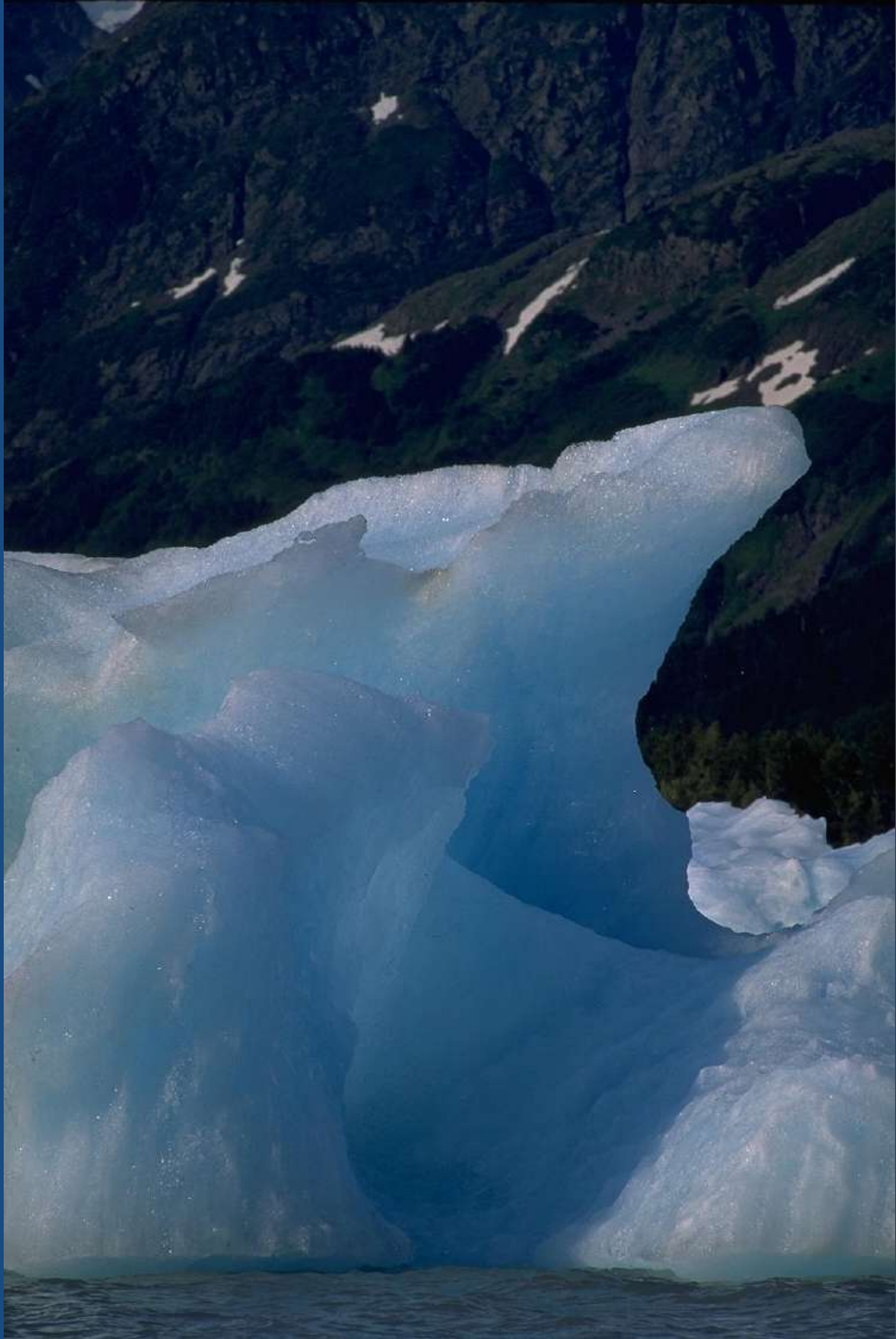
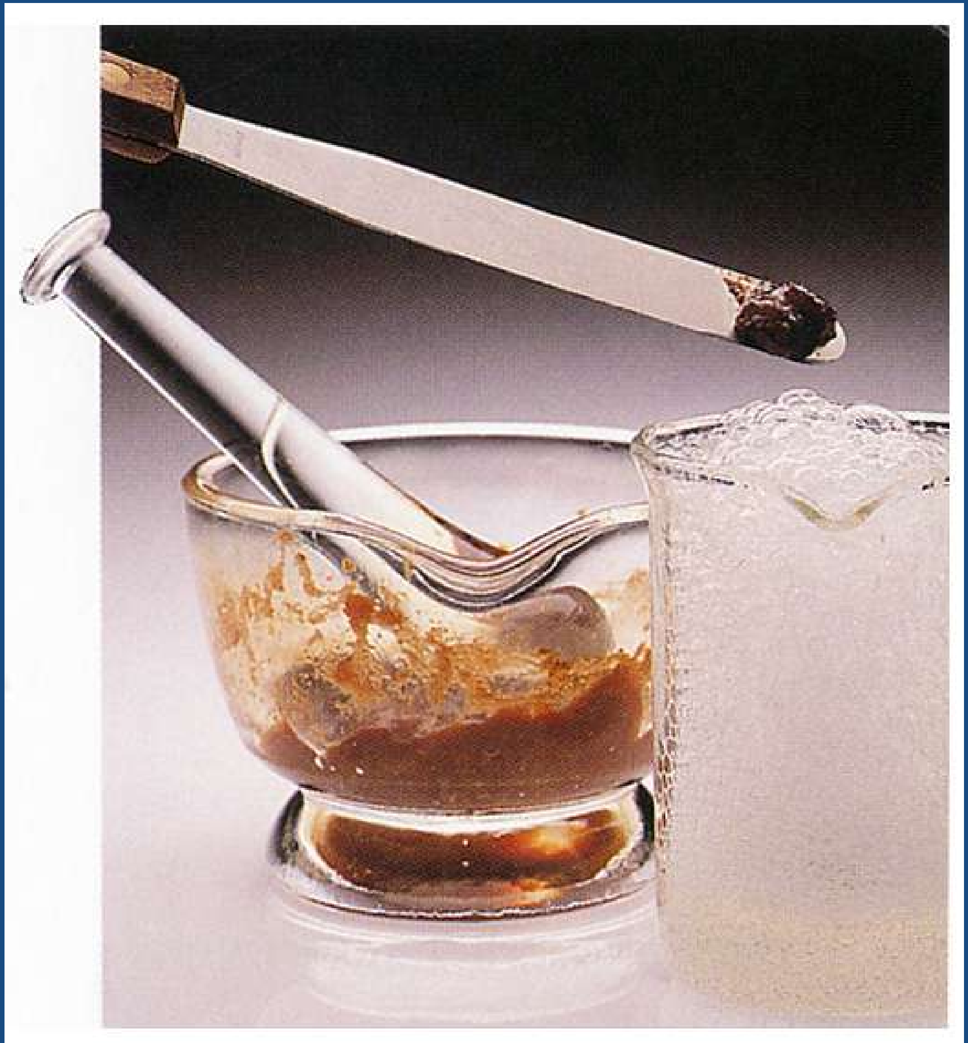
chapter 8
reactions in aqueous solutions

warning: another big chapter
built on previous chapters!

- the most important rxns in our lives happen in water
- here we look at some rxns that **take place in water**
- and look at **why** they happen
- and learn to **predict** what they are making



8.1 predicting whether a reaction will occur



- why do reactants “want” to form products anyway?
- those are **driving forces**, the most common are…

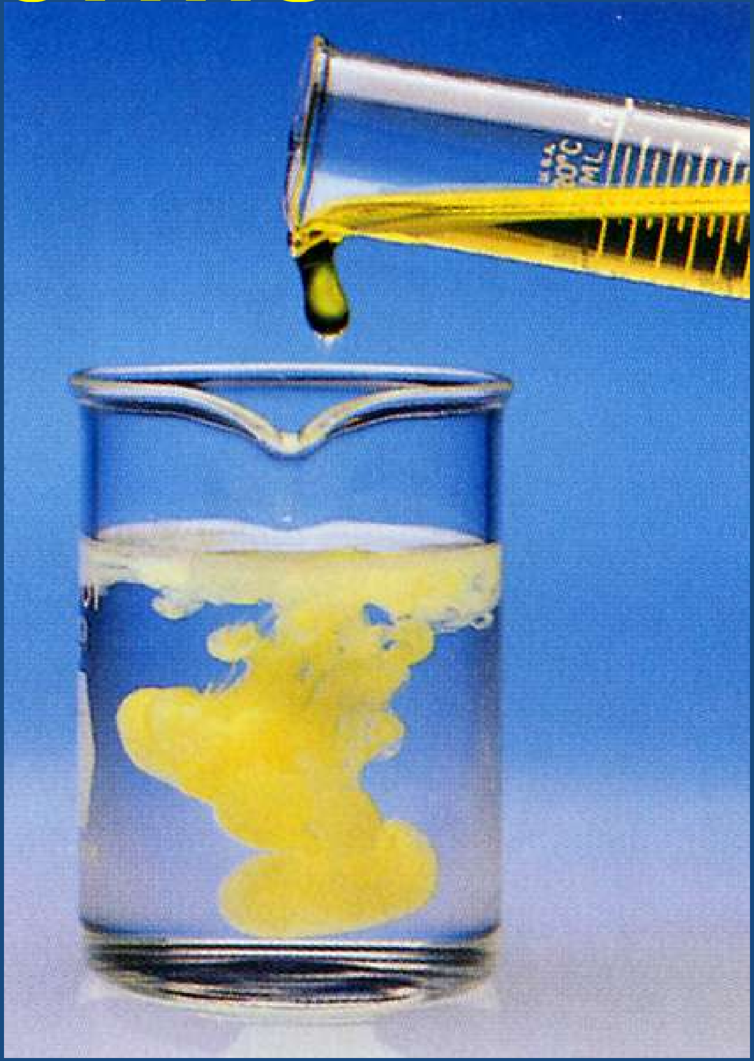
Reaction will happen if:

1. formation of a solid
2. formation of water
3. transfer of electrons
4. formation of a gas

- if these might result, the reaction is probably going to happen

8.2 reactions in which a solid forms

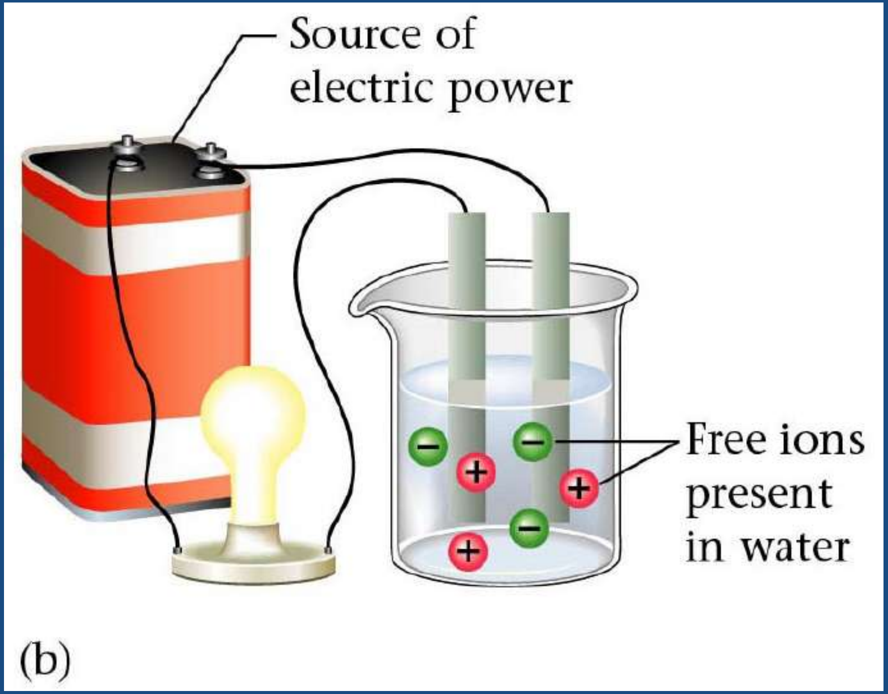
- one driving force is the formation of a solid
- solid = **precipitate**
- called **precipitation rxn**
- *when a rxn like this happens, can we figure out what was formed?*



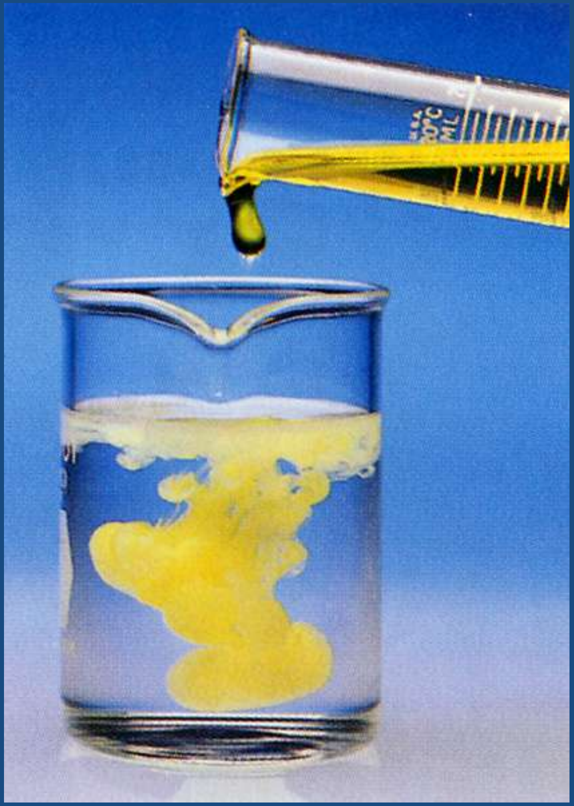
- first we have to consider what is even a *possible* product
- how? who are the players? why will they get together? no problem! relax, fercryinoutloud!

