Electrical conductivity

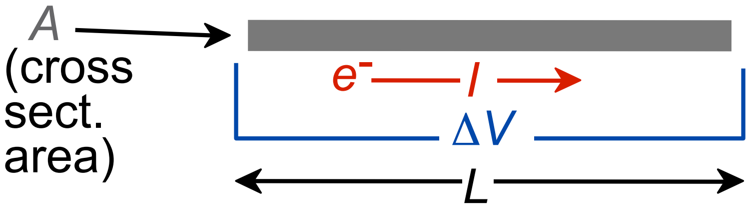
- Ohm's Law:

$$\Delta V = I\,R$$

voltage drop (volts = J/C)
C = Coulomb

current (amps = C/s)

resistance (Ohms)



- Resistivity, ρ and Conductivity, σ:

-- geometry-independent forms of Ohm's Law

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

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

E: electric field intensity

resistivity (Ohm-m)

J: current density

- Resistance:

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

conductivity

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

Conductivity: comparison

- Room T values (Ohm-m)$^{-1}$ = (Ω - m)$^{-1}$

METALS	conductors
Silver	6.8×10^{7}
Copper	6.0×10^{7}
Iron	1.0×10^{7}

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}

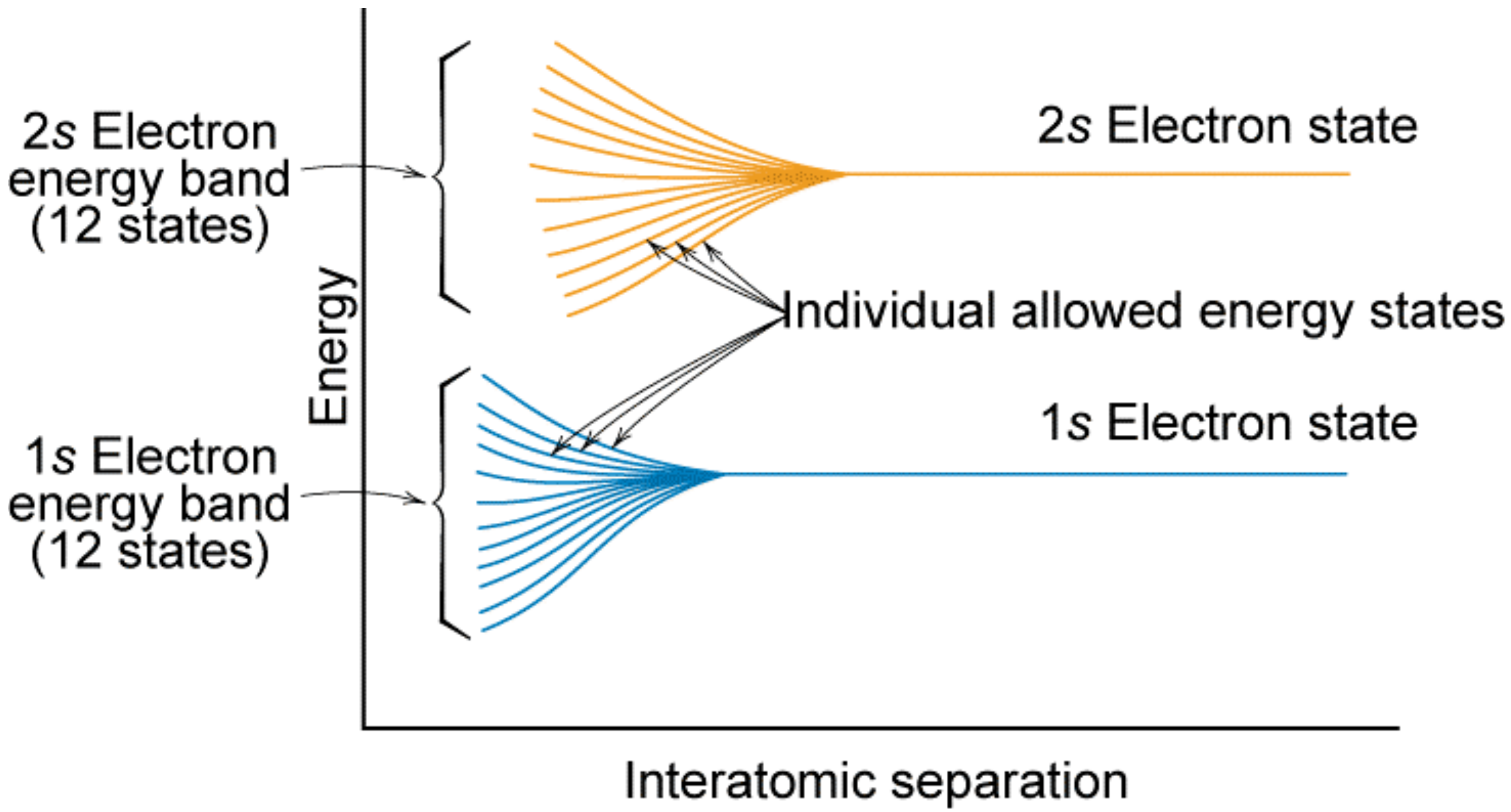
semiconductors

POLYMERS	
Polystyrene	$<10^{-14}$
Polyethylene	10^{-15}-10^{-17}

insulators

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

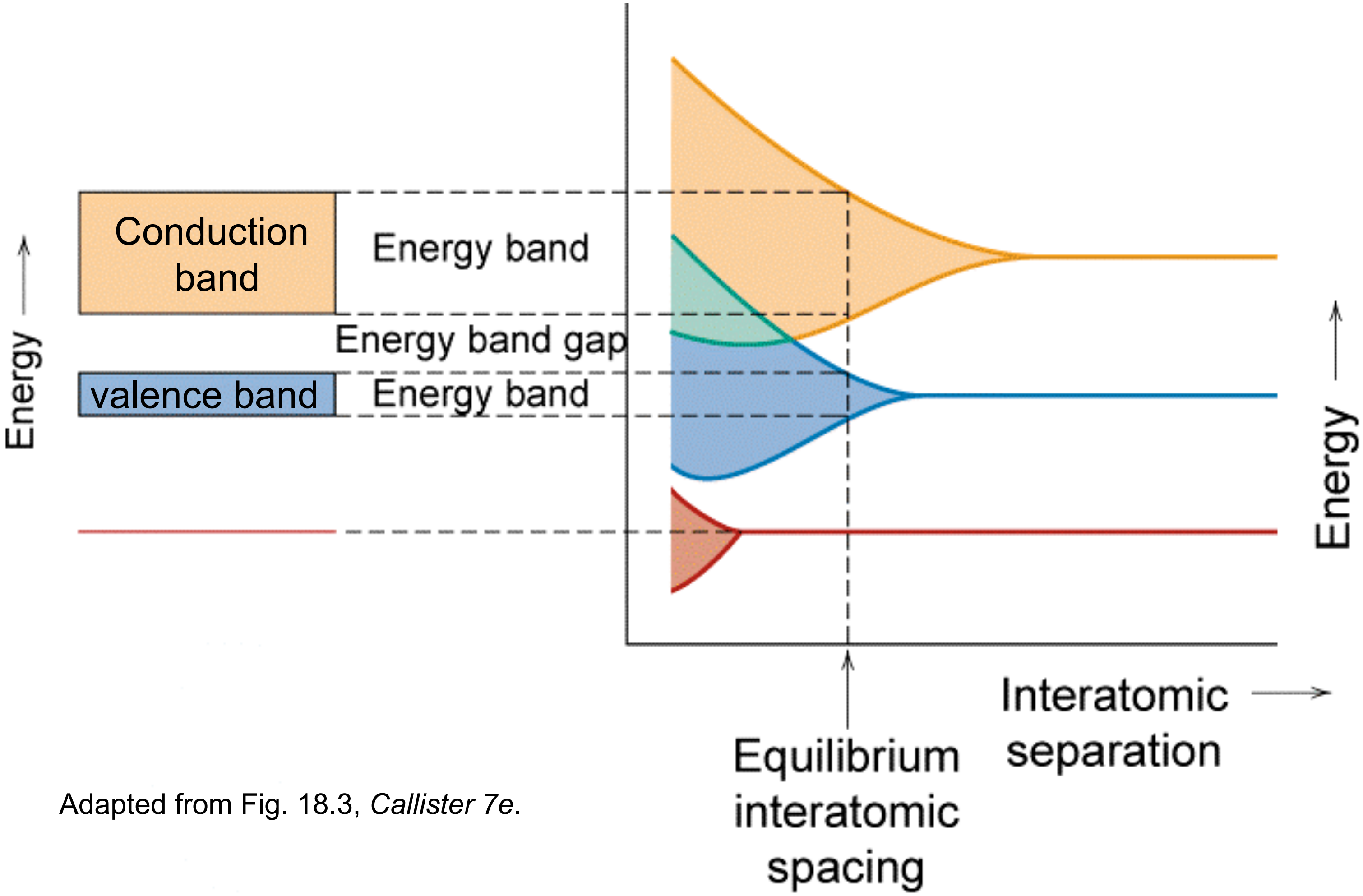
Electronic band structure



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

Electronic band structure

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

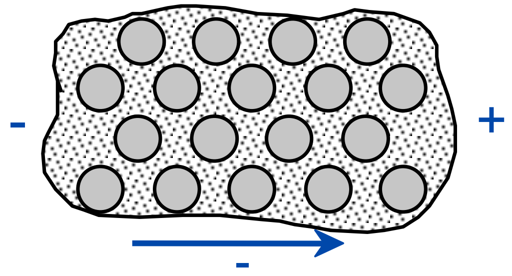


Adapted from Fig. 18.3, *Callister 7e*.

Conduction and electron transport

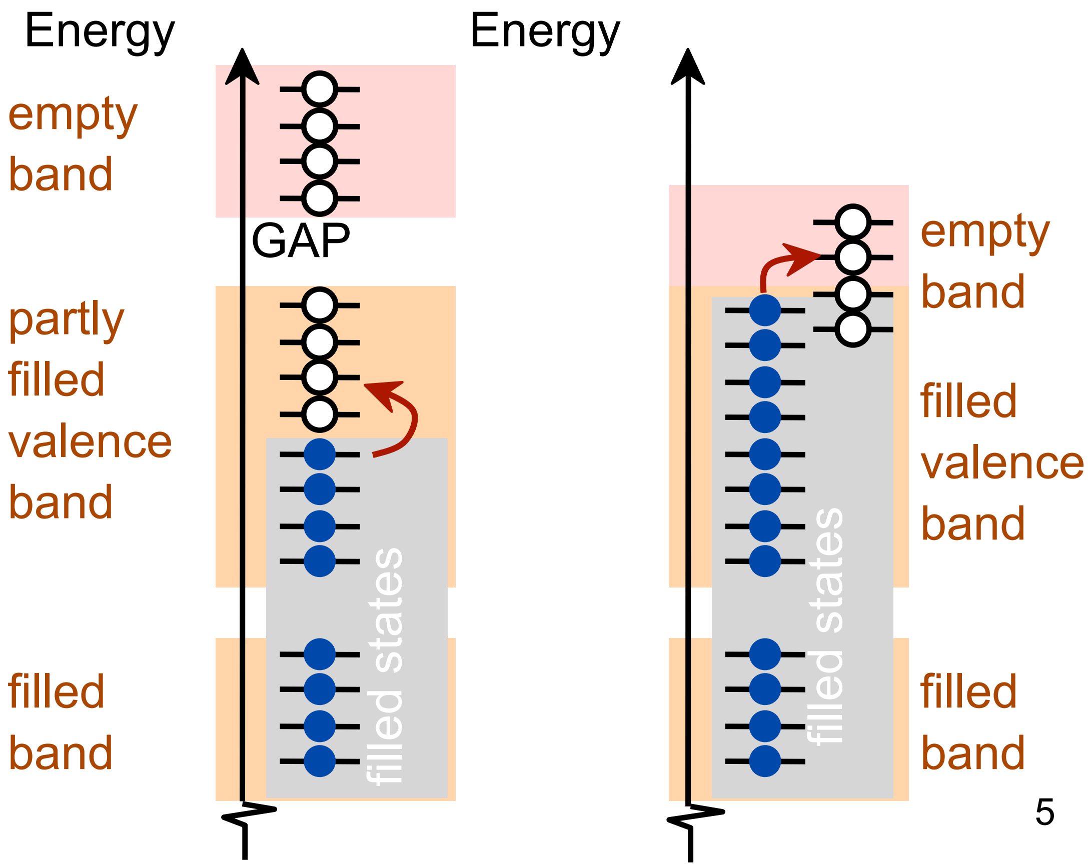
- Metals (Conductors):

