

## Unit 7: Redox Reactions and Electrochemistry

### Chapter 19: Redox Reactions and Electrochemistry

#### 4.4: Oxidation-Reduction Reactions

**Reduction-Oxidation Reactions (Redox Rxn)**: - chemical reactions where there is a transfer of electron(s).

**Oxidation States (Oxidation Number)**: - a number that is arbitrary assigned to an atom in an element, molecule, and polyatomic ions to account for the number of electrons in *redox* reaction.

#### Rules for Assigning Oxidation Numbers:

1. **Natural Elements (include diatomic and polyatomics) have an Oxidation Number of 0.**

**Examples:** Na<sub>(s)</sub>, O<sub>2(g)</sub>, O<sub>3(g)</sub>, H<sub>2(g)</sub>, F<sub>2(g)</sub>, P<sub>4(s)</sub>, and Hg<sub>(l)</sub> all have an oxidation number of 0.

2. **Single Atomic Ions have an Oxidation Number Equals to its Charge.**

**Example:** K<sup>+</sup> has an oxidation number of +1.

3. **Oxygen in Binary Compound and Polyatomic Ions has an Oxidation Number of -2.**

**Examples:** CO<sub>2</sub>, CO, SO<sub>3</sub>, SO<sub>2</sub>, CO<sub>3</sub><sup>2-</sup>, SO<sub>4</sub><sup>2-</sup> and H<sub>2</sub>O all have an oxidation number of -2 for oxygen.

**An exception occurs in peroxides (compound containing O<sub>2</sub><sup>2-</sup>) where the oxygen has an oxidation number of -1.**

4. **Hydrogen in Binary Compounds and Polyatomic Ions has an Oxidation Number of +1.**

**Examples:** H<sub>2</sub>O, HCl, HBr, CH<sub>4</sub>, NH<sub>4</sub><sup>+</sup> and H<sub>2</sub>S all has an oxidation number of + 1 for hydrogen.

5. **In Binary Compounds, the Atom that has the most attraction to electrons (HIGHER Electronegativity) is assigned the NEGATIVE Oxidation Number. This Negative Oxidation Number is the SAME as its Ionic Charge.**

**Examples:** HF: F is more electronegative. Thus, F has an oxidation number of -1.

NH<sub>3</sub>: N is more electronegative. Thus, N has an oxidation number of -3.

H<sub>2</sub>S: S is more electronegative. Thus, S has an oxidation number of -2.

6. **The Sum of all Oxidation Numbers is 0 for all Electrically Neutral Compounds.**

**Examples:** CO: Oxidation numbers: O = -2; **C = +2** [(+2) + (-2) = 0]

SO<sub>2</sub>: Oxidation numbers: O = -2; **S = +4** [(+4) + 2(-2) = 0]

7. **The Sum of all Oxidation Numbers is Equal to the Overall Charge for all Polyatomic Ions.**

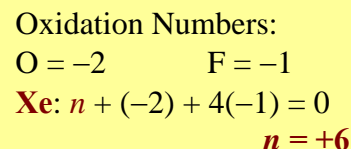
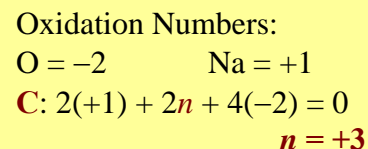
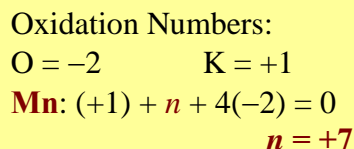
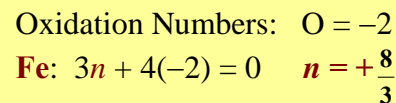
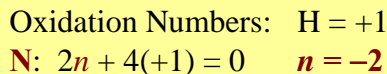
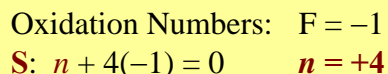
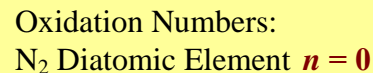
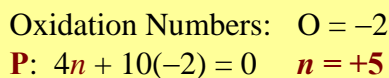
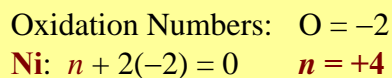
**Examples:** CO<sub>3</sub><sup>2-</sup>: Oxidation numbers: O = -2; **C = +4** [(+4) + 3(-2) = -2]

SO<sub>4</sub><sup>2-</sup>: Oxidation numbers: O = -2; **S = +6** [(+6) + 4(-2) = -2]

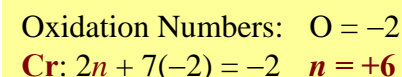
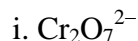
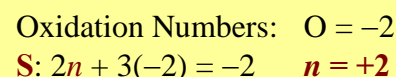
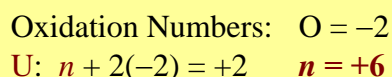
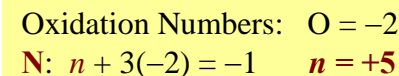
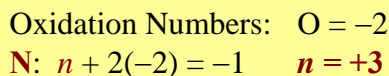
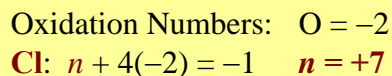
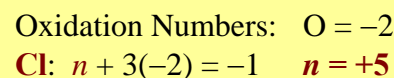
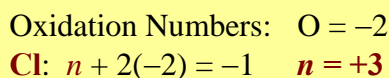
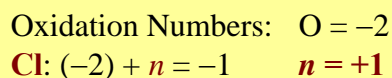
**Note:** Same Atom from different chemical species might NOT have the Same Oxidation Number.

We write the charges of ionic species as *n*<sup>+</sup> or *n*<sup>-</sup>. Oxidation numbers are written as +*n* or -*n*.

a.  $\text{NiO}_2$



a.  $\text{OCl}^-$

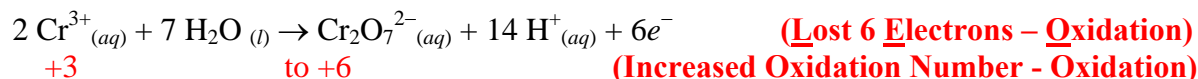


- an **INCREASE in the number of Oxygen Atoms in the species** is a sign of oxidation reaction.
- a **DECREASE in the number of HYDROGEN atoms in the species** is a sign of oxidation reaction.

$$\text{Fe}_{(s)} \rightarrow \text{Fe}^{3+}_{(aq)} + 3e^{-}$$

0      to    +3

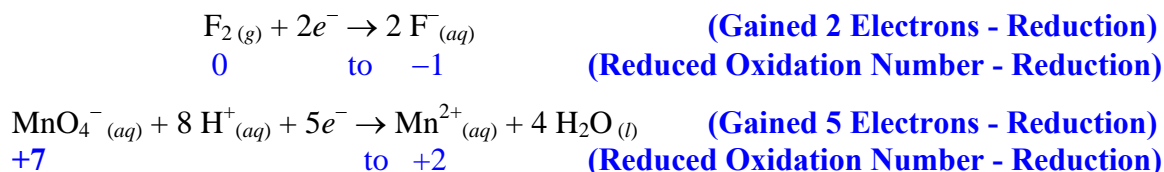
**(Lost 3 Electrons - Oxidation)**  
**(Increased Oxidation Number - Oxidation)**



**Reduction Reactions:** - reactions that **GAIN Electrons** (**GER** – “**G**aining **E**lectrons” – **Reduction**) or a **DECREASE (Reduction) in Oxidation Number**.

- a **DECREASE in the number of Oxygen Atoms in the species** is a sign of reduction reaction.
- an **INCREASE in the number of HYDROGEN atoms in the species** is a sign of reduction reaction.

**Examples:**



**Half-Reactions:** - part of the redox reaction where it shows either the oxidation reaction or the reduction reaction.

- electrons are usually present in either side of the half-reaction.
- **Oxidation half-reaction has Electrons on the Product Side (Losing Electrons).**
- **Reduction half-reaction has Electrons on the Reactant Side (Gaining Electrons).**

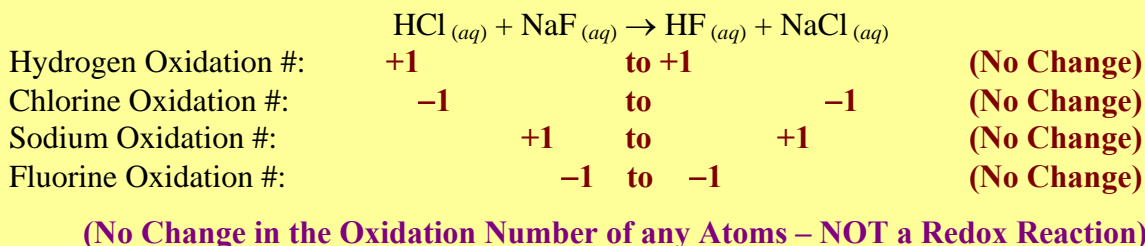
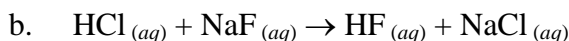
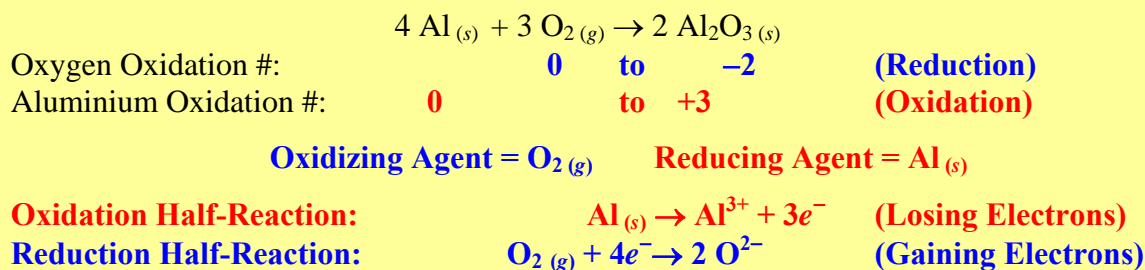
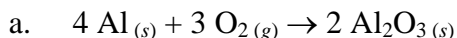
**Oxidizing Agent:** - a chemical species that **Accepts (Gains) Electrons from an Oxidized species**.

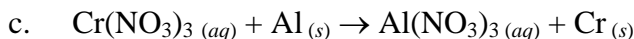
- it **helps another species to oxidize** but **itself being reduced** (gained electrons or decreased in oxidation number).
- in another words, **Reducing Species = Oxidizing Agent (GER-OA)**

**Reducing Agent:** - a chemical species that **Donates (Lose) Electrons from a Reduced species**.

- it **helps another species to reduce** but **itself being oxidized** (lost electrons or increased in oxidation number).
- in another words, **Oxidizing Species = Reducing Agent (LEO-RA)**

**Example 2:** Classify if the following reactions are redox reaction. For each of the redox reaction identified, label the reducing agent and oxidizing agent. Propose a reduction half-reaction and oxidation half-reaction.





An initial examination reveals that  $\text{NO}_3^-$  did not change in oxidation numbers

Complete Ionic Equation:  $\text{Cr}^{3+}(\text{aq}) + 3\text{NO}_3^-(\text{aq}) + \text{Al}(\text{s}) \rightarrow \text{Al}^{3+}(\text{aq}) + 3\text{NO}_3^-(\text{aq}) + \text{Cr}(\text{s})$

Net Ionic Equation:  $\text{Cr}^{3+}(\text{aq}) + \text{Al}(\text{s}) \rightarrow \text{Al}^{3+}(\text{aq}) + \text{Cr}(\text{s})$

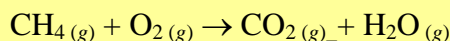
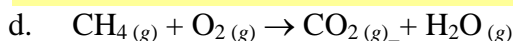
Chromium Oxidation #:  $+3$  to  $0$  (Reduction)

Aluminium Oxidation #:  $0$  to  $+3$  (Oxidation)

Oxidizing Agent =  $\text{Cr}^{3+}(\text{aq})$  Reducing Agent =  $\text{Al}(\text{s})$

Oxidation Half-Reaction:  $\text{Al}(\text{s}) \rightarrow \text{Al}^{3+} + 3e^-$  (Losing Electrons)

Reduction Half-Reaction:  $\text{Cr}^{3+}(\text{aq}) + 3e^- \rightarrow \text{Cr}(\text{s})$  (Gaining Electrons)



Oxygen Oxidation #:  $0$  to  $-2$  (Reduction)

Carbon Oxidation #:  $-4$  to  $+4$  (Oxidation)

Hydrogen Oxidation #:  $+1$  to  $+1$  (No Change)

Oxidizing Agent =  $\text{O}_2(\text{g})$  Reducing Agent =  $\text{CH}_4(\text{g})$

### Assignment

4.4 pg. 126–127 #35 to 50

## 19.1: Redox Reactions

### Balancing Oxidation-Reduction Reaction by Half-Reaction Method:

1. Identify the atom that is undergoing a change in its oxidation number. Find out the change in oxidation number. Break up any Soluble Ionic Compound.

2. Balance the Oxidation Number by Adding Electrons to the side of the HIGHER Oxidation Number. The Number of Electrons Added is the Difference in the Oxidation Number.

**Examples:**  $\text{Sn}^{2+}(\text{aq}) \rightarrow \text{Sn}^{4+}(\text{aq})$  (Sn changes from +2 to +4. Hence, add  $2e^-$  to the right side.)  
 $\text{Sn}^{2+}(\text{aq}) \rightarrow \text{Sn}^{4+}(\text{aq}) + 2e^-$  (Charges and Elements are Balanced)

