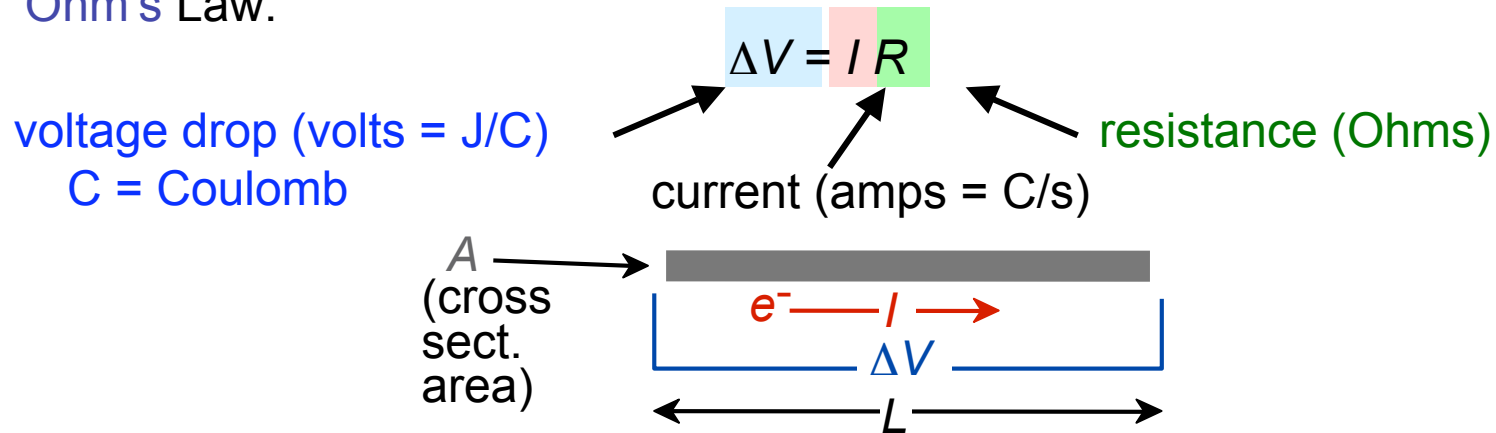


Electrical conductivity

- Ohm's Law:



- Resistivity, ρ and Conductivity, σ :

-- geometry-independent forms of Ohm's Law

-- Resistivity is a material property & is independent of sample

E : electric field intensity

$\frac{\Delta V}{L} = \frac{I}{A} \rho$

resistivity (Ohm-m)

J : current density

The diagram shows the equation $\frac{\Delta V}{L} = \frac{I}{A} \rho$. An arrow labeled 'E: electric field intensity' points to the fraction $\frac{\Delta V}{L}$. An arrow labeled 'resistivity (Ohm-m)' points to the symbol ρ . An arrow labeled 'J: current density' points to the fraction $\frac{I}{A}$.

- Resistance:

$$R = \frac{\rho L}{A} = \frac{L}{A \sigma}$$

conductivity $\rightarrow \sigma = \frac{1}{\rho}$

The diagram shows the equation $R = \frac{\rho L}{A} = \frac{L}{A \sigma}$. An arrow labeled 'conductivity' points to the symbol σ in the second part of the equation. The symbol σ is enclosed in a purple box, and the symbol ρ in the denominator is enclosed in a green box.

Conductivity: comparison

- Room T values $(\text{Ohm}\cdot\text{m})^{-1} = (\Omega \cdot \text{m})^{-1}$

METALS

Silver

6.8×10^7

Copper

6.0×10^7

Iron

1.0×10^7

conductors

CERAMICS

Soda-lime glass

10^{-10} - 10^{-11}

Concrete

10^{-9}

Aluminum oxide

$<10^{-13}$

SEMICONDUCTORS

Silicon

4×10^{-4}

Germanium

2×10^0

GaAs

10^{-6}

semiconductors

POLYMERS

Polystyrene

$<10^{-14}$

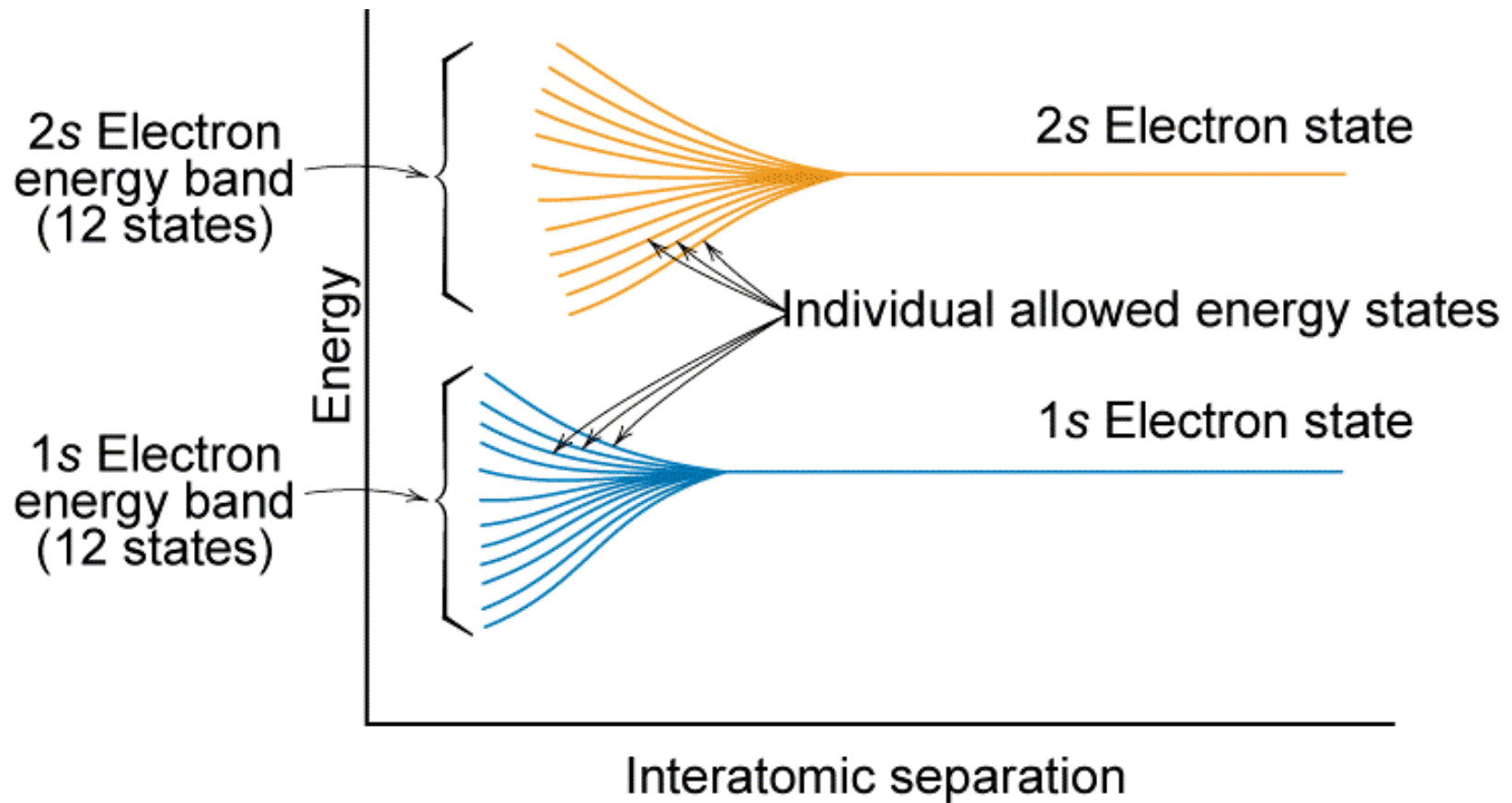
Polyethylene

10^{-15} - 10^{-17}

insulators

Selected values from Tables 18.1, 18.3, and 18.4, *Callister 7e*.