-- Thermal energy puts
 many electrons into
 a higher energy state.



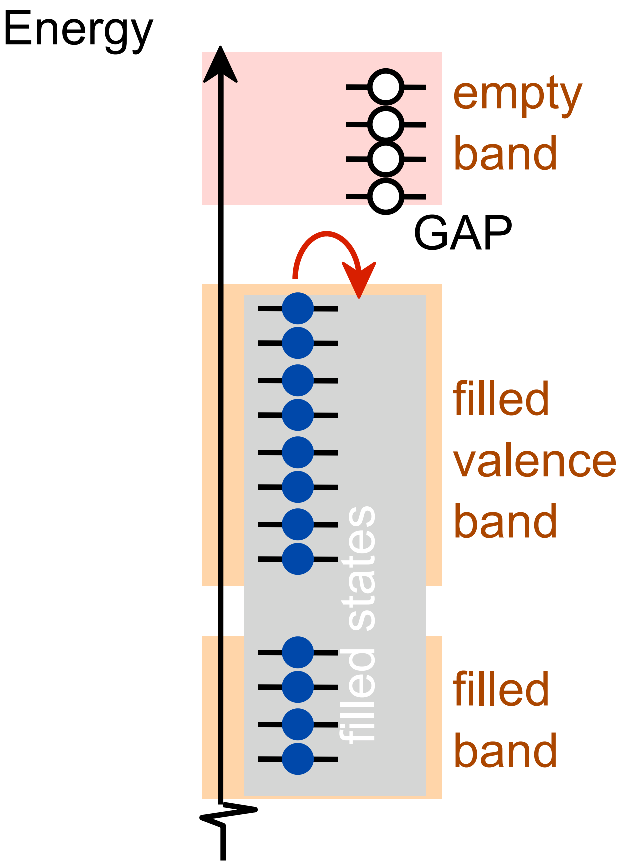
- Energy States:

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

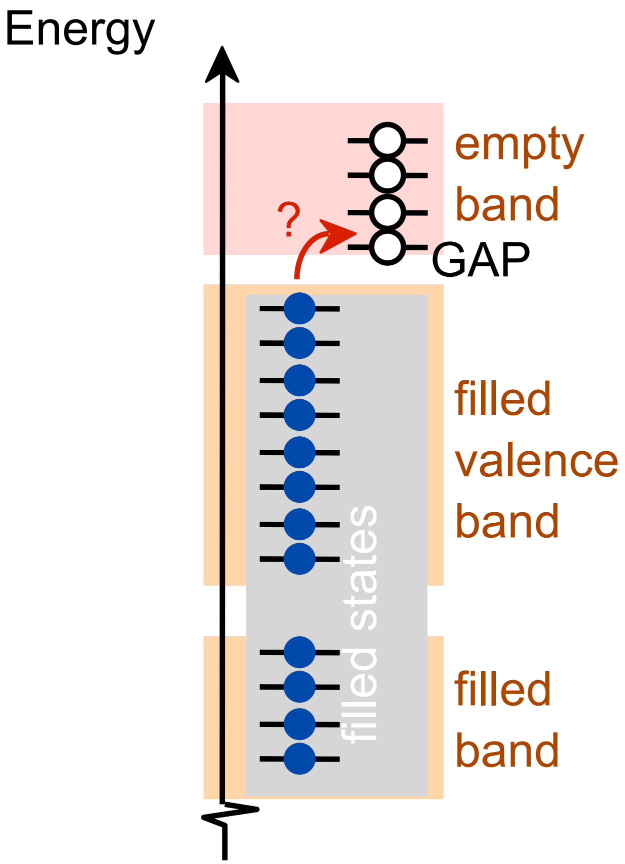


Energy states: Insulators & semiconductors

- Insulators:
  -- Higher energy states not accessible due to gap (> 2 eV).

