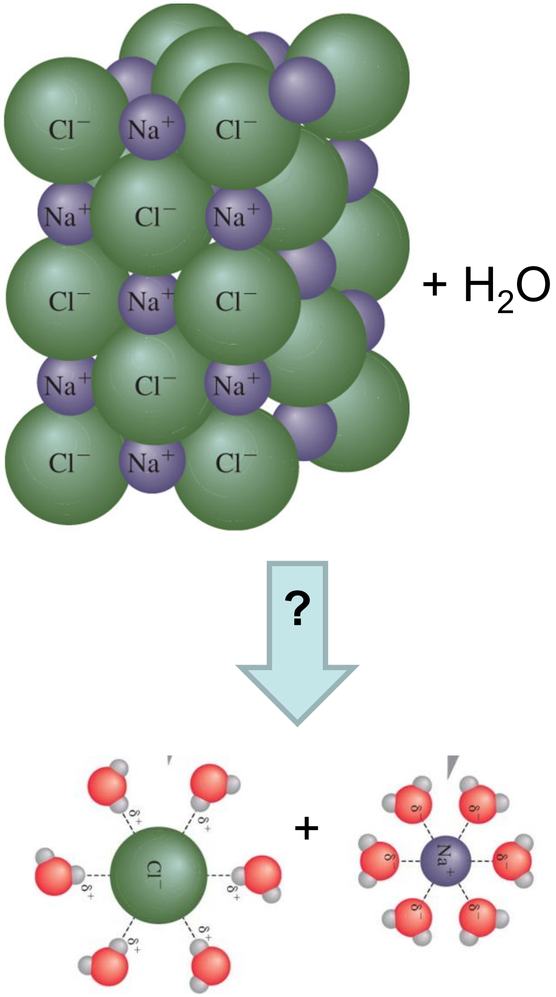
3. Add water until liquid level is even with 1000 mL mark.

4. Stopper and mix well.

Volumetric flask

Solubility of Ionic Compounds in Water

Competition: electrostatics in the ionic crystal versus interactions with a large number of water molecules…