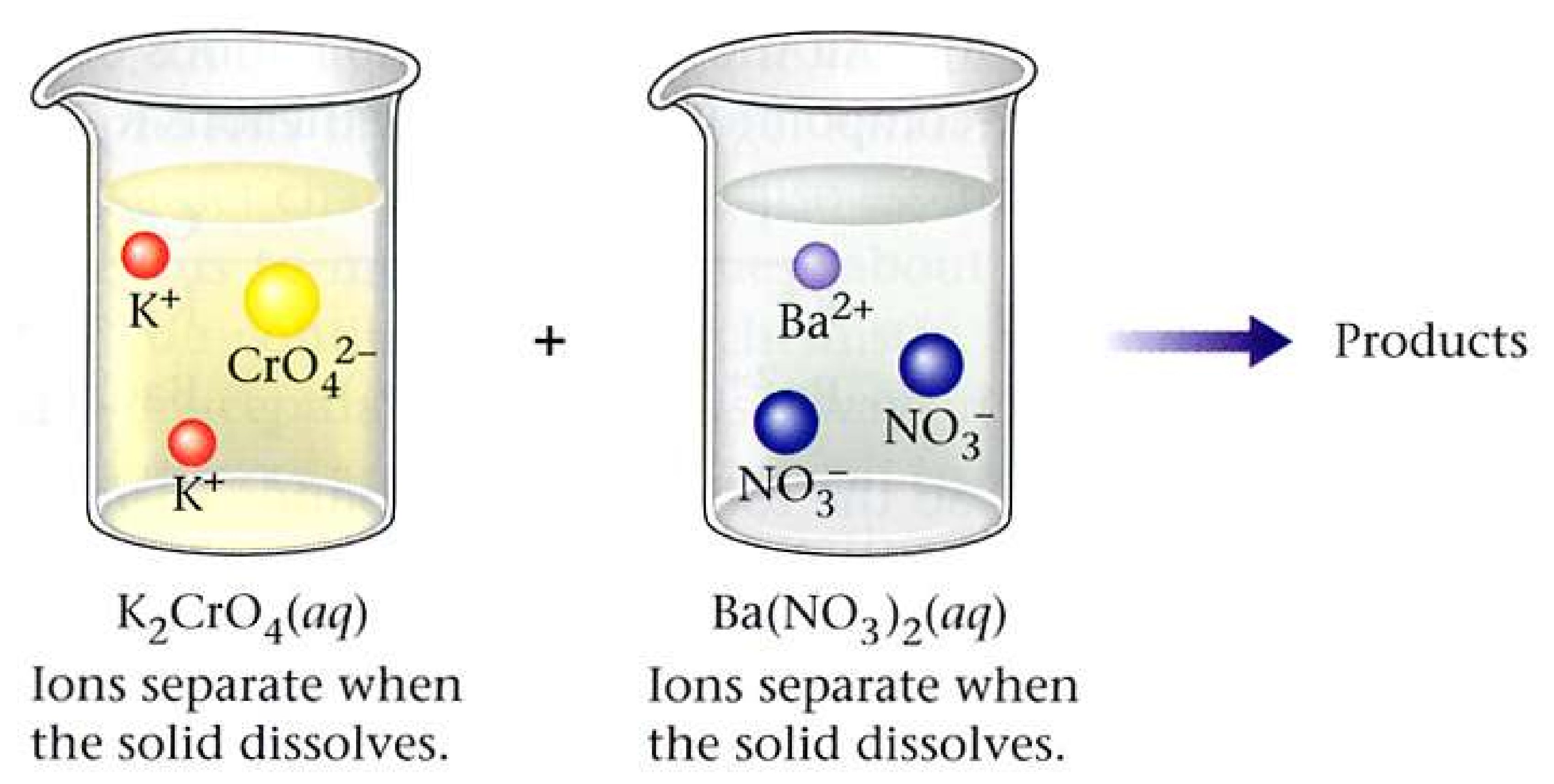
what happens when an ionic compound dissolves in water?

- virtually every time an ionic cmpd dissolves in water all the ions separate!
- = **dissociation**
- we know this b/c ionic solns are great conductors of electricity



- when each ionic cmpd "unit" breaks up into its ions the cmpd is called a **strong electrolyte**
- important point! *when ionic cmpds dissolve their separated ions are floating around (duh!)*
- for the opening picture…
- K_2CrO_4 + $Ba(NO_3)_2$ --> Products looks like this…





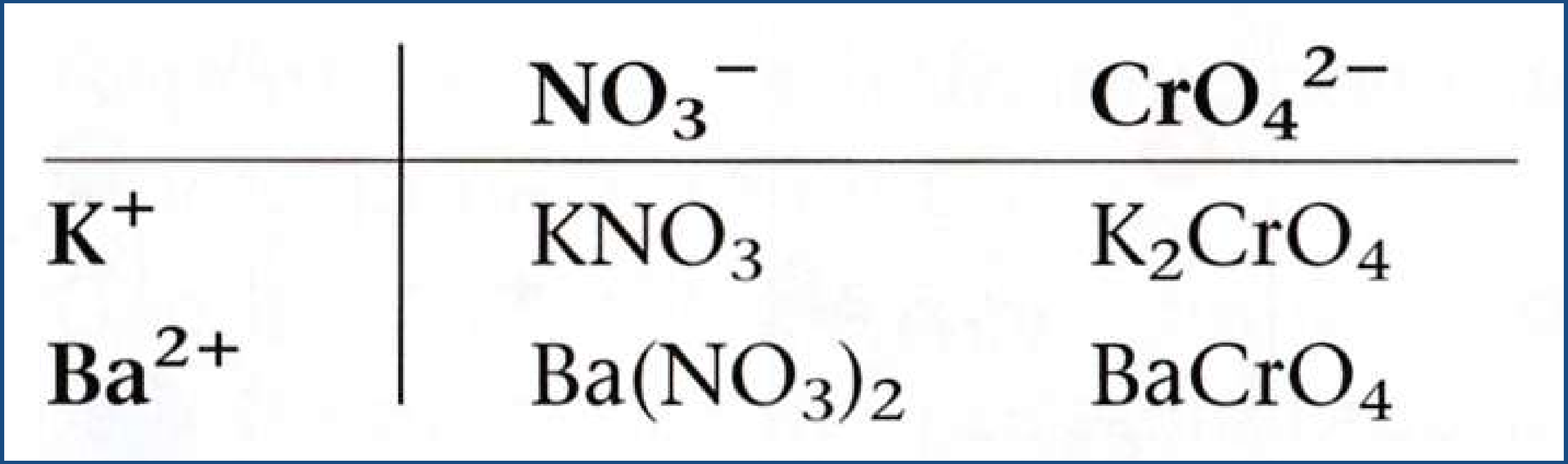
$K_2CrO_4(aq)$
Ions separate when
the solid dissolves.

$Ba(NO_3)_2(aq)$
Ions separate when
the solid dissolves.

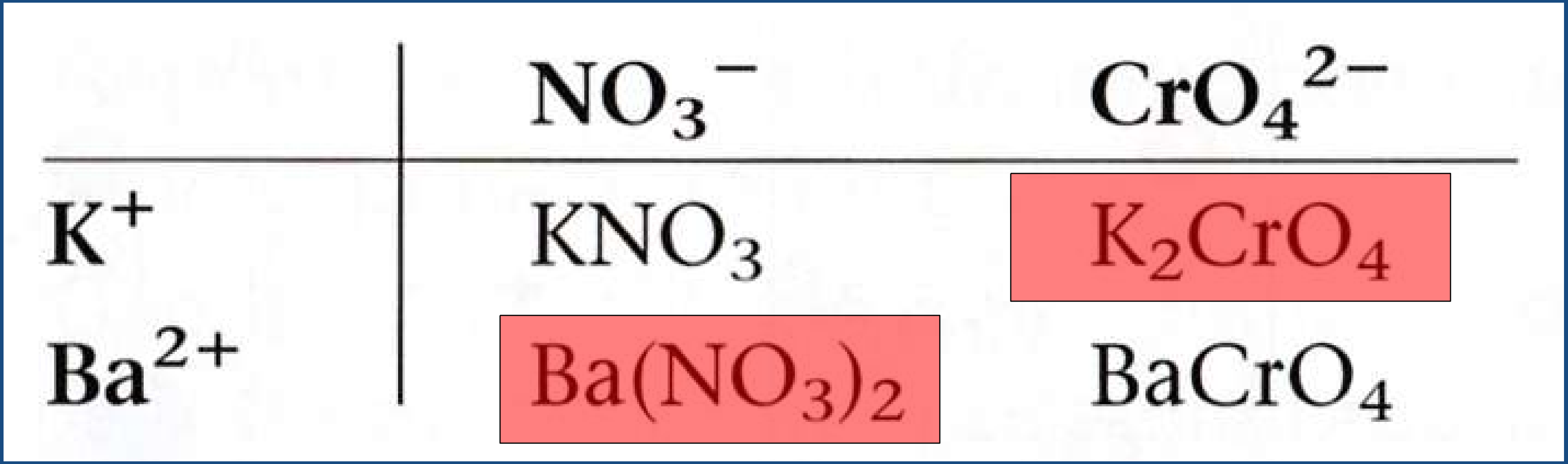
- *but which ions are getting together to form the yellow precipitate?*

how to decide which products form

- whatever forms has to be a cation/anion combo
- opposites attract
- the only possible combos are these below
- *but which is the precipitate?*



	NO_3^-	CrO_4^{2-}
K^+	KNO_3	K_2CrO_4
Ba^{2+}	$Ba(NO_3)_2$	$BaCrO_4$



	NO_3^-	CrO_4^{2-}
K^+	KNO_3	K_2CrO_4
Ba^{2+}	$Ba(NO_3)_2$	$BaCrO_4$

- it fer sure ain’t the reactants; why would they react?
- so the ppt is either **KNO_3** or **$BaCrO_4$**
- but which???
- an experienced chemist knows, but…
- ***you can use their years of experience by…***

using solubility rules

- after a b-zillion experiments solubility rules have been pretty well established, but first...
- **soluble** solid means it readily dissolves
- **insoluble** or **slightly soluble** means nothing/very little dissolves
- *nicely summarized on Table 8.1 and Fig 8.3*

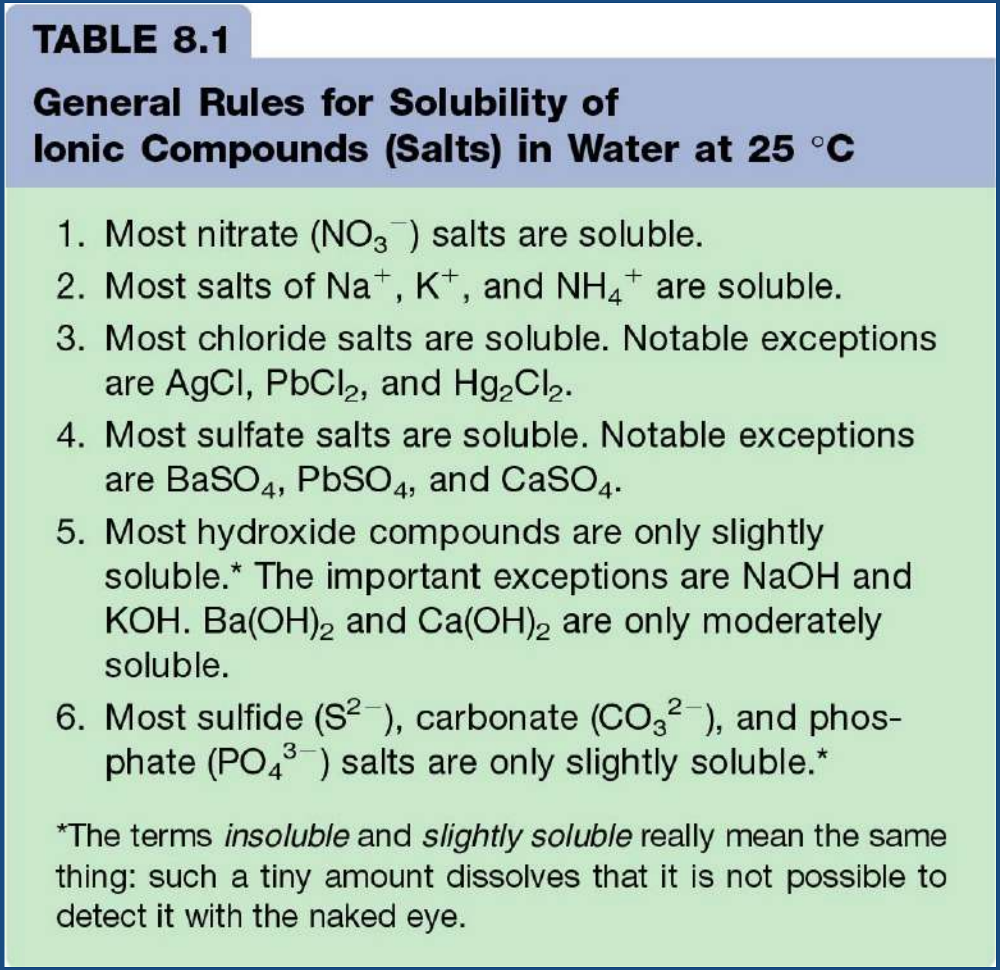
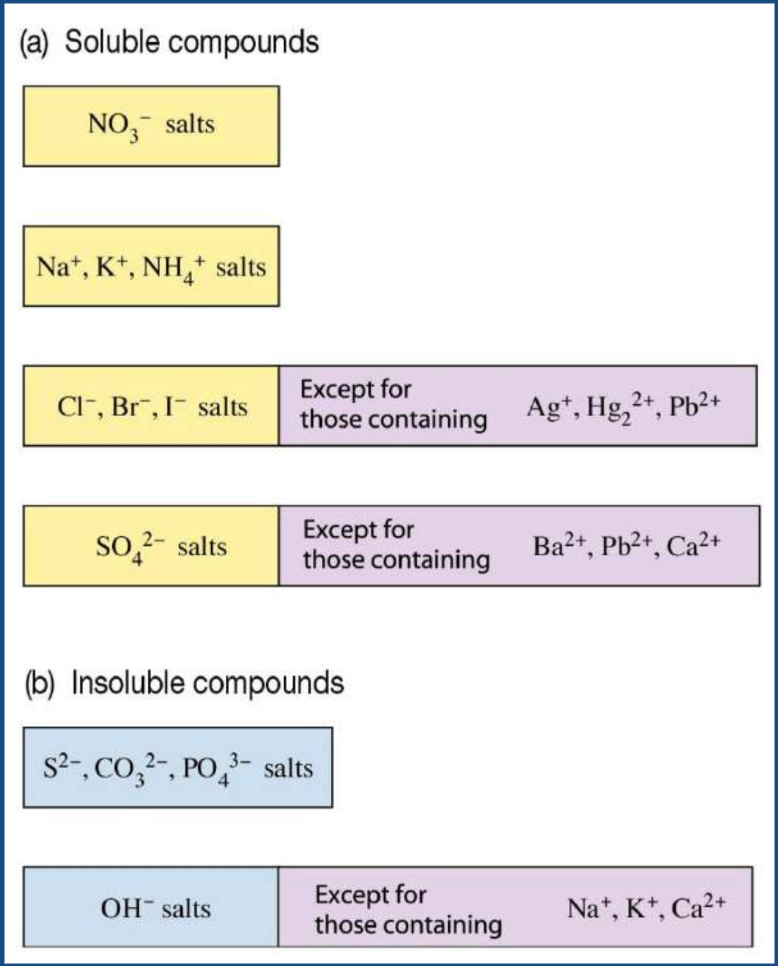


TABLE 8.1

General Rules for Solubility of Ionic Compounds (Salts) in Water at 25 °C

1. Most nitrate (NO_3^-) salts are soluble.
2. Most salts of Na^+, K^+, and NH_4^+ are soluble.
3. Most chloride salts are soluble. Notable exceptions are AgCl, $PbCl_2$, and Hg_2Cl_2.
4. Most sulfate salts are soluble. Notable exceptions are $BaSO_4$, $PbSO_4$, and $CaSO_4$.
5. Most hydroxide compounds are only slightly soluble.* The important exceptions are NaOH and KOH. $Ba(OH)_2$ and $Ca(OH)_2$ are only moderately soluble.
6. Most sulfide (S^{2-}), carbonate (CO_3^{2-}), and phosphate (PO_4^{3-}) salts are only slightly soluble.*

*The terms *insoluble* and *slightly soluble* really mean the same thing: such a tiny amount dissolves that it is not possible to detect it with the naked eye.