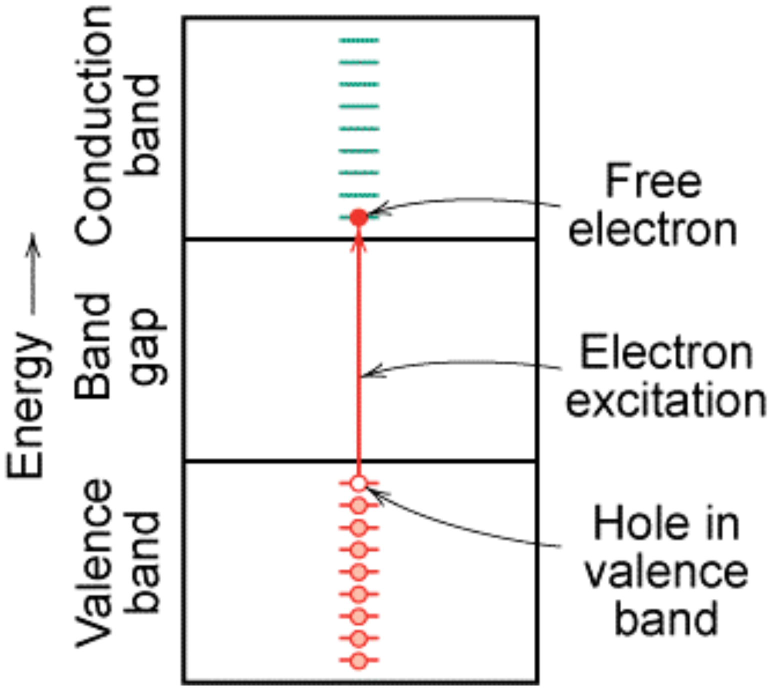


- Semiconductors:
  -- Higher energy states separated by smaller gap (< 2 eV).



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

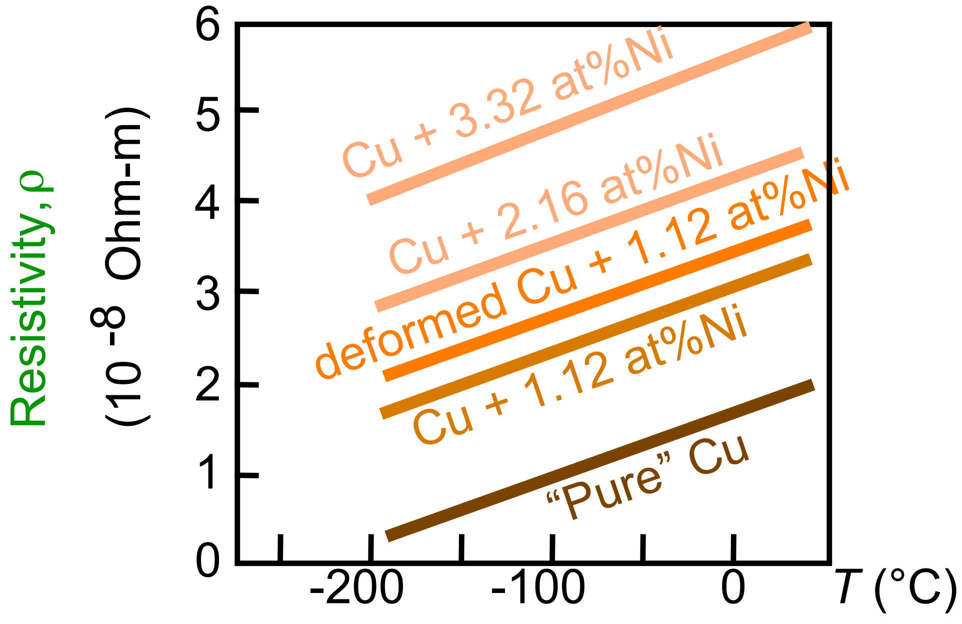
∴ $\sigma\uparrow$ as $T\uparrow$

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.



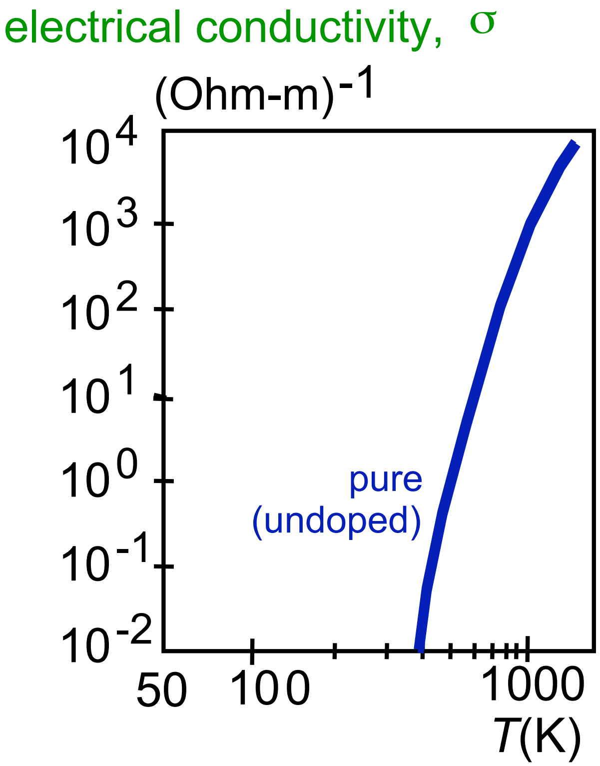
Adapted from Fig. 18.8, *Callister 7e*. (Fig. 18.8 adapted from J.O. Linde, *Ann. Physik* **5**, p. 219 (1932); and C.A. Wert and R.M. Thomson, *Physics of Solids*, 2nd ed., McGraw-Hill Book Company, New York, 1970.)