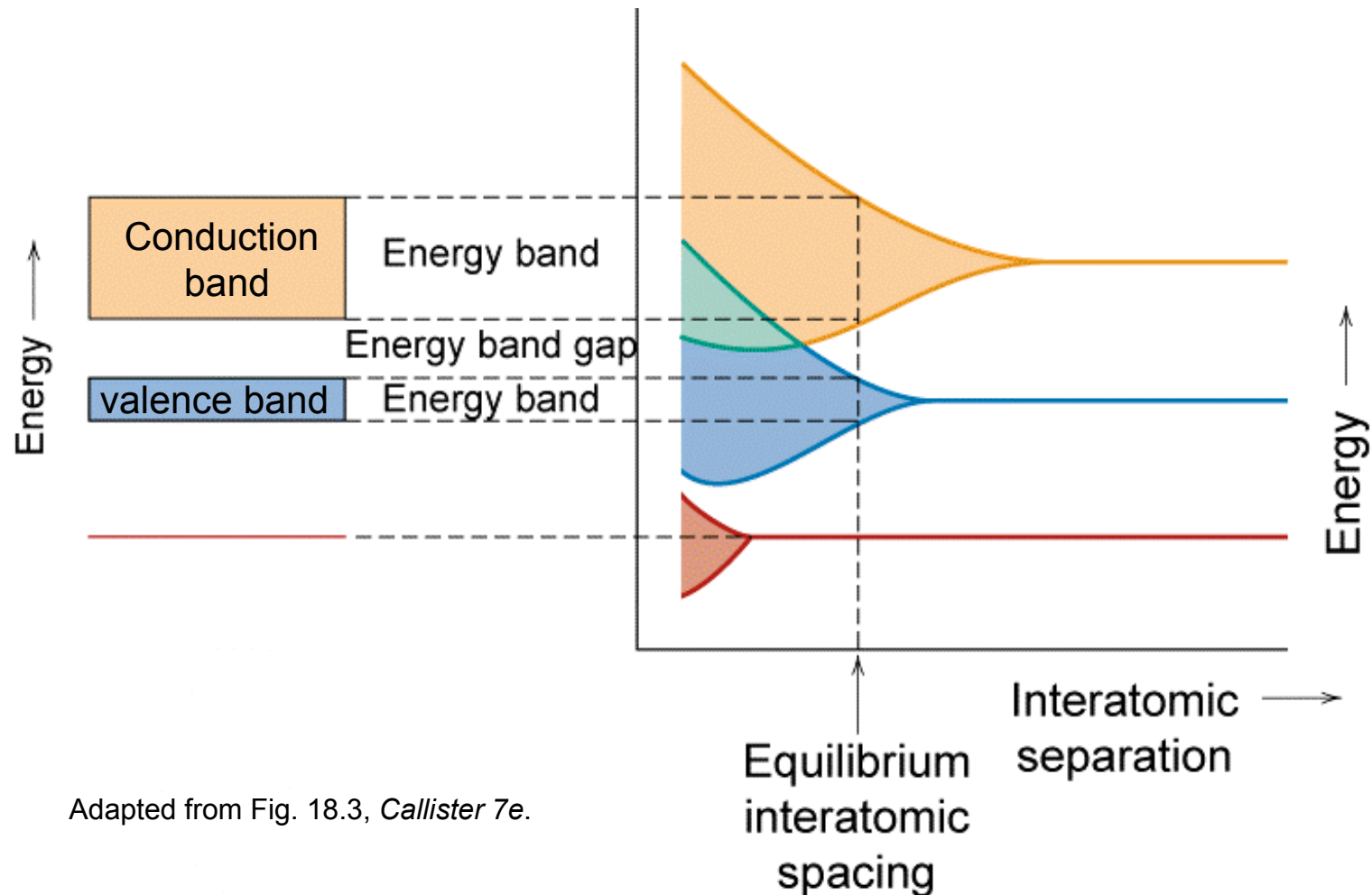
Electronic band structure



Adapted from Fig. 18.2, *Callister 7e*.

Electronic band structure

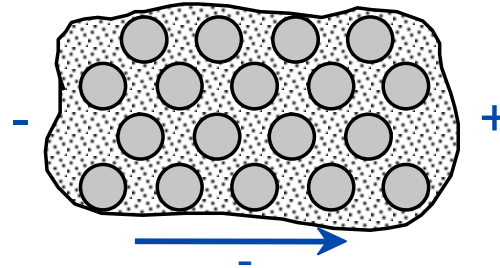
- Valence band – filled – highest occupied energy levels
- Conduction band – empty – lowest unoccupied energy levels



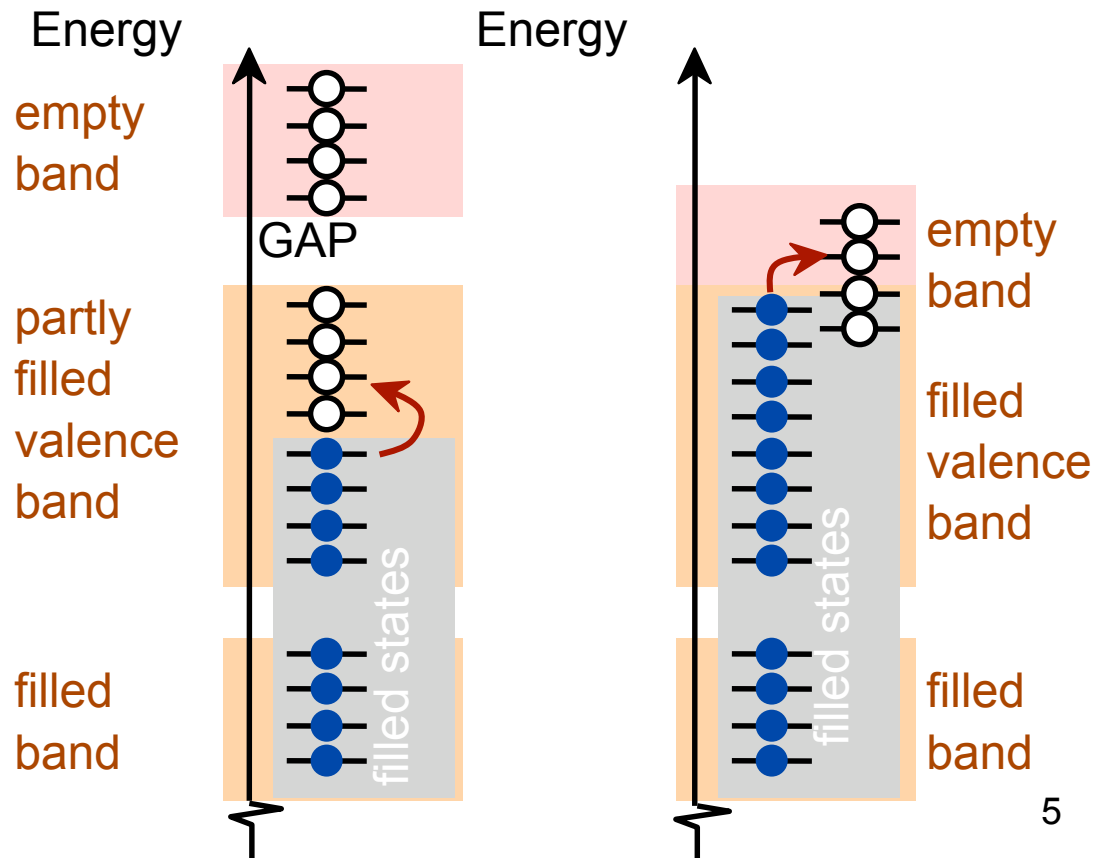
Adapted from Fig. 18.3, *Callister 7e*.