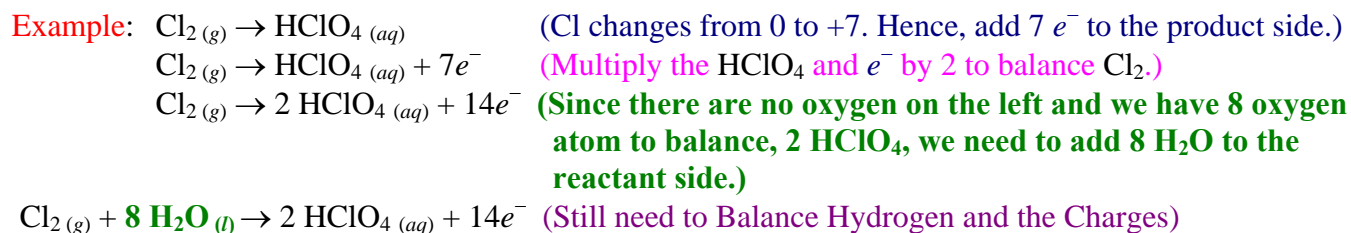
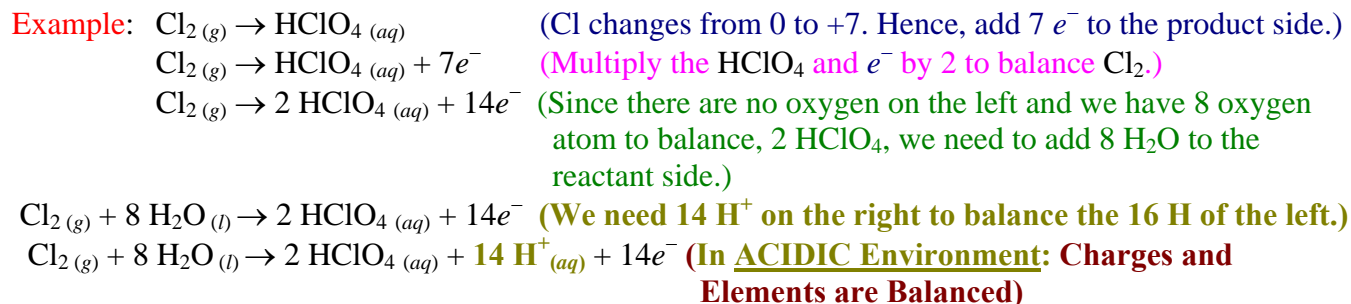
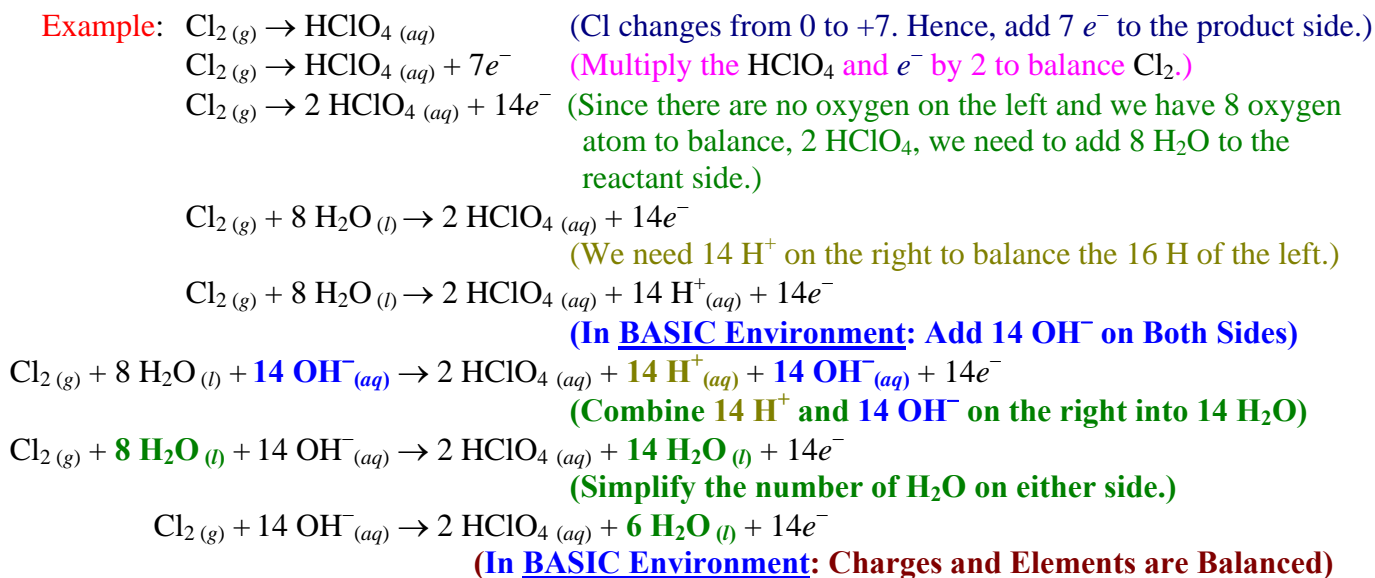
$\text{Fe}^{3+}(\text{aq}) \rightarrow \text{Fe}^{2+}(\text{aq})$  (Fe changes from +3 to +2. Hence, add  $1e^-$  to the left side.)  
 $\text{Fe}^{3+}(\text{aq}) + e^- \rightarrow \text{Fe}^{2+}(\text{aq})$  (Charges and Elements are Balanced)

$\text{Cl}_2(\text{g}) \rightarrow \text{HClO}_4(\text{aq})$  (Cl changes from 0 to +7. Hence, add  $7e^-$  to the product side.)  
 $\text{Cl}_2(\text{g}) \rightarrow \text{HClO}_4(\text{aq}) + 7e^-$  (Still need to Balance Hydrogen, Oxygen and the Charges)

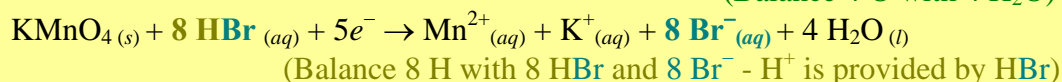
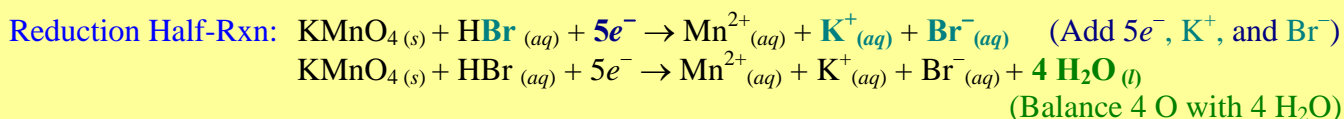
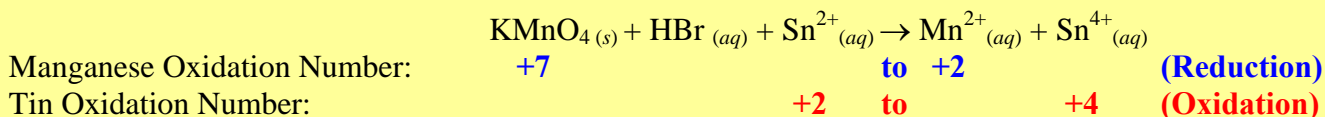
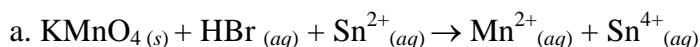
3. To balance the rest of the Half-Reaction (if necessary after step 2):

a. Balance the Chemical Species Containing the Atom undergoing the Change in Oxidation Number. This is achieved by Multiplying the BOTH the Chemical Species and the Number of Electrons just added by the New Coefficient.

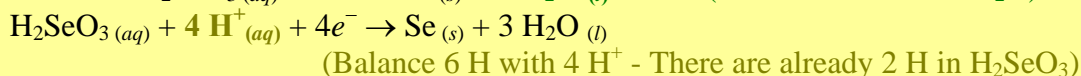
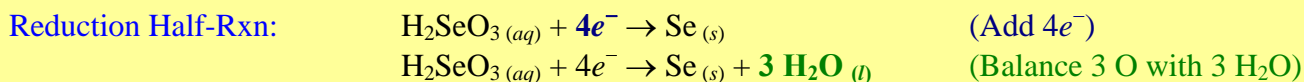
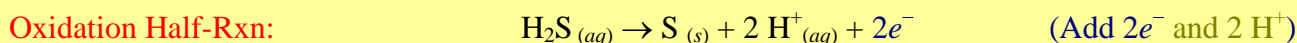
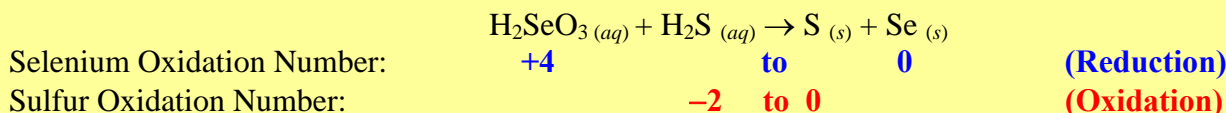
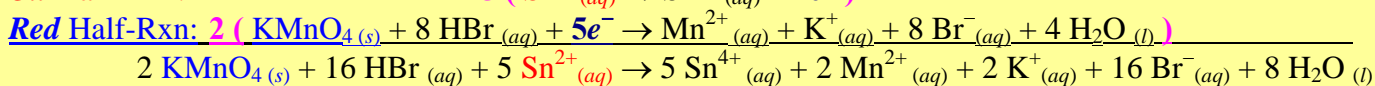
**Example:**  $\text{Cl}_2(\text{g}) \rightarrow \text{HClO}_4(\text{aq})$  (Cl changes from 0 to +7. Hence, add  $7e^-$  to the product side.)  
 $\text{Cl}_2(\text{g}) \rightarrow \text{HClO}_4(\text{aq}) + 7e^-$  (Multiply the  $\text{HClO}_4$  and  $e^-$  by 2 to balance  $\text{Cl}_2$ .)  
 $\text{Cl}_2(\text{g}) \rightarrow 2\text{HClO}_4(\text{aq}) + 14e^-$  (Still need to Balance Hydrogen, Oxygen and the Charges)

**b. Balance the Oxygen atom by adding H<sub>2</sub>O(l) to the side that has less oxygen atom.****c. Balance the Hydrogen atom by adding H<sup>+</sup>(aq) to the side that has less hydrogen atom.****d. In Basic Environment, Add the Same Number of OH<sup>-</sup> as H<sup>+</sup> to BOTH Sides. Combine H<sup>+</sup> and OH<sup>-</sup> that are on the Same Side into H<sub>2</sub>O. Simplify the H<sub>2</sub>O on Both Sides.****4. Always CHECK if the half-reaction is Balanced for All Elements and Charges.****5. Do Steps 1 to 4 again for the another atom that changes oxidation number.****6. Combine the redox half-reactions by balancing the electrons. There should be electrons on the product side of the oxidation half-reaction and the reactant side of the reduction half-reaction.**

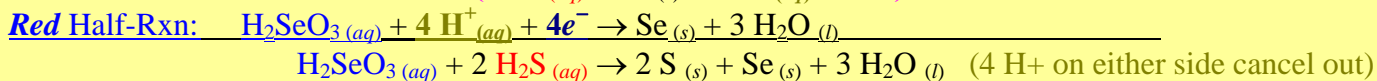
**Example 1:** Balance the following equation in acidic environment. Identify the oxidizing agent and reduction agent.



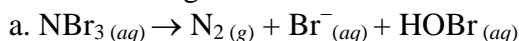
**Combine Oxidation and Reaction Half-Reactions by Equating the Number of Electrons.**



**Combine Oxidation and Reaction Half-Reactions by Equating the Number of Electrons.**



**Example 2:** Balance the following equation in basic environment. Identify the oxidizing agent and reduction agent.



$\text{NBr}_3(\text{aq}) \rightarrow \text{N}_2(\text{g}) + \text{Br}^-(\text{aq}) + \text{HOBr}(\text{aq})$

Nitrogen Oxidation Number: **+3 to 0** **(Reduction)**  
 Bromine Oxidation Number: **-1 to (-1) +1** **(Oxidation)**

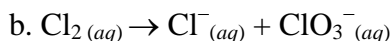
**Reduction Half-Rxn:**  $\text{NBr}_3(\text{aq}) + 3e^- \rightarrow \text{N}_2(\text{g}) + 3\text{Br}^-(\text{aq})$  (Add  $3e^-$  and  $3\text{Br}^-$ )  
 $2\text{NBr}_3(\text{aq}) + 6e^- \rightarrow \text{N}_2(\text{g}) + 6\text{Br}^-(\text{aq})$  (Multiply  $e^-$ ,  $\text{NBr}_3$  and  $\text{Br}^-$  by 2 to balance  $\text{N}_2$ )

**Oxidation Half-Rxn:**  $\text{Br}^-(\text{aq}) \rightarrow \text{HOBr}(\text{aq}) + 2e^-$  (Add  $2e^-$  - Have to separate  $\text{Br}^-$  from  $\text{NBr}_3$ . Otherwise, there is no way to balance N)  
 $\text{Br}^-(\text{aq}) + \text{H}_2\text{O}(\text{l}) \rightarrow \text{HOBr}(\text{aq}) + 2e^-$  (Balance O with  $\text{H}_2\text{O}$ )  
 $\text{Br}^-(\text{aq}) + \text{H}_2\text{O}(\text{l}) + \text{OH}^-(\text{aq}) \rightarrow \text{HOBr}(\text{aq}) + \text{H}^+(\text{aq}) + \text{OH}^-(\text{aq}) + 2e^-$  (Balance H with  $\text{H}^+$ , but add equal  $\text{OH}^-$  to both sides – Basic Environment)  
 $\text{Br}^-(\text{aq}) + \text{H}_2\text{O}(\text{l}) + \text{OH}^-(\text{aq}) \rightarrow \text{HOBr}(\text{aq}) + \text{H}_2\text{O}(\text{l}) + 2e^-$  (Simplify  $\text{H}_2\text{O}$  on both sides)  
 $\text{Br}^-(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{HOBr}(\text{aq}) + 2e^-$  (Check Balancing on Charges and Elements)

Combine Oxidation and Reaction Half-Reactions by Equating the Number of Electrons.

**Red Half-Rxn:**  $2\text{NBr}_3(\text{aq}) + 6e^- \rightarrow \text{N}_2(\text{g}) + 6\text{Br}^-(\text{aq})$   
**Ox Half-Rxn:**  $3(\text{Br}^-(\text{aq}) + \text{OH}^-(\text{aq}) \rightarrow \text{HOBr}(\text{aq}) + 2e^-)$   
 $2\text{NBr}_3(\text{aq}) + 3\text{OH}^-(\text{aq}) \rightarrow \text{N}_2(\text{g}) + 3\text{Br}^-(\text{aq}) + 3\text{HOBr}(\text{aq})$  (Simplify  $\text{Br}^-$  on both sides)

**Oxidizing Agent and Reducing Agent =  $\text{NBr}_3(\text{aq})$**



$\text{Cl}_2(\text{aq}) \rightarrow \text{Cl}^-(\text{aq}) + \text{ClO}_3^-(\text{aq})$

Chloride Oxidation Number: **0 to -1** **(Reduction)**  
 Chlorate Oxidation Number: **0 to +5** **(Oxidation)**

**Oxidation Half-Rxn:**  $\text{Cl}_2(\text{g}) \rightarrow \text{ClO}_3^-(\text{aq}) + 5e^-$  (Add  $5e^-$ )  
 $\text{Cl}_2(\text{g}) \rightarrow 2\text{ClO}_3^-(\text{aq}) + 10e^-$  (Multiply  $e^-$  and  $\text{ClO}_3^-$  by 2 to balance  $\text{Cl}_2$ )  
 $\text{Cl}_2(\text{g}) + 6\text{H}_2\text{O}(\text{l}) \rightarrow 2\text{ClO}_3^-(\text{aq}) + 10e^-$  (Balance 6 O with 6  $\text{H}_2\text{O}$ )  
 $\text{Cl}_2(\text{g}) + 6\text{H}_2\text{O}(\text{l}) + 12\text{OH}^-(\text{aq}) \rightarrow 2\text{ClO}_3^-(\text{aq}) + 12\text{H}^+(\text{aq}) + 12\text{OH}^-(\text{aq}) + 10e^-$  (Balance H with  $\text{H}^+$ , but add equal  $\text{OH}^-$  to both sides – Basic Environment)  
 $\text{Cl}_2(\text{g}) + 6\text{H}_2\text{O}(\text{l}) + 12\text{OH}^-(\text{aq}) \rightarrow 2\text{ClO}_3^-(\text{aq}) + 12\text{H}_2\text{O}(\text{l}) + 10e^-$  (Simplify  $\text{H}_2\text{O}$  on both sides)  
 $\text{Cl}_2(\text{g}) + 12\text{OH}^-(\text{aq}) \rightarrow 2\text{ClO}_3^-(\text{aq}) + 6\text{H}_2\text{O}(\text{l}) + 10e^-$  (Check Balancing)

**Reduction Half-Rxn:**  $\text{Cl}_2(\text{g}) + e^- \rightarrow \text{Cl}^-(\text{aq})$  (Add  $1e^-$ )  
 $\text{Cl}_2(\text{g}) + 2e^- \rightarrow 2\text{Cl}^-(\text{aq})$  (Multiply  $e^-$  and  $\text{Cl}^-$  by 2 to balance  $\text{Cl}_2$ )

Combine Oxidation and Reaction Half-Reactions by Equating the Number of Electrons.