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

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

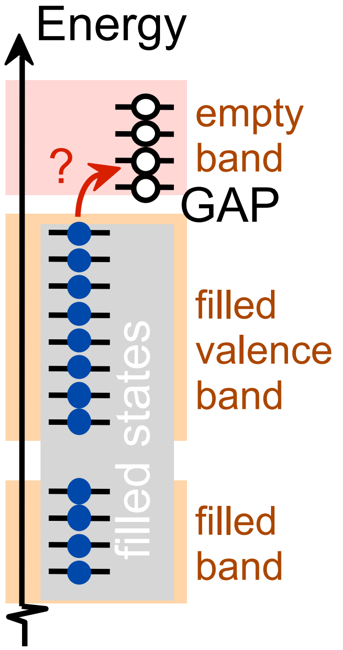
Pure semiconductors: Conductivity vs T

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



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

$$\sigma_{\text{undoped}} \propto e^{-E_{gap}/kT}$$



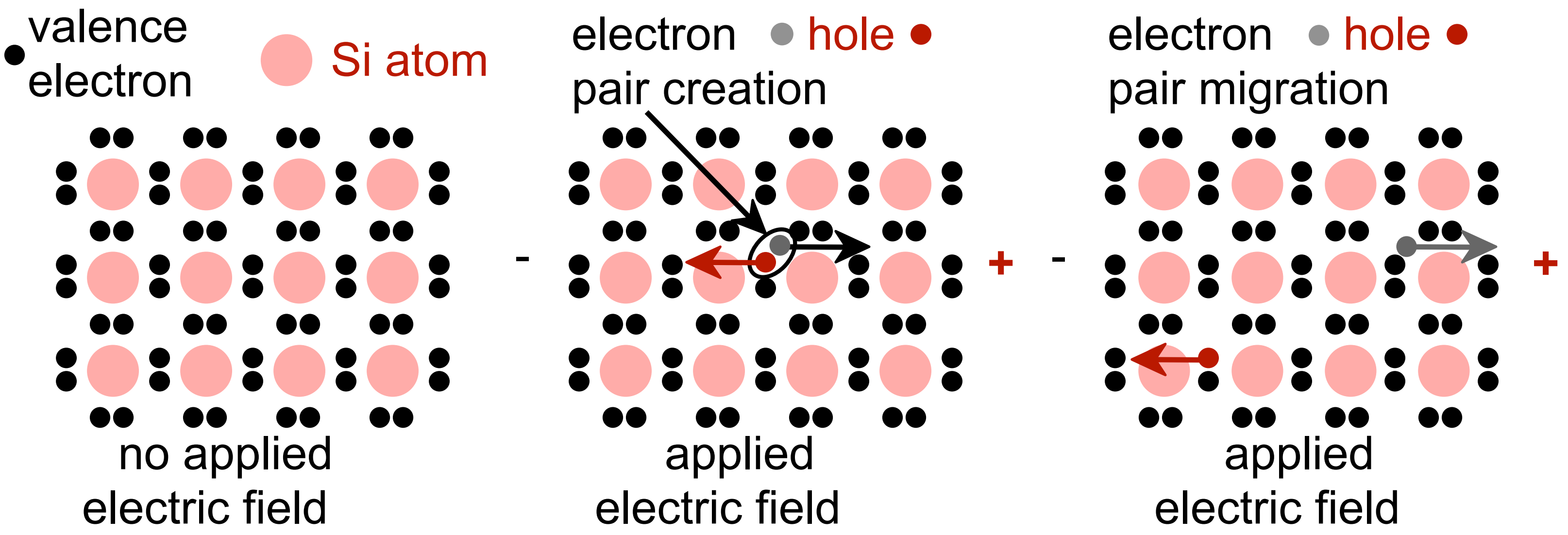
electrons can cross gap at higher T

material	band gap (eV)
Si	1.11
Ge	0.67
GaP	2.25
CdS	2.40

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

Conduction in terms of electron and hole migration

- Concept of electrons and holes:



no applied electric field

applied electric field

applied electric field

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

- Electrical Conductivity given by:

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

\# holes/m^3

hole mobility

\# electrons/m^3

electron mobility

Intrinsic vs extrinsic conduction

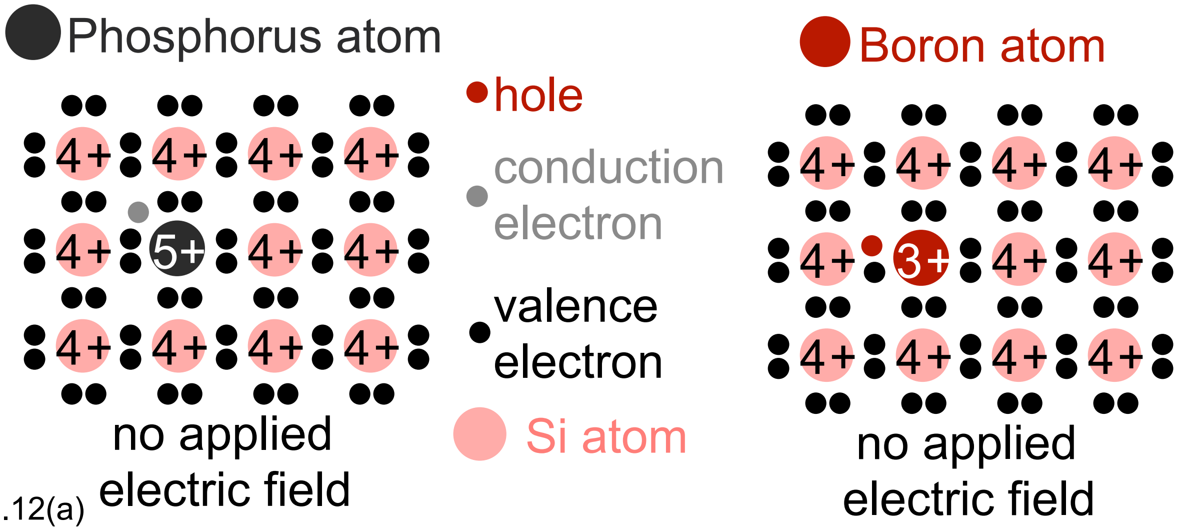
- Intrinsic:
  \# electrons = # holes ($n = p$)
  --case for pure Si

- Extrinsic:
  --$n \neq p$
  --occurs when impurities are added with a different
  \# valence electrons than the host (e.g., Si atoms)

- *n*-type Extrinsic: ($n >> p$)

- *p*-type Extrinsic: ($p >> n$)