Conduction and electron transport

- Metals (**Conductors**):
 - Thermal energy puts many electrons into a higher energy state.

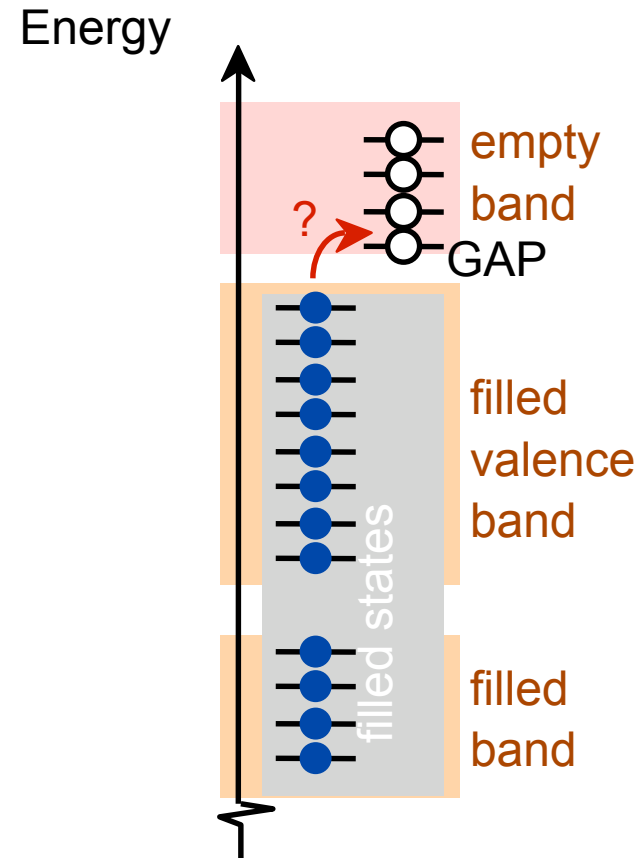
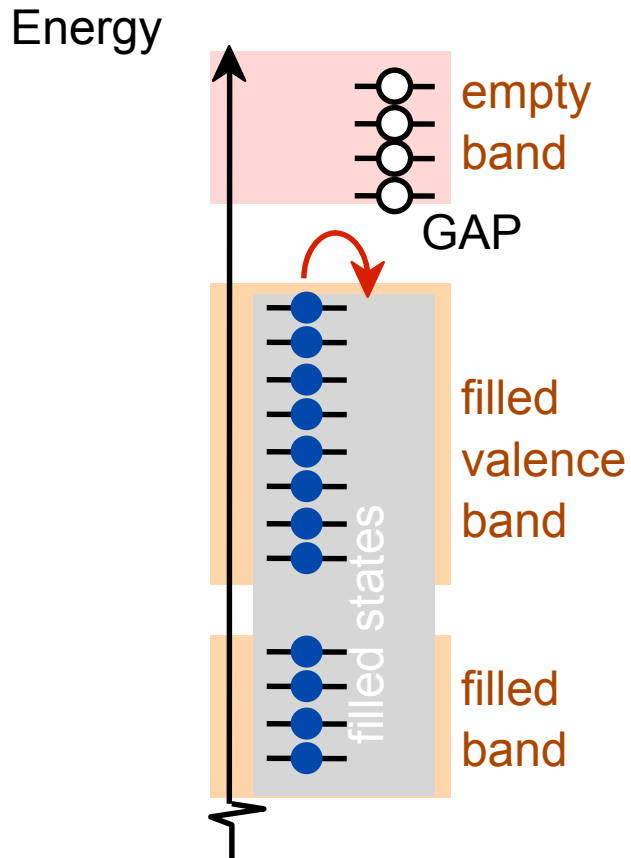


- Energy States:
 - for metals nearby energy states are accessible by thermal fluctuations.



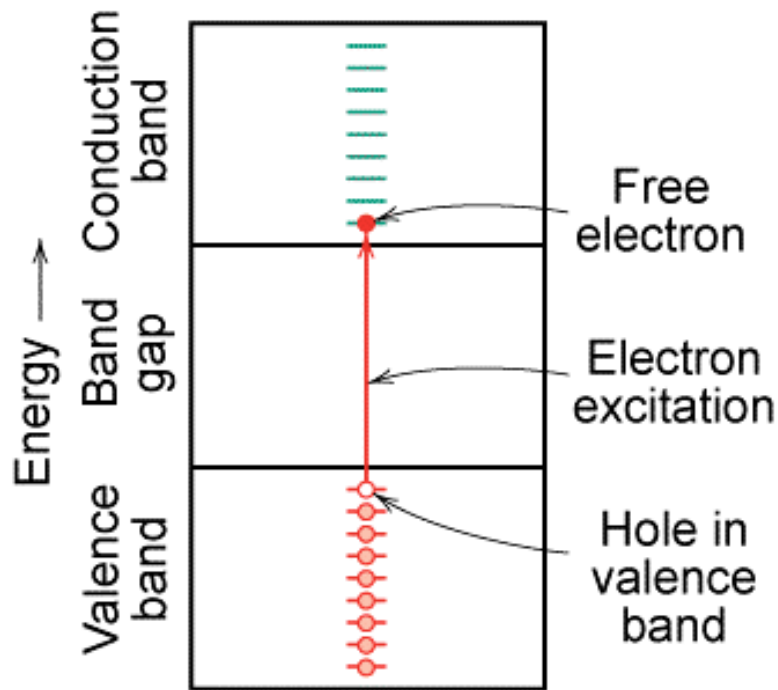
Energy states: Insulators & semiconductors

- Insulators:
 - Higher energy states not accessible due to gap (> 2 eV).
- Semiconductors:
 - Higher energy states separated by smaller gap (< 2 eV).



Charge carriers

Adapted from Fig. 18.6 (b), Callister 7e.