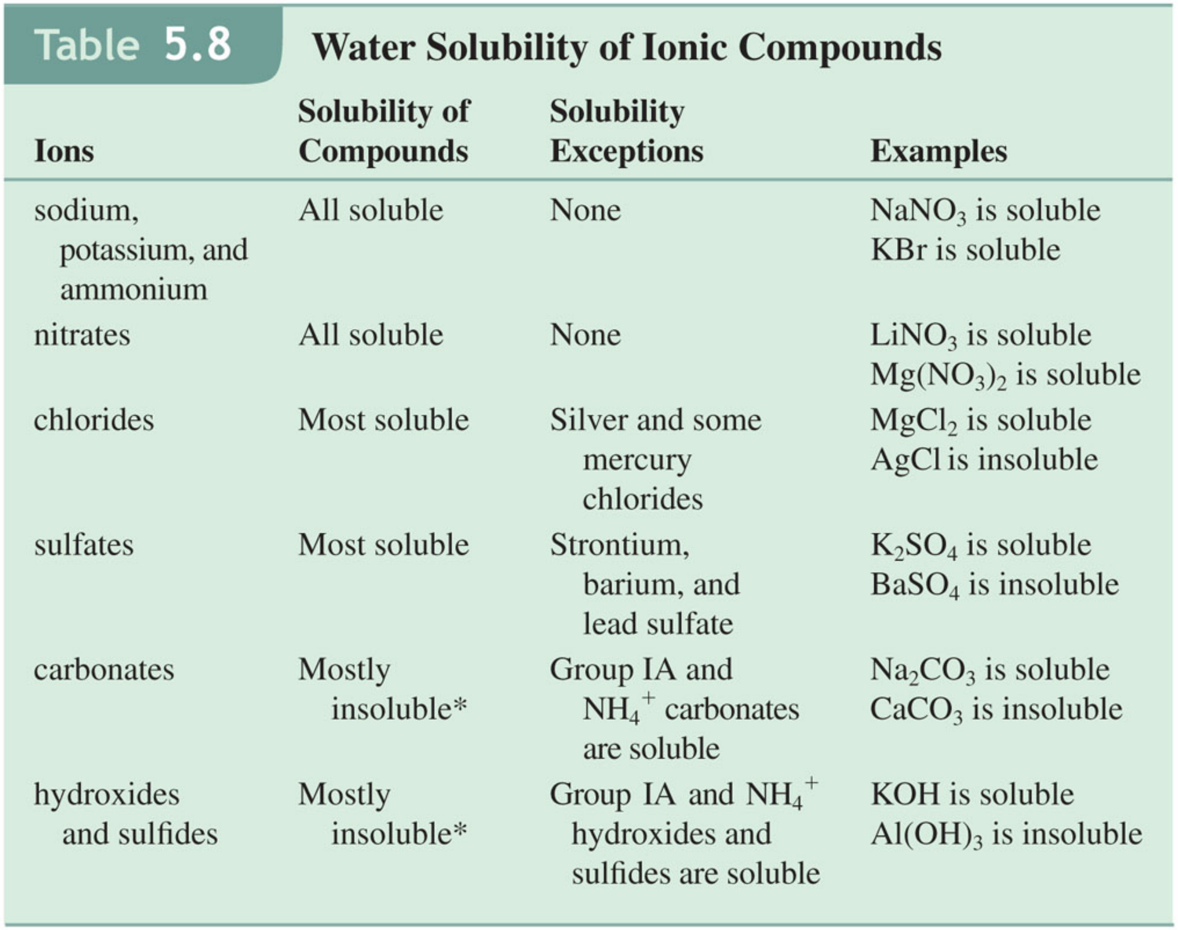


Table 5.8 Water Solubility of Ionic Compounds

Ions	Solubility of Compounds	Solubility Exceptions	Examples
sodium, potassium, and ammonium	All soluble	None	$NaNO_3$ is soluble KBr is soluble
nitrates	All soluble	None	$LiNO_3$ is soluble $Mg(NO_3)_2$ is soluble
chlorides	Most soluble	Silver and some mercury chlorides	$MgCl_2$ is soluble AgCl is insoluble
sulfates	Most soluble	Strontium, barium, and lead sulfate	K_2SO_4 is soluble $BaSO_4$ is insoluble
carbonates	Mostly insoluble*	Group IA and NH_4^+ carbonates are soluble	Na_2CO_3 is soluble $CaCO_3$ is insoluble
hydroxides and sulfides	Mostly insoluble*	Group IA and NH_4^+ hydroxides and sulfides are soluble	KOH is soluble $Al(OH)_3$ is insoluble

*Insoluble means that the compounds have extremely low solubilities in water (less than 0.01 M). All ionic compounds have at least a very small solubility in water.

