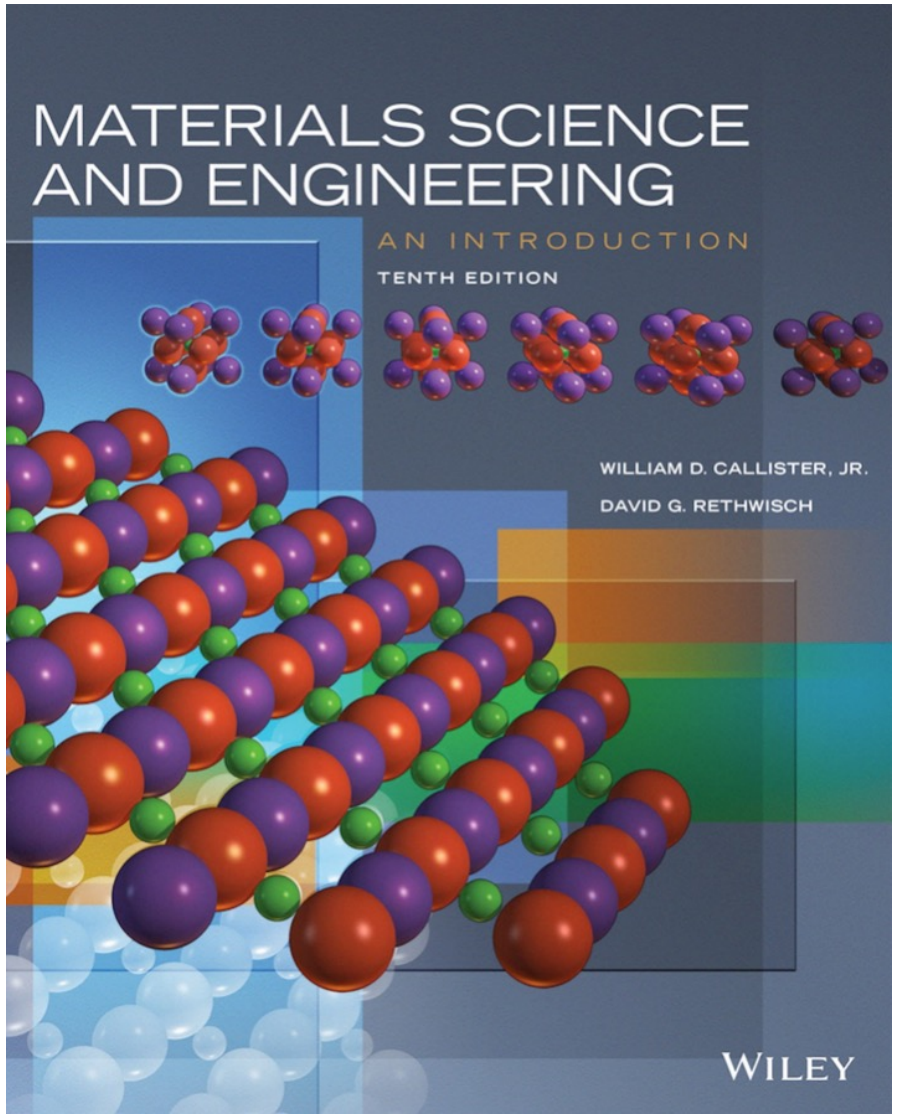
Lecture 9: Electrical properties

Prof. Nathan Szymanski
nszymanski@seas.ucla.edu
Department of Materials Science & Engineering

Reading for this subject



Chapter 18 Electrical Properties

This discussion will closely follow **Chapter 18** of Callister, **pages 649-692** of the 10th edition.