$\sigma \approx n|e|\mu_e$



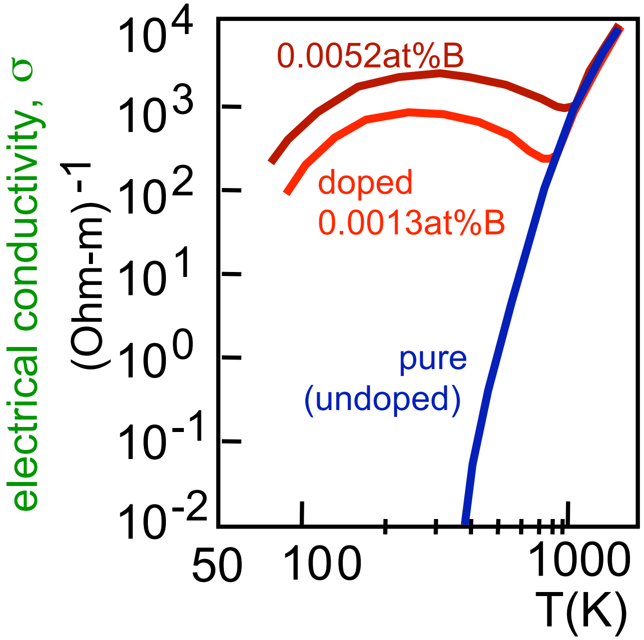
$\sigma \approx p|e|\mu_h$

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

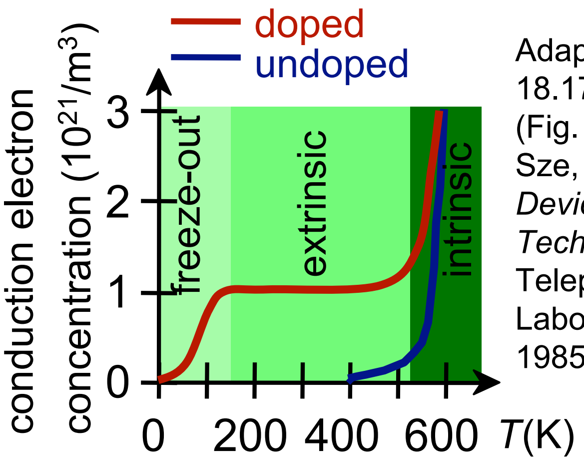
Doped semiconductor: conductivity vs. T

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

- Comparison: intrinsic vs extrinsic conduction...
  -- extrinsic doping level: $10^{21}/m^3$ 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* >> 450 K: "intrinsic"



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



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

$$\boxed{\sigma = n|e|\mu_e + p|e|\mu_e}$$

- for intrinsic semiconductor $n = p$

$\therefore \qquad \sigma = n|e|(\mu_e + \mu_n)$

- Ex: GaAs

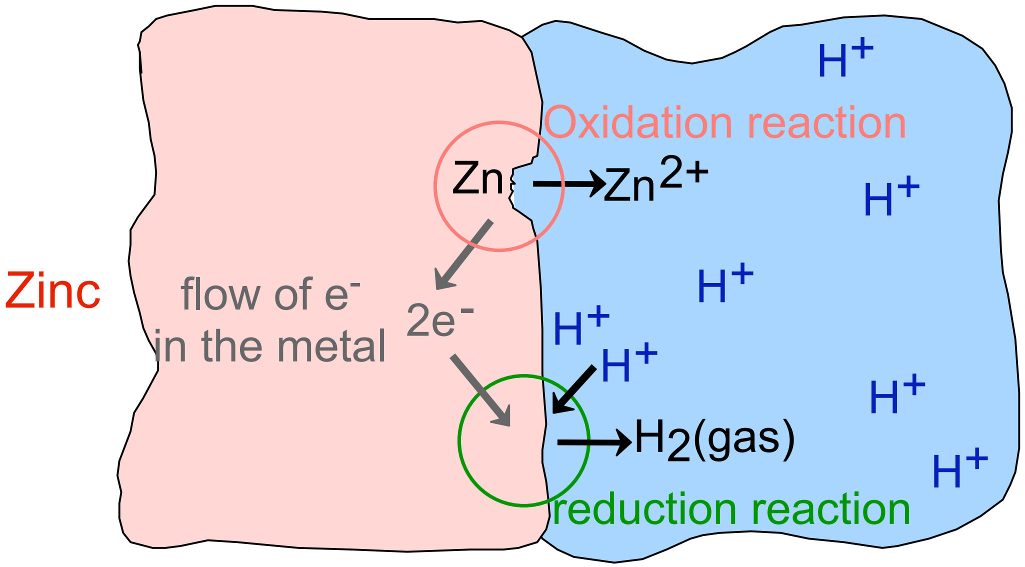
$$n = \frac{\sigma}{|e|(\mu_e + \mu_n)} = \frac{10^{-6}(\Omega \cdot \mathrm{m})^{-1}}{(1.6x10^{-19}\mathrm{C})(0.85 + 0.45\ \mathrm{m}^2/\mathrm{V} \cdot \mathrm{s})}$$

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

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

Corrosion of zinc in acid

- Two reactions are necessary:
  - -- oxidation reaction: $Zn \rightarrow Zn^{2+} + 2e^-$
  - -- reduction reaction: $2H^+ + 2e^- \rightarrow H_2(gas)$



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

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

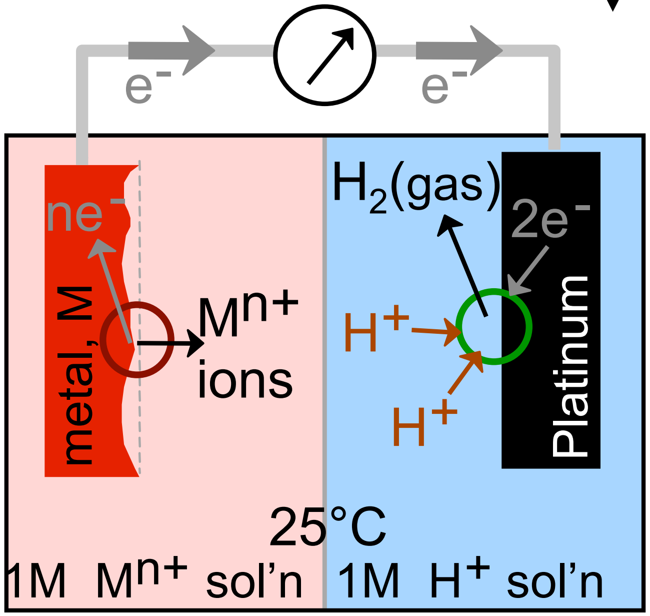
-- in a neutral or base solution

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$$

Standard hydrogen (EMF) test

- Two outcomes:

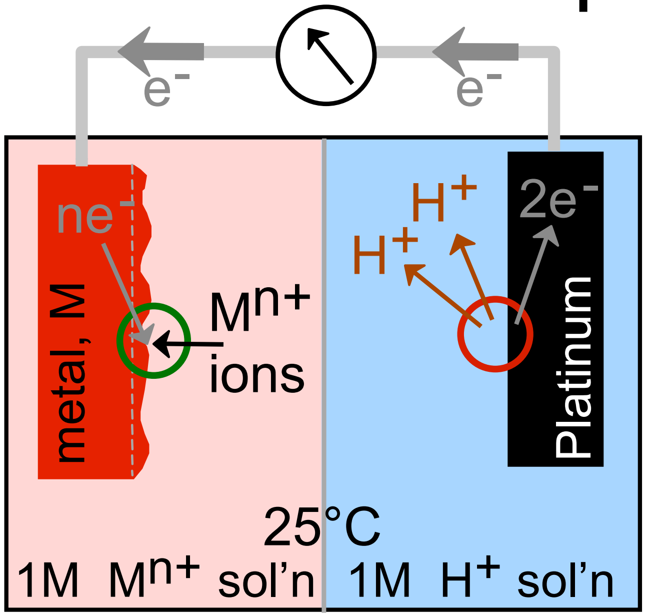
--Metal sample mass ↓



--Metal is the anode (-)

$V^{o}_{metal} < 0$ (relative to Pt)

--Metal sample mass ↑



--Metal is the cathode (+)

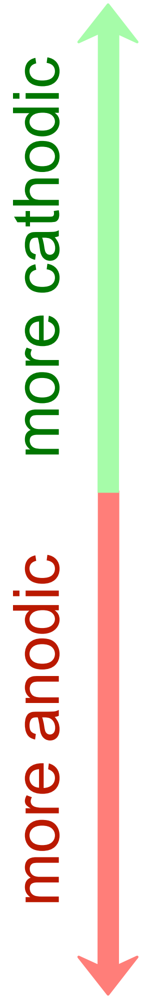
$V^{o}_{metal} > 0$ (relative to Pt)

Standard Electrode Potential

Adapted from Fig. 17.2, *Callister 7e*.

Standard EMF series

- EMF series

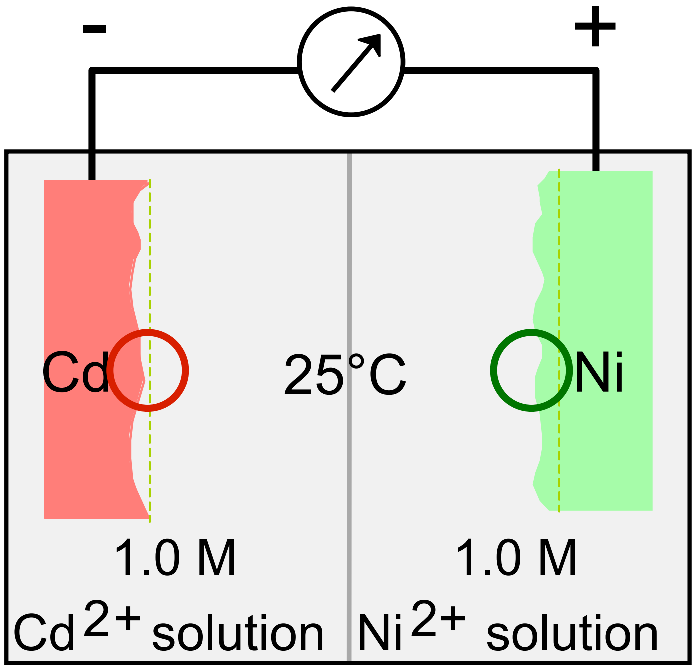


metal	V^o_{metal}
Au	+1.420 V
Cu	+0.340
Pb	- 0.126
Sn	- 0.136
Ni	- 0.250
Co	- 0.277
Cd	- 0.403
Fe	- 0.440
Cr	- 0.744
Zn	- 0.763
Al	- 1.662
Mg	- 2.363
Na	- 2.714
K	- 2.924

$\Delta V^o =$ 0.153V

Data based on Table 17.1, *Callister 7e*.

- Metal with smaller V^o_{metal} corrodes.
- Ex: Cd-Ni cell

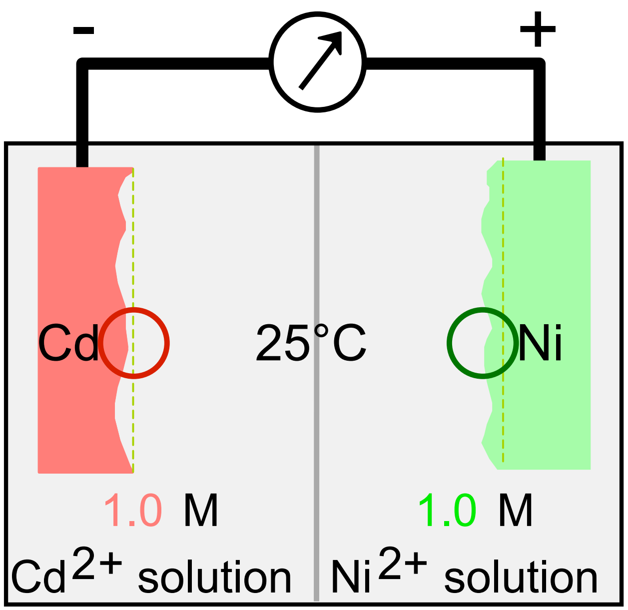


Adapted from Fig. 17.2, *Callister 7e*.