(a) Soluble compounds

NO_3^- salts

Na^+, K^+, NH_4^+ salts

Cl^-, Br^-, I^- salts | Except for those containing Ag^+, Hg_2^{2+}, Pb^{2+}

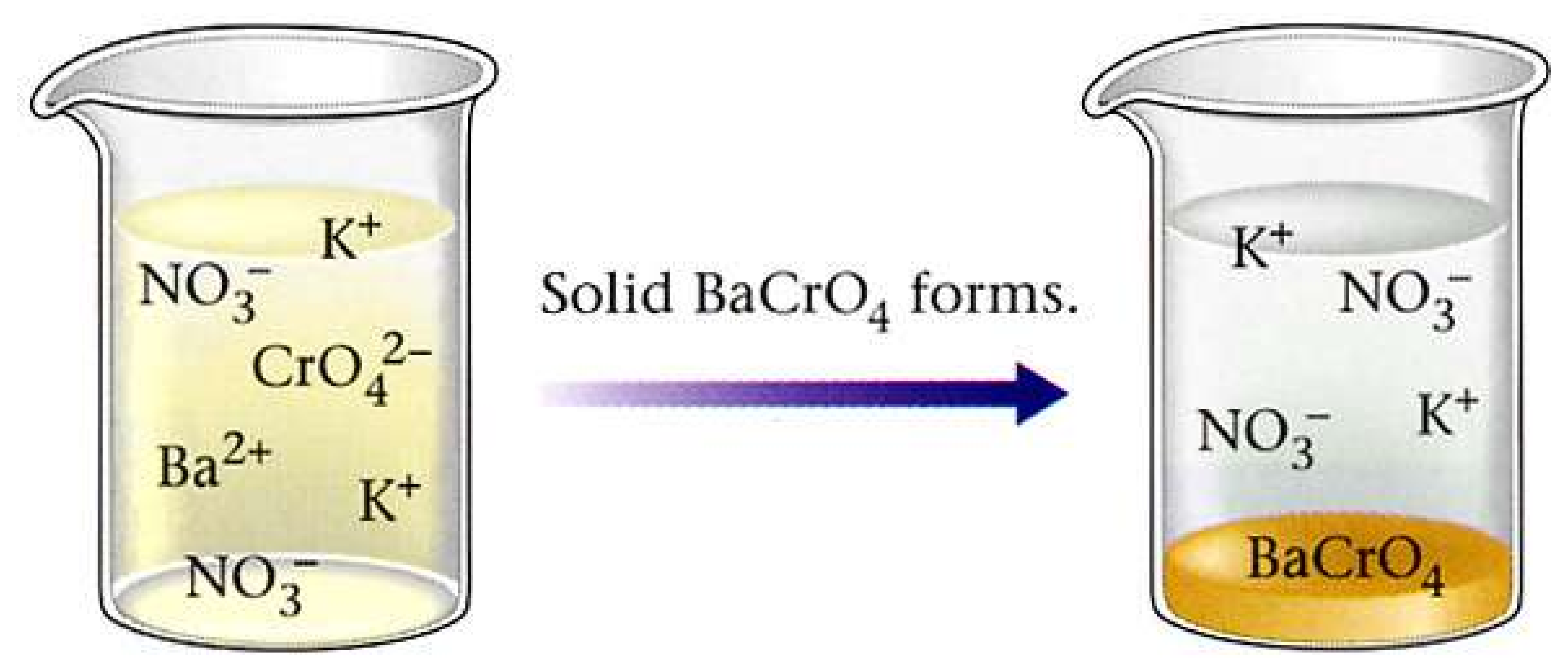
SO_4^{2-} salts | Except for those containing Ba^{2+}, Pb^{2+}, Ca^{2+}

(b) Insoluble compounds

S^{2-}, CO_3^{2-}, PO_4^{3-} salts

OH^- salts | Except for those containing Na^+, K^+, Ca^{2+}

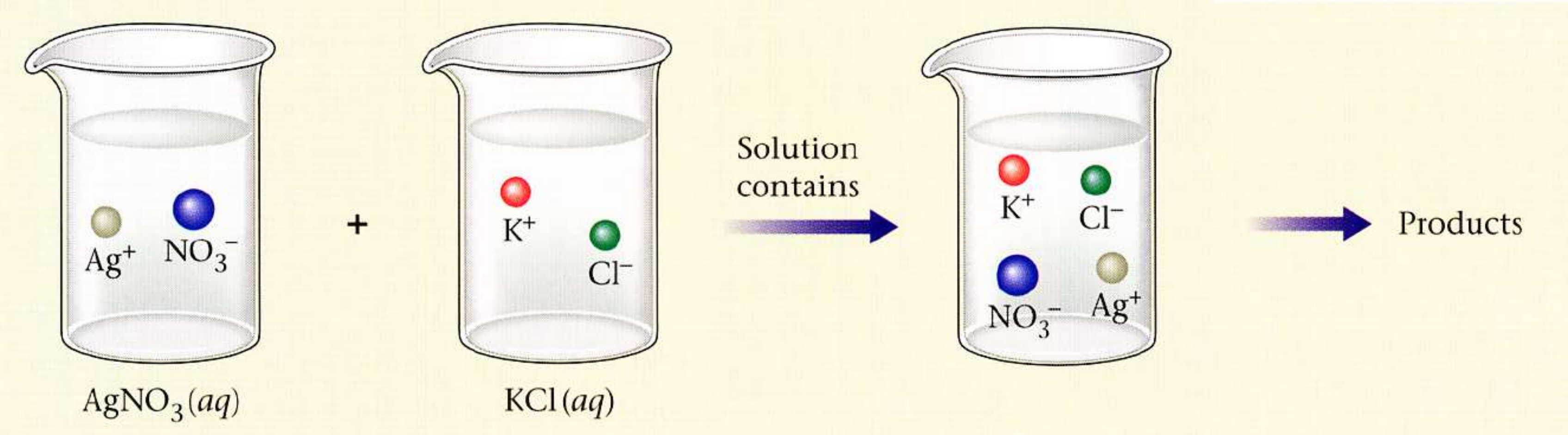
- use whichever helps you most (p 218); **they are your friends ;)**



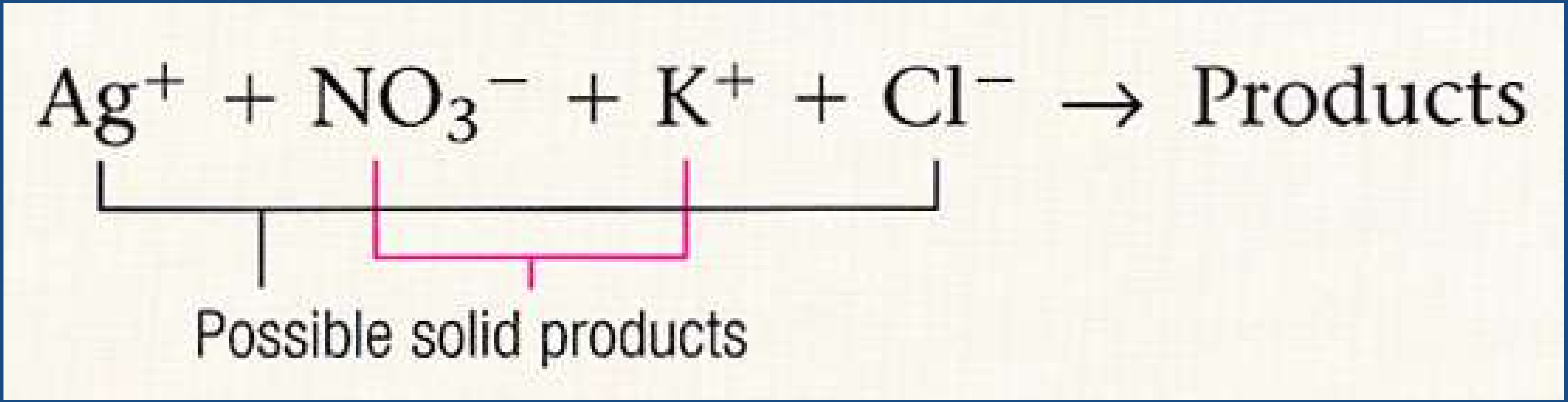
- using these rules we see that this is what really happened
- the insoluble product, the precipitate, was $BaCrO_4$
- ready to try an example?

example

- when aqueous solns of silver nitrate and potassium chloride are mixed a white solid forms; what is it? and what's the equation?
- **$AgNO_{3(aq)}$ + $KCl_{(aq)}$ ---> white solid**
- the players are Ag^+, NO_3^- and K^+, Cl^-
- which two are getting together???



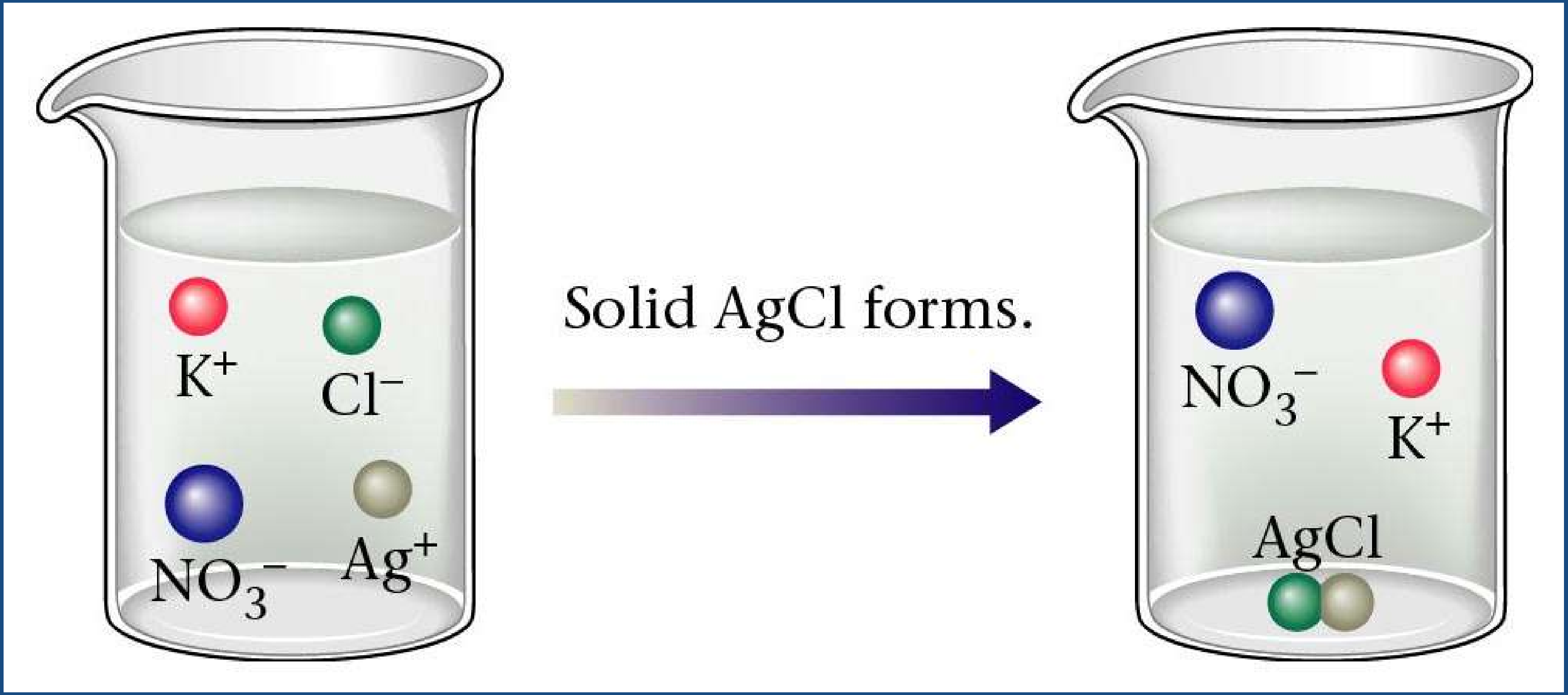
- Table 8.1 says all nitrates are soluble so **no** to the nitrate possibility (KNO_3)
- BUT it says chlorides are soluble *except those including Ag!!!*
- so the white solid is the Ag^+/Cl^- combo, AgCl, so…

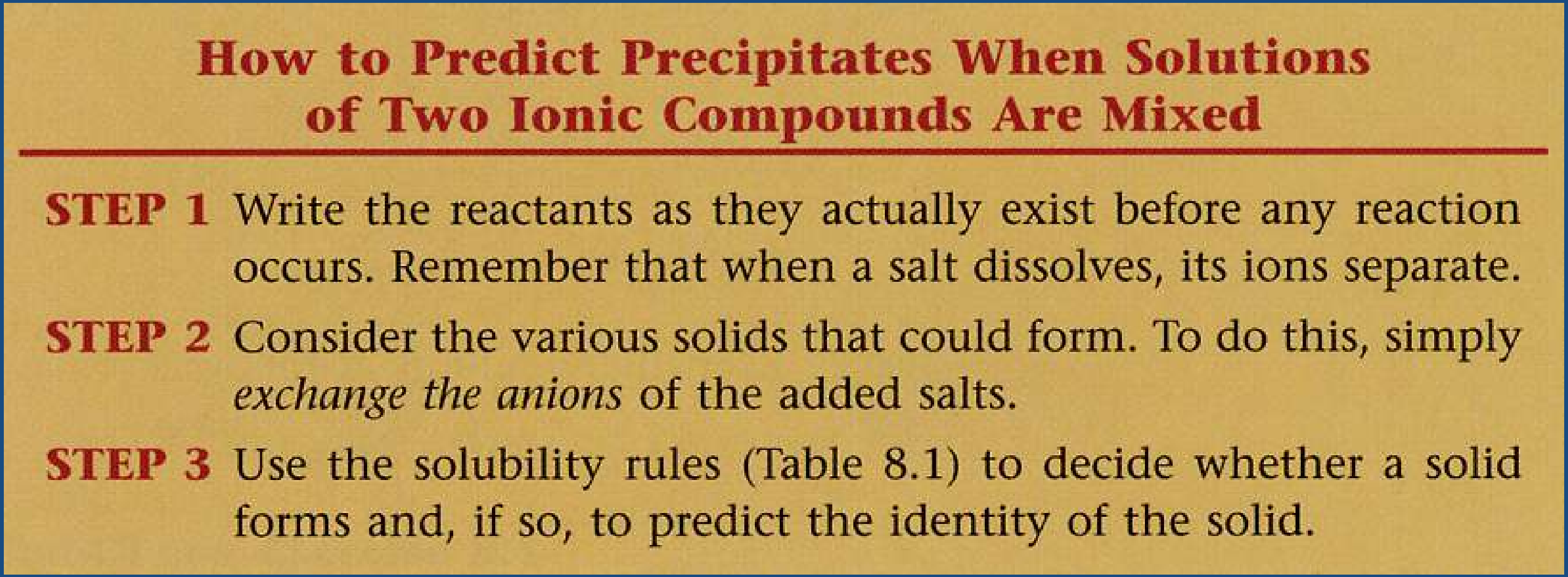


$$Ag^+ + NO_3^- + K^+ + Cl^- \rightarrow \text{Products}$$

- the full balanced equation is:

$AgNO_{3(aq)}$ + $KCl_{(aq)}$ ---> $AgCl_{(s)}$ + $KNO_{3(aq)}$





How to Predict Precipitates When Solutions of Two Ionic Compounds Are Mixed

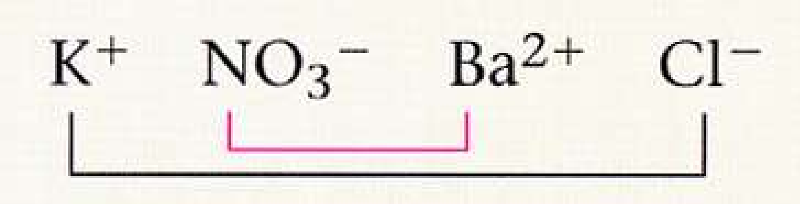
STEP 1 Write the reactants as they actually exist before any reaction occurs. Remember that when a salt dissolves, its ions separate.

STEP 2 Consider the various solids that could form. To do this, simply *exchange the anions* of the added salts.