Last time, we discussed applications of ceramics









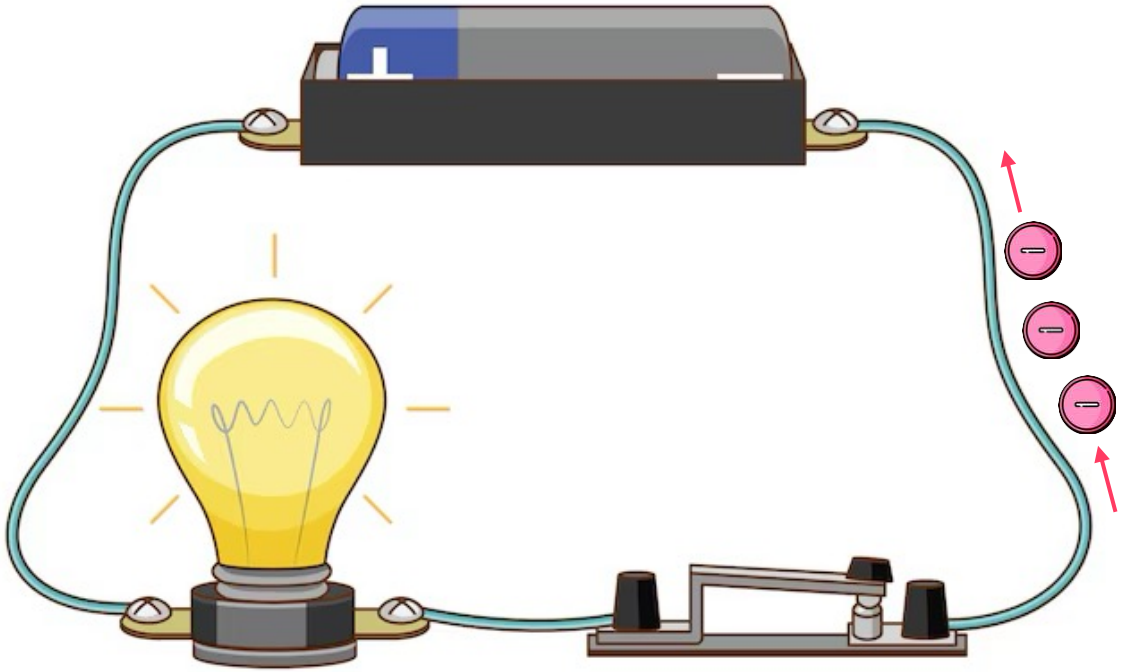


We largely discussed their **mechanical** and **thermal properties…**

Same goes for our discussion of metals

Last time, we discussed applications of ceramics

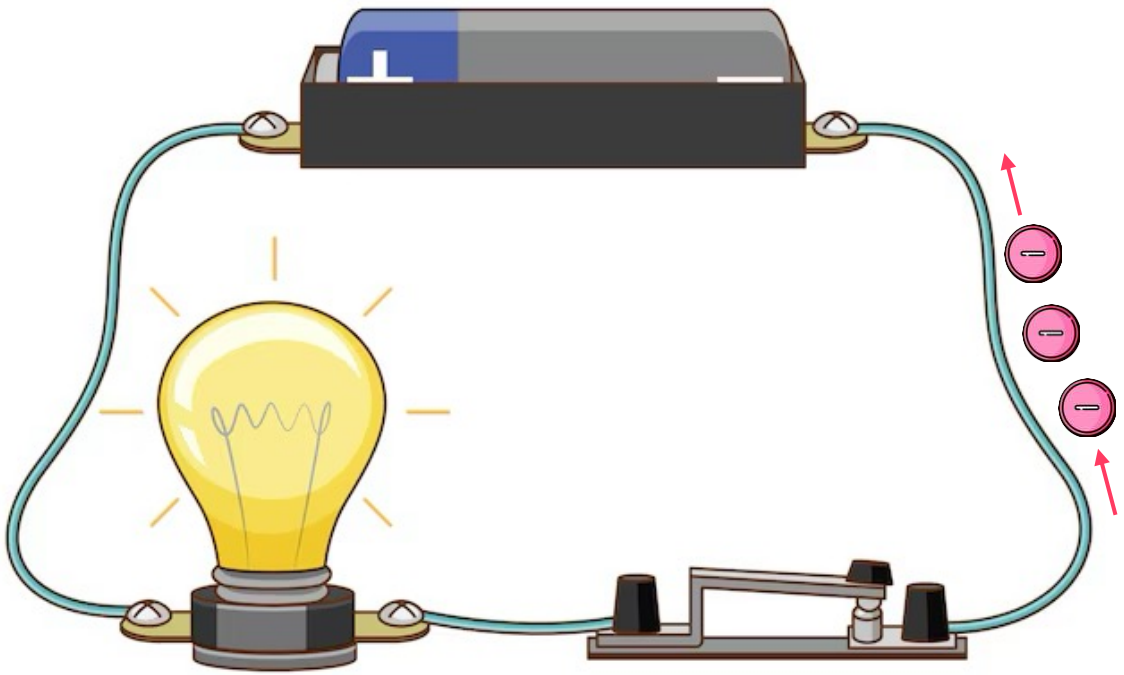
We have yet to discuss
electrical properties!