**Ox Half-Rxn:**  $\text{Cl}_2(\text{g}) + 12\text{OH}^-(\text{aq}) \rightarrow 2\text{ClO}_3^-(\text{aq}) + 6\text{H}_2\text{O}(\text{l}) + 10e^-$   
**Red Half-Rxn:**  $5(\text{Cl}_2(\text{g}) + 2e^- \rightarrow 2\text{Cl}^-(\text{aq}))$   
 $6\text{Cl}_2(\text{g}) + 12\text{OH}^-(\text{aq}) \rightarrow 10\text{Cl}^-(\text{aq}) + 2\text{ClO}_3^-(\text{aq}) + 6\text{H}_2\text{O}(\text{l})$

**Oxidizing Agent and Reducing Agent =  $\text{Cl}_2(\text{g})$**



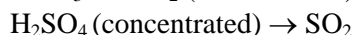
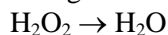
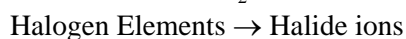
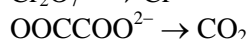
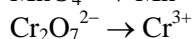
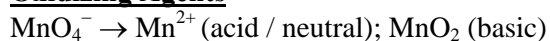
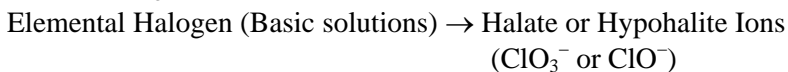
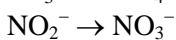
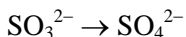
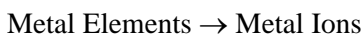
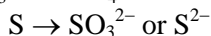
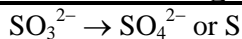
**Predicting Observations of a Redox Reaction:**

1. Look for **new solid** form or **gas** evolved.
2. Some of the **metal ions and polyatomic ions have different colours** (see table below).
3. There might be **pH changes** as  $[H^+]$  or  $[OH^-]$  increases or decreases as the redox reaction proceeds forward.

**Some General Ions Colours in Solution for Row 1 of the Transition Metals**

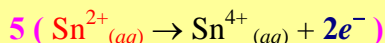
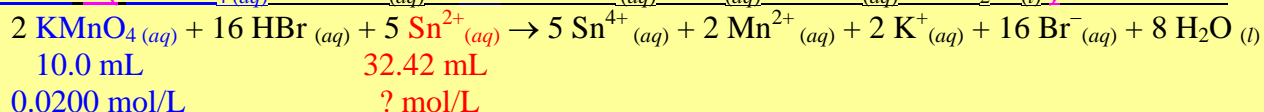
Ionic Species		Solution Concentrations	
		1.0 M	0.010 M
Dichromate	$Cr_2O_7^{2-}$	orange	pale orange
Chromate	$CrO_4^{2-}$	yellow	pale yellow
Chromium (III)	$Cr^{3+}$	blue-green	green
Cobalt (III)	$Co^{3+}$	yellow	pale yellow
Hexa-cyano-cobalt (III)	$Co(CN)_6^{3-}$	yellow	pale yellow
Hexa-ammine-cobalt (III)	$Co(NH_3)_6^{3+}$	yellow	pale yellow
Cobalt (II)	$Co^{2+}$	red	pink
Copper (II)	$Cu^{2+}$	blue	pale blue
Copper (I)	$Cu^+$	blue-green	pale blue-green
Iron (III)	$Fe^{3+}$	reddish-brown	pink
Tri-thiocyano-iron (III)	$Fe(SCN)_3$	red	pink
Hexa-cyano-iron (III)	$Fe(CN)_6^{3-}$	red	pink
Iron (II)	$Fe^{2+}$	lime green	colourless
Hexa-cyano-iron (II)	$Fe(CN)_6^{4-}$	yellow	pale yellow
Permanganate	$MnO_4^-$	deep purple	purple-pink
Manganese (IV)	$Mn^{4+}$	dark brown	reddish-brown
Manganese (II)	$Mn^{2+}$	pinkish-red	colourless
Nickel (II)	$Ni^{2+}$	green	pale green
Hexa-ammine-nickel (II)	$Ni(NH_3)_6^{2+}$	blue	pale blue
Vanadium (V)	$V^{5+}$	yellow	pale yellow
Vanadium (IV)	$V^{4+}$	blue	pale blue
Vanadium (III)	$V^{3+}$	blue-green	pale blue-green
Vanadium (II)	$V^{2+}$	violet	light purple



Some Common Oxidizing and Reducing AgentsOxidizing AgentsReducing AgentsSpecies that can be BOTH Oxidizing and Reducing Agents**Redox Titration:** - a titration involving redox half reactions to determine the concentration of an ion.- **does not need any indicator** as the analyte ion tends to have a colour of its own.Stoichiometry of Redox Titration:

1. Balance the Redox Reaction using the Half-Reaction Method.
2. Find the moles of the given reagent (usually with the titrant where the concentration and volume added are known).
3. Set up mole ratio and determine the number of moles of the analyte ion at equivalence point.
4. Calculate the concentration of the analyte ion.

**Example 4:** 10.0 mL of 0.0200 M acidified  $\text{KMnO}_4$  (aq) is titrated with an unknown concentration of  $\text{Sn}^{2+}$  solution. The average volume of  $\text{Sn}^{2+}$  added was 32.42 mL. Use the answer of example 1a. of this section as the equation for this redox reaction. Determine the concentration of  $\text{Sn}^{2+}$ . Comment on any qualitative observations.

**Ox Half-Rxn:****Red Half-Rxn:**  $2 (\text{KMnO}_4_{(aq)} + 8 \text{HBr}_{(aq)} + 5e^- \rightarrow \text{Mn}^{2+}_{(aq)} + \text{K}^+_{(aq)} + 8 \text{Br}^-_{(aq)} + 4 \text{H}_2\text{O}_{(l)})$ 

$$\textcircled{1} n_{\text{KMnO}_4} = CV = (0.0200 \text{ mol/L}) (10.0 \text{ mL}) = 0.200 \text{ mmol}$$

$$\textcircled{2} n_{\text{Sn}^{2+}} = 0.200 \text{ mmol KMnO}_4 \times \frac{5 \text{ mol Sn}^{2+}}{2 \text{ mol KMnO}_4} = 0.500 \text{ mmol Sn}^{2+}$$

$$\textcircled{3} [\text{Sn}^{2+}] = \frac{n}{V} = \frac{0.5000 \text{ mmol}}{32.43 \text{ mL}} = 0.015417823 \text{ mol/L}$$

$$[\text{Sn}^{2+}] = 0.0154 \text{ mol/L}$$

Qualitative Observations:

1.  $\text{MnO}_4^-$  is purple pink colour at around 0.0200 M. As  $\text{Sn}^{2+}$  is added from the buret,  $\text{MnO}_4^-$  in the flask will turn into  $\text{Mn}^{2+}$ , which is colourless at low concentration.
2. The acidified  $\text{Sn}^{2+}$  solution initially had a low pH but the pH will increase as  $\text{HBr}_{(aq)}$  is consumed in the titration.

Assignment

19.1 pg. 675–676 #1 and 2

**19.2 & 19.3: Galvanic Cells & Standard Reduction Potentials**

**Electrochemistry**: - the branch of chemistry that studies the relationship between chemical energy and electrical energy.

**Electrochemical Cells**: - an apparatus that **Converts Chemical Energy to Electrical Energy**.

- commonly known as **Galvanic Cells** or **Voltaic Cells**.
- it consists of two containers of solutions (electrolytes) and the electrodes (usually metals called anode and cathode), as well as a connection between these two containers (salt bridge, porous cup, or porous disk), and a wire connecting the two electrodes.
- involve **Spontaneous Redox Reaction** and a **Positive Cell Potential** (see section 19.3)

**Electrodes**: - metals or other elements that serve as the site of redox reactions in a galvanic cell.

- in the case of a gaseous or liquid element, a carbon rod or platinum plating (inert material) is used as the solid electrode.

**Anode**: - the terminal where **oxidation** is taken place and commonly marked as the **Negative terminal**.  
(LEOA-RA: **Losing Electrons Oxidation Anode – Reducing Agent)**

**Cathode**: - the terminal where **reduction** is taken place and commonly marked as the **Positive terminal**.  
(GERC-OA: **Gaining Electrons Reduction Cathode – Oxidizing Agent)**

**Salt Bridge**: - an upside down U-tube filled with electrolytes like  $\text{KCl}_{(aq)}$  to prevent charge build-up. (The ions in the salt bridge do NOT get mixed into the half-cells, nor do the electrolytes in the half-cells travelled into the salt bridge.)  
- also serves as the separator between the two half cells.  
- other equipment like **porous disk** and **porous cup** (clay porcelain cup) can be used instead of a salt bridge.

**Cell Potential** ( $E_{\text{cell}}$ ): - sometimes called **electromotive force** (emf).  
- the amount of **electrical energy in terms of electric charges**.

**Volts** (V): - the amount of **work (energy) in J per charge (q) coulomb (unit symbol: C) of electrons** transferred between two potentials (anode and cathode).  
- commonly refer to as **potential difference**.

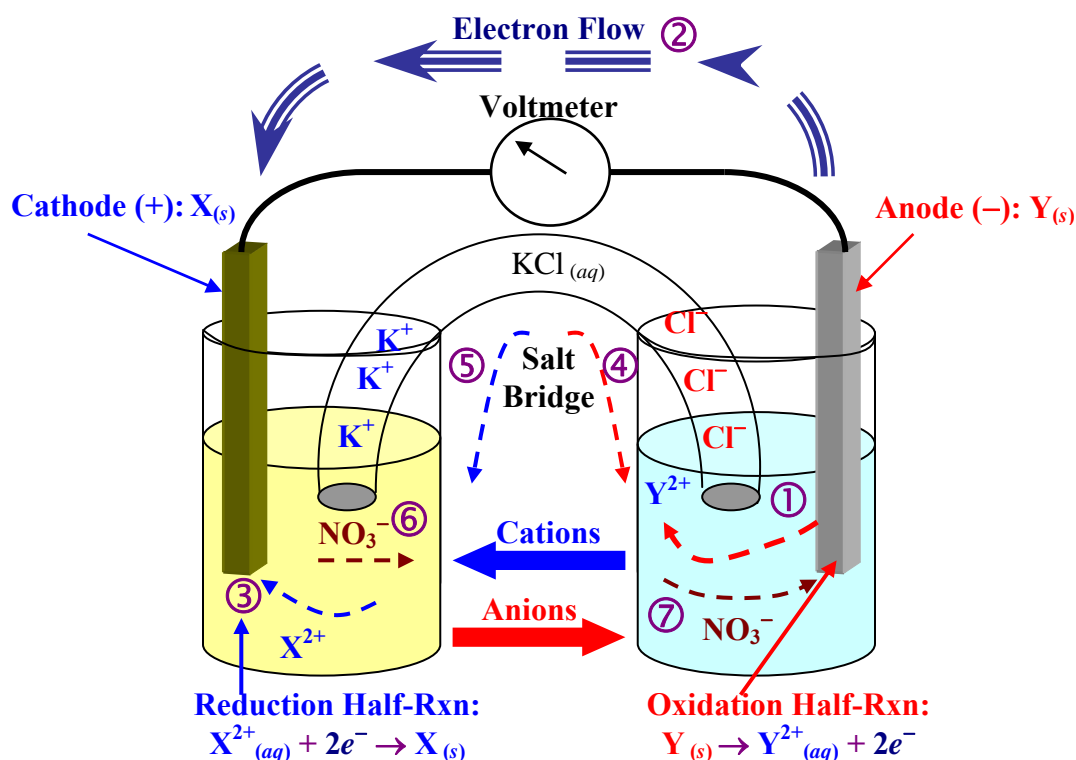
**Potentiometer**: - a electric device that measures potential difference between the cathode and anode.  
- sometimes refer to as a **voltmeter**.

**Galvanic Cells**

1. **Electrons move from Anode (–) to Cathode (+).**
2. **Cations move towards the Cathode.**
3. **Anions move towards the Anode.**

**Anode (–): (LEOA-RA: Losing Electrons Oxidation Anode – Reducing Agent)**

**Cathode (+): (GERC-OA: Gaining Electrons Reduction Cathode – Oxidizing Agent)**



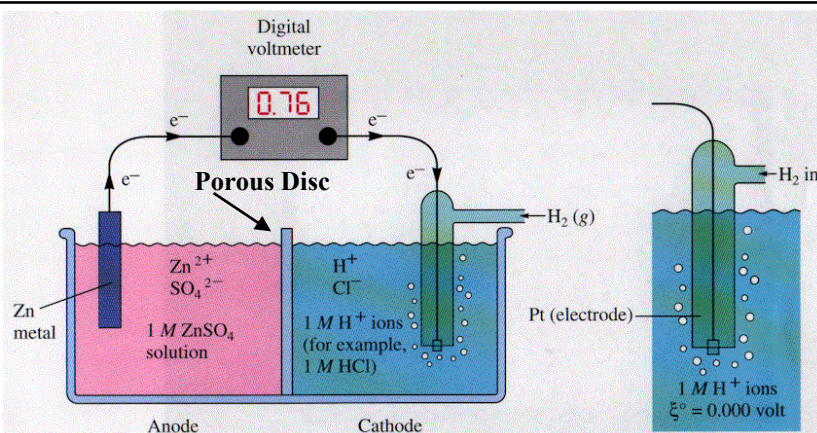
(Above) A typical electrochemical cells with a salt bridge using an upside down U-tube.

**Check out Voltaic Cell Animations at**

<http://www.sgc.peachnet.edu/users/larnold/WWW/courses/1212/rev1212.html>

### Galvanic Cell Step by Step

- ①  $Y^{2+}$  leaves  $Y_{(s)}$  at the Anode.
- ② Electrons produced at the Anode (-) move to Cathode (+) causing a potential difference that is measured by the voltmeter.
- ③ Electrons arrived at the Cathode combining with  $X^{2+}$  to form  $X_{(s)}$ .
- ④  $Cl^{-}$  from the salt bridge migrate towards the anode half-cells to counteract charge buildup by  $Y^{2+}$
- ⑤ As a result,  $K^{+}$  from the salt bridge travel towards the cathode half-cell
- ⑥  $NO_3^{-}$  (anions to bring in cations electrolytes into the half-cells) in the cathode half-cell moves toward the salt bridge (and thus towards the anode) because of  $K^{+}$  charge buildup inside the salt bridge.
- ⑦ Similarly,  $NO_3^{-}$  in the anode half-cell moves towards the anode because the anode metal is becoming too positive (electrons are leaving at the anode metal).



Galvanic cells using a porous cup (left) and platinum electrode because of the gaseous cathode (right).

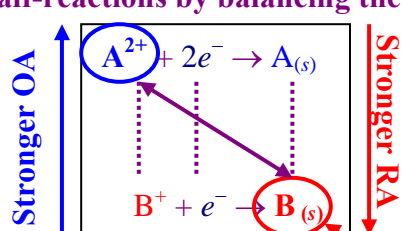
**Standard Hydrogen Potential:** - the reduction potential of hydrogen ions to hydrogen gas is assigned a voltage of 0 at standard conditions (25°C and 1 atm).  $(2 \text{H}^+_{(aq)} + 2e^- \rightarrow \text{H}_{2(g)} \quad E^\circ = 0.00 \text{ V})$

**Standard Reduction Potential:** - the electric potentials of reduction half-reactions as compared with hydrogen under standard condition (25°C and 1.0 mol/L of electrolytes or 1.0 atm of gaseous element (see Table on the next page).