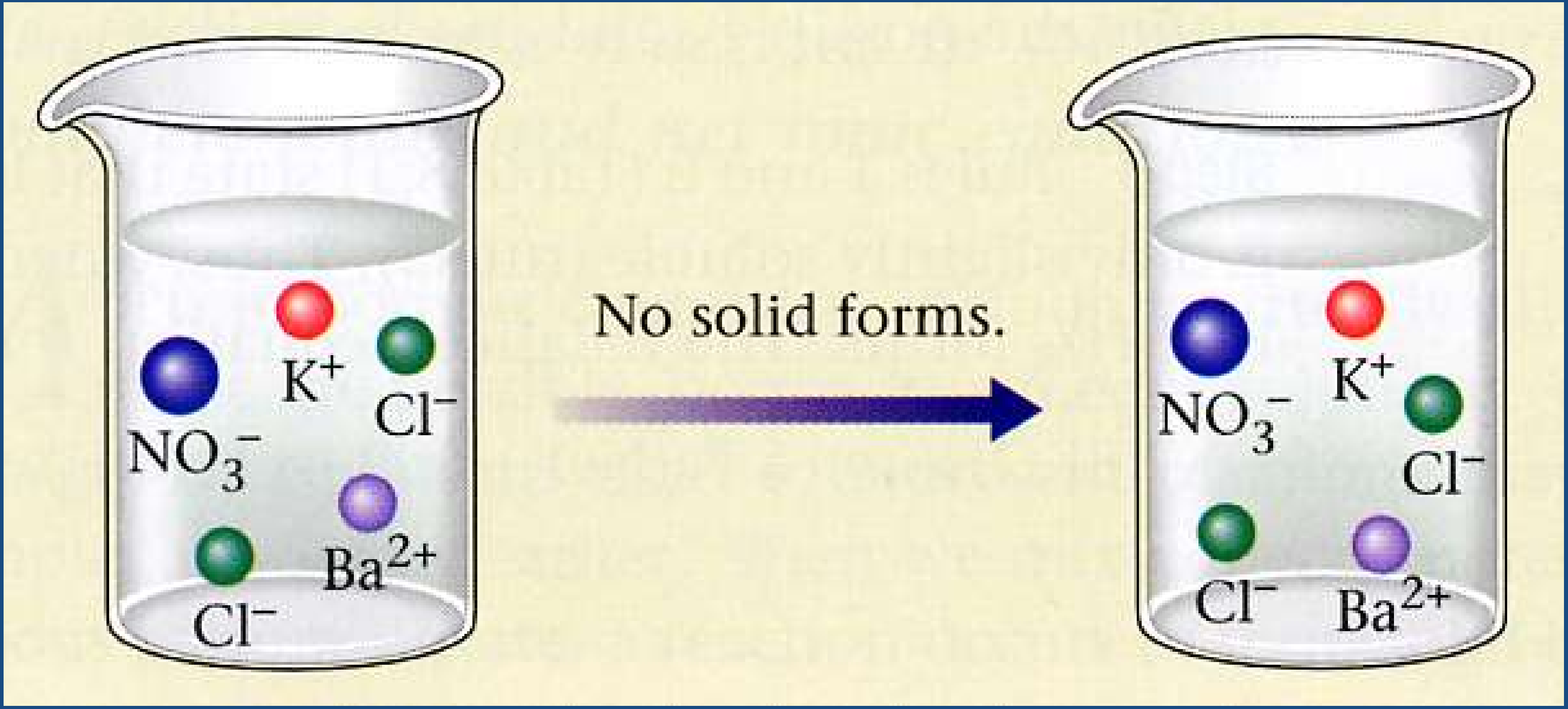
STEP 3 Use the solubility rules (Table 8.1) to decide whether a solid forms and, if so, to predict the identity of the solid.

example

- *what will happen when* $KNO_{3(aq)}$ *and* $BaCl_{2(aq)}$ *get together? what is the equation?*



players

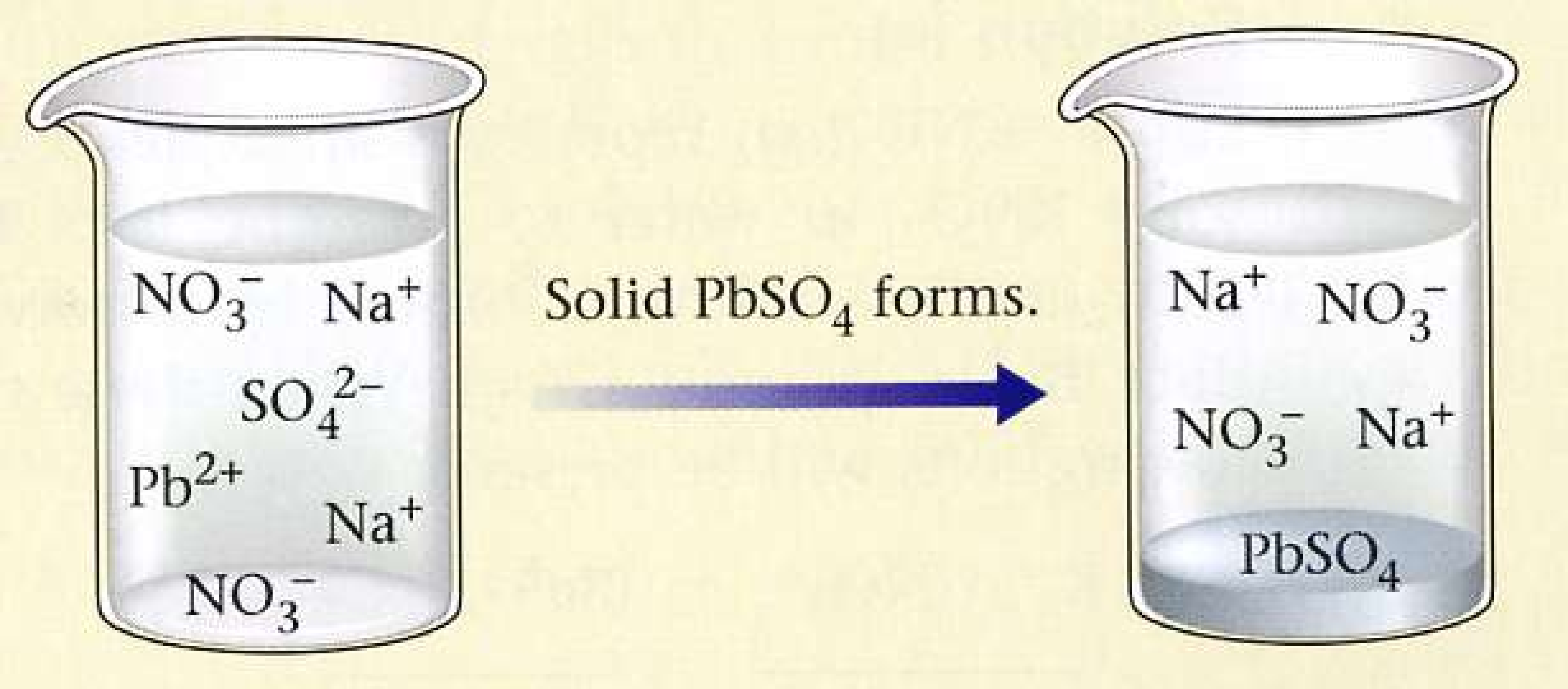


NR!

example

- *what will happen when* $Na_2SO_{4(aq)}$ *and* $Pb(NO_3)_{2(aq)}$ *get together? what is the equation?*
- players are:

$$Na^+ \quad SO_4^{2-} \quad Pb^{2+} \quad NO_3^-$$



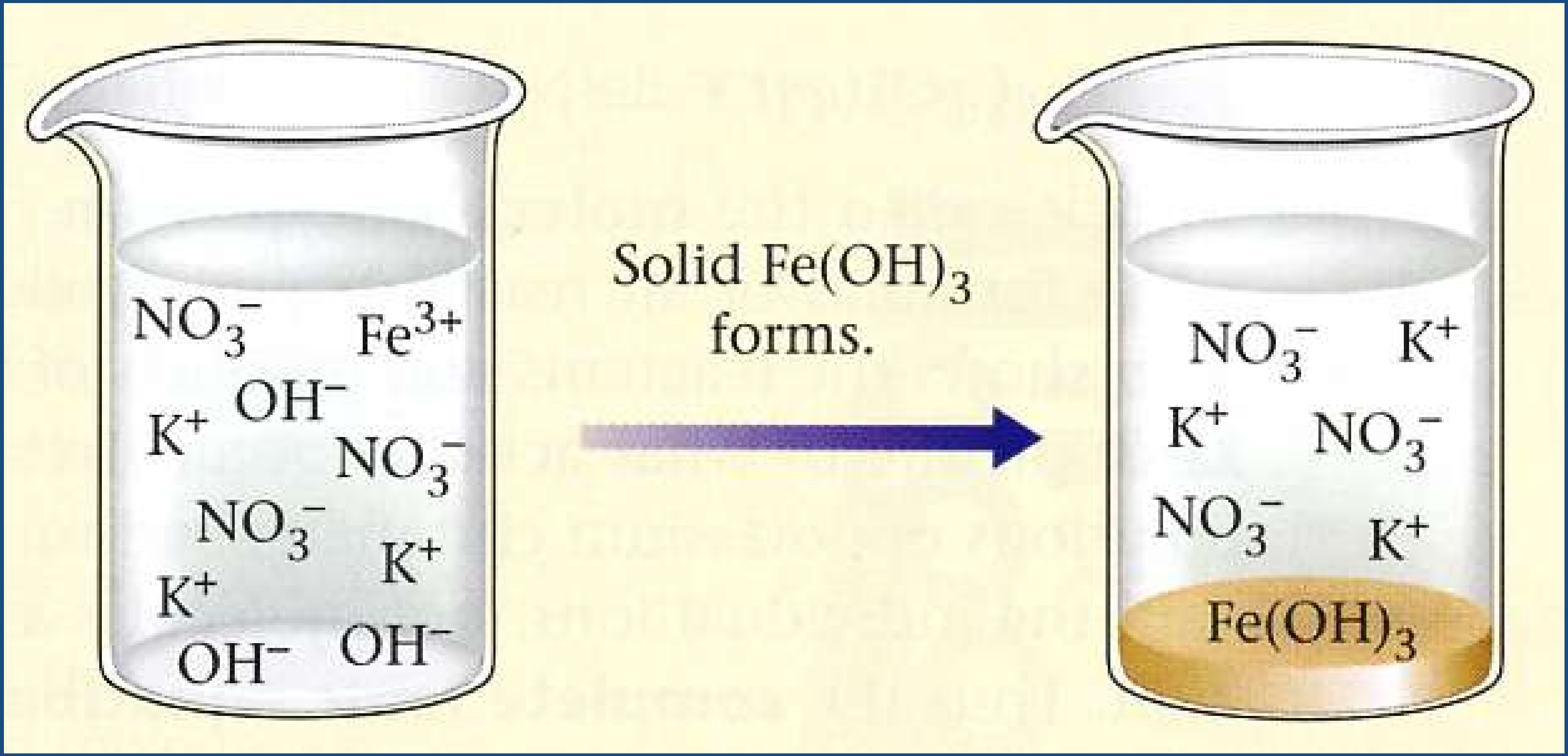
$Na_2SO_{4(aq)} + Pb(NO_3)_{2(aq)} \dashrightarrow PbSO_{4(s)} + 2NaNO_{3(aq)}$

- notice again the solid has a little $_{(s)}$ after it, and the whole thing got balanced

example

- *what will happen when $KOH_{(aq)}$ and $Fe(NO_3)_{3(aq)}$ get together? what is the equation?*
- players are:

$K^+OH^-Fe^{3+}NO_3^-$



$3KOH_{(aq)} + Fe(NO_3)_{3(aq)}$ --> $Fe(OH)_{3(s)}$ + $3KNO_{3(aq)}$

- notice again the solid has a little $_{(s)}$ after it, and the whole thing got balanced

8.3 Describing Reactions in Aqueous Solutions

- remember: 2 ionic cmpds might dissolve in water
- cations from one can react w/ anions from another to form precipitate
- this whole reaction with all players fully dressed is the **molecular equation**: All compounds represented in full form
- e.g.…

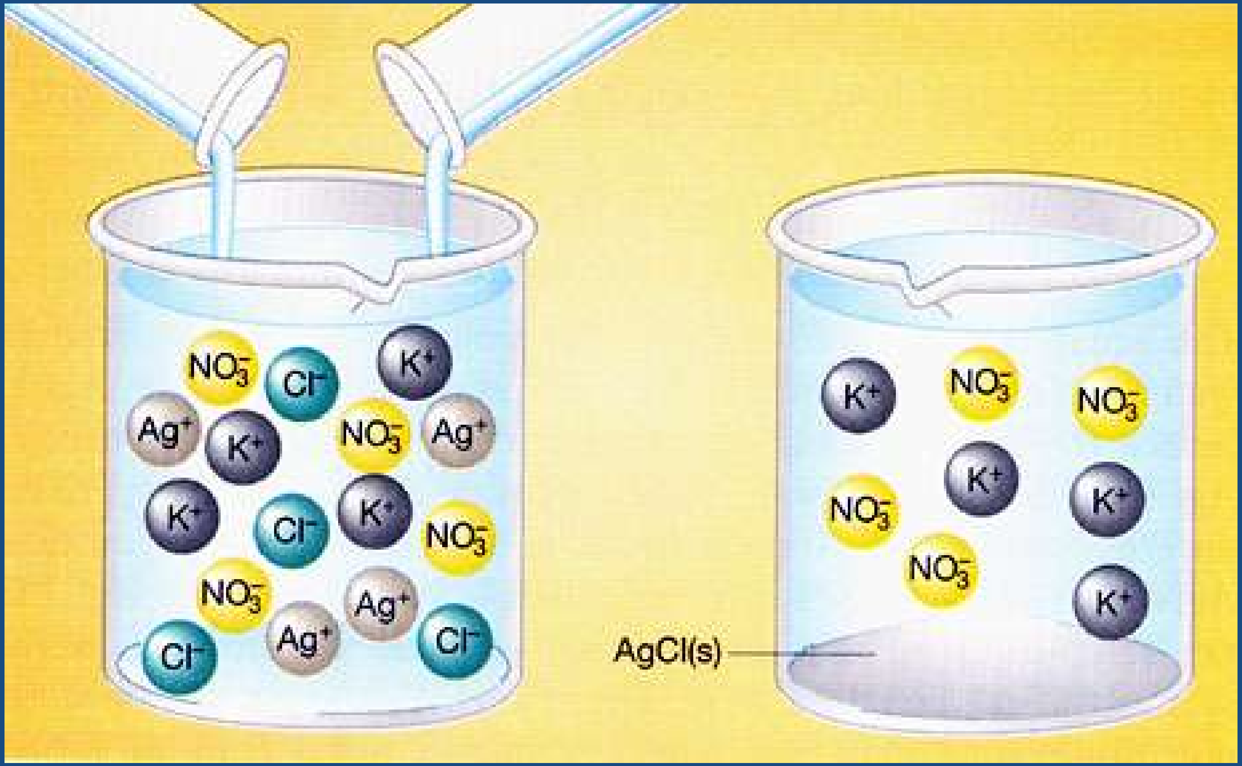
$$AgNO_{3(aq)} + KCl_{(aq)} \rightarrow AgCl_{(s)} + KNO_{3(aq)}$$

- eq from above can *show* dissociation in a ***complete* ionic equation: all compounds shown "broken" up**

$Ag^{+}_{(aq)} + NO_3{}^{-}_{(aq)} + K^{+}_{(aq)} + Cl^{-}_{(aq)}$

$\rightarrow AgCl_{(s)} + K^{+}_{(aq)} + NO_3{}^{-}_{(aq)}$

- why didn't AgCl get broken up? (b/c it's a solid)
- check the Solubility Table!