Two charge carrying mechanisms

- Electron** – negative charge
- Hole** – equal & opposite positive charge

Move at different speeds - **drift velocity**

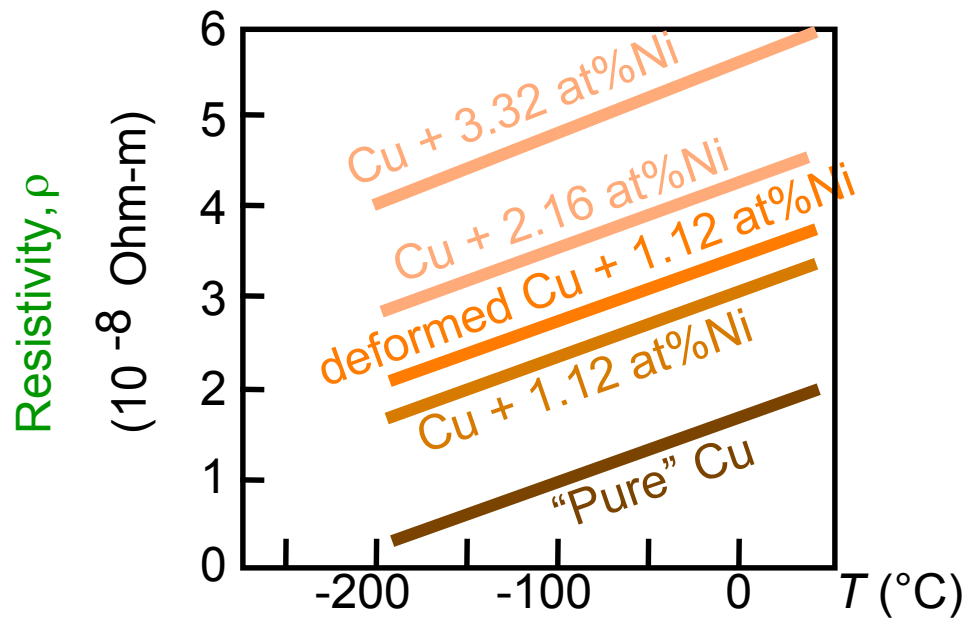
Higher temp. promotes more electrons into the conduction band

$$\therefore \sigma \uparrow \text{ as } T \uparrow$$

Electrons scattered by impurities, grain boundaries, etc.

Charge carriers

- Imperfections increase resistivity
 - grain boundaries
 - dislocations
 - impurity atoms
 - vacancies
- These act to scatter electrons so that they take a less direct path.



- Resistivity increases with:
 - temperature
 - wt% impurity
 - %CW

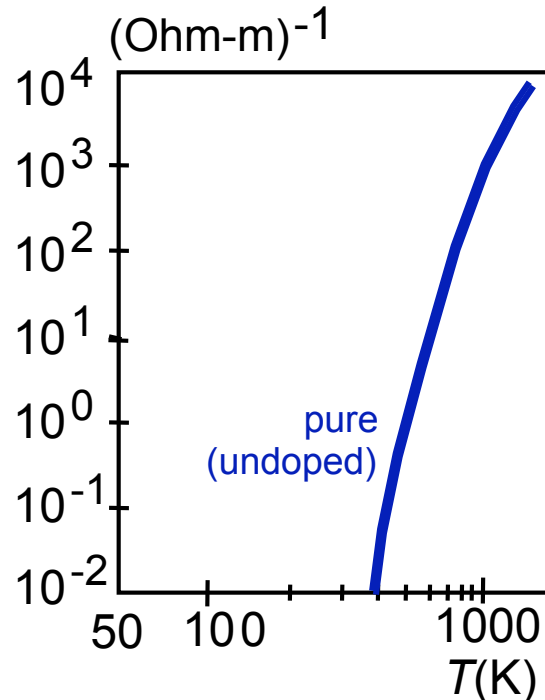
$$\rho = \rho_{\text{thermal}} + \rho_{\text{impurity}} + \rho_{\text{deformation}}$$

Adapted from Fig. 18.8, *Callister 7e*. (Fig. 18.8 adapted from J.O. Linde, *Ann. Physik* **5**, p. 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd ed., McGraw-Hill Book Company, New York, 1970.)