Ohm's law relates current to voltage

How easily do electrons flow through this circuit?

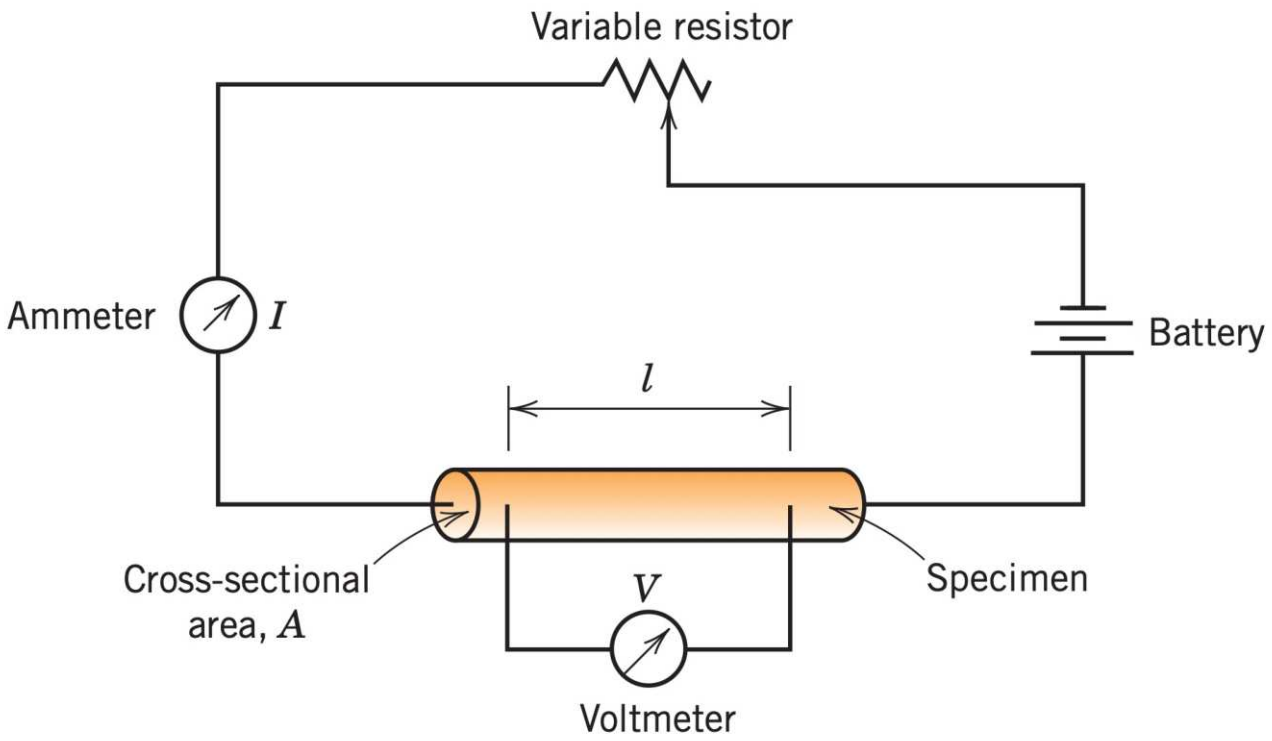


$$V = IR$$

Applied voltage — Current — Resistance

- Voltage (V = J/C) gives the "driving force"
- Current (A = C/s) describes the flow of electrons
- Resistance (Ω) measures difficulty of electron flow