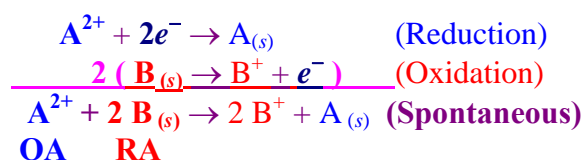
- since the table are of reduction half reactions, the **strongest oxidizing agent is listed on the left and decreasing in strength as one moves down the table**. (This makes sense, as we know  $\text{F}_{2(g)}$  is the most electronegative, and thereby is the strongest oxidizing agent – likes to gain electrons.)
- conversely, the **weakest reducing agent is listed on the right and increasing in strengths as one moves down the table**. (This also makes sense, since Alkali metals like to lose electrons, they make excellent reducing agents.)
- **metals are reducing agents as they prefer to lose electrons to become cations (oxidation).**
- **non-metals (especially halogens) are usually oxidizing agent as they tend to gain electrons to become anions (reduction).**
- strong oxidizing for common laboratory agents are acidify  $\text{MnO}_4^-$  and  $\text{Cr}_2\text{O}_7^{2-}$ .

### Procedure to Predict Spontaneity Redox Reactions Under Standard Conditions:

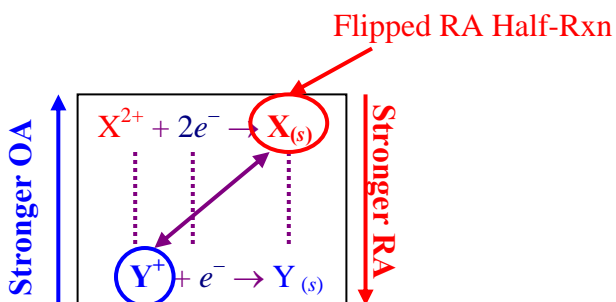
1. Locate the chemical species on the Table of Relative Strength of Standard Reduction Potentials. There should be one on the Left Side of the table and one on the right side. The reactions represent the reduction and oxidation half-reactions of the redox reaction.
2. **Spontaneous Reaction:** - redox reactions that **will proceed forward** where **chemical energy** converts to **electrical energy** (galvanic cells).
  - the **Oxidizing Agent (OA) on the LEFT is HIGHER than the Reducing Agent (RA) on the RIGHT**.
  - **FLIP the Reducing Agent – Oxidation Half-Reaction (LOWER Half-Reaction) and ADD the two half-reactions by balancing the electrons.**



$\text{A}^{2+}$  will react with  $\text{B}_{(s)}$



3. **Non-Spontaneous Reaction:** - redox reactions that **will NOT proceed forward** unless there is an external energy source to start and maintain the chemical reaction (electrolytic cell – see section 19.8)
  - the **Oxidizing Agent (OA) on the LEFT is LOWER than the Reducing Agent (RA) on the RIGHT**.
  - **FLIP the Reducing Agent – Oxidation Half-Reaction (HIGHER Half-Reaction) and ADD the two half-reactions by balancing the electrons.**



$\text{X}_{(s)}$  will NOT react with  $\text{Y}^+$

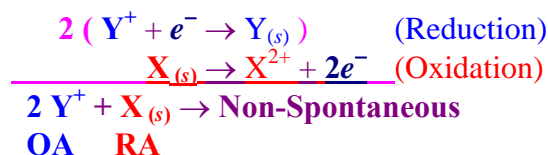




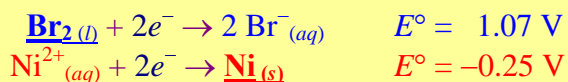
Table of Selected Standard Electrode Potentials<sup>\*</sup>

Reduction Half-Reaction		Electrical Potential (V) $E^\circ$
$\text{F}_{2(g)} + 2\text{e}^- \rightleftharpoons 2\text{F}^-_{(aq)}$	.....	+2.87
$\text{PbO}_{2(s)} + \text{SO}_4^{2-}_{(aq)} + 4\text{H}^+_{(aq)} + 2\text{e}^- \rightleftharpoons \text{PbSO}_{4(s)} + 2\text{H}_2\text{O}_{(l)}$	.....	+1.69
$\text{MnO}_4^-_{(aq)} + 8\text{H}^+_{(aq)} + 5\text{e}^- \rightleftharpoons \text{Mn}^{2+}_{(aq)} + 4\text{H}_2\text{O}_{(l)}$	.....	+1.51
$\text{Au}^{3+}_{(aq)} + 3\text{e}^- \rightleftharpoons \text{Au}_{(s)}$	.....	+1.50
$\text{ClO}_4^-_{(aq)} + 8\text{H}^+_{(aq)} + 8\text{e}^- \rightleftharpoons \text{Cl}^-_{(aq)} + 4\text{H}_2\text{O}_{(l)}$	.....	+1.39
$\text{Cl}_{2(g)} + 2\text{e}^- \rightleftharpoons 2\text{Cl}^-_{(aq)}$	.....	+1.36
$2\text{HNO}_{2(aq)} + 4\text{H}^+_{(aq)} + 4\text{e}^- \rightleftharpoons \text{N}_2\text{O}_{(g)} + 3\text{H}_2\text{O}_{(l)}$	.....	+1.30
$\text{Cr}_2\text{O}_7^{2-}_{(aq)} + 14\text{H}^+_{(aq)} + 6\text{e}^- \rightleftharpoons 2\text{Cr}^{3+}_{(aq)} + 7\text{H}_2\text{O}_{(l)}$	.....	+1.23
$\text{O}_{2(g)} + 4\text{H}^+_{(aq)} + 4\text{e}^- \rightleftharpoons 2\text{H}_2\text{O}_{(l)}$	.....	+1.23
$\text{MnO}_{2(aq)} + 4\text{H}^+_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Mn}^{2+}_{(aq)} + 2\text{H}_2\text{O}_{(l)}$	.....	+1.22
$\text{Br}_{2(l)} + 2\text{e}^- \rightleftharpoons 2\text{Br}^-_{(aq)}$	.....	+1.07
$\text{Hg}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Hg}_{(l)}$	.....	+0.85
$\text{OCl}^-_{(aq)} + \text{H}_2\text{O}_{(l)} + 2\text{e}^- \rightleftharpoons \text{Cl}^-_{(aq)} + 2\text{OH}^-_{(aq)}$	.....	+0.84
$2\text{NO}_3^-_{(aq)} + 4\text{H}^+_{(aq)} + 2\text{e}^- \rightleftharpoons \text{N}_2\text{O}_{4(g)} + 2\text{H}_2\text{O}_{(l)}$	.....	+0.80
$\text{Ag}^+_{(aq)} + \text{e}^- \rightleftharpoons \text{Ag}_{(s)}$	.....	+0.80
$\text{Fe}^{3+}_{(aq)} + \text{e}^- \rightleftharpoons \text{Fe}^{2+}_{(aq)}$	.....	+0.77
$\text{O}_{2(g)} + 2\text{H}^+_{(aq)} + 2\text{e}^- \rightleftharpoons \text{H}_2\text{O}_{2(l)}$	.....	+0.70
$\text{I}_{2(s)} + 2\text{e}^- \rightleftharpoons 2\text{I}^-_{(aq)}$	.....	+0.54
$\text{O}_{2(g)} + 2\text{H}_2\text{O}_{(l)} + 4\text{e}^- \rightleftharpoons 4\text{OH}^-_{(aq)}$	.....	+0.40
$\text{Cu}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Cu}_{(s)}$	.....	+0.34
$\text{SO}_4^{2-}_{(aq)} + 4\text{H}^+_{(aq)} + 2\text{e}^- \rightleftharpoons \text{H}_2\text{SO}_{3(aq)} + \text{H}_2\text{O}_{(l)}$	.....	+0.17
$\text{Sn}^{4+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Sn}^{2+}_{(aq)}$	.....	+0.15
$\text{S}_{(s)} + 2\text{H}^+_{(aq)} + 2\text{e}^- \rightleftharpoons \text{H}_2\text{S}_{(aq)}$	.....	+0.14
$\text{AgBr}_{(s)} + \text{e}^- \rightleftharpoons \text{Ag}_{(s)} + \text{Br}^-_{(aq)}$	.....	+0.07
$2\text{H}^+_{(aq)} + 2\text{e}^- \rightleftharpoons \text{H}_{2(g)}$	.....	0.00
$\text{Pb}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Pb}_{(s)}$	.....	-0.13
$\text{Sn}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Sn}_{(s)}$	.....	-0.14
$\text{AgI}_{(s)} + \text{e}^- \rightleftharpoons \text{Ag}_{(s)} + \text{I}^-_{(aq)}$	.....	-0.15
$\text{Ni}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Ni}_{(s)}$	.....	-0.26
$\text{Co}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Co}_{(s)}$	.....	-0.28
$\text{PbSO}_{4(s)} + 2\text{e}^- \rightleftharpoons \text{Pb}_{(s)} + \text{SO}_4^{2-}_{(aq)}$	.....	-0.36
$\text{Se}_{(s)} + 2\text{H}^+_{(aq)} + 2\text{e}^- \rightleftharpoons \text{H}_2\text{Se}_{(aq)}$	.....	-0.40
$\text{Cd}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Cd}_{(s)}$	.....	-0.40
$\text{Cr}^{3+}_{(aq)} + \text{e}^- \rightleftharpoons \text{Cr}^{2+}_{(aq)}$	.....	-0.41
$\text{Fe}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Fe}_{(s)}$	.....	-0.45
$\text{NO}_2^-_{(aq)} + \text{H}_2\text{O}_{(l)} + \text{e}^- \rightleftharpoons \text{NO}_{(g)} + 2\text{OH}^-_{(aq)}$	.....	-0.46
$\text{Ag}_2\text{S}_{(s)} + 2\text{e}^- \rightleftharpoons 2\text{Ag}_{(s)} + \text{S}^{2-}_{(aq)}$	.....	-0.69
$\text{Zn}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Zn}_{(s)}$	.....	-0.76
$2\text{H}_2\text{O}_{(l)} + 2\text{e}^- \rightleftharpoons \text{H}_{2(g)} + 2\text{OH}^-_{(aq)}$	.....	-0.83
$\text{Cr}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Cr}_{(s)}$	.....	-0.91
$\text{Se}_{(s)} + 2\text{e}^- \rightleftharpoons \text{Se}^{2-}_{(aq)}$	.....	-0.92
$\text{SO}_4^{2-}_{(aq)} + \text{H}_2\text{O}_{(l)} + 2\text{e}^- \rightleftharpoons \text{SO}_3^{2-}_{(aq)} + 2\text{OH}^-_{(aq)}$	.....	-0.93
$\text{Al}^{3+}_{(aq)} + 3\text{e}^- \rightleftharpoons \text{Al}_{(s)}$	.....	-1.66
$\text{Mg}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Mg}_{(s)}$	.....	-2.37
$\text{Na}^+_{(aq)} + \text{e}^- \rightleftharpoons \text{Na}_{(s)}$	.....	-2.71
$\text{Ca}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Ca}_{(s)}$	.....	-2.87
$\text{Ba}^{2+}_{(aq)} + 2\text{e}^- \rightleftharpoons \text{Ba}_{(s)}$	.....	-2.91
$\text{K}^+_{(aq)} + \text{e}^- \rightleftharpoons \text{K}_{(s)}$	.....	-2.93
$\text{Li}^+_{(aq)} + \text{e}^- \rightleftharpoons \text{Li}_{(s)}$	.....	-3.04

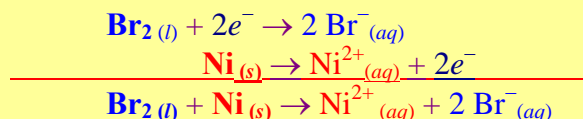
\*For 1.0 mol/L solutions at 298.15 K (25°C) and a pressure of 101.325 kPa

**Example 1:** Predict the whether the following reactions will react and write the complete redox reactions.

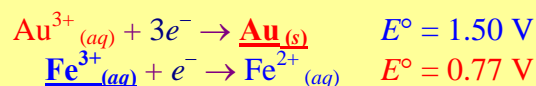
a.  $\text{Br}_2(l)$  with  $\text{Ni}(s)$



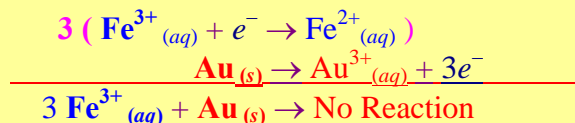
Since  $\text{Br}_2$  (OA) is higher than  $\text{Ni}$  (RA), the reaction will be spontaneous.



b.  $\text{Au}(s)$  with  $\text{Fe}^{3+}(aq)$

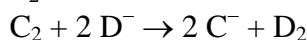
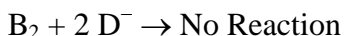
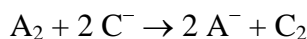


Since  $\text{Fe}^{3+}$  (OA) is lower than  $\text{Au}$  (RA), the reaction will be non-spontaneous.

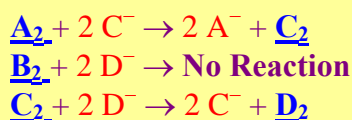


Because gold does not oxidized easily, this is the main reason why gold is so valuable!

**Example 2:** Four elements, A, B, C, and D, form diatomic molecules and negative ions. Arranged the elements in order from most reactive to least reactive if the following observations are made



The diatomic elements undergo reduction to become anions. For example,  $\text{A}_2 + 2e^- \rightarrow 2\text{A}^-$ . Thus, the elements are oxidizing agents.



#### Strength of Oxidizing Agents



Putting all the inequalities together, we have



**Example 3:** As part of a laboratory procedure, a student recorded observations after placing strips of metal into aqueous solutions according to the following combinations. The results are recorded using “✓” representing a reaction and “✗” representing no reaction. Organize the oxidizing agents from the strongest to the weakest.

Metals / Ions	$\text{A}^{2+}(aq)$	$\text{B}^{2+}(aq)$	$\text{C}^{2+}(aq)$	$\text{D}^{2+}(aq)$
$\text{A}(s)$	-----	✓	✗	✓
$\text{B}(s)$	✗	-----	✗	✗
$\text{C}(s)$	✓	✓	-----	✓
$\text{D}(s)$	✗	✓	✗	-----

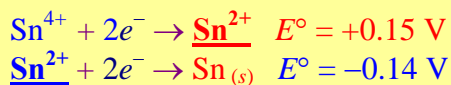
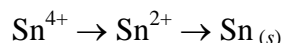
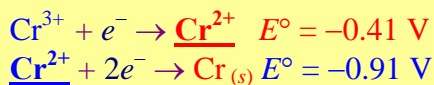
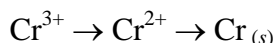
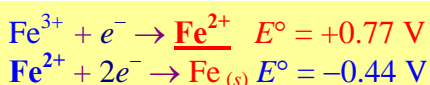
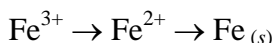
The Oxidizing Agent are the ions because they Reduced (Gained Electrons) to produce their metal elements. For example,  $\text{A}^{2+} + 2e^- \rightarrow \text{A}(s)$ .