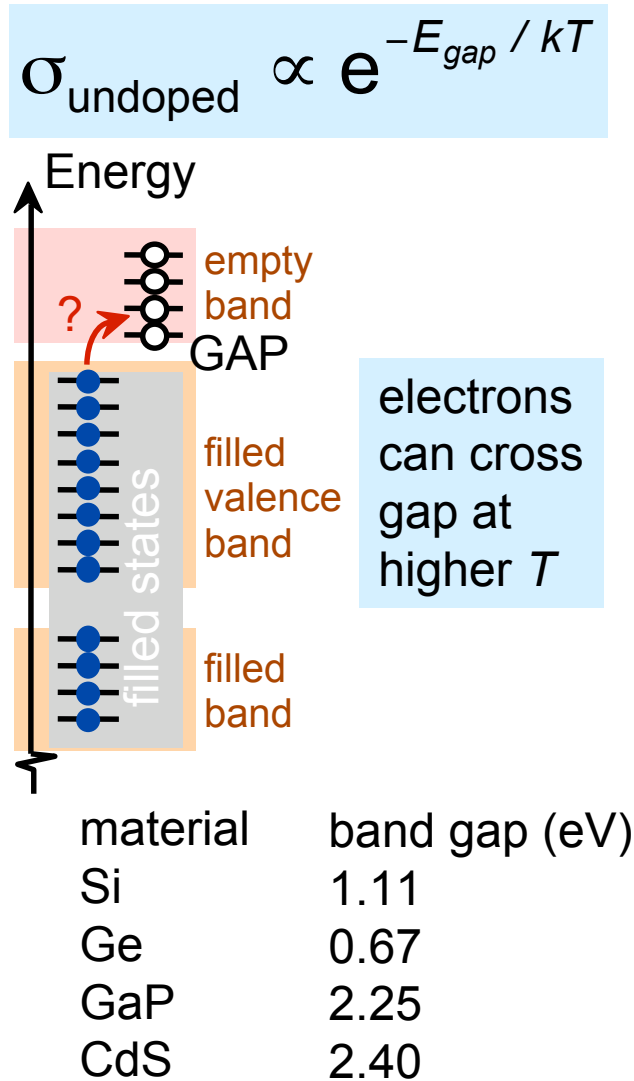
Pure semiconductors: Conductivity vs T

- Data for **Pure Silicon**:
 - σ increases with T
 - opposite to metals

electrical conductivity, σ



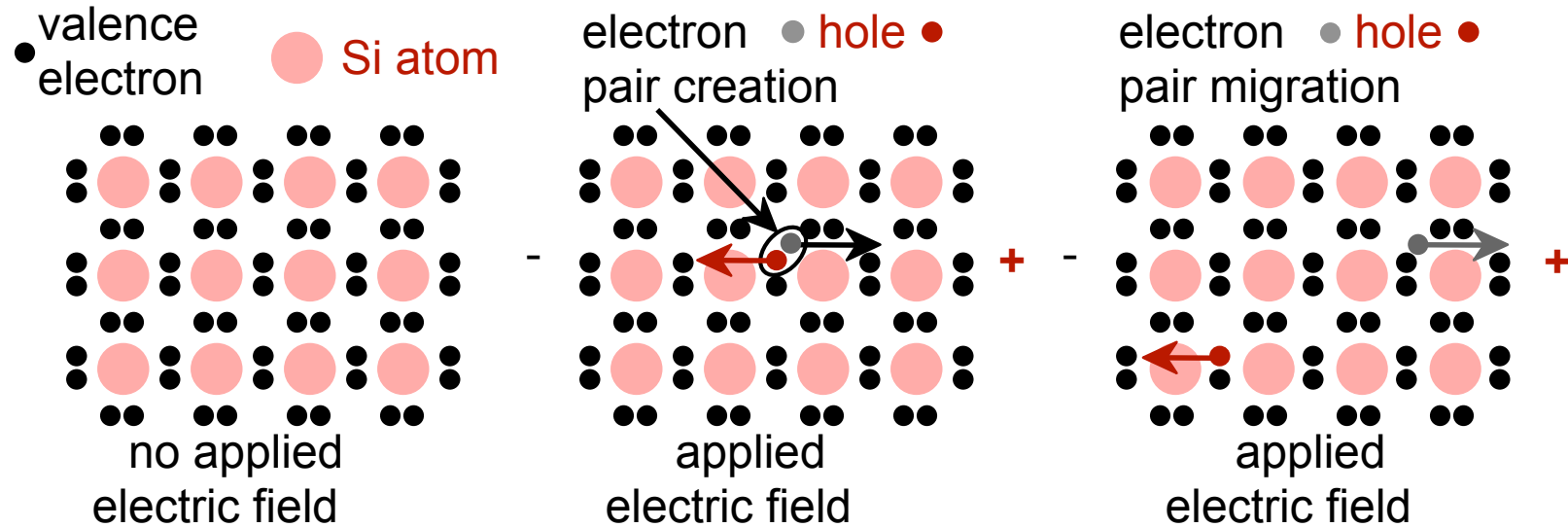
Adapted from Fig. 19.15, *Callister 5e*. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, *Phys. Rev.* **75**, p. 865, 1949.)



Selected values from Table 18.3, *Callister 7e*.

Conduction in terms of electron and hole migration

- Concept of electrons and holes:



Adapted from Fig. 18.11, *Callister 7e*.

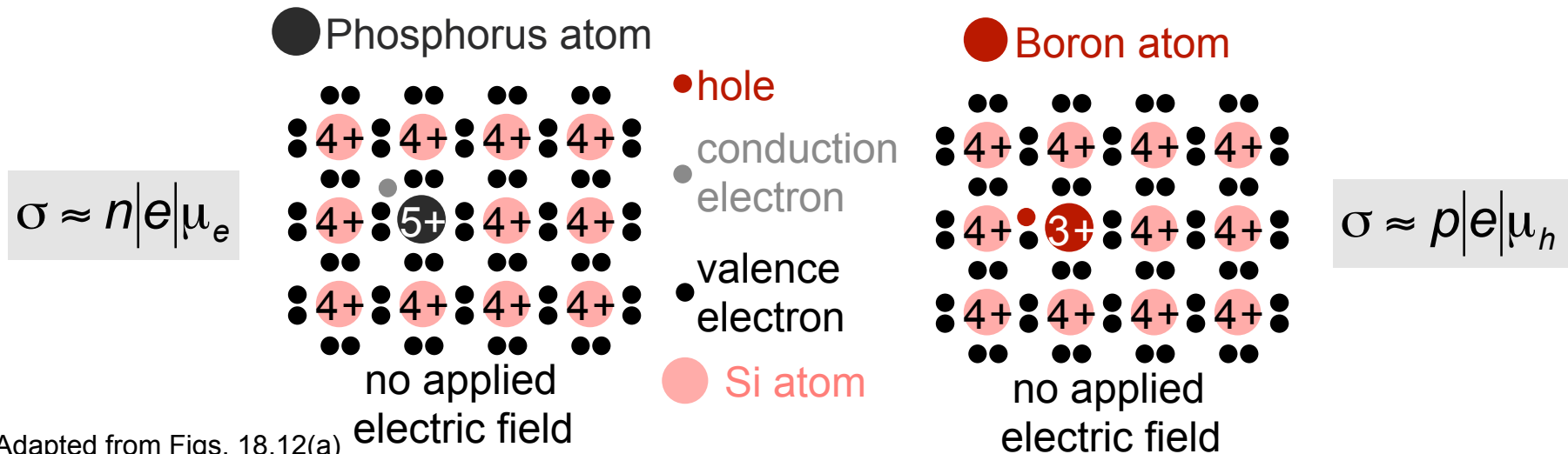
- Electrical Conductivity given by:

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

electrons/m³ → n
 # holes/m³ → p
 electron mobility → μ_e
 hole mobility → μ_h

Intrinsic vs extrinsic conduction

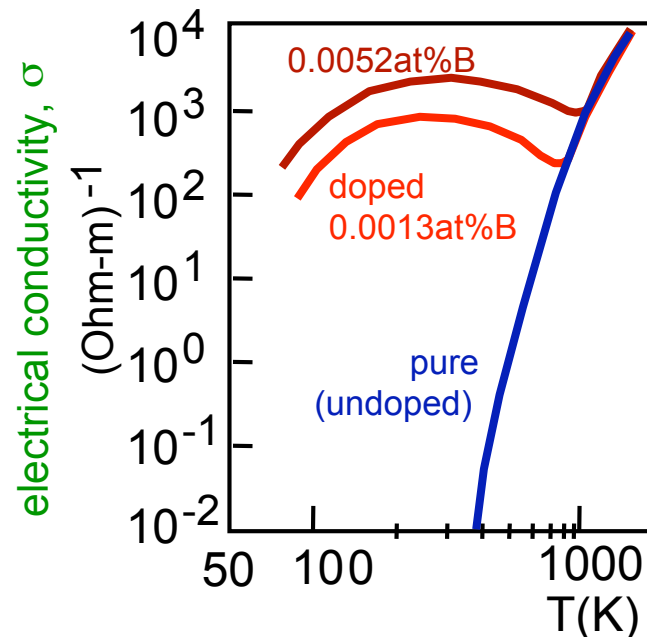
- **Intrinsic:**
electrons = # holes ($n = p$)
--case for pure Si
- **Extrinsic:**
-- $n \neq p$
--occurs when impurities are added with a different # valence electrons than the host (e.g., Si atoms)
- **n -type Extrinsic:** ($n \gg p$)
- **p -type Extrinsic:** ($p \gg n$)



Adapted from Figs. 18.12(a) & 18.14(a), Callister 7e.