Ohm's law relates current to voltage



Resistance depends on specimen geometry – *e.g.*, a longer path will have more resistance

Resistivity is an inherent material property

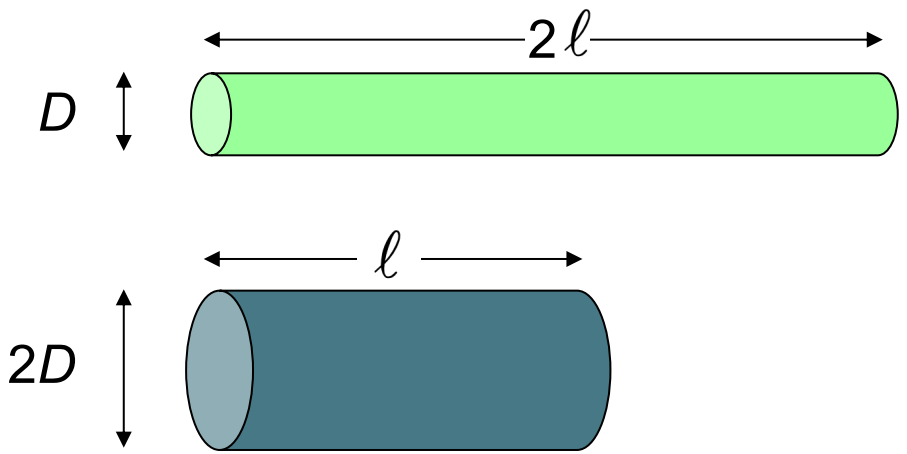
$$R = \boldsymbol{\rho} l / A$$

(units: Ω·m)

- Voltage (V = J/C) gives the "driving force"
- Current (A = C/s) describes the flow of electrons
- Resistance (Ω) measures difficulty of electron flow

The effect of sample geometry on resistance

Assuming both specimen are made of the same material, which will have greater resistance?



$$R_1 = \frac{2\rho\ell}{\pi\left(\frac{D}{2}\right)^2} = \frac{8\rho\ell}{\pi D^2}$$

$$R_2 = \frac{\rho\ell}{\pi\left(\frac{2D}{2}\right)^2} = \frac{\rho\ell}{\pi D^2} = \frac{R_1}{8}$$

The second specimen will have **8× greater current** given the same applied voltage because: 1) it has a **wider area** for electrons to flow through, and 2) those electrons must **travel less distance**.

Water through a pipe



Re-framing Ohm's law in a more useful way

Current density (I/area) → $J = \sigma \mathcal{E}$ ← Electric field intensity (V/length)

Electrical conductivity

$\sigma = 1/\rho$

Measures ease of electron flow

(units: S/m)