The Strongest Oxidizing Agent is the ion that is MOST Reactive (look at the above table vertically). Thus, in order of decreasing strength (reactivity):



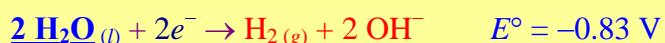
**Chemical Species that are BOTH Oxidizing Agent and Reducing Agent:** - some of the transition metals have more than one monoatomic ionic charges can have the intermediate charge species act as reducing agent as well as oxidizing agent.

**Examples:** Iron (II), Chromium (II) and Tin (II)



$\text{H}_2\text{O}_{(l)}$  as an Oxidizing Agent (Left Side of the Table)

$\text{H}_2\text{O}_{(l)}$  as an Reducing Agent (Right Side of the Table)



**Standard Cell Potential:** - the cell potential under standard conditions ( $E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} + E^\circ_{\text{anode}}$ )

- when Flipping the Reducing Agent's Half-Reaction, **reverse the Sign of  $E^\circ$  to obtain  $E^\circ_{\text{anode}}$ .**
- **do NOT Multiply  $E^\circ$  when using electrons to balance complete redox reactions.**

**Line Notation:** - a notation using lines to represent the electrode and electrolytes as well as the half-cell separations of a galvanic cell.

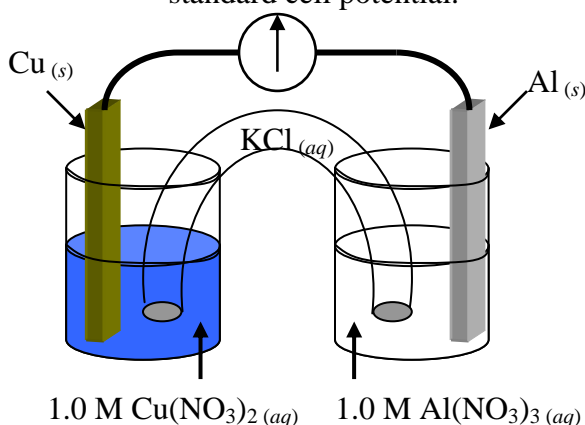
- single line, |, separates electrode and its electrolyte; double line, ||, represents salt bridge, porous cup or porous disk.
- **ALWAYS write the Anode on the LEFT hand side.**

#### Line Notation and Standard Cell Potential of Galvanic Cells

**Anode | Anode's Electrolyte || Cathode's Electrolyte | Cathode**

$$E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} + E^\circ_{\text{anode}} \quad (E^\circ_{\text{cell}} > 0 \text{ means Spontaneous Reaction})$$

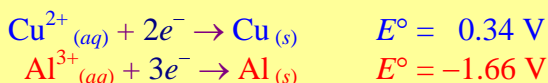
**Example 4:** For a galvanic cell using copper and aluminum electrodes as shown below, identify anode and cathode. Indicate movements of ions and electrons. Write the line notation and calculate the standard cell potential.



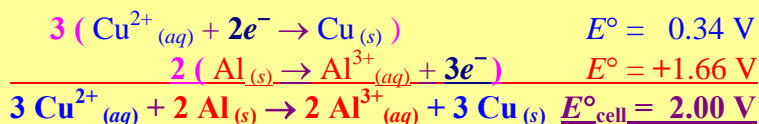
**Cathode (+)      Anode (-)**

$e^-$  flow  
Cations ( $\text{Cu}^{2+}$  and  $\text{Al}^{3+}$ )

Anion ( $\text{NO}_3^-$ )



Since the half-reactions for  $\text{Cu}_{(s)}$  is higher than  $\text{Al}_{(s)}$ ,  $\text{Cu}^{2+}$  will be reduced ( $\text{Cu}_{(s)}$  is the Cathode) and  $\text{Al}_{(s)}$  will be oxidized (Anode – flipped half-reaction and voltage).



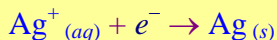
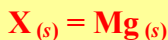
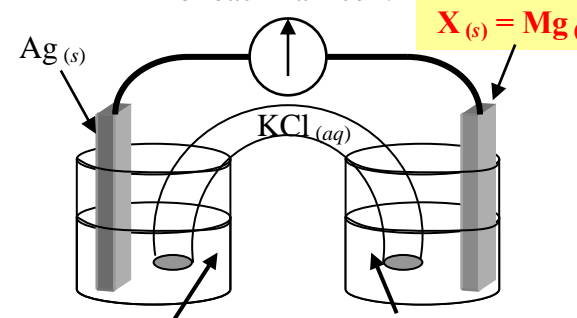
**Note:** We do NOT multiply  $E^\circ$ .

**Line Notation:**





**Example 2:** A galvanic cell has silver cathode and unknown anode as shown below. Calculate the reduction half-reaction voltage for this unknown anode and identify it if the overall standard cell potential is 3.17 V. Indicate ions and electrons movements, and possible solutions (with concentrations) for each half-cell.



$$E^\circ = +0.80 \text{ V}$$



$$E^\circ = ? \text{ V}$$

Since the  $Ag^+(aq)$  will be reduced (Cathode),  $Ag(s)$  must be higher than  $X(s)$  for a spontaneous reaction to occur,  $X^{n+}$  will be oxidized ( $X(s)$  is the Anode – flipped half-reaction and voltage).

$$E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} + E^\circ_{\text{anode}}$$

$$3.17 \text{ V} = 0.80 \text{ V} + E^\circ_{\text{anode}}$$

$$E^\circ_{\text{anode}} = 2.37 \text{ V}$$



Standard Conditions means using 1.0 M

Cathode (+)

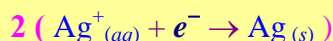
Anode (-)

$e^-$  flow

Cations ( $Ag^+$  and  $Mg^{2+}$ )

Anion ( $NO_3^-$ )

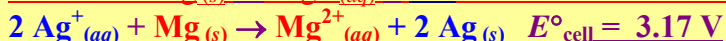
Since anode voltage was flipped, its reduction half-reaction has a voltage of  $-2.37 \text{ V}$  ( $Mg(s)$  from the Table).



$$E^\circ = 0.80 \text{ V}$$



$$E^\circ = +2.37 \text{ V}$$



$$E^\circ_{\text{cell}} = 3.17 \text{ V}$$

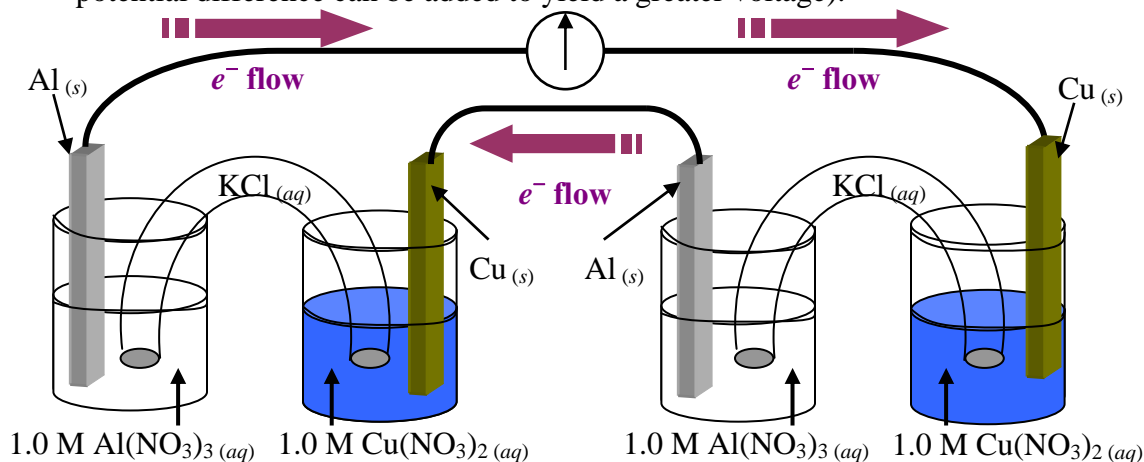
Note: We do NOT multiply  $E^\circ$ .

### Assignment

19.2 & 19.3 pg. 676 #3 to 6, 11 to 18

## 19.6: Batteries and Fuel Cells

**Batteries:** - portable galvanic cells that are commonly in series (cells that connect in a way such that the potential difference can be added to yield a greater voltage).



Anode (-)

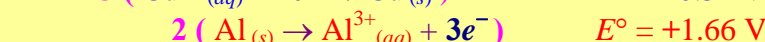
Cathode (+)

Anode (-)

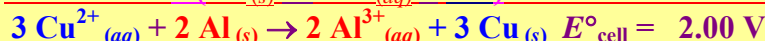
Cathode (+)



$$E^\circ = 0.34 \text{ V}$$



$$E^\circ = +1.66 \text{ V}$$



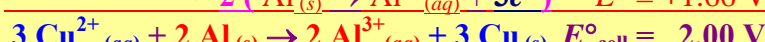
$$E^\circ_{\text{cell}} = 2.00 \text{ V}$$



$$E^\circ = 0.34 \text{ V}$$



$$E^\circ = +1.66 \text{ V}$$



$$E^\circ_{\text{cell}} = 2.00 \text{ V}$$

Total Voltage

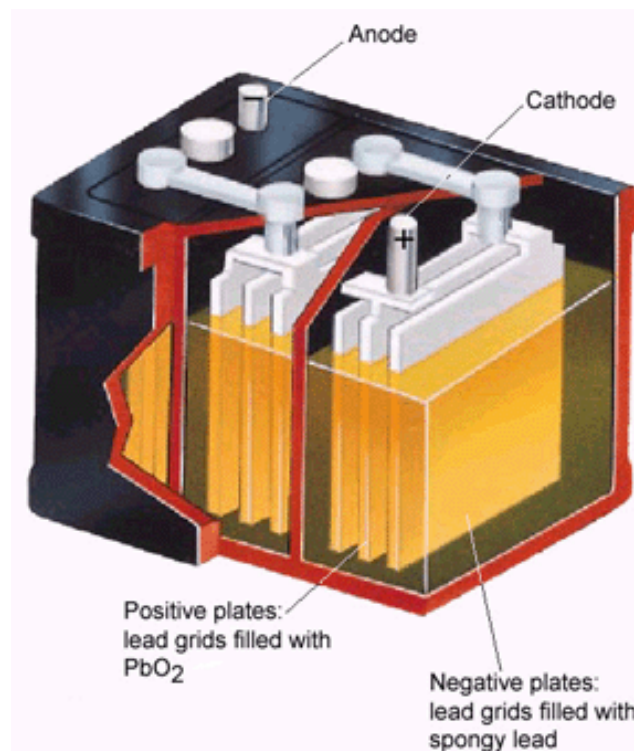
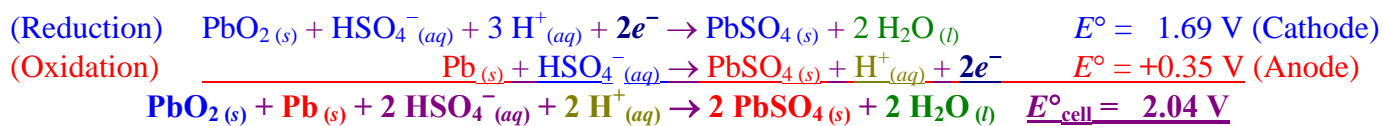
$$= 2.00 \text{ V} + 2.00 \text{ V} = 4.00 \text{ V}$$

Different Types of Batteries:

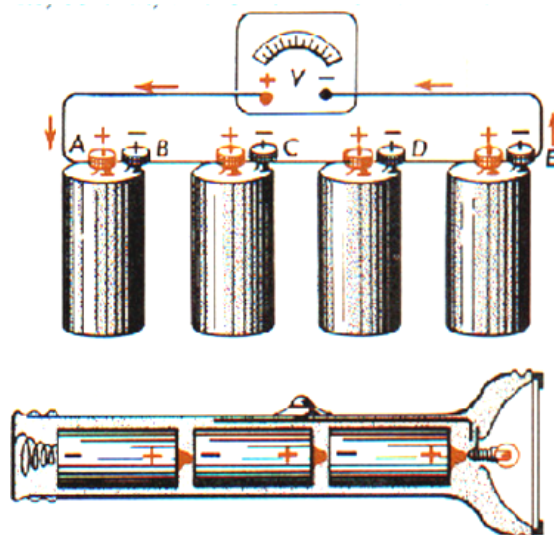
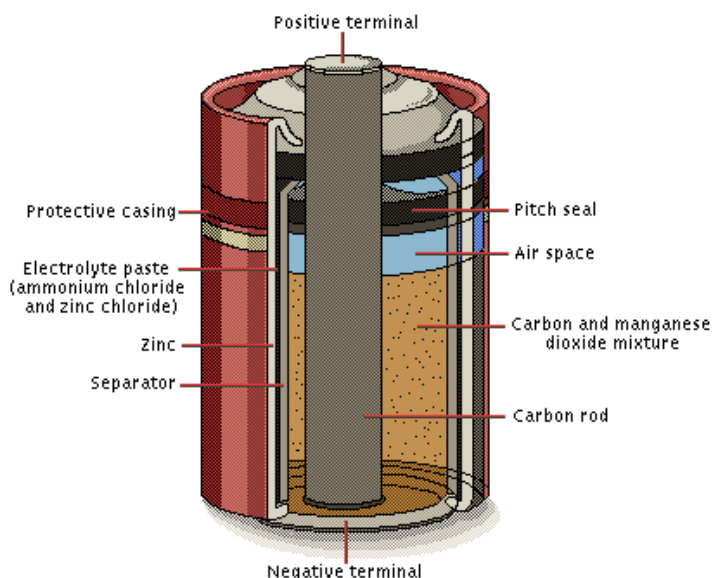
1. **Lead-Acid Battery:** - a **rechargeable battery** commonly used in automobiles to start and maintain the sparks needed for the combustion of the gasoline engine.
- consists of **Pb<sub>(s)</sub> as the anode** and **PbO<sub>2</sub> (s) as the cathode** in an **acidic (H<sub>2</sub>SO<sub>4</sub> (aq)) environment**. (Since solid lead is used, the lead-acid battery tends to be heavy. The **sulfuric acid** used in this type of battery is commonly known as **battery acid**.)
  - the battery is **in series with six identical galvanic cells** giving it  $6 \times 2\text{V} = \underline{12\text{ V}}$  of total potential difference.



A typical lead-acid battery for automobiles (above) and its inner working (right)

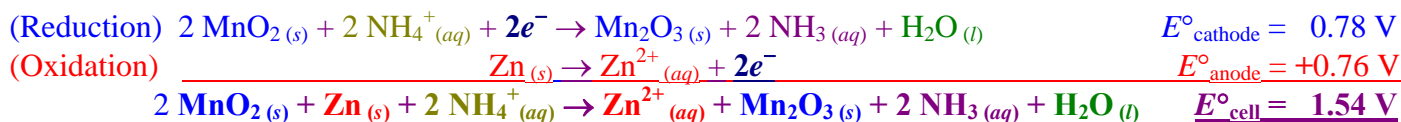
Lead-Acid Battery Redox Reaction for One of the Six Identical Cells

2. **Dry Cell:** - a **non-rechargeable battery** commonly used in electronic devices such as, radios, calculators, and electronic toys.
- Zinc-Carbon Dry Cell:** - consists of **Zn<sub>(s)</sub> as the anode** and both **MnO<sub>2</sub> (s) (cathode with a carbon rod)** and the **acid (NH<sub>4</sub>Cl<sub>(s)</sub>)** are in a **dry paste** – hence the term “dry” cell.
  - Alkaline Dry Cell:** - in a **basic environment**, the **NH<sub>4</sub>Cl** is replaced with **NaOH or KOH**, and zinc oxidized to **ZnO<sub>(s)</sub>** at the anode.
    - some dry cell battery is **in series with six identical Zn-C or alkaline dry cells**, giving it  $6 \times 1.5\text{V} = \underline{9\text{ V}}$  of total potential difference.