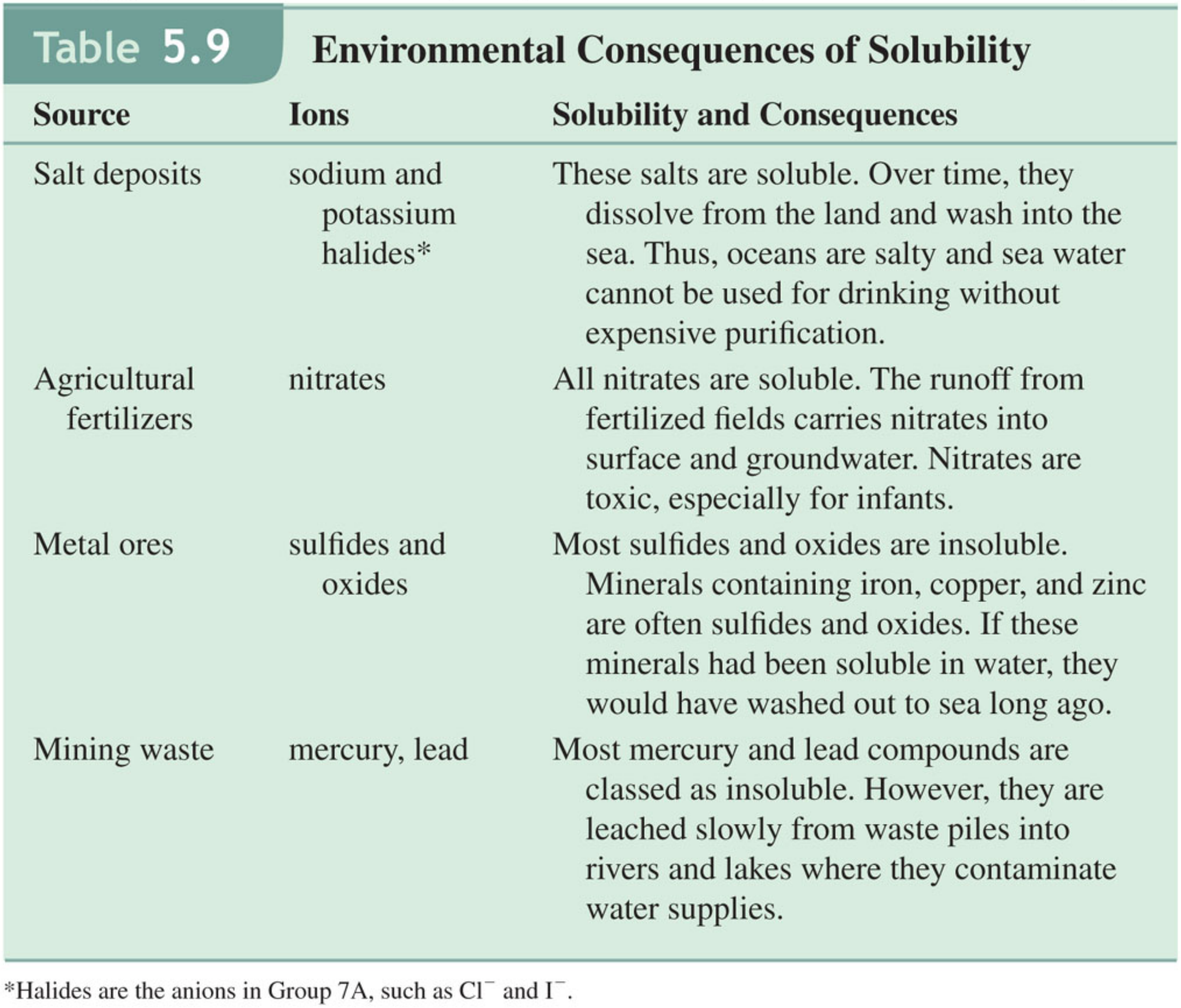


Table 5.9 Environmental Consequences of Solubility

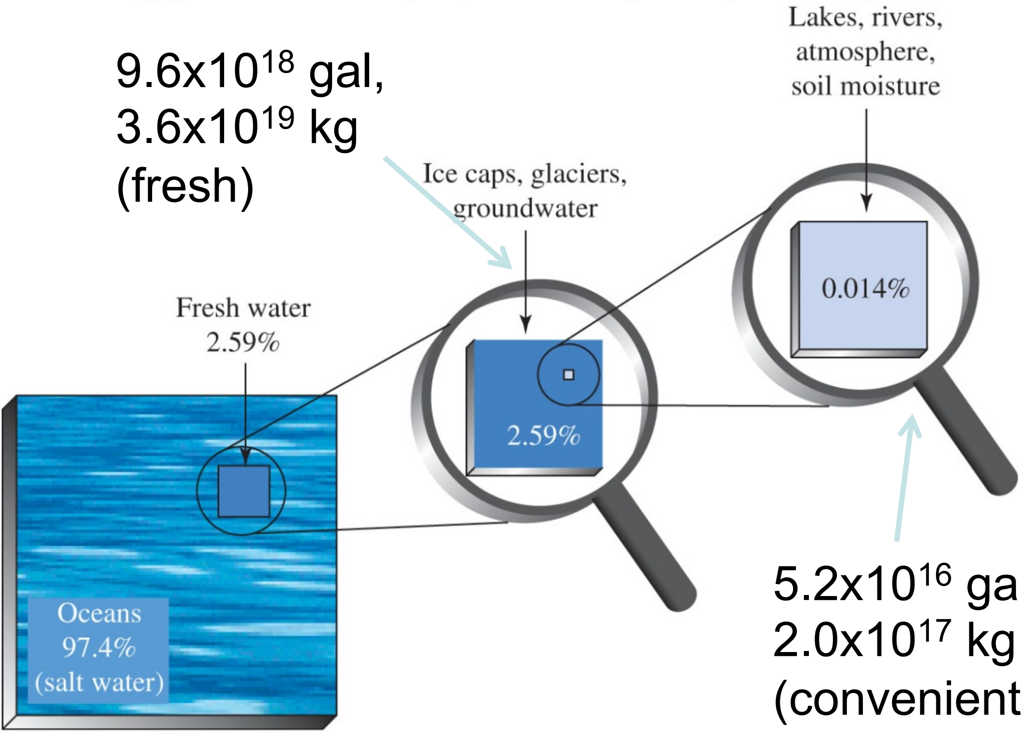
Source	Ions	Solubility and Consequences
Salt deposits	sodium and potassium halides*	These salts are soluble. Over time, they dissolve from the land and wash into the sea. Thus, oceans are salty and sea water cannot be used for drinking without expensive purification.
Agricultural fertilizers	nitrates	All nitrates are soluble. The runoff from fertilized fields carries nitrates into surface and groundwater. Nitrates are toxic, especially for infants.
Metal ores	sulfides and oxides	Most sulfides and oxides are insoluble. Minerals containing iron, copper, and zinc are often sulfides and oxides. If these minerals had been soluble in water, they would have washed out to sea long ago.
Mining waste	mercury, lead	Most mercury and lead compounds are classed as insoluble. However, they are leached slowly from waste piles into rivers and lakes where they contaminate water supplies.

*Halides are the anions in Group 7A, such as Cl^- and I^-.

(Drinking) Water Sources

How much water is there in the world?

$3.7x10^{20}$ gallons, $1.4x10^{21}$ kg



$9.6x10^{18}$ gal, $3.6x10^{19}$ kg (fresh)

$5.2x10^{16}$ gal, $2.0x10^{17}$ kg (convenient)