Effect of solution concentration

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

$$V^{o}_{\mathrm{Ni}} - V^{o}_{\mathrm{Cd}} = 0.153$$

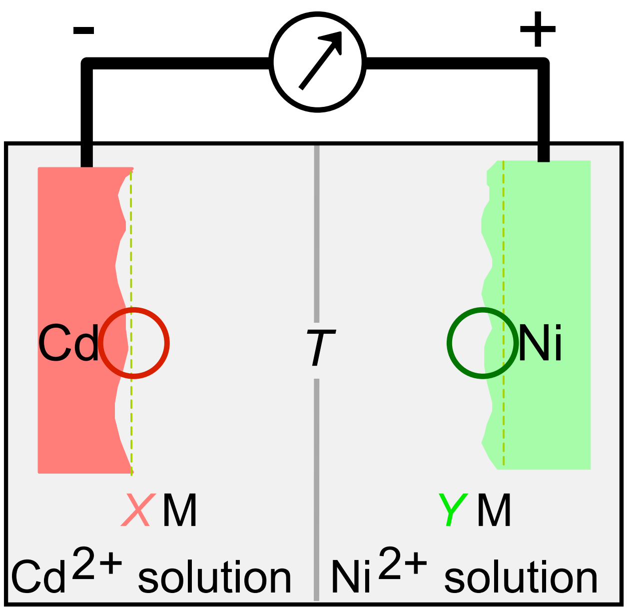


- Ex: Cd-Ni cell with non-standard solutions

$$V_{\mathrm{Ni}} - V_{\mathrm{Cd}} = V^{o}_{\mathrm{Ni}} - V^{o}_{\mathrm{Cd}} - \frac{RT}{nF} \ln \frac{X}{Y}$$

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

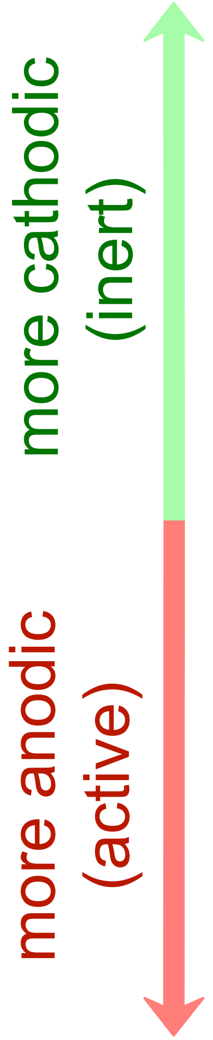
F = Faraday's constant = 96,500 C/mol.



- Reduce V_{Ni} - V_{Cd} by
  --increasing *X*
  --decreasing *Y*

Galvanic series

- Ranks the reactivity of metals/alloys in seawater



Platinum
Gold
Graphite
Titanium
Silver
316 Stainless Steel
Nickel (passive)
Copper
Nickel (active)
Tin
Lead
316 Stainless Steel
Iron/Steel
Aluminum Alloys
Cadmium
Zinc
Magnesium

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.

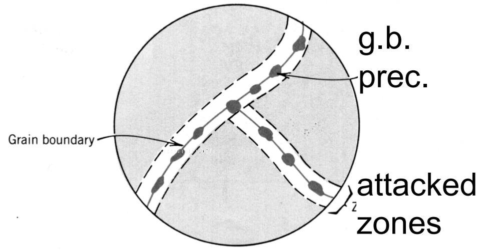


Fig. 17.18, *Callister 7e*.

- **Stress corrosion**

Stress & corrosion work together at crack tips.

Forms of corrosion

- **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.

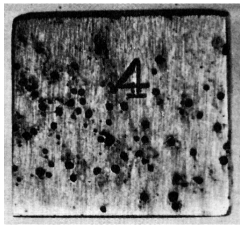


Fig. 17.17, *Callister 7e*. (Fig. 17.17 from M.G. Fontana, *Corrosion Engineering*, 3rd ed., McGraw-Hill Book Company, 1986.)

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

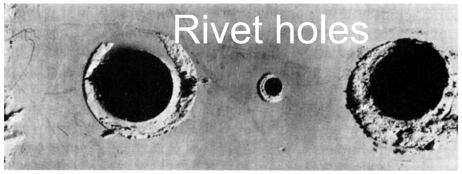


Fig. 17.15, *Callister 7e*. (Fig. 17.15 is courtesy LaQue Center for Corrosion Technology, Inc.)

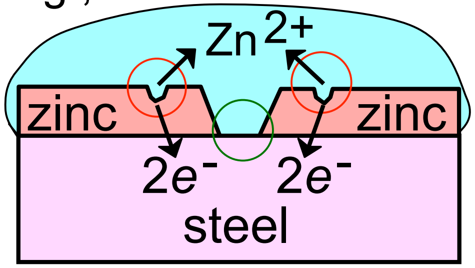
Controlling corrosion

- 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!).

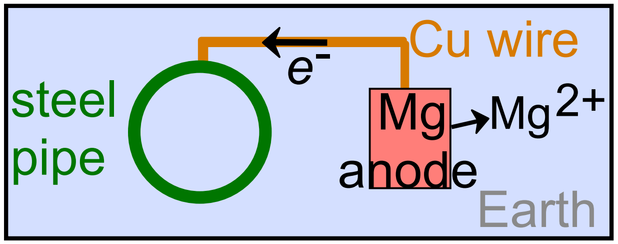
- Cathodic (or sacrificial) protection
  -- Attach a more anodic material to the one to be protected.

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.)