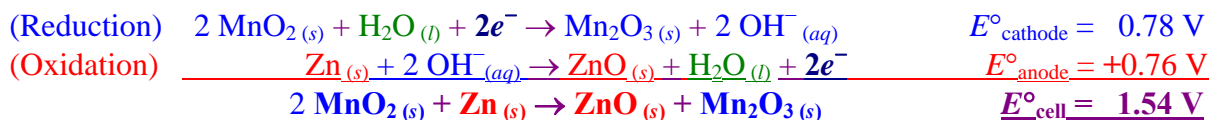


A cutaway view of an acidic Zn-C dry cell (above). When dry cells are connected in series, their voltages can be added (top right). The inside of a 9 V battery reveals that there are six 1.5 V Zn-C dry cells connected in series (right).

### Redox Reaction for an Acidic Zinc-Carbon Dry Cell Battery

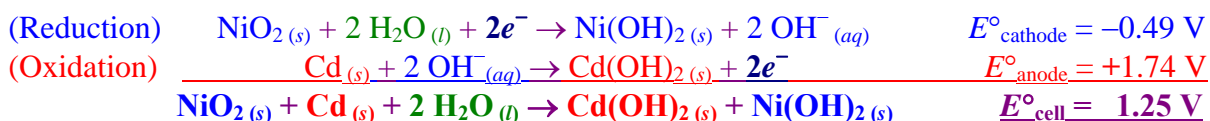


### Redox Reaction for a Basic (Alkaline) Zinc-Carbon Dry Cell Battery

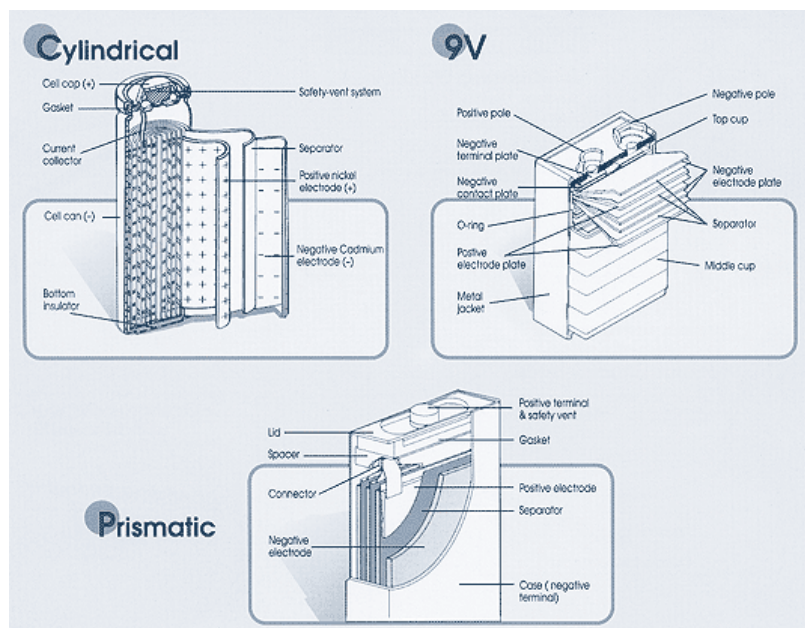


3. **Nickel Cadmium Battery:** - a dry cell with the same set up as alkaline dry cell but it can be **recharged** (a lot lighter than lead-acid batteries).  
 - it can developed a “memory” problem, so after each recharged cycled, the battery tends to have a shorter “life-span”. This can be corrected by completely discharging the battery before recharging it fully for the next usage cycle.  
 - cadmium is an expensive metal, and cannot be disposed easily due to its toxicity. Special care must be taken to recycle Ni-Cd batteries.

### Redox Reaction for a Ni-Cd Dry Cell Battery







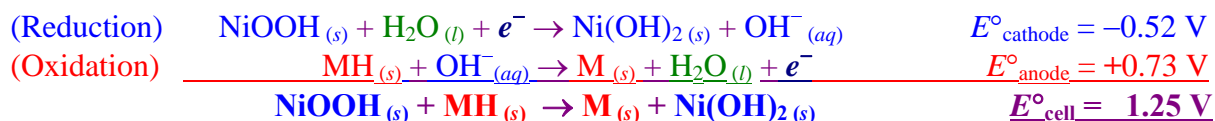
Ni-Cd Rechargeable Batteries has  $E^\circ_{\text{cell}} = 1.2 \text{ V}$  (above). The cell constructions of various Ni-Cd batteries (left).

- 4. Nickel Metal-Hydride Battery:** - a rechargeable dry cell that does not have a “memory” problem and can last 40 times longer than the Ni-Cd battery.
- the expensive and toxic cadmium is replaced by an inexpensive and environmentally friendly **metal-hydride** (a mixture of many metals alloys, including V, Ti, Zr, Ni, Cr, Co, and Fe).
  - Ni-MH batteries are used in cellular phones, digital cameras, laptop computers, emergency backup lightings, power tools and even electric vehicles.
  - its design is similar to that of the Ni-Cd battery and yields the same  $E^\circ_{\text{cell}}$ .

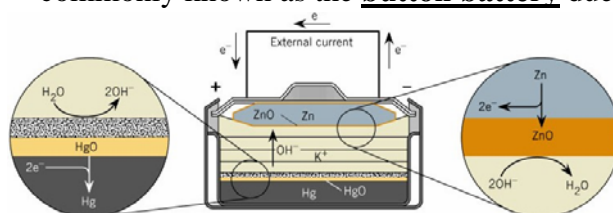


Ni-MH batteries for portable electronic devices such as digital cameras.

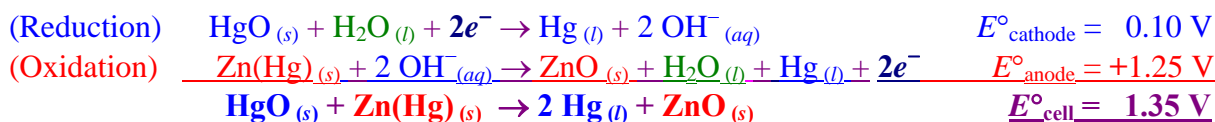
#### Redox Reaction for a Ni-MH Dry Cell Battery



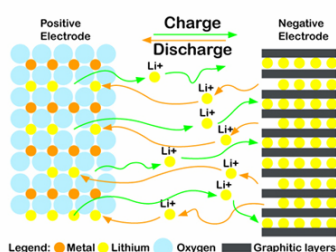
- 5. Mercury Oxide Battery:** - a non-rechargeable dry cell due to its small size has found its uses in small electronic devices like watches.
- consists of **amalgamated zinc-mercury  $\text{Zn(Hg)}_{(s)}$  as the anode** and both  **$\text{HgO}_{(s)}$  (cathode)** and the **bases  $\text{KOH}_{(s)}$  and  $\text{Zn(OH)}_{2(s)}$**  are in a **dry paste**.
  - commonly known as the **button battery** due to its small size.



#### Redox Reaction for a Mercury Oxide Battery



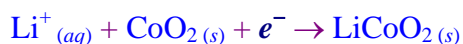
6. **Lithium-Ion Battery:** - a rechargeable battery that can be recharged for hundreds of time.



- anode is made out of conducting carbon based material such as graphite.
- cathode is made of a transition metal oxide such as  $\text{CoO}_2$ , which can hold  $\text{Li}^+$  ion. Lithium is light (small molar mass) and has the greatest reducing strength, making it ideal for a rechargeable battery.
- the high reactivity of lithium means that a non-aqueous electrolyte such as an organic solvent with dissolved salt must be used.

### Redox Reaction for a Lithium-Ion Battery

(Reduction)

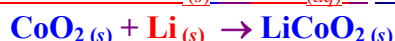


$$E^\circ_{\text{cathode}} = 0.35 \text{ V}$$

(Oxidation)



$$E^\circ_{\text{anode}} = +3.05 \text{ V}$$



$$E^\circ_{\text{cell}} = 3.40 \text{ V}$$

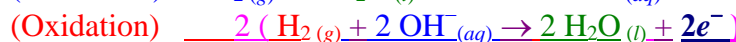
7. **Fuel Cell:** - a galvanic cell where there is a continuous supply of reactants.

- the **hydrogen-oxygen fuel cell** produces water as a product and hence is an ideal power source for zero-emission vehicles

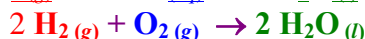
### Redox Reaction for a Hydrogen Fuel Cell



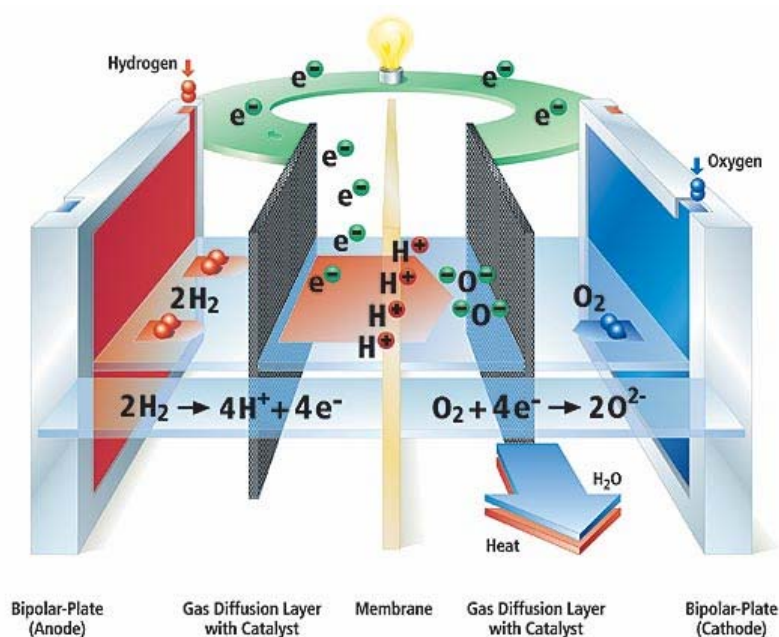
$$E^\circ_{\text{cathode}} = 0.40 \text{ V}$$



$$E^\circ_{\text{anode}} = +0.83 \text{ V}$$



$$E^\circ_{\text{cell}} = 1.23 \text{ V}$$



Schematic of a Hydrogen Fuel Cell (above).



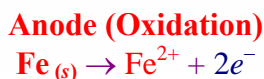
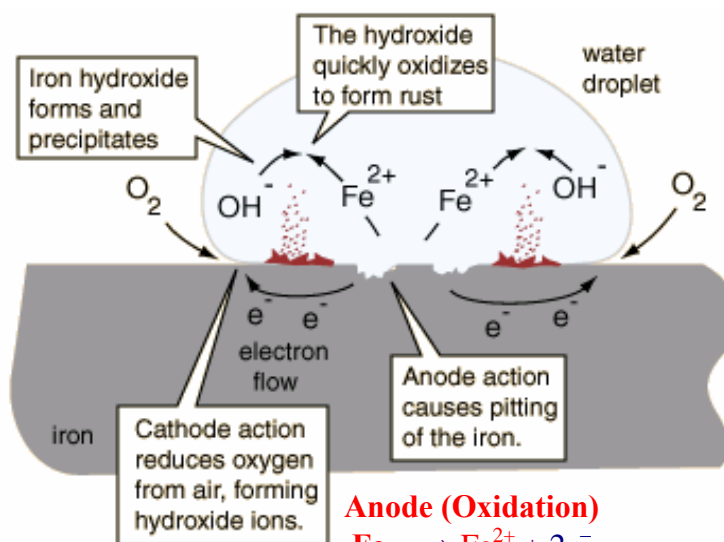
Ford Hydrogen Fuel Cell Vehicle (FCV): The hydrogen tank (at 5000 psi) is stored inside the trunk (above). Under the hood with the fuel cell engine (below).



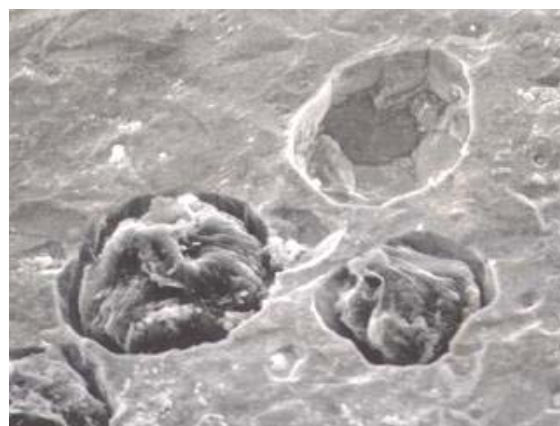
(Left) The Hydrogen Fueling Station at the city of Chicago. Shown in the photo is Chicago's Fuel Cell Public Transit Vehicle. The solar panel, next to the hydrogen storage tank (vertical column), is used to supply power needed to decompose water into hydrogen and oxygen. Hence, from the production of hydrogen gas to its usage in the fuel cell vehicles, it is 100% environmentally friendly.

**19.7: Corrosion****Corrosion:** - oxidation of metal into metal-oxides.

- from the Standard Reduction Potential Table, metals are generally strong reducing agent (bottom right side). Because metals tend to have low electronegativity, they lose electrons easily to form cations (oxidation).
- since solid gold is the weakest of all metal reducing agents, it lacks the ability to oxidize and hence gold is considered a precious metal where all currencies are based on.



(Above) The electrochemical corrosion of iron where oxygen (oxidizing agent – cathode) is reacting with iron (reducing agent – anode) to form rust. Electrochemical cell action driven by the energy of oxidation continues the corrosion process.



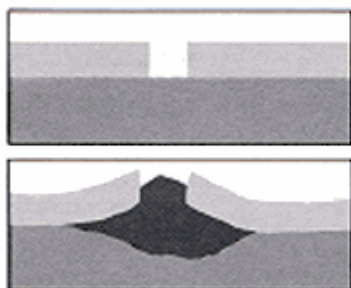
(Above) This view was taken with a scanning electron microscope (1200 ×) and shows the corroded surface of a piece of iron metal. The corrosion was artificially induced by subjecting the iron metal to an ionizing potential while being submerged in a sodium silicate solution. The iron dissolves from the surface as it oxidizes, forming a cavity (20 microns diameter). The oxidized iron mixes with the silicate solution and forms a glassy insoluble material that reforms in the cavity.

**Ways to Prevent Corrosion:**

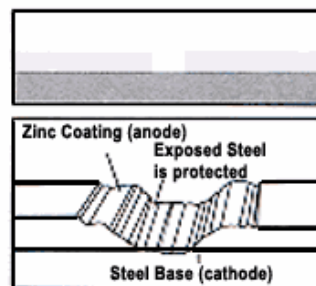
- 1. Painting:** - putting a protective coating like paint on metals covers the metal surfaces so oxidation of the metal cannot take place.
  - if the paint coating is scratched, oxidation will occur on the metal. Any rust needs to be removed before a fresh coat of paint is put on.
- 2. Alloys:** - by mixing metals in various percentages to form an alloy, the reduction potential increases.
  - stainless steel is composed of iron and carbon, which has a higher reduction potential than iron metal. Therefore, stainless steels do not rust.
  - **Surface Alloy:** - when alloy is coated of the metal surface by bombardment of alloy metals in gaseous ions form (alloying plasma – ion gas that consists of alloys to be coated). This makes a cheaper alternative than making the entire material out of alloy.