Ogallala Aquifer

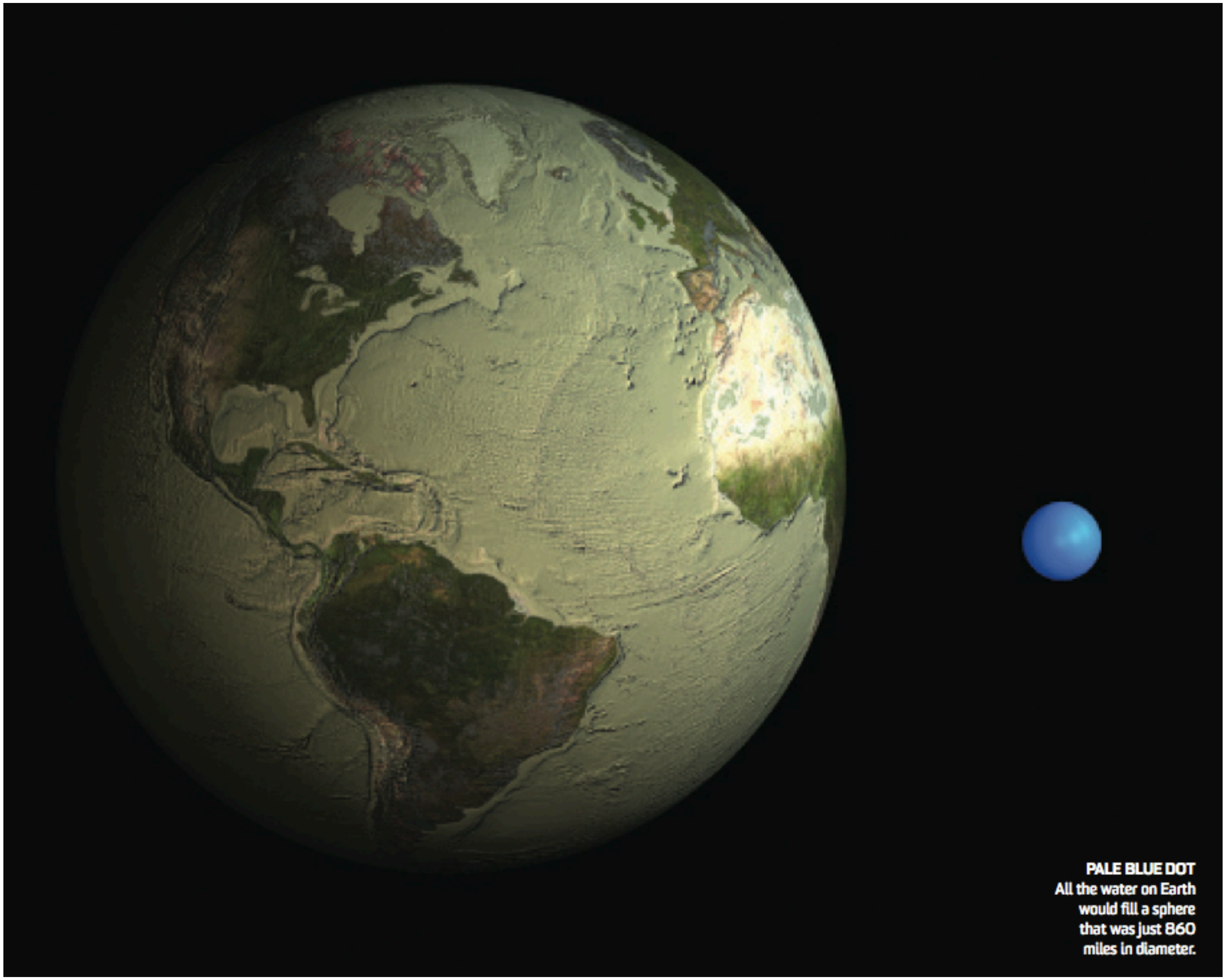
Surface water: lakes, rivers, reservoirs
drinking H_2O source for most major cities

Ground water: aquifers
drinking H_2O source for most rural areas

US water usage (10^9 gallons/day) in 2000:

194 thermal electric power, 137 irrigation
43 domestic, 19 industrial, 14 miscellaneous

World’s Water



Elizabeth Royte
POPULAR SCIENCE
July 2012, p52-53

The 750Gt Carbon in the atmosphere would fill a sphere ½ mile in diameter as a liquid

Protecting our Drinking Water

Maximum contaminant level goal (**MCLG**):

maximum level of a contaminant in drinking water at which there is no known adverse effect on humans

Maximum contaminant level (**MCL**):