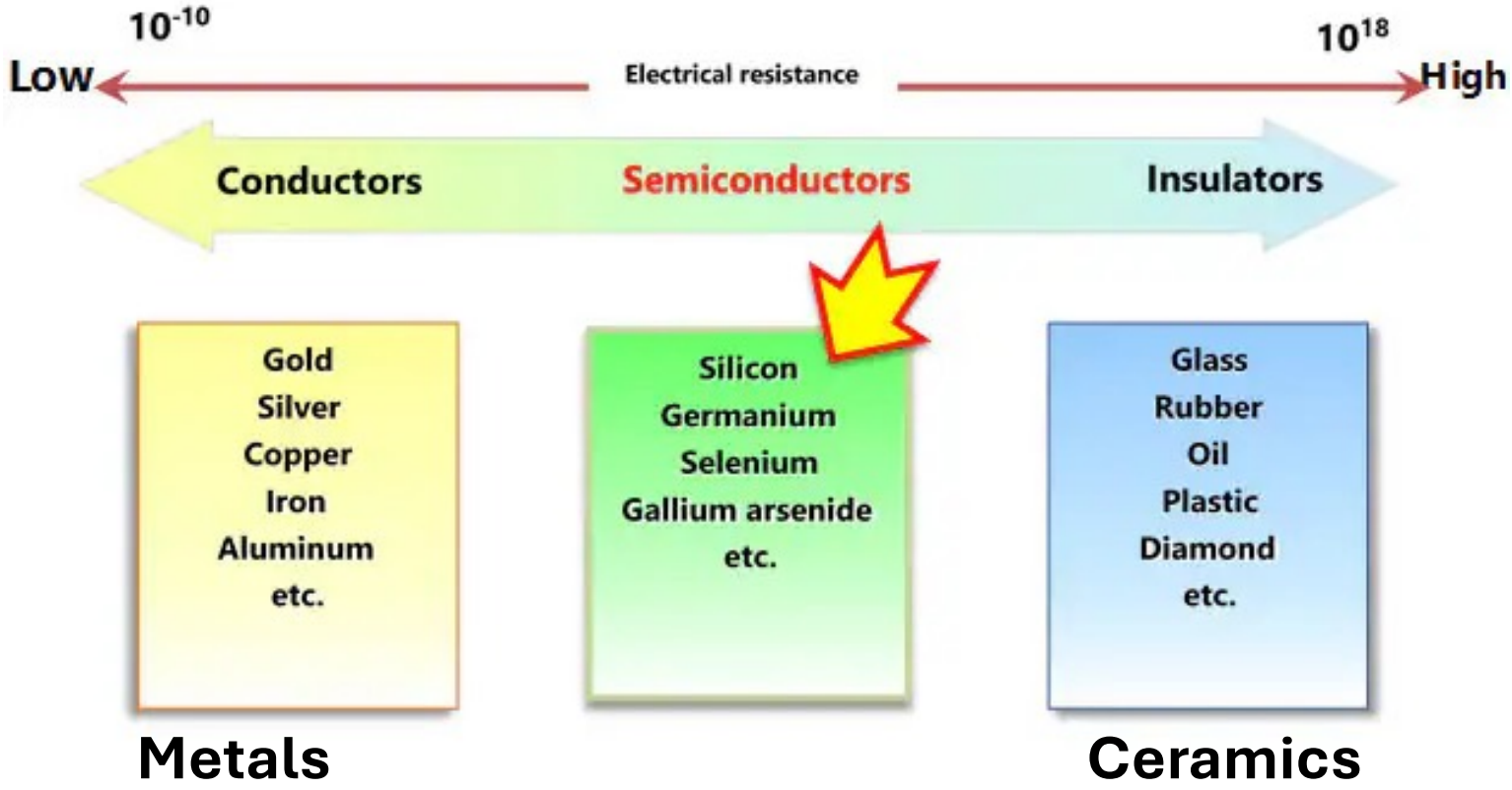


Re-framing Ohm's law in a more useful way

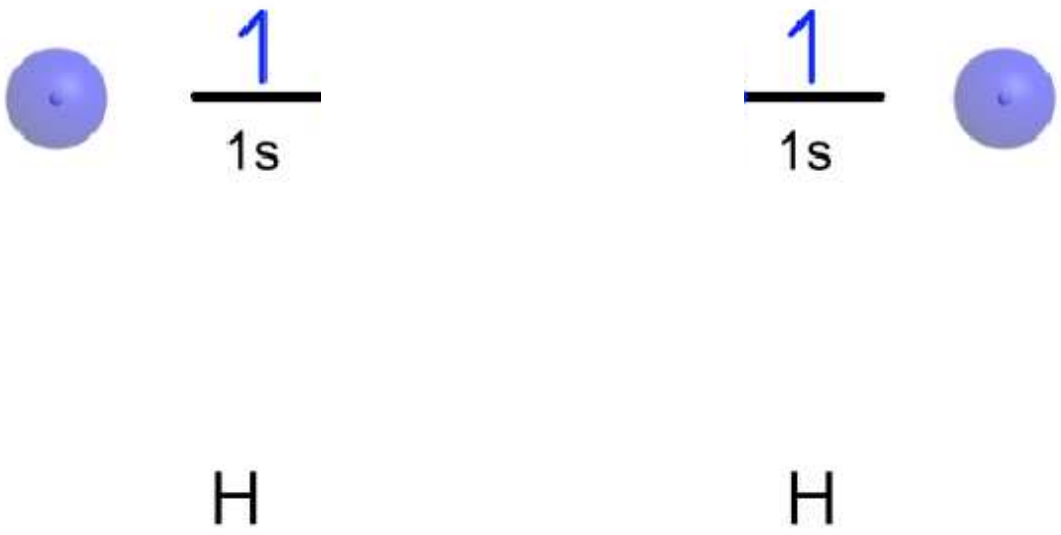
$$J = \sigma \mathcal{E}$$

Materials exhibit a ***huge*** range of conductivities: ~28 orders of magnitude!

Units: $(\Omega \cdot \mathrm{m})^{-1}$