3. **Galvanization**: - the plating of a metal with a lower reduction potential (higher oxidizing potential – stronger reducing agents like zinc or magnesium) on to the metal intended for protection.
- the oxygen will likely react with the stronger reducing agent metal, leaving the other metal unreacted.
  - the metal with the lower reduction potential is in effect protecting the other metal, hence we call this the galvanizing metal **sacrificial metal**.
  - galvanized metal last longer than zinc and does not need reapplication because it is “self-healing” when scratched (see below).

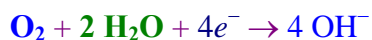
*Rust undercuts scratched paint***PAINT ON STEEL**

This is what happens at a scratch on painted steel. The exposed steel corrodes and forms a pocket of rust. Because rust is much more voluminous than steel, the pocket swells. This lifts the paint film from the metal surface to form a blister. Both the corrosion pit and the blister continue to grow.

*Zinc protects base steel even when scratched***GALVANIZED STEEL**

This is what happens at a scratch on galvanized steel. The zinc coating sacrifices itself slowly by galvanic action to protect the base steel. This sacrificial action continues as long as any zinc remains in the immediate area.

**Example:** Zinc is often used to galvanize iron metal.

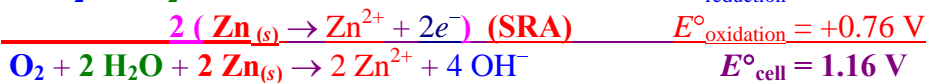
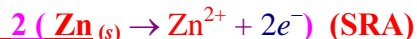
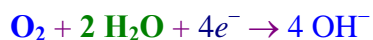


$$E^\circ_{\text{reduction}} = 0.40 \text{ V}$$

$$E^\circ_{\text{reduction}} = -0.44 \text{ V}$$

$$E^\circ_{\text{reduction}} = -0.76 \text{ V}$$

Zinc will be oxidized first (sacrificed) before iron.



$$E^\circ_{\text{reduction}} = 0.40 \text{ V}$$

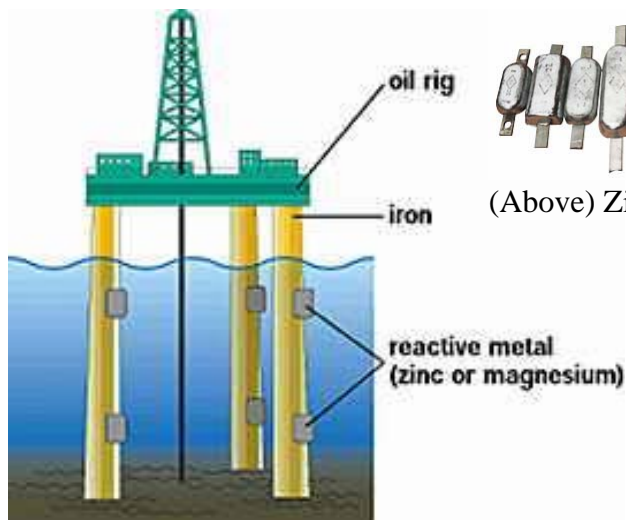
$$E^\circ_{\text{oxidation}} = +0.76 \text{ V}$$

$$E^\circ_{\text{cell}} = 1.16 \text{ V}$$

**O<sub>2</sub>-Zn<sub>(s)</sub> has a Higher Voltage than E<sub>cell</sub> of O<sub>2</sub>-Fe<sub>(s)</sub>. Therefore, it is More Spontaneous.**



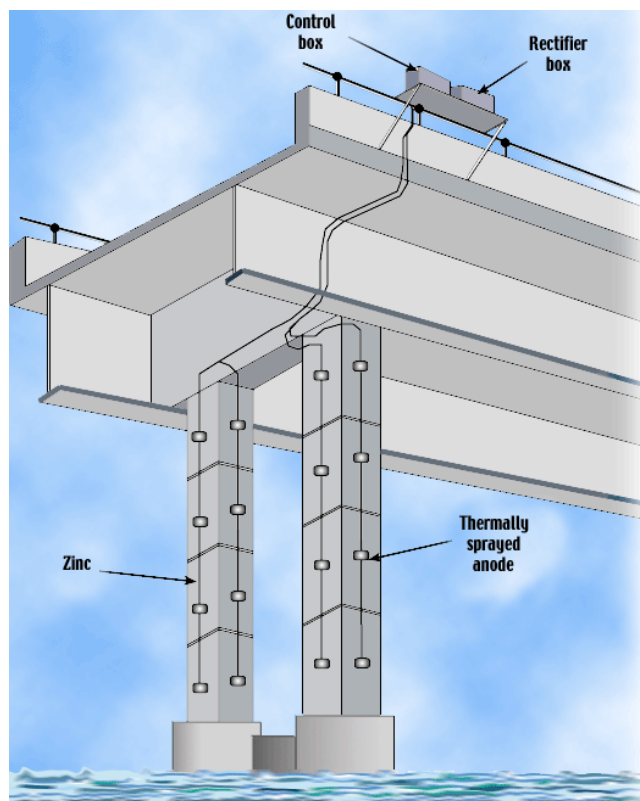
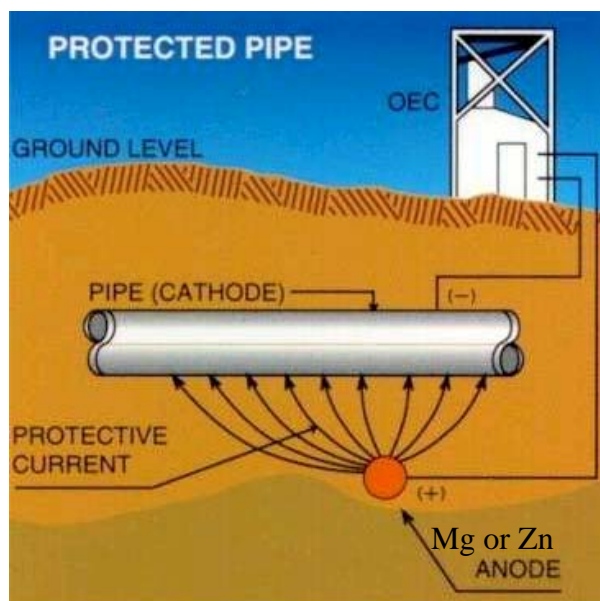
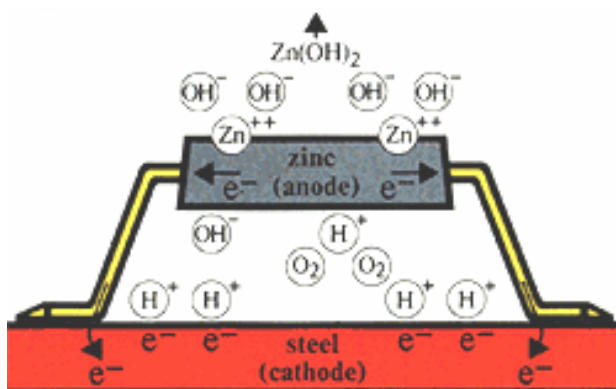
(Above and right) Deep-sea structures like offshore oil drilling platforms used sacrificial metals to protect the main structure from corrosion



(Above) Zinc sacrificial metals.



4. **Cathodic Protection** - it is similar to galvanization, in an electrolytic environment (sea water and underground water), the sacrificial metal – the most active metal (anode) will oxidize first. Electrons flow to the protected less reactive metal (cathode). When the anode supplies current, it will gradually dissolve into ions in the electrolyte, and at the same time produce electrons, which the cathode will receive through the metallic connection with the anode. The result is that the cathode will be negatively polarised and hence be protected against corrosion.
- unlike galvanization, we do not need to “coat” the protected metal. However, the anode metal has to be replaced over time.
  - find its usage for any metal placed underground (gas pipes and gas tanks) and structures or marine transport over the seas and oceans (like bridges, offshore oil rigs and ships)



The basic principle behind cathodic protection (top left). Sacrificial metals are placed on columns of the sea-bridge (above) and underground with a metal pipe (left). All are connected by wires to facilitate the process of cathodic protection.

### Assignment

19.6 pg. 677 #35 and 36

19.7 pg. 677 #39 to 41

**19.8: Electrolysis**

**Electrolysis:** - a power supply (external source of electricity) is used to cause a chemical change to occur.

**Electrolytic Cells:** - an apparatus that **Converts Electrical Energy to Chemical Energy**.

- it consists of **one or two containers of solutions** (electrolytes) and the electrodes (usually metals called anode and cathode), as well as a connection between these two containers (salt bridge, porous cup, or porous disk – if two containers are used), and a wire connecting the two electrodes along with a **power source**.

**Anode:** - the terminal where **oxidation** is taken place and commonly marked as the **Positive terminal**.

**Cathode:** - the terminal where **reduction** is taken place and commonly marked as the **Negative terminal**.

**Cell Potential ( $E_{\text{cell}}$ ):** - for **electrolytic cells, the cell potential is Negative (Non-Spontaneous)**.

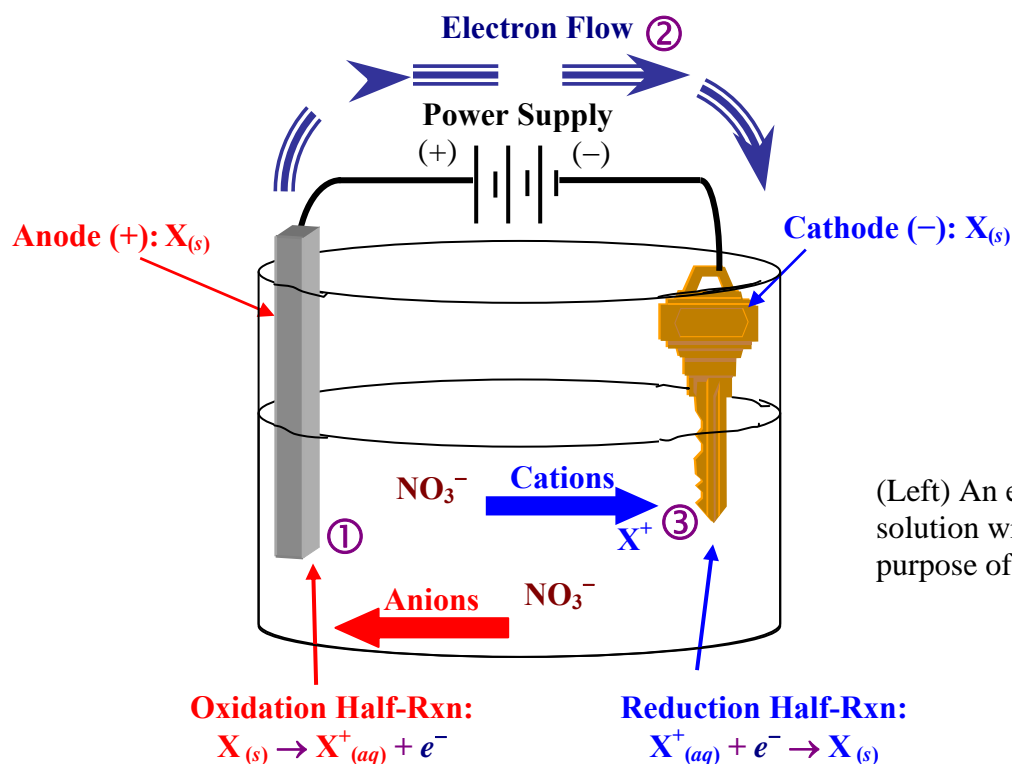
- the  **$E^{\circ}_{\text{cell}}$  of an electrolytic cell is the minimum voltage** needed to start and maintain the chemical reaction. ( $E^{\circ}_{\text{cell}} = E^{\circ}_{\text{cathode}} + E^{\circ}_{\text{anode}}$ )

**Electrolytic Cells**

1. Electrons move from **Anode (+) to Cathode (-)**.
2. Cations move *towards* the Cathode.
3. Anions move *towards* the Anode.

**Anode (+):** (LEOA–RA: **L**osing **E**lectrons **O**xidation **A**node – **R**educing **A**gent)

**Cathode (-):** (GERC–OA: **G**aining **E**lectrons **R**eduction **C**athode – **O**xidizing **A**gent)



(Left) An electrolytic cell of a single solution with a power supply for the purpose of electroplating.

Electrolytic Cell of a Single Solution Step by Step

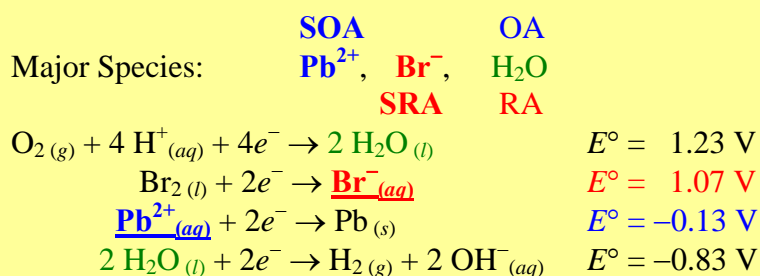
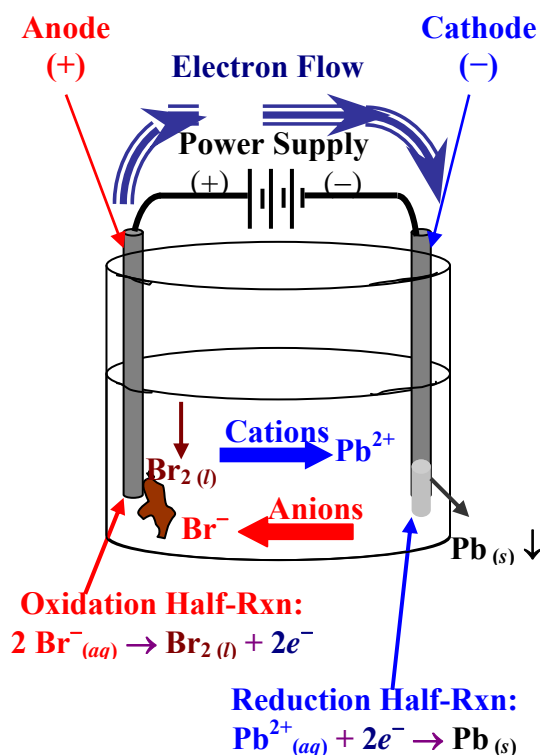
- ①  $X^+$  leaves  $X_{(s)}$  at the Anode because the power supply “pumps” the electrons from  $X_{(s)}$ . At the same time, the bottom of the anode becomes more positive. This is corrected by the anions (like  $NO_3^-$ ) migrating towards the cathode.
- ② Electrons produced at the Anode (–) move to Cathode (+).
- ③  $X^+$  migrates towards the Cathode (+) to produce  $X_{(s)}$  in order to complete the reduction half reaction. This can also be explained that  $X^+$  migrate towards the cathode because electrons are moving into the bottom of the cathode making that region more negative.

Determining the Redox Reaction for Electrolytic Cell

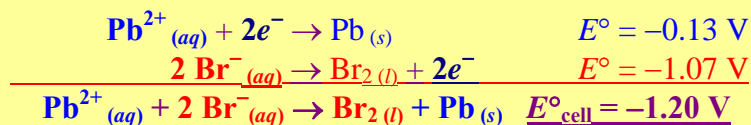
1. List ALL ions in the solution as well as water.
2. Identify the strongest oxidizing and reducing reagents.
3. Balance each of the reduction and oxidation half reactions.
4. Add both half reactions to form a complete redox reaction.
5. Calculate the  $E^\circ_{\text{cell}}$  of the overall reaction.