sets the legal limit for concentration of a contaminant

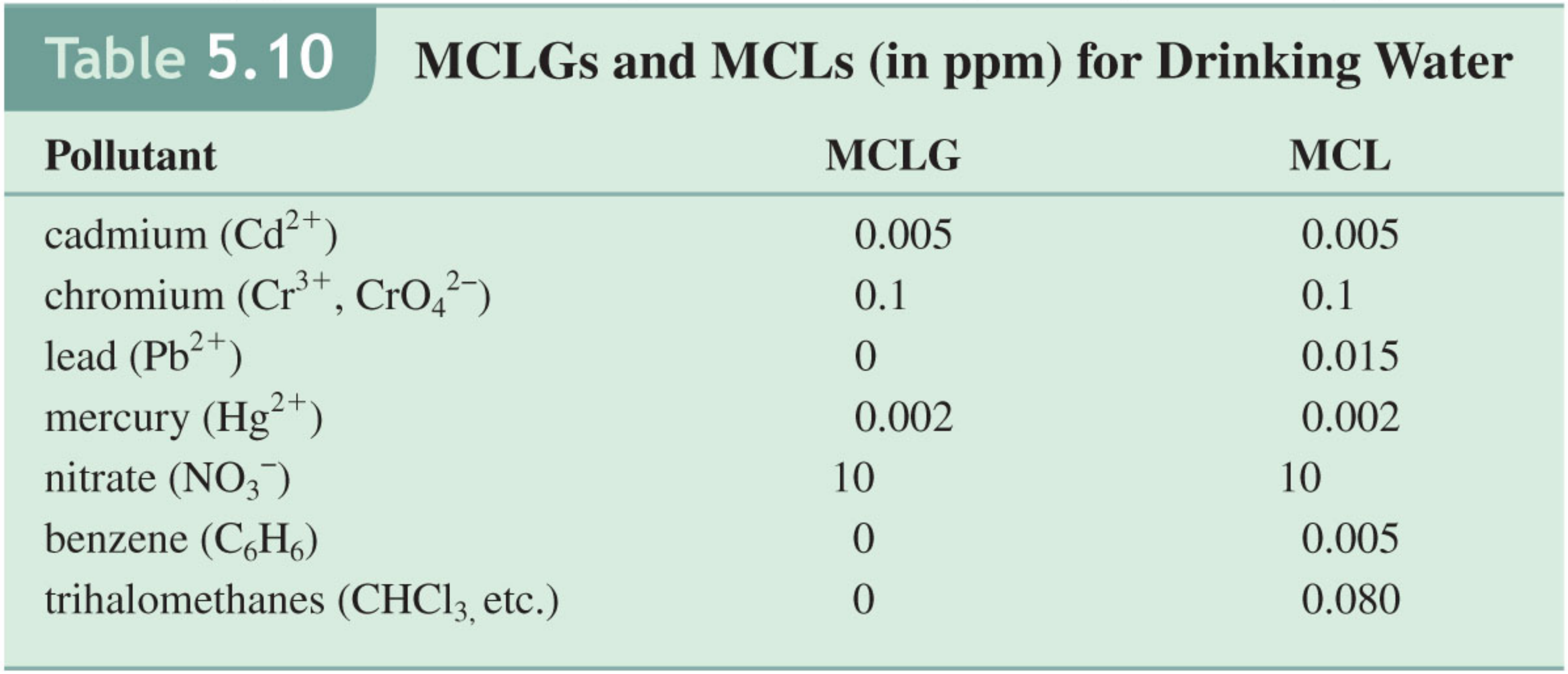
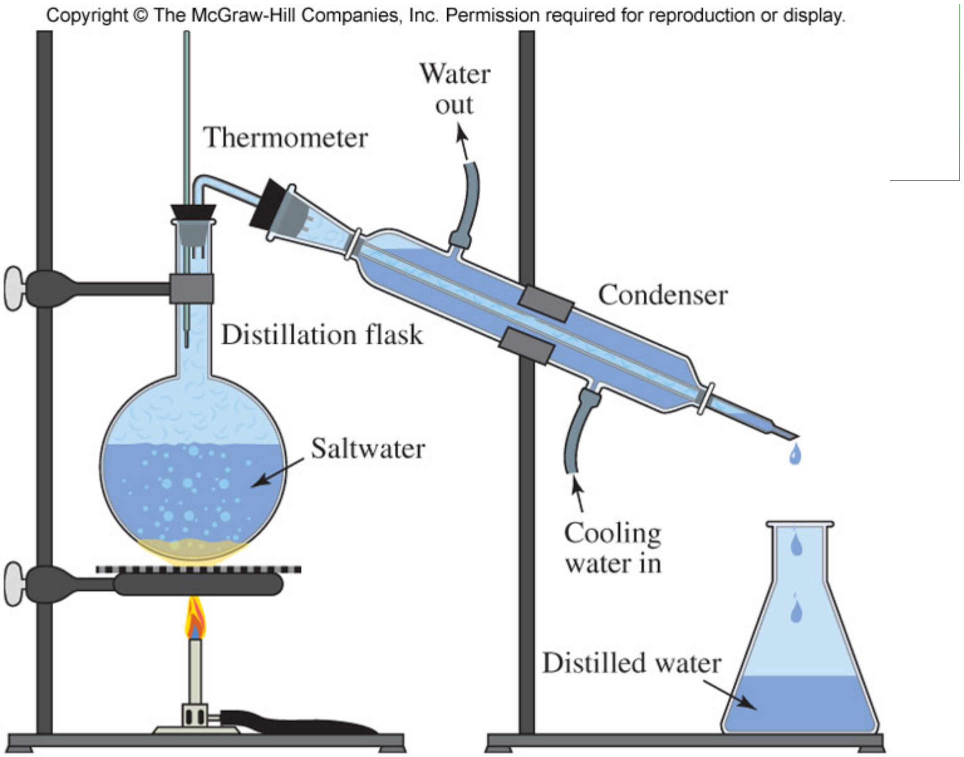