- K^+ and NO_3^- aren't playing! = **spectator ions: DO NOT participate in reaction**
- resulting equation *after spectators are thrown out* = **net ionic equation**
- $Ag^+_{(aq)} + Cl^-_{(aq)} \rightarrow AgCl_{(s)}$

examples: write molecular, ionic, net ionic

- *aqueous potassium hydroxide is mixed with aqueous iron(III) nitrate to form solid iron(III) hydroxide and aqueous potassium nitrate*
- $KOH(aq) + Fe(NO_3)_3(aq) \rightarrow Fe(OH)_3(s) + KNO_3(aq)$
- $3KOH(aq) + Fe(NO_3)_3(aq) \rightarrow Fe(OH)_3(s) + 3KNO_3(aq)$
- $3K^+ + 3OH^- + Fe^{3+} + 3NO_3^- \rightarrow Fe(OH)_3(s) + 3K^+ + 3NO_3^-$
- $3OH^- + Fe^{3+} \rightarrow Fe(OH)_3(s)$

examples: write molecular, ionic, net ionic

- *aqueous sodium sulfide is mixed with aqueous copper(II) nitrate to form solid copper(II) sulfide and aqueous sodium nitrate*
- $Na_2S(aq)$ + $Cu(NO_3)_2(aq)$ --> $CuS(s)$ + $NaNO_3(aq)$
- $Na_2S(aq)$ + $Cu(NO_3)_2(aq)$ --> $CuS(s)$ + $2NaNO_3(aq)$
- $2Na^+$ + S^{2-} + Cu^{2+} + $2NO_3^-$ --> $CuS(s)$ + $2Na^+ + 2NO_3^-$
- S^{2-} + Cu^{2+} --> $CuS(s)$

examples: write molecular, ionic, net ionic

- *aqueous nickel(II) nitrate is mixed with aqueous potassium carbonate to form solid nickel(II) carbonate and aqueous potassium nitrate*
- $Ni(NO_3)_2(aq) + K_2CO_3(aq) \dashrightarrow NiCO_3(s) + KNO_3(aq)$
- $Ni(NO_3)_2(aq) + K_2CO_3(aq) \dashrightarrow NiCO_3(s) + 2KNO_3(aq)$
- $Ni^{2+} + 2NO_3^{-} + 2K^{+} + CO_3^{2-} \dashrightarrow NiCO_3(s) + 2K^{+} + 2NO_3^{-}$
- $Ni^{2+} + CO_3^{2-} \dashrightarrow NiCO_3(s)$

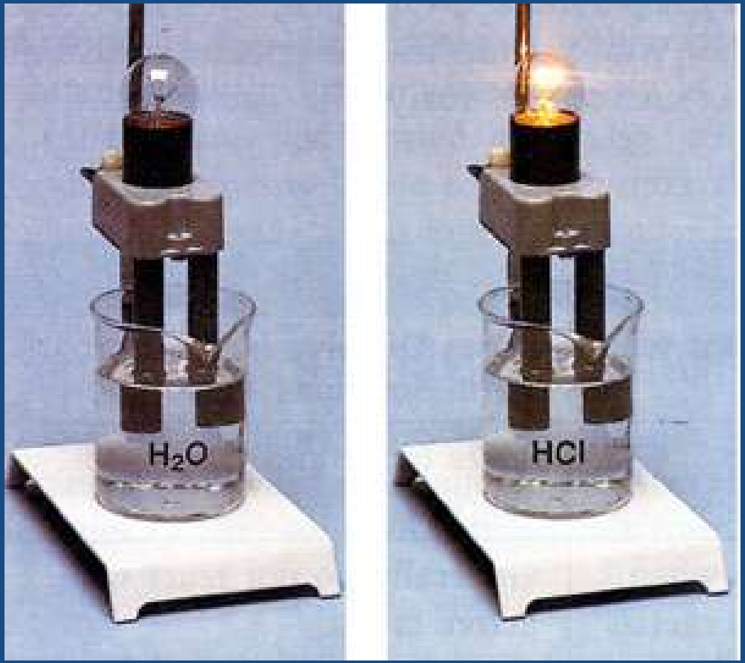
examples: write molecular, ionic, net ionic

- *aqueous potassium hydroxide is mixed with aqueous iron(III) nitrate to form solid iron(III) hydroxide and aqueous potassium nitrate*
- $KOH(aq) + Fe(NO_3)_3(aq) \dashrightarrow Fe(OH)_3(s) + KNO_3(aq)$
- $3KOH(aq) + Fe(NO_3)_3(aq) \dashrightarrow Fe(OH)_3(s) + 3KNO_3(aq)$
- $3K^{+} + 3OH^{-} + Fe^{3+} + 3NO_3^{-} \dashrightarrow Fe(OH)_3(s) + 3K^{+} + 3NO_3^{-}$
- $3OH^{-} + Fe^{3+} \dashrightarrow Fe(OH)_3(s)$

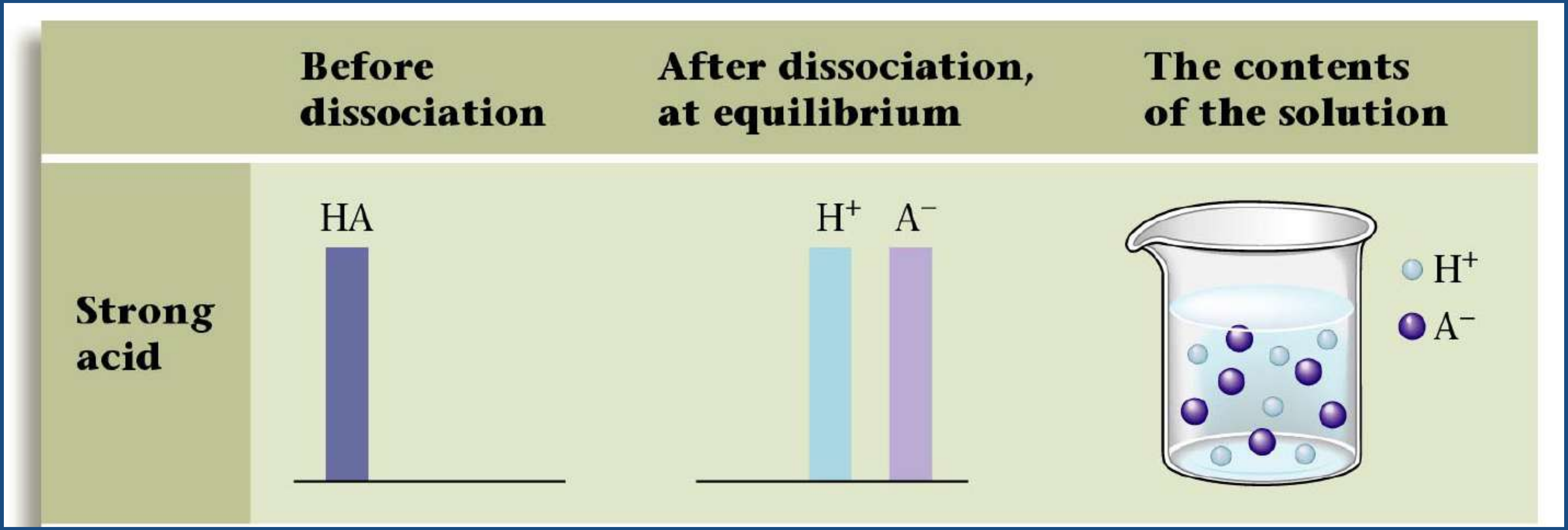
8.4 reactions that form water: acids and bases

- here we introduce two new things: acids and bases
- **acids** are sour
- have been known for centuries (mostly as “mineral acids”)

- their nature was first discovered by **Svante Arrhenius**
- they always behaved as strong electrolytes for him, so they must be ionized in water
- ***Arr said they give off H+ ions (protons) when dissolved in water***



- some acids ionized 100%!
- they are called **strong acids**
- like HCl, HNO_3, H_2SO_4



- **bases** (aka alkalis) are slippery and taste bitter
- Arr defined a base as a substance that coughed up an OH^- ion
- those that 100% ionize (e.g. KOH & NaOH) are called **strong bases**

- when an acid soln and a base soln get together, the H^+ react with the OH^- to make…
- **water!**
- *to make water was one of our driving forces!*
- *the other product is a* ***salt*** (ionic cmpd)

example

- *nitric acid reacts with aqueous potassium hydroxide. write mol, ionic, and net ionic equation*
- $HNO_3(aq)$ + $KOH(aq)$ --> $H_2O(l)$ + $KNO_3(aq)$
- H^+ + NO_3^- + K^+ + $OH-$ --> H_2O + K^+ + NO_3^-
- **H^+ + $OH-$ --> H_2O**

example

- *hydrobromic acid (a strong acid) reacts with aqueous sodium hydroxide. write mol, ionic, and net ionic equation*
- $HBr(aq) + NaOH(aq) \text{-->} H_2O(l) + NaBr(aq)$
- $H^+ + Br^- + Na^+ + OH\text{-} \text{-->} H_2O + Na^+ + Br^-$
- **$H^+ + OH\text{-} \text{-->} H_2O$**

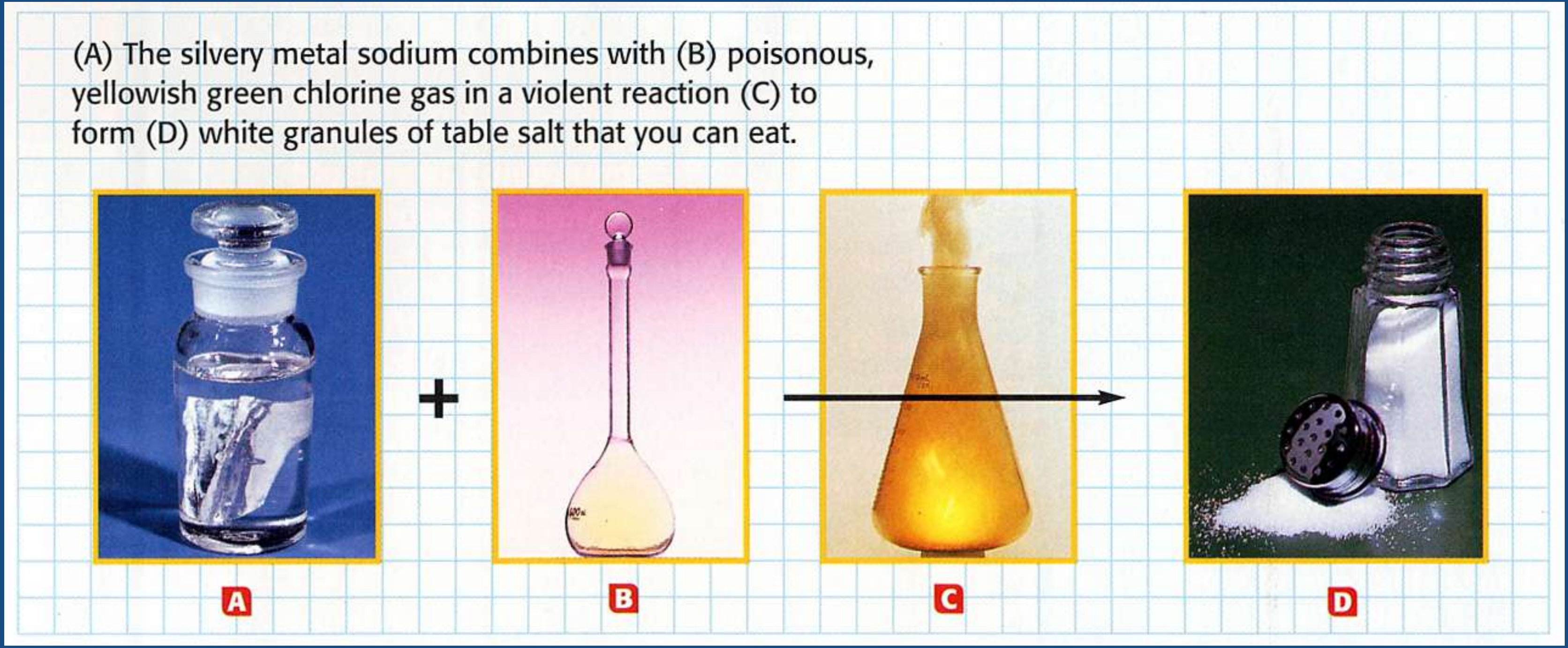
example

- *sulfuric acid (a strong acid) reacts with aqueous potassium hydroxide. write mol, ionic, and net ionic equation*
- $H_2SO_{4(aq)}$ + $2KOH_{(aq)}$ --> $2H_2O_{(l)}$ + $K_2SO_{4(aq)}$
- $2H^+$ + SO_4^{2-} + $2K^+$ + $2OH^-$ --> $2H_2O$ + $2K^+$ + SO_4^{2-}
- **H^+ + OH^- --> H_2O**

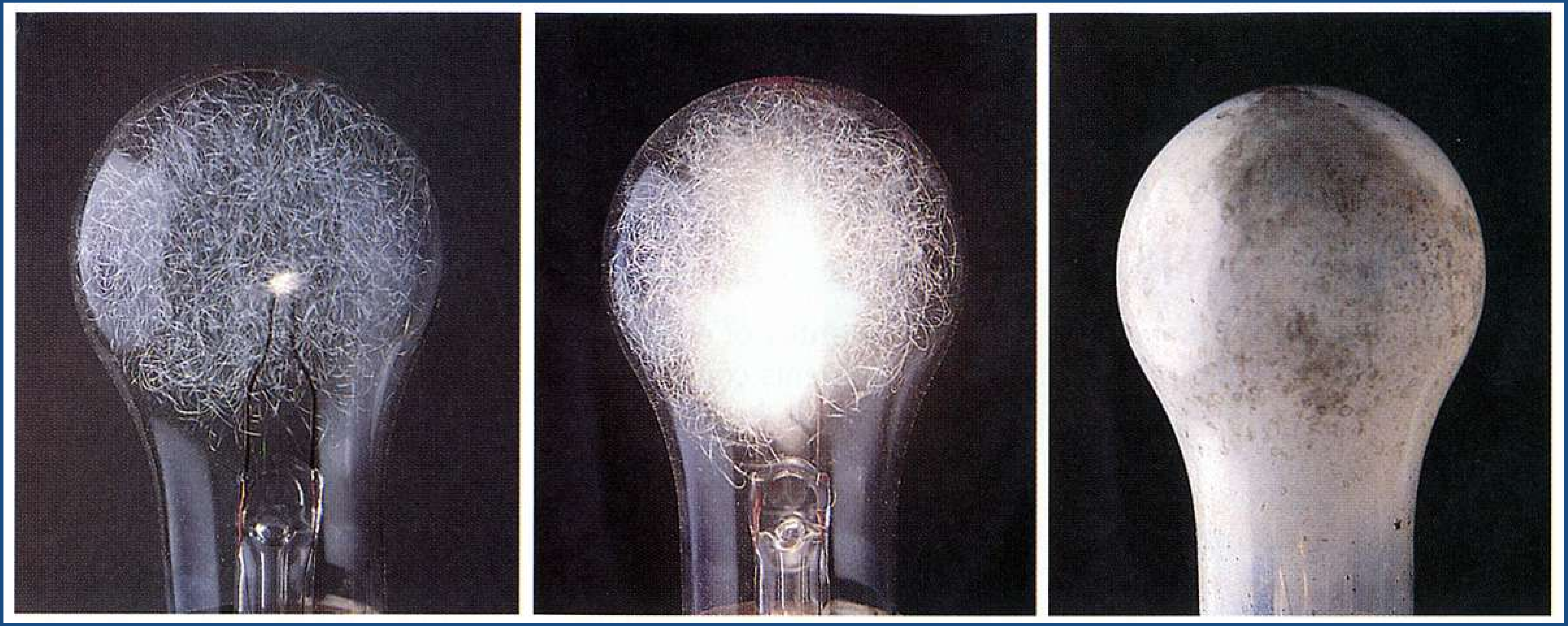
8.5 reactions of metals with nonmetals (oxidation-reduction)