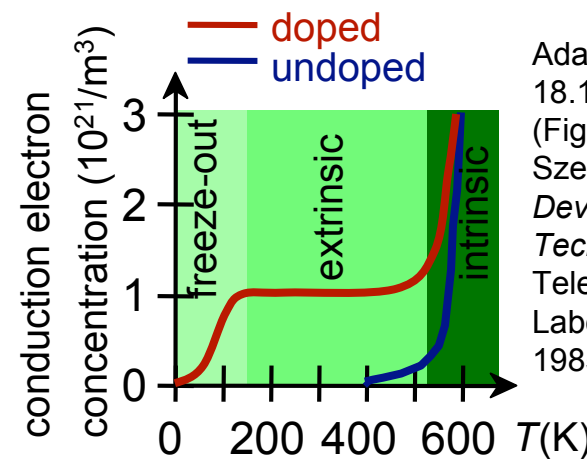
Doped semiconductor: conductivity vs. T

- Data for Doped Silicon:
 - σ increases with doping
 - reason: imperfection sites lower the activation energy to produce mobile electrons.



Adapted from Fig. 19.15, *Callister 5e*. (Fig. 19.15 adapted from G.L. Pearson and J. Bardeen, *Phys. Rev.* **75**, p. 865, 1949.)

- Comparison: **intrinsic** vs extrinsic conduction...
 - extrinsic doping level: $10^{21}/\text{m}^3$ of a n -type donor impurity (such as P).
 - for $T < 100$ K: "freeze-out", thermal energy insufficient to excite electrons.
 - for 150 K $< T < 450$ K: "extrinsic"
 - for $T \gg 450$ K: "intrinsic"



Adapted from Fig. 18.17, *Callister 7e*. (Fig. 18.17 from S.M. Sze, *Semiconductor Devices, Physics, and Technology*, Bell Telephone Laboratories, Inc., 1985.)

Doped semiconductor: conductivity vs. T

Intrinsic Conductivity

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

- for intrinsic semiconductor $n = p$
 $\therefore \sigma = n|e|(\mu_e + \mu_h)$

- Ex: GaAs

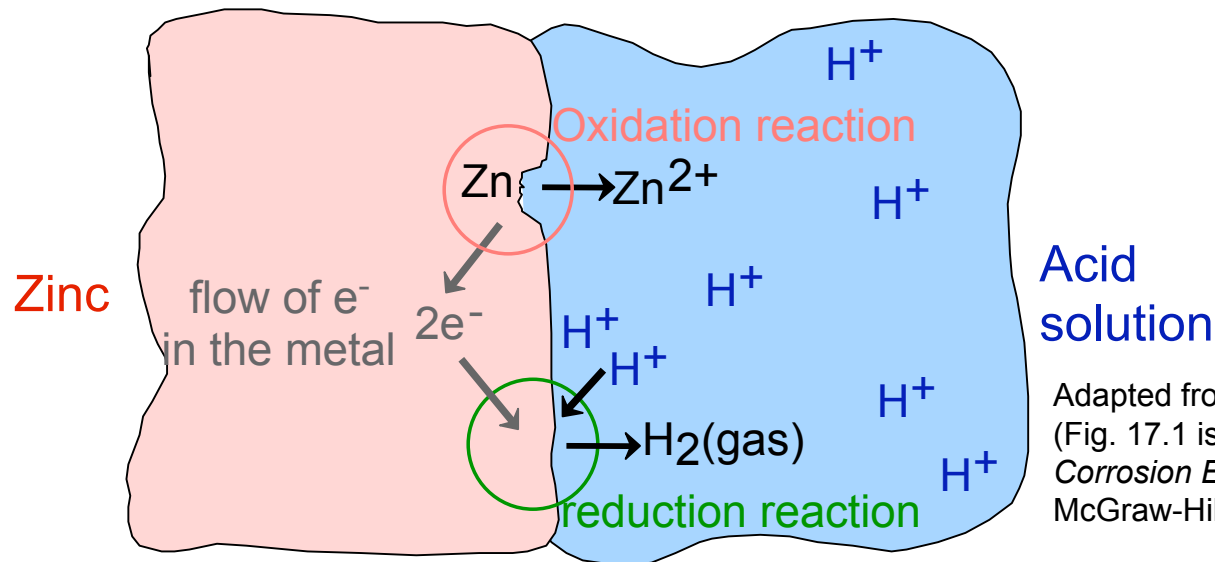
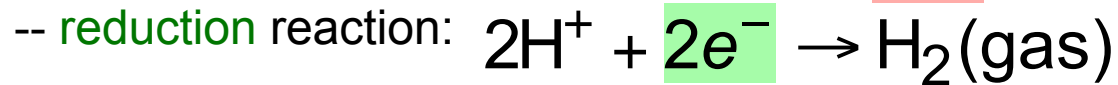
$$n = \frac{\sigma}{|e|(\mu_e + \mu_h)} = \frac{10^{-6} (\Omega \cdot \text{m})^{-1}}{(1.6 \times 10^{-19} \text{ C})(0.85 + 0.45 \text{ m}^2/\text{V} \cdot \text{s})}$$

For GaAs $n = 4.8 \times 10^{24} \text{ m}^{-3}$

For Si $n = 1.3 \times 10^{16} \text{ m}^{-3}$

Corrosion of zinc in acid

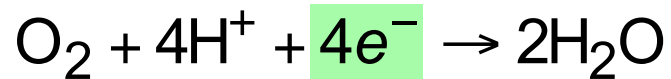
- Two reactions are necessary:



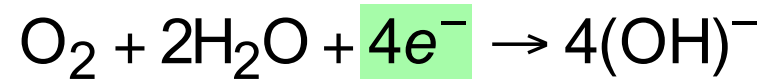
Adapted from Fig. 17.1, *Callister 7e*.
(Fig. 17.1 is from M.G. Fontana,
Corrosion Engineering, 3rd ed.,
McGraw-Hill Book Company, 1986.)

- Other reduction reactions:

-- in an acid solution



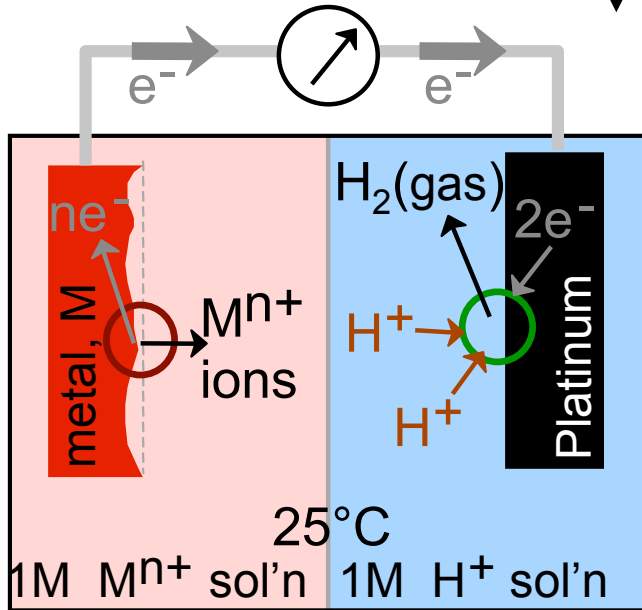
-- in a neutral or base solution



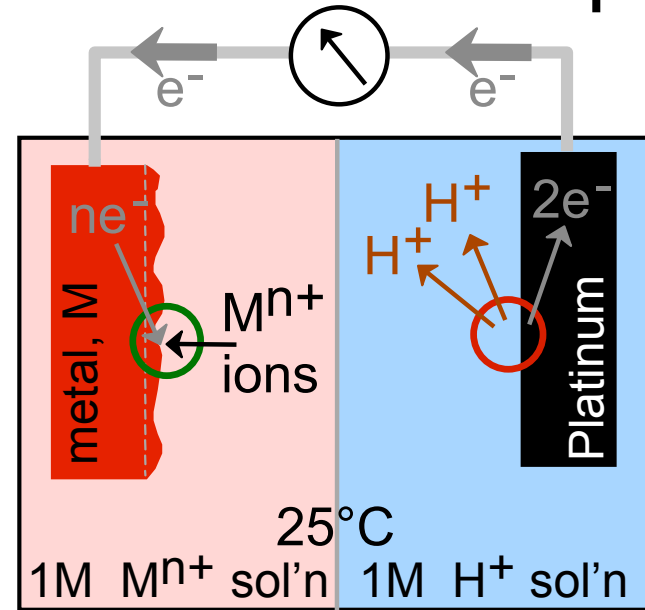
Standard hydrogen (EMF) test

- Two outcomes:

--Metal sample mass ↓



--Metal sample mass ↑



--Metal is the anode (-)

$$V_{\text{metal}}^{\circ} < 0 \quad (\text{relative to Pt})$$

--Metal is the cathode (+)

$$V_{\text{metal}}^{\circ} > 0 \quad (\text{relative to Pt})$$

Standard Electrode Potential

Adapted from Fig. 17.2, Callister 7e.

Standard EMF series

- EMF series

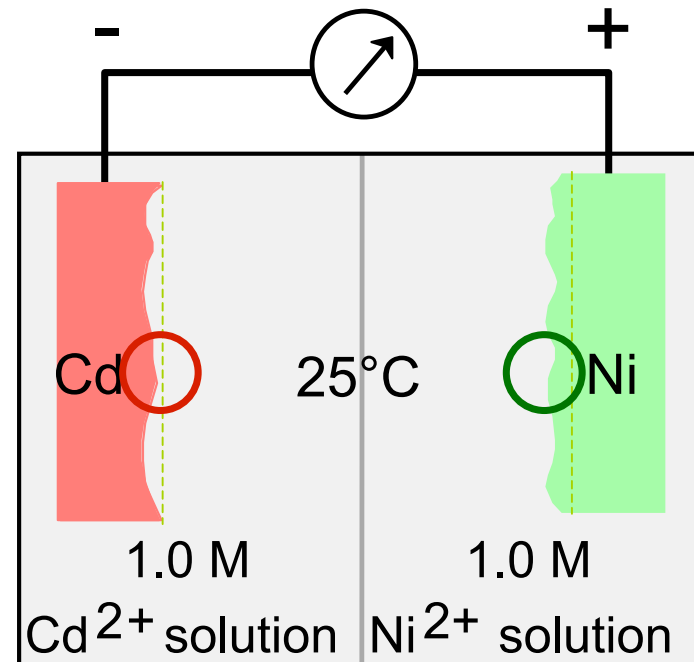
metal	V_{metal}°
Au	+1.420 V
Cu	+0.340
Pb	-0.126
Sn	-0.136
Ni	-0.250
Co	-0.277
Cd	-0.403
Fe	-0.440
Cr	-0.744
Zn	-0.763
Al	-1.662
Mg	-2.363
Na	-2.714
K	-2.924

more cathodic ↑

more anodic ↓

$\Delta V^{\circ} = 0.153\text{V}$

- Metal with smaller V_{metal}° corrodes.
- Ex: Cd-Ni cell



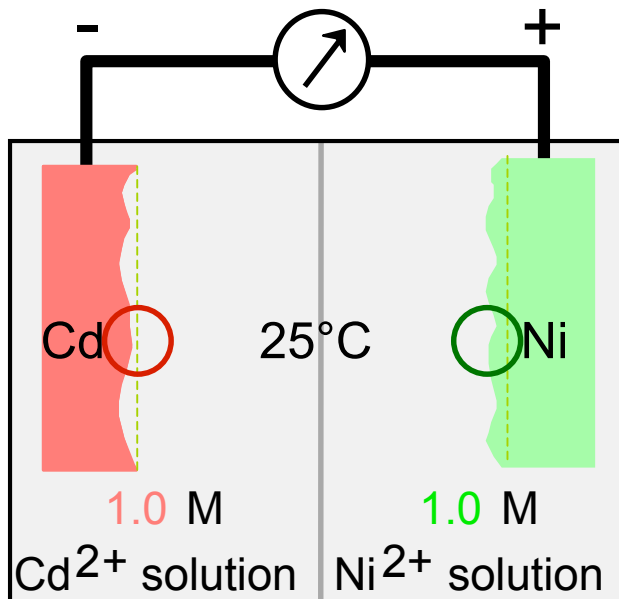
Data based on Table 17.1,
Callister 7e.

Adapted from Fig. 17.2, Callister 7e.

Effect of solution concentration

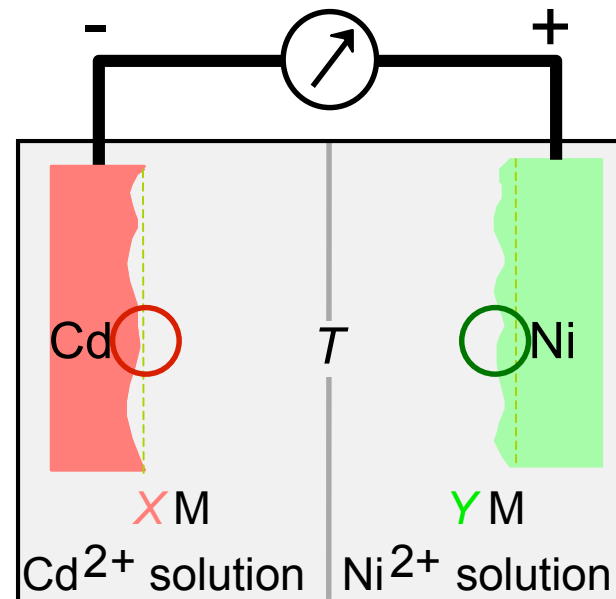
- Ex: Cd-Ni cell with standard 1 M solutions

$$V_{\text{Ni}}^{\circ} - V_{\text{Cd}}^{\circ} = 0.153$$



- Ex: Cd-Ni cell with non-standard solutions

$$V_{\text{Ni}} - V_{\text{Cd}} = V_{\text{Ni}}^{\circ} - V_{\text{Cd}}^{\circ} - \frac{RT}{nF} \ln \frac{X}{Y}$$