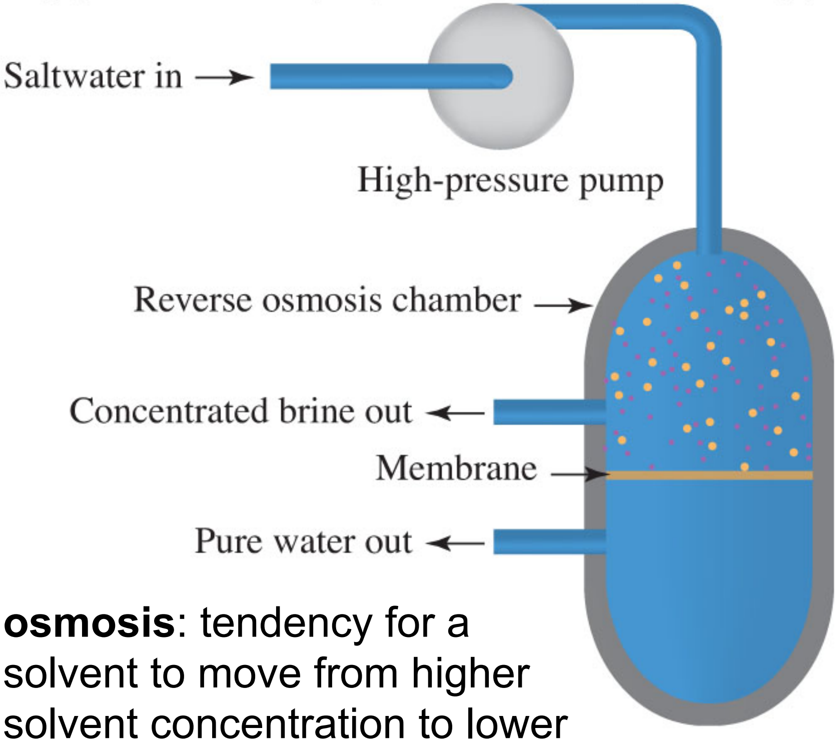
Table 5.10 MCLGs and MCLs (in ppm) for Drinking Water

Pollutant	MCLG	MCL
cadmium (Cd^{2+})	0.005	0.005
chromium (Cr^{3+}, CrO_4^{2-})	0.1	0.1
lead (Pb^{2+})	0	0.015
mercury (Hg^{2+})	0.002	0.002
nitrate (NO_3^-)	10	10
benzene (C_6H_6)	0	0.005
trihalomethanes ($CHCl_3$, etc.)	0	0.080

Desalination

Most (~98%) water is salt water.
Water can be **desalinated** by **reverse osmosis** or **distillation** (but both require energy)





osmosis: tendency for a solvent to move from higher solvent concentration to lower solvent concentration (why you can't live on seawater)

0.31 kJ/g to heat H_2O from 25˚C to 100˚C
2.26 kJ/g to boil H_2O
How much energy to distill 1 gallon of H_2O?
(need to break H-bonds)

$$1\text{ gallon} \times \frac{3.785\text{ L}}{1\text{ gallon}} \times \frac{1000\text{g}}{1\text{ L}} \times \frac{2.57\text{kJ}}{1\text{ g}} = 9.7x10^{3}\text{kJ}$$

$43x10^9$ gal/day for domestic use (USA)

$$43x10^{9}\text{ gallons/day} \times \frac{9.7x10^{3}\text{kJ}}{1\text{ gallon}} \times \frac{365\text{days}}{1\text{ year}} = 1.52x10^{15}\text{kJ/year}$$

=1.52 EJ/year (the total US annual energy use is 100 EJ/year)