**Example 1:** Determine the redox net-ionic reaction and the  $E^\circ_{\text{cell}}$  for the following solutions when two inert electrodes (carbon) are connected with an operating power supply. Draw and label a diagram for the set up. Suggest any possible observations for these electrolytic cells.

a.  $PbBr_2(aq)$



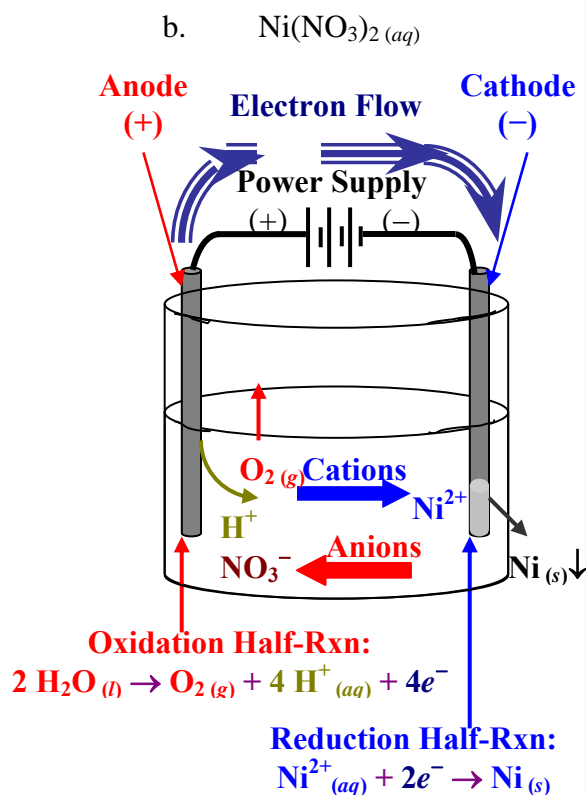
We can see that this is a **Non-Spontaneous Rxn** because the half-reactions for  $Br^-_{(aq)}$  is higher than  $Pb^{2+}_{(aq)}$ .  $Pb^{2+}$  will be reduced (Cathode) and  $Br^-$  will be oxidized (Anode – half-rxn needs to flip).



Minimum Voltage Needed = 1.20 V

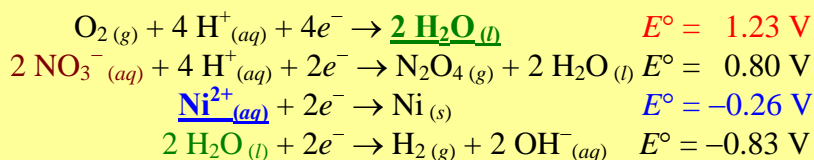
Possible Observations:

1.  $Pb_{(s)}$  will be plated on the cathode.
2.  $Br_{2(l)}$  (brown liquid) can be found near the anode.

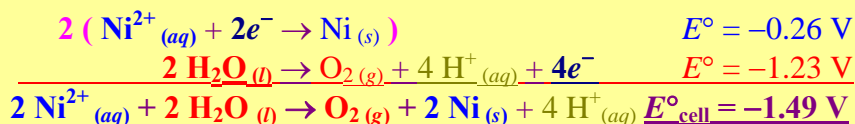


Major Species:

SOA  $\text{Ni}^{2+}$ , OA  $\text{NO}_3^-$ ,  $\text{H}_2\text{O}$   
 SRA



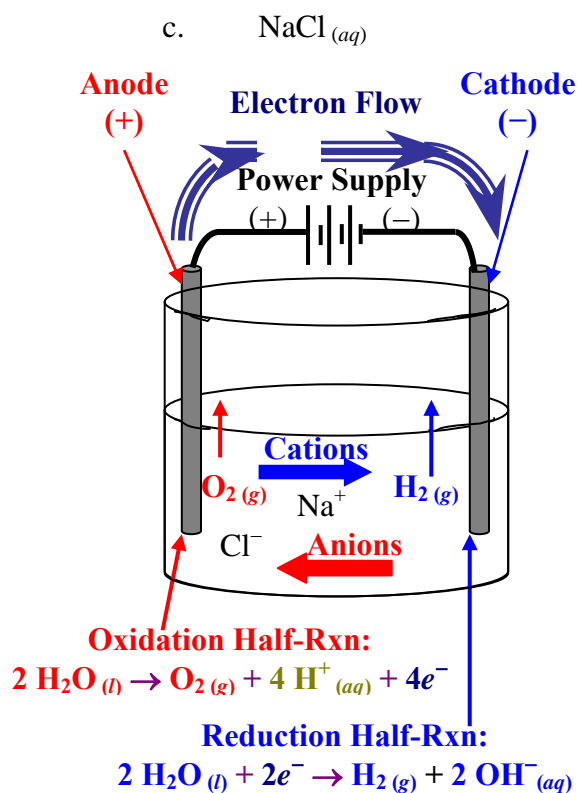
$\text{NO}_3^-$  is neither an oxidizing agent because the solution has no  $\text{H}^+$ . We can see that this is a Non-Spontaneous Rxn because the half-reactions for  $\text{H}_2\text{O}(\text{l})$  is higher than  $\text{Ni}^{2+}(\text{aq})$ .  $\text{Ni}^{2+}$  will be reduced (Cathode) and  $\text{H}_2\text{O}$  will be oxidized (Anode – half-rxn needs to flip).



Minimum Voltage Needed = 1.49 V

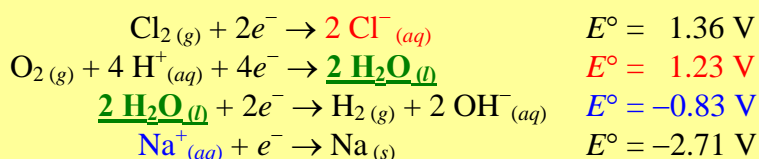
Possible Observations:

- $\text{Ni}(\text{s})$  will be plated on the cathode.
- $\text{O}_2(\text{g})$  will be bubbling out of the anode.
- pH of the solution will decrease as  $[\text{H}^+]$  increases.

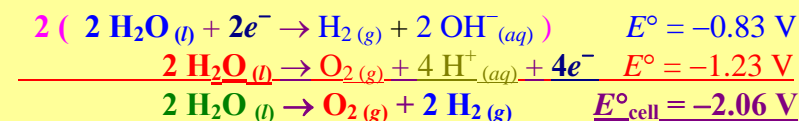


Major Species:

OA  $\text{Na}^+$ ,  $\text{Cl}^-$ , SOA  $\text{H}_2\text{O}$   
 RA SRA



We can see that this is a Non-Spontaneous Rxn because the half-reactions for  $\text{H}_2\text{O}(\text{l})$  as a reducing agent is higher than  $\text{H}_2\text{O}(\text{l})$  as an oxidizing agent.  $\text{H}_2\text{O}$  will be reduced at the Cathode and  $\text{H}_2\text{O}$  will be oxidized at the Anode – half-rxn needs to flip.

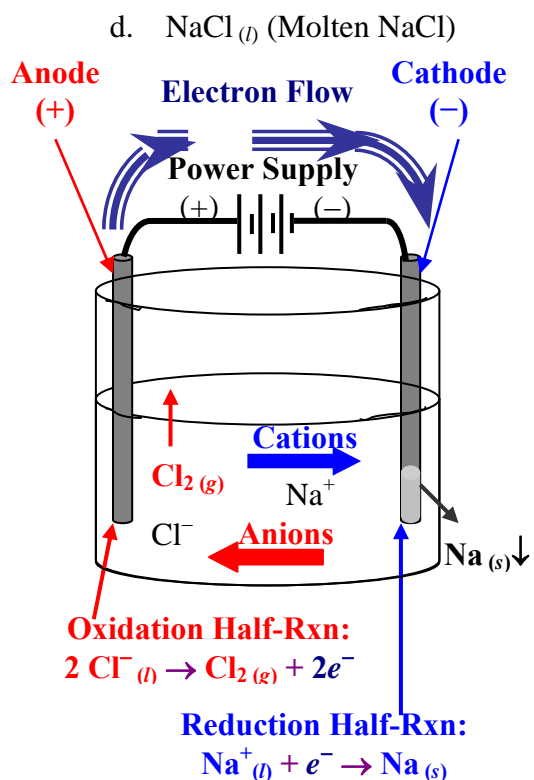


Minimum Voltage Needed = 2.06 V

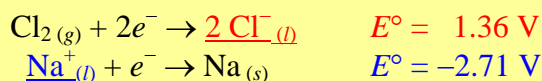
$\text{NaCl}(\text{aq})$  does not decompose into its elements but rather electrolysis of  $\text{H}_2\text{O}$  is taking place. This is because the  $\text{Na}^+$  and  $\text{Cl}^-$  are weaker oxidizing and reducing agents compared to  $\text{H}_2\text{O}$ .

Possible Observations:

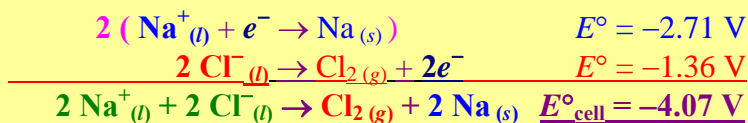
- $\text{H}_2(\text{g})$  bubbles out at the cathode.
- $\text{O}_2(\text{g})$  bubbles out of the anode.



Major Species:  $\text{Na}^+_{(l)}$ ,  $\text{Cl}^-_{(l)}$



We can see that this is a Non-Spontaneous Rxn because the half-reactions for  $\text{Cl}^-_{(l)}$  as a reducing agent is higher than  $\text{Na}^+_{(l)}$  as an oxidizing agent.  $\text{Na}^+$  will be reduced at the Cathode and  $\text{Cl}^-$  will be oxidized at the Anode – half-rxn needs to flip.



Minimum Voltage Needed = 4.07 V

Molten  $\text{NaCl}_{(l)}$  decomposes into its elements in this case because there is no  $\text{H}_2\text{O}$  present.

Possible Observations:

1.  $\text{Na}_{(s)}$  is plating out at the cathode.
2.  $\text{Cl}_{2(g)}$  bubbles out of the anode.

### Moles of Electrons in Electroplating

$$n_{e^-} = \frac{It}{F}$$

$n_{e^-}$  = moles of electrons in half-reaction  
 $t$  = time (seconds)

$I$  = Current (A or C/s)  
 $F = 9.65 \times 10^4 \text{ C/mol}$

**Example 2:** If a 30.0 A of current flow through an electrolytic cell containing molten aluminum oxide for 1.00 hour. What mass of aluminum will be deposited at the cathode?

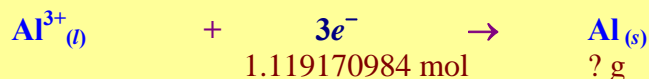
$$I = 30.0 \text{ A} = 30.0 \text{ C/s}$$

$$t = 1.00 \text{ hour} = 60.0 \text{ min} = 3600 \text{ s}$$

$$F = 9.65 \times 10^4 \text{ C/mol}$$

$$n_{e^-} = ?$$

$$n_{e^-} = \frac{It}{F} = \frac{(30.0 \text{ C/s})(3600 \text{ s})}{(9.65 \times 10^4 \text{ C/mol})} = 1.119170984 \text{ mol}$$



$$M_{\text{Al}} = 26.98 \text{ g/mol}$$

$$m_{\text{Al}} = ?$$

$$n_{\text{Al}} = 1.119170984 \text{ mol } e^- \times \frac{1 \text{ mol Al}}{3 \text{ mol } e^-} = 0.3730569948 \text{ mol Al}$$

$$m_{\text{Al}} = (0.3730569948 \text{ mol Al})(26.98 \text{ g/mol}) \quad m_{\text{Al}} = 10.1 \text{ g}$$

**Example 3:** A student wishes to plate 11.74 g of Ni<sub>(s)</sub> onto a piece of metal using 2.00 mol/L solution of NiBr<sub>2</sub>. How long should the student run a 0.500 A current in order to produce the desired mass of nickel?

$$\begin{array}{lcl}
 I = 0.500 \text{ A} = 0.500 \text{ C/s} & \text{Ni}^{2+}_{(aq)} & + \quad 2e^{-} \quad \rightarrow \quad \text{Ni}_{(s)} \\
 F = 9.65 \times 10^4 \text{ C/mol} & & \\
 m_{\text{Ni}} = 11.74 \text{ g} & & \\
 M_{\text{Ni}} = 58.69 \text{ g/mol} & & \\
 n_{e^{-}} = ? & & \\
 t = ? & & 
 \end{array}$$

$$\begin{array}{lcl}
 & 11.74 \text{ g Ni} & \\
 n_{\text{Ni}} = \frac{11.74 \text{ g Ni}}{58.69 \text{ g/mol}} & = & 0.2000340774 \text{ mol Ni} \\
 & & \\
 n_{e^{-}} = 0.2000340774 \text{ mol Ni} \times \frac{2 \text{ mol } e^{-}}{1 \text{ mol Ni}} & = & 0.4000681547 \text{ mol } e^{-} \\
 & & \\
 n_{e^{-}} = \frac{It}{F} & t = \frac{n_{e^{-}} F}{I} = & \frac{(0.4000681547 \text{ mol})(9.65 \times 10^4 \text{ C/mol})}{(0.500 \text{ C/s})} \\
 & & \\
 & t = 77213.15386 \text{ s} \times \frac{1 \text{ hr}}{3600 \text{ s}} & \quad t = 21.4 \text{ hours}
 \end{array}$$

**Example 4:** A certain electrolytic cell produced 39.00 g of Cl<sub>2</sub> from molten NaCl. The time it took for this process was 80.0 minutes. What was the average current ran during this time?

$$\begin{array}{lcl}
 m_{\text{Cl}_2} = 39.0 \text{ g} & 2 \text{ Cl}^{-}_{(l)} & \rightarrow \quad \text{Cl}_{2(g)} \quad + \quad 2e^{-} \\
 M_{\text{Cl}_2} = 70.906 \text{ g/mol} & & \\
 t = 80.0 \text{ min} = 4800 \text{ s} & & \\
 F = 9.65 \times 10^4 \text{ C/mol} & & \\
 n_{e^{-}} = ? & & \\
 I = ? & & 
 \end{array}$$

$$\begin{array}{lcl}
 & 39.0 \text{ g Cl}_2 & \\
 n_{\text{Cl}_2} = \frac{39.0 \text{ g Cl}_2}{70.906 \text{ g/mol}} & = & 0.5500239754 \text{ mol Cl}_2 \\
 & & \\
 n_{e^{-}} = 0.5500239754 \text{ mol Cl}_2 \times \frac{2 \text{ mol } e^{-}}{1 \text{ mol Cl}_2} & = & 1.100047951 \text{ mol } e^{-} \\
 & & \\
 n_{e^{-}} = \frac{It}{F} & I = \frac{n_{e^{-}} F}{t} = & \frac{(1.100047951 \text{ mol})(9.65 \times 10^4 \text{ C/mol})}{(4800 \text{ s})} \quad I = 22.1 \text{ A}
 \end{array}$$

### Assignment

**19.8 pg. 677–678 #43, 44, 46 to 48, 51 to 55, 57 to 59**