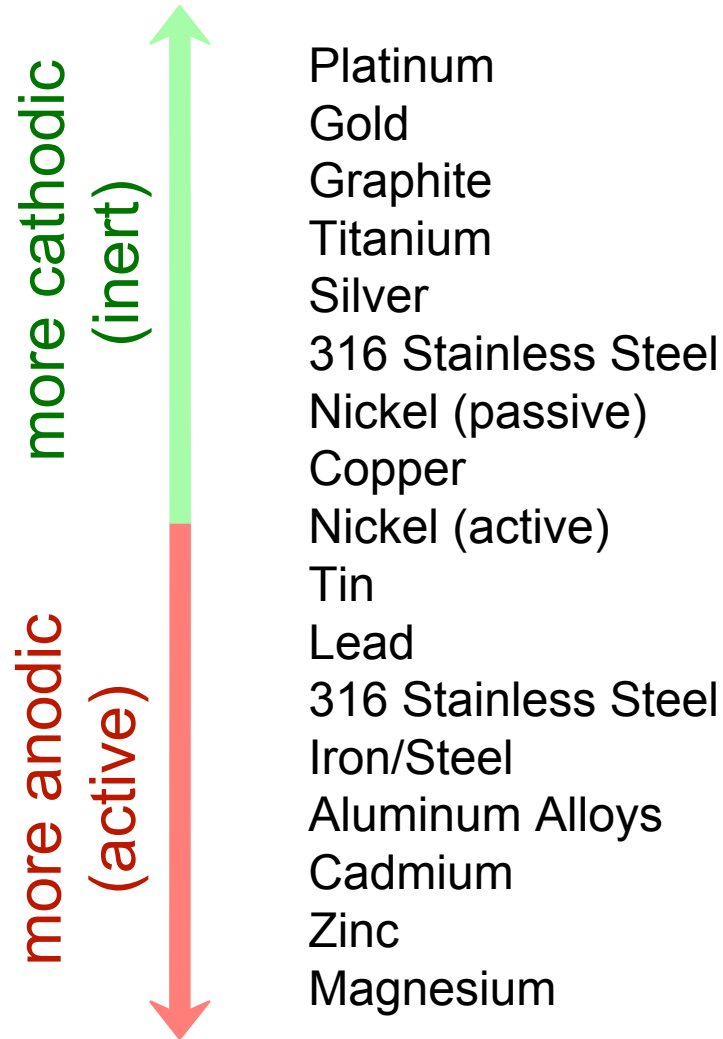
$n = \#e^-$
per unit
oxid/red
reaction
(= 2 here)

$F =$
Faraday's
constant
= 96,500
C/mol.

- Reduce $V_{\text{Ni}} - V_{\text{Cd}}$ by
 - increasing X
 - decreasing Y

Galvanic series

- Ranks the reactivity of metals/alloys in seawater



Based on Table 17.2, *Callister 7e*. (Source of Table 17.2 is M.G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill Book Company, 1986.)

Forms of corrosion

- **Uniform Attack**

Oxidation & reduction occur uniformly over surface.

- **Selective Leaching**

Preferred corrosion of one element/constituent (e.g., Zn from brass (Cu-Zn)).

- **Intergranular**

Corrosion along grain boundaries, often where special phases exist.

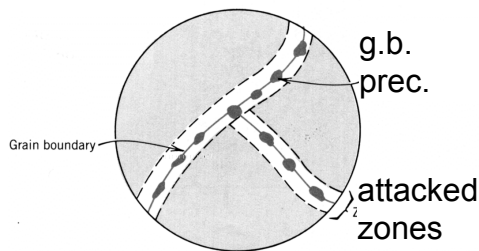
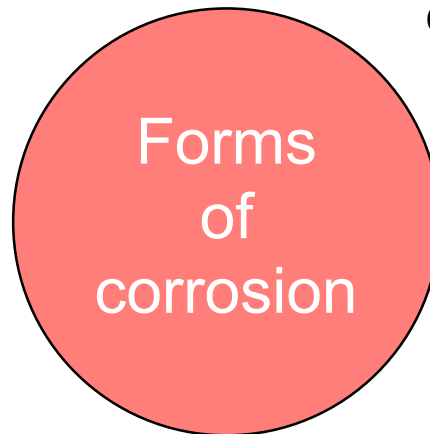


Fig. 17.18, Callister 7e.

- **Stress corrosion**

Stress & corrosion work together at crack tips.



- **Galvanic**

Dissimilar metals are physically joined. The more anodic one corrodes. (see Table 17.2) Zn & Mg very anodic.

- **Erosion-corrosion**

Break down of passivating layer by erosion (pipe elbows).

- **Pitting**

Downward propagation of small pits & holes.

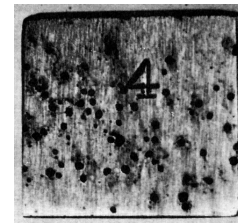


Fig. 17.17, Callister 7e. (Fig. 17.17 from M.G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill Book Company, 1986.)

- **Crevice** Between two pieces of the same metal.

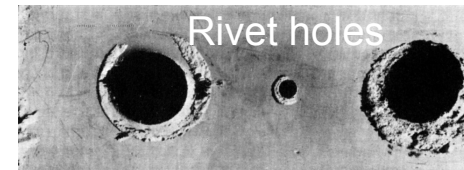
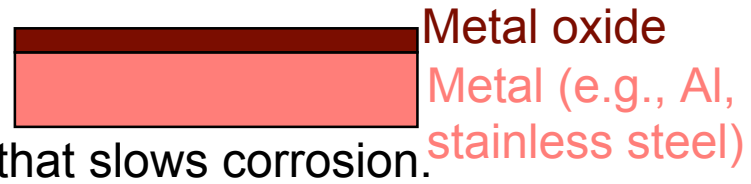


Fig. 17.15, Callister 7e. (Fig. 17.15 is courtesy LaQue Center for Corrosion Technology, Inc.)

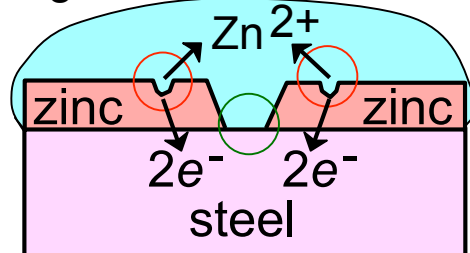
Controlling corrosion

- Self-protecting metals!
 - Metal ions combine with O to form a thin, adhering oxide layer that slows corrosion.



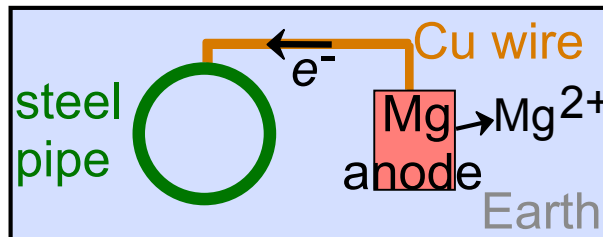
- Reduce T (slows kinetics of oxidation and reduction)
- Add inhibitors
 - Slow oxidation/reduction reactions by removing reactants (e.g., remove O_2 gas by reacting it w/an inhibitor).
 - Slow oxidation reaction by attaching species to the surface (e.g., paint it!).
- Cathodic (or sacrificial) protection
 - Attach a more anodic material to the one to be protected.

e.g., zinc-coated nail



Adapted from Fig. 17.23, Callister 7e.

e.g., Mg Anode



Adapted from Fig. 17.22(a), Callister 7e. (Fig. 17.22(a) is from M.G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill Book Co., 1986.)