- we spent a lot of time learning how to name the results of metals getting together with nonmetals
- now we learn exactly **why** they get together

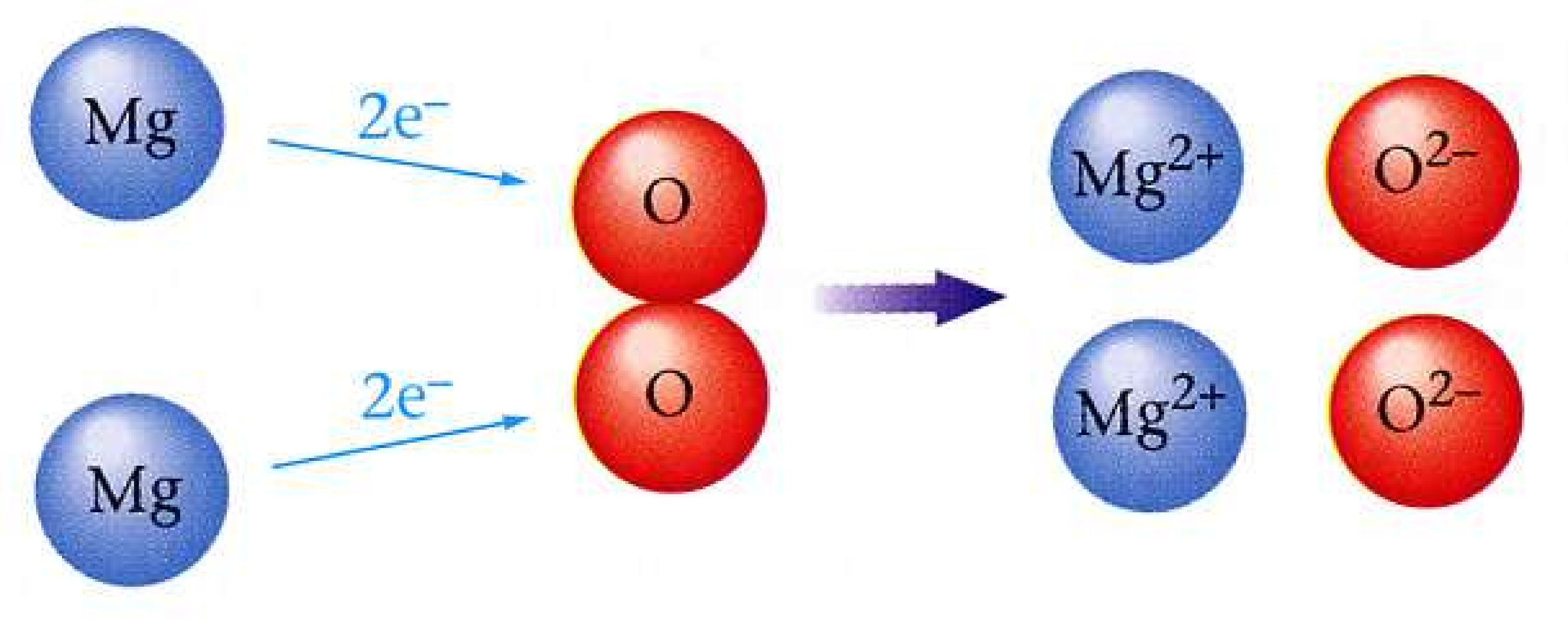
- when NaCl is made, how does the Na become Na+ and the Cl become Cl-?
- **transfer of electrons (Redox reaction)**
- the tendency to transfer electrons from a metal to a nonmetal is ***the third driving force***


(A) The silvery metal sodium combines with (B) poisonous, yellowish green chlorine gas in a violent reaction (C) to form (D) white granules of table salt that you can eat.

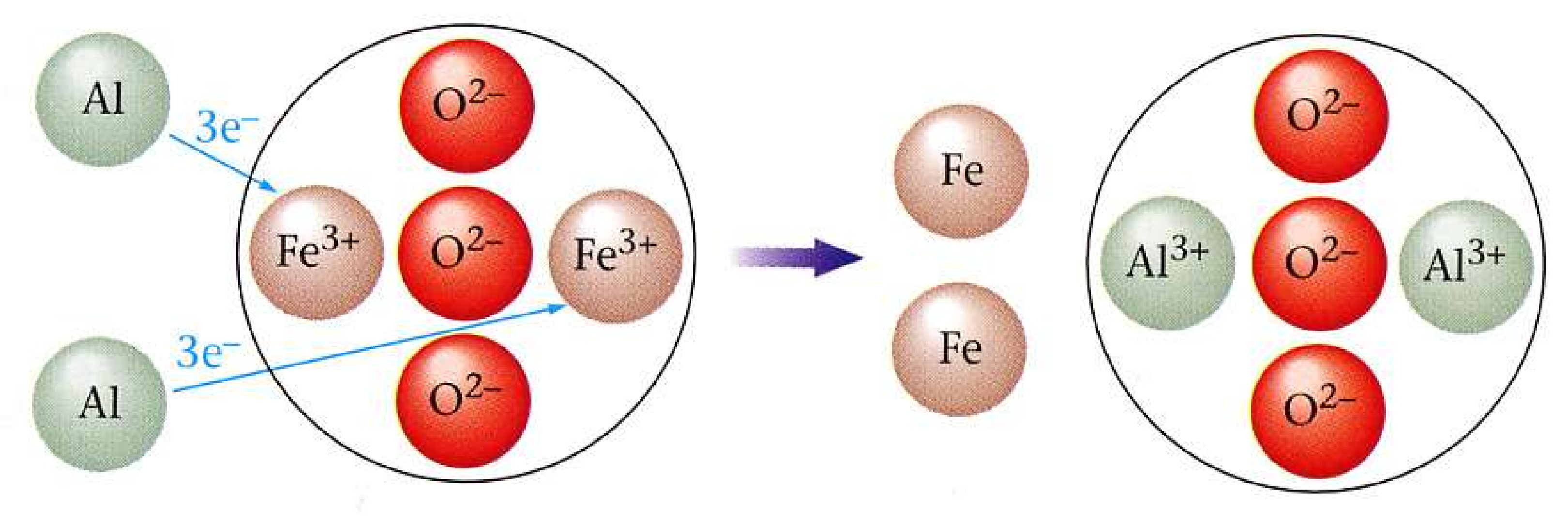
- a reaction that involves a transfer of electrons is called an **oxidation-reduction reaction**
- aka **redox**



- **$2Mg + O_2 \text{ --> } 2MgO$**
- the Mg used to be neutral; now it has a 2+ charge
- the oxygen used to be neutral; now it has a -2 charge
- **how???**


Mg
2e$^-$
O
Mg
2e$^-$
O
Mg^{2+}
O^{2-}
Mg^{2+}
O^{2-}

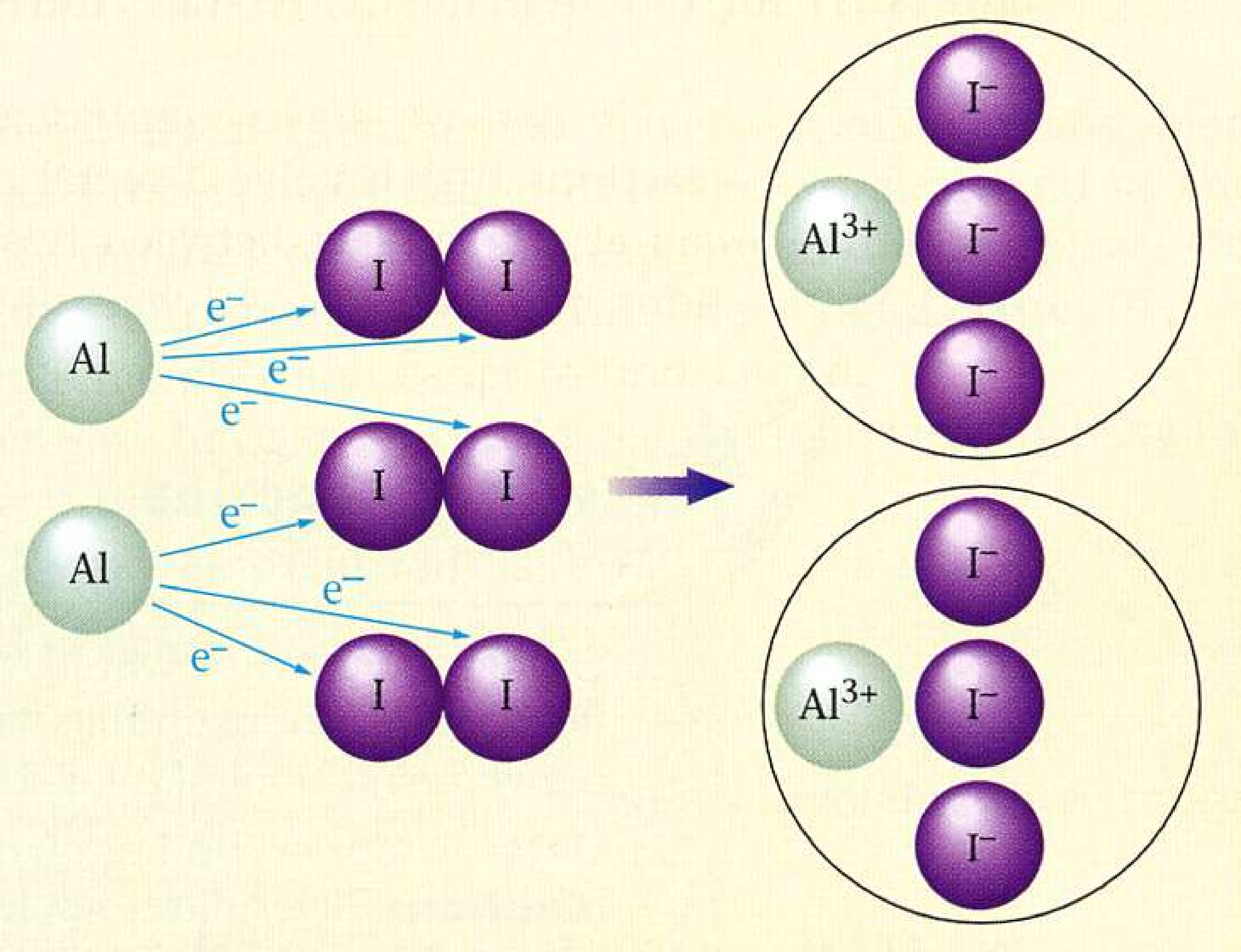
- another example:
  $2Al + Fe_2O_3$ -->
  $2Fe + Al_2O_3$
- notice what happened to Al:
  Al ---> Al^{3+}
- **Al lost 3 electrons**
- **Fe gained 3 e-**:
  Fe^{3+} --> Fe


Al
3e⁻
O²⁻
Fe³⁺
O²⁻
Fe³⁺
3e⁻
Al
O²⁻
Fe
Fe
O²⁻
Al³⁺
O²⁻
Al³⁺
O²⁻

example

- what happened here?

  $2Al + 3I_2 \text{-->} 2AlI_3$
- Al became Al^{3+} by losing 3 electrons
- I went from neutral to I^-; by gaining an electron


Al
Al
e⁻
e⁻
e⁻
e⁻
e⁻
e⁻
I
I
I
I
I
I
Al3+
I⁻
I⁻
I⁻
Al3+
I⁻
I⁻
I⁻

example

- **$2Cs + F_2$ --> $2CsF$**
- *what happened with the electrons?*
- Cs went from neutral to Cs^+
- it lost an electron
- **Cs --> $Cs^+ + e^-$**
- F went from neutral to F^-
- it gained an electron
- **$F + e-$ --> F^-**

example

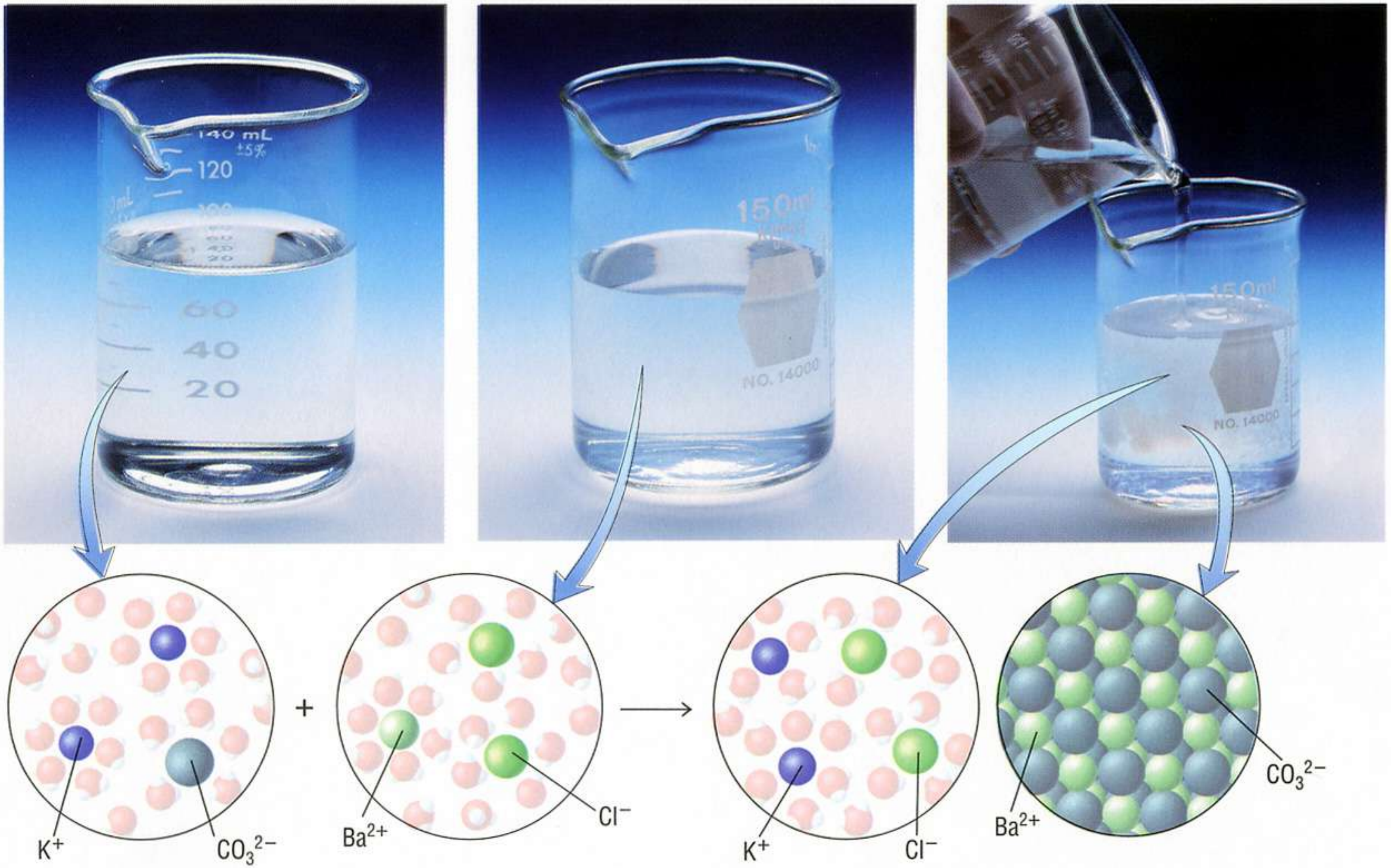
- **$2Na + Br_2$ --> $2NaBr$**
- *how many e- were lost or gained?*
- Na went from neutral to Na+, so it lost an electron:
- **Na --> Na^+ + e^-**
- Br went from neutral to Br^- so it gained one:
- **Br + e^- --> Br^-**

- one more thing: any reaction which involves sucking up an oxygen is ***also*** a **redox reaction** (in fact, it got its name from that); e.g...
- **CH_4 + $2O_2$ --> CO_2 + $2H_2O$**
- more on that in CHM B

8.6 ways to classify reactions

- there are literally millions of different rxns (as with animals)
- here we will intro classifying them
- we will classify the rxns involving those driving forces

- the precipitation reactions are also called **double-displacement rxns**
- remember this?:
  $AgNO_3(aq) + KCl(aq) \text{ ---> } AgCl(s) + KNO_3(aq)$
- could also be called dd rxns because **two things are getting displaced**; there is a double swap of ions:
- **AB + CD --> AD + CB**

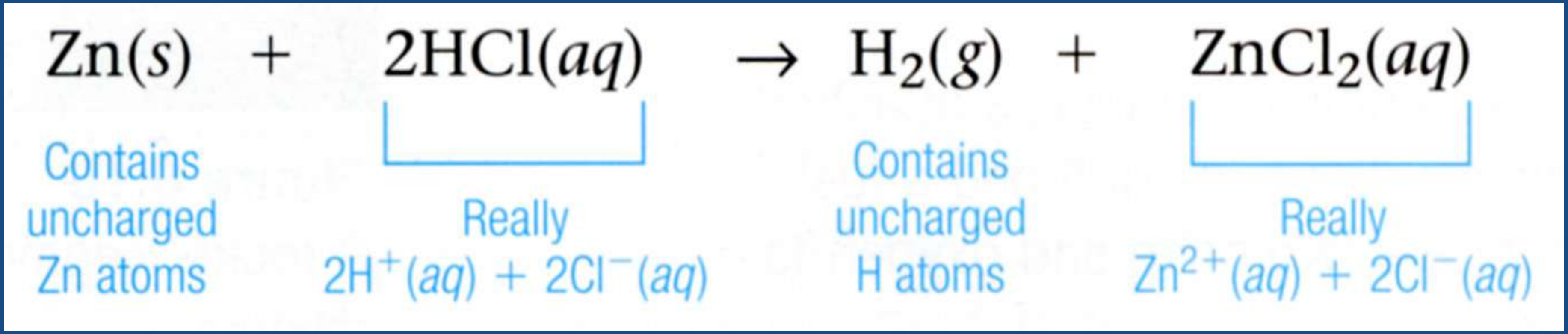


$K_2CO_3(aq)$	+	$BaCl_2(aq)$	$\longrightarrow$	$2KCl(aq)$	+	$BaCO_3(s)$
Potassium carbonate		Barium chloride		Potassium chloride		Barium carbonate

- those rxns whose net ionic equation were:
  $H^+ + OH^-$ --> H_2O
- they are also known as **acid-base rxns**

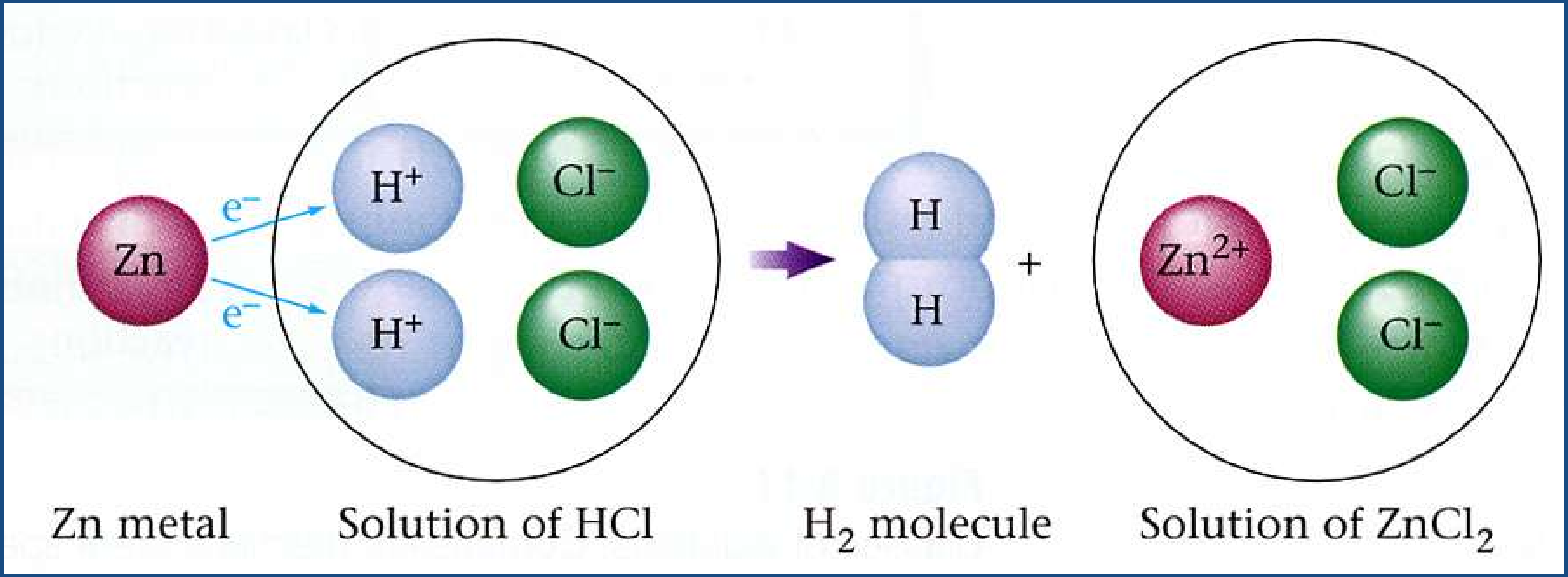
- (repeat alert!)
  the rxns we just did which involve transferring electrons from a metal to a nonmetal are **oxidation-reduction rxns**

- one we haven't discussed is the formation of a gas as a driving force
- one common rxn here goes something like this: $Zn(s) + 2HCl(aq) \text{-->} H_2(g) + ZnCl_2(aq)$
- let's break this equation down and see what's happening…

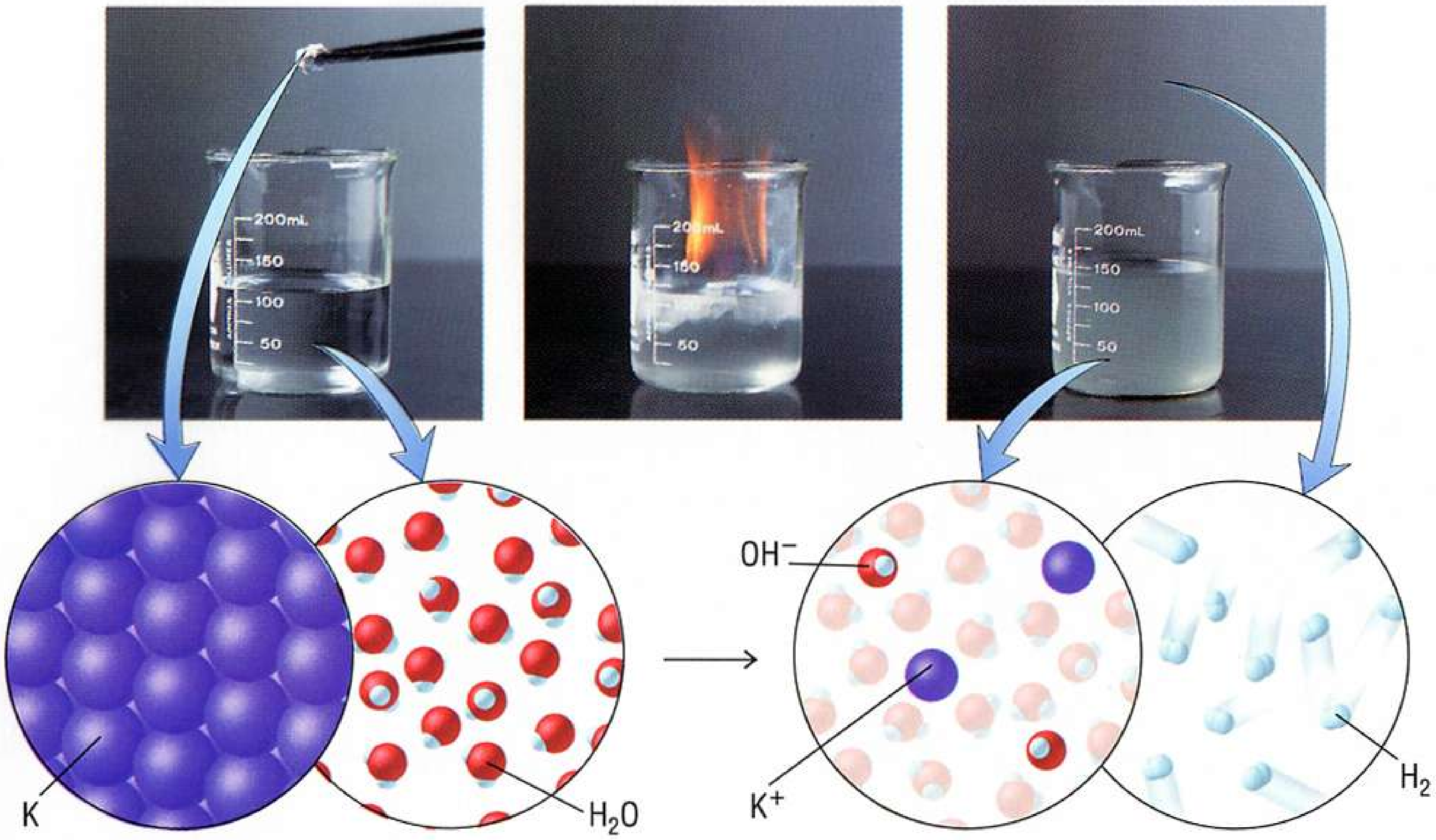


$$Zn(s) + 2HCl(aq) \rightarrow H_2(g) + ZnCl_2(aq)$$

- do you see the transfer of electrons here? it can be classified as a **redox rxn**, but!



- notice only a **single** type of ion has been exchanged (not a double exchange as before)
- these are also called **single-replacement rxns**
- → A + BC --> B + AC

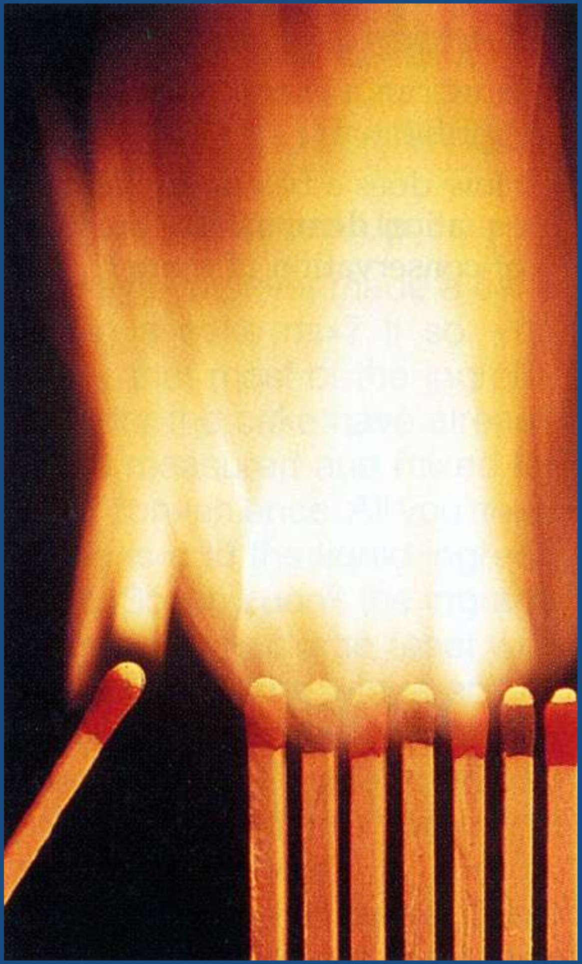


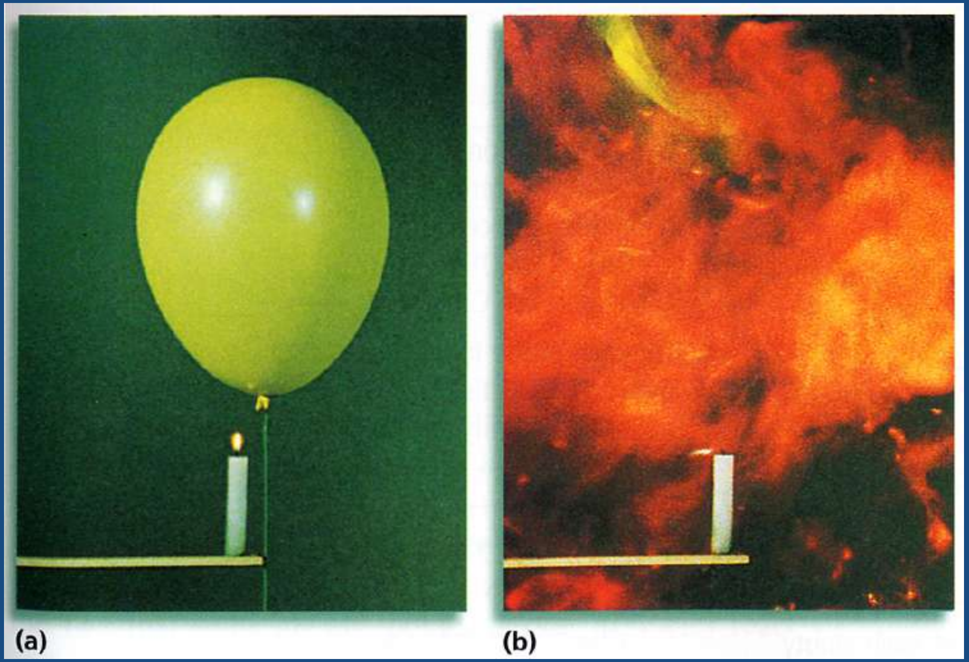
$2K(s)$ + $2H_2O(l)$ $\longrightarrow$ $2KOH(aq)$ + $H_2(g)$

Potassium Water Potassium hydroxide Hydrogen

8.7 other ways to classify reactions

- so far most common are:
  ppt rxns
  acid-base rxns
  redox rxns
- here are some other well-known and often used…

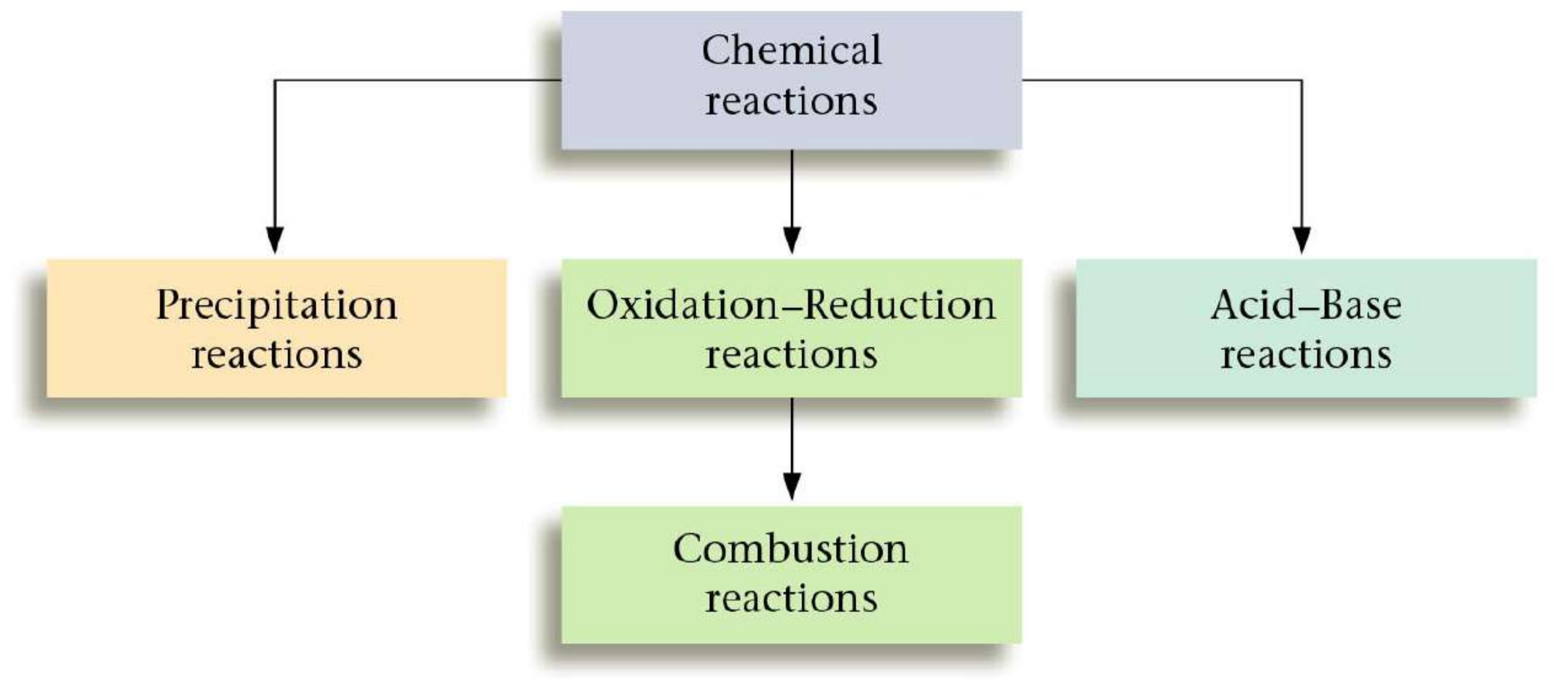




combustion rxns

- some redox reactions involve **burning something in oxygen to give of heat and light producing CO_2 AND H_2O**
- called **combustion rxns**, like the burning of lab gas:
- → $CH_4 + 2O_2 \text{-->} CO_2 + 2H_2O$

a summary so far



Chemical reactions

Precipitation reactions

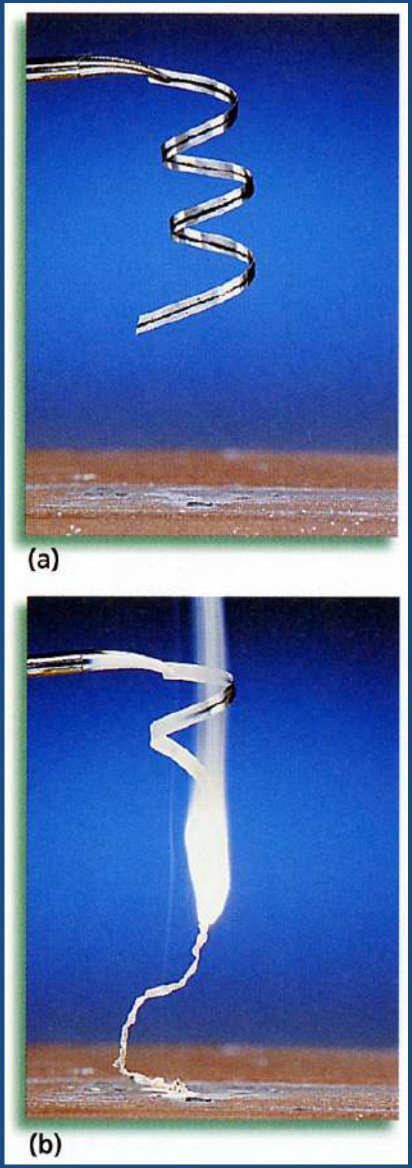
Oxidation–Reduction reactions

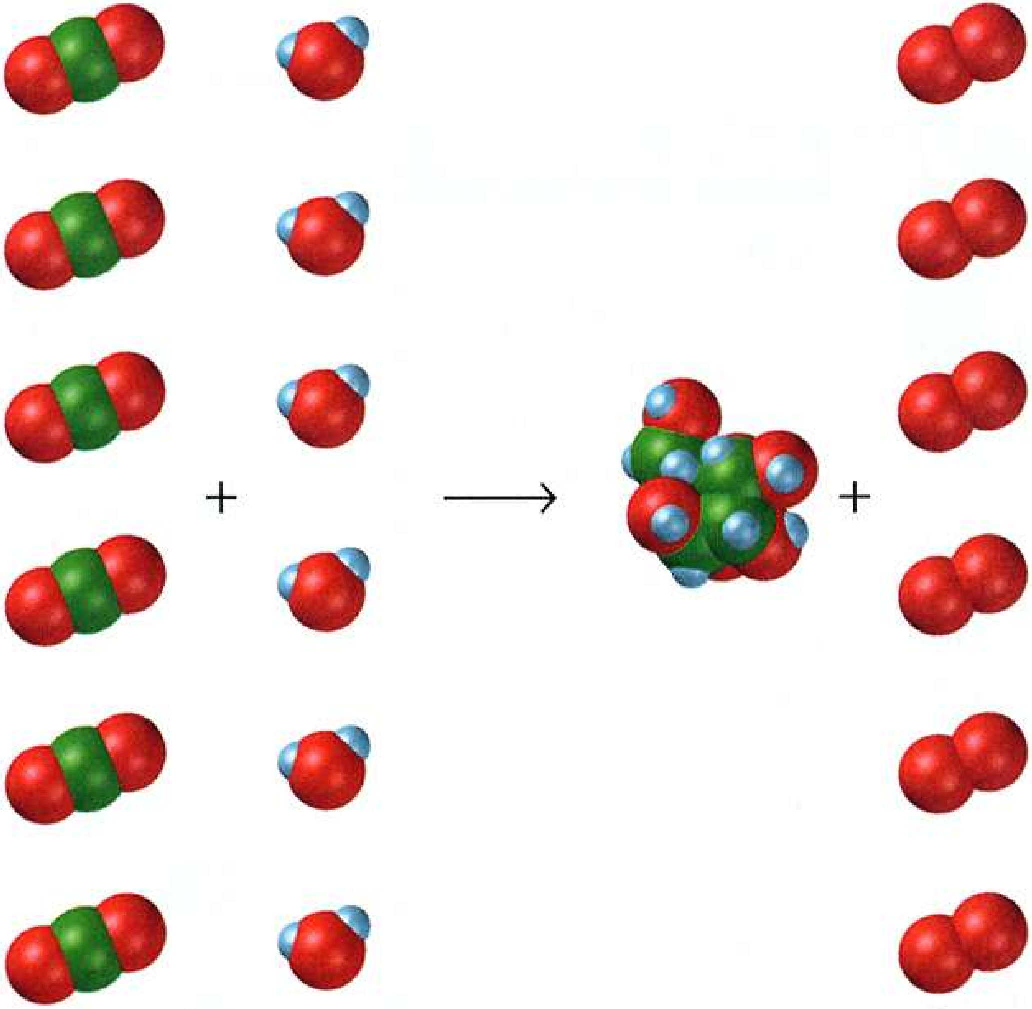
Acid–Base reactions

Combustion reactions

synthesis (combing) rxns

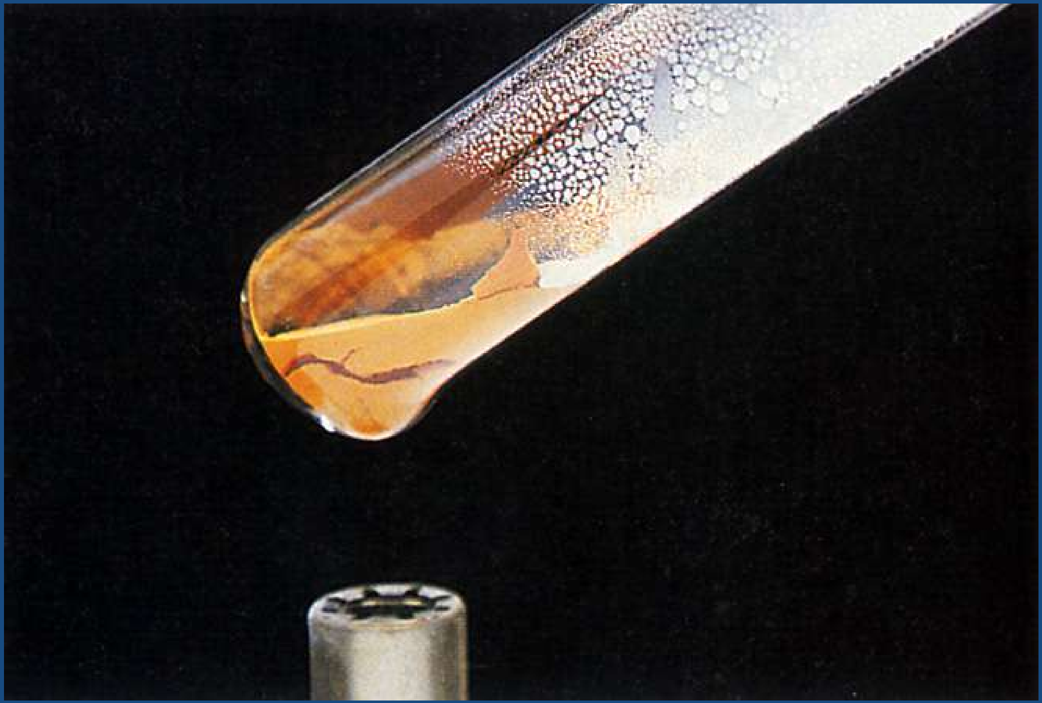
- 2+ become 1
- when a cmpd is formed from simpler stuff
- = **synthesis rxn**
- $C + O_2$ --> CO_2
- $N_2 + O_2$ --> $2NO$
- $Mg + F_2$ --> MgF_2
- can you see that all these are also redox rxns?





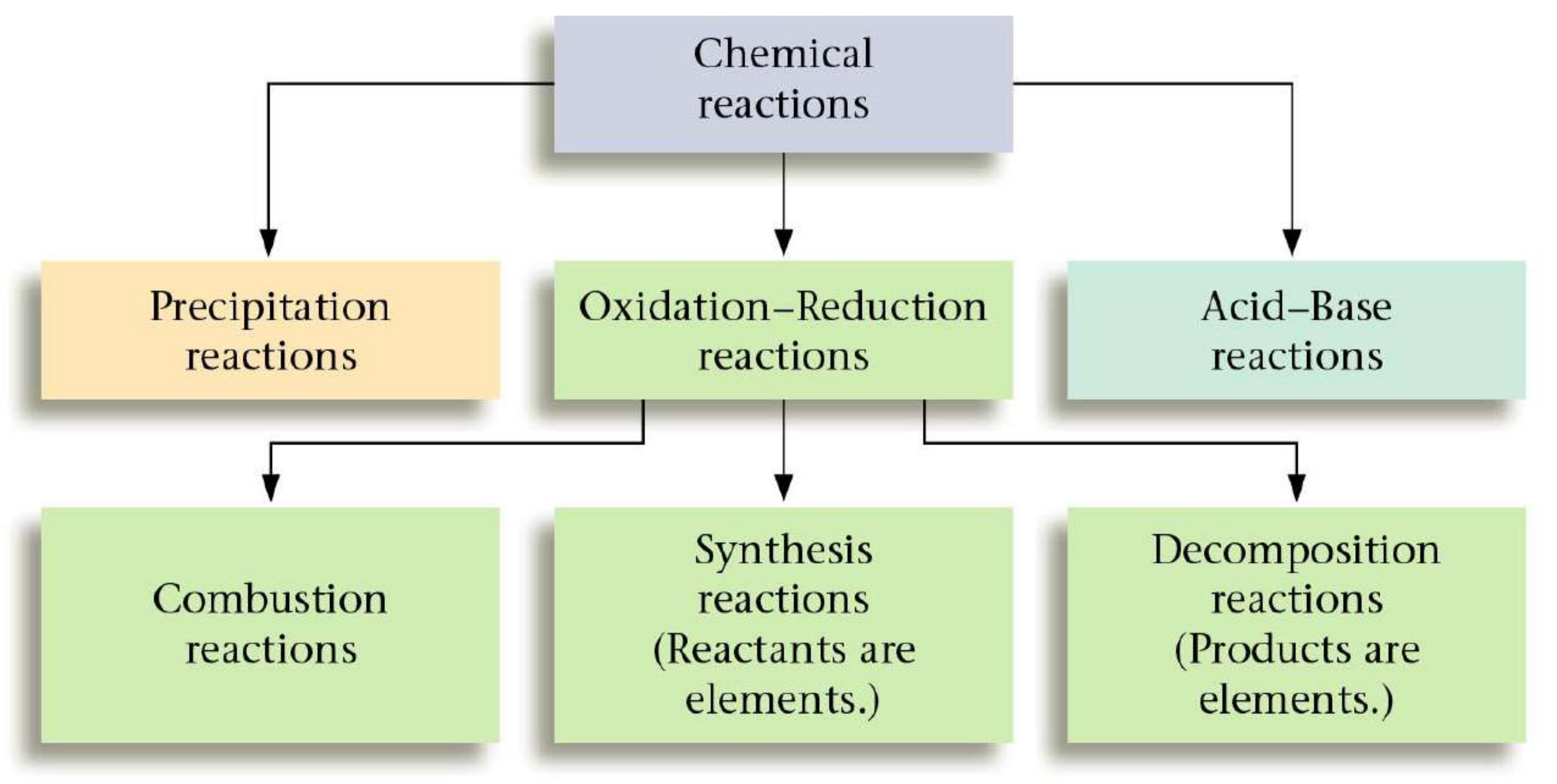
$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2$$

decomposition rxns



- guess what? here **something decomposes, or breaks down**
- $2H_2O \text{ --> } 2H_2 + O_2$
- $2HgO \text{ --> } 2Hg + O_2$
- $2NaCl \text{ --> } 2Na + Cl_2$
- just *opposite of synthesis* and are a subclass of redox again (1 becomes 2+)
- here's a summary…

a summary



Chemical reactions

Precipitation reactions

Oxidation–Reduction reactions

Acid–Base reactions

Combustion reactions

Synthesis reactions (Reactants are elements.)

Decomposition reactions (Products are elements.)

examples

- $4NH_3 + 5O_2$ --> $4NO + 6H_2O$
- *redox; combustion*
- $S_8 + 8O_2$ --> $8SO_2$
- *redox; synthesis/combustion*
- $2Al + 3Cl_2$ --> $2AlCl_3$
- *redox: synthesis*

examples

- 2AlN --> 2Al + N_2
- *redox; decomposition*
- $BaCl_{2(aq)}$ + $Na_2SO_{4(aq)}$ --> $BaSO_{4(s)}$ + $2NaCl_{(aq)}$
- *ppt (and double disp)*
- 2Cs + Br_2 --> 2CsBr
- *redox; synthesis*

examples

- KOH + HCl --> H_2O + KCl
- *acid-base (and dd)*
- $2C_2H_2$ + $5O_2$ --> $4CO_2$ + $2H_2O$
- *redox; combustion*
- 2Ni + $4O_2$ --> 2NiO
- *redox; synthesis*