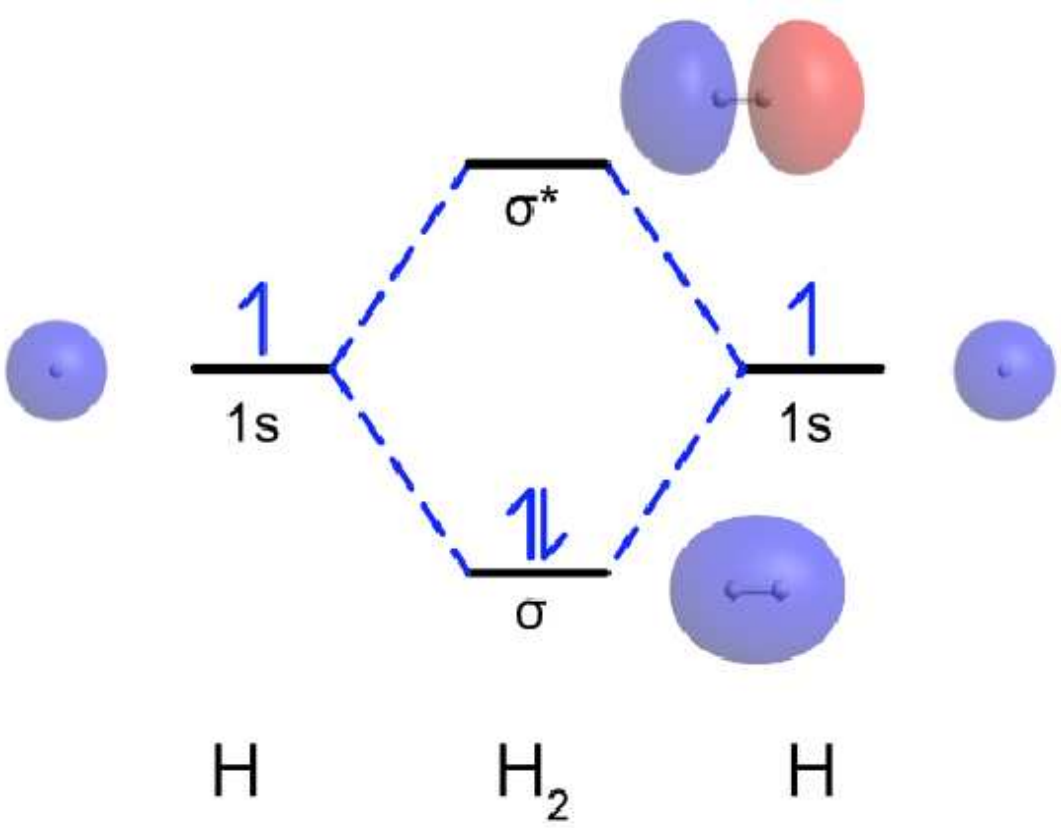


These huge differences in conductivity can be traced back to the electronic structure



Consider two isolated hydrogen atoms. Each has a **single relevant energy level**, occupied by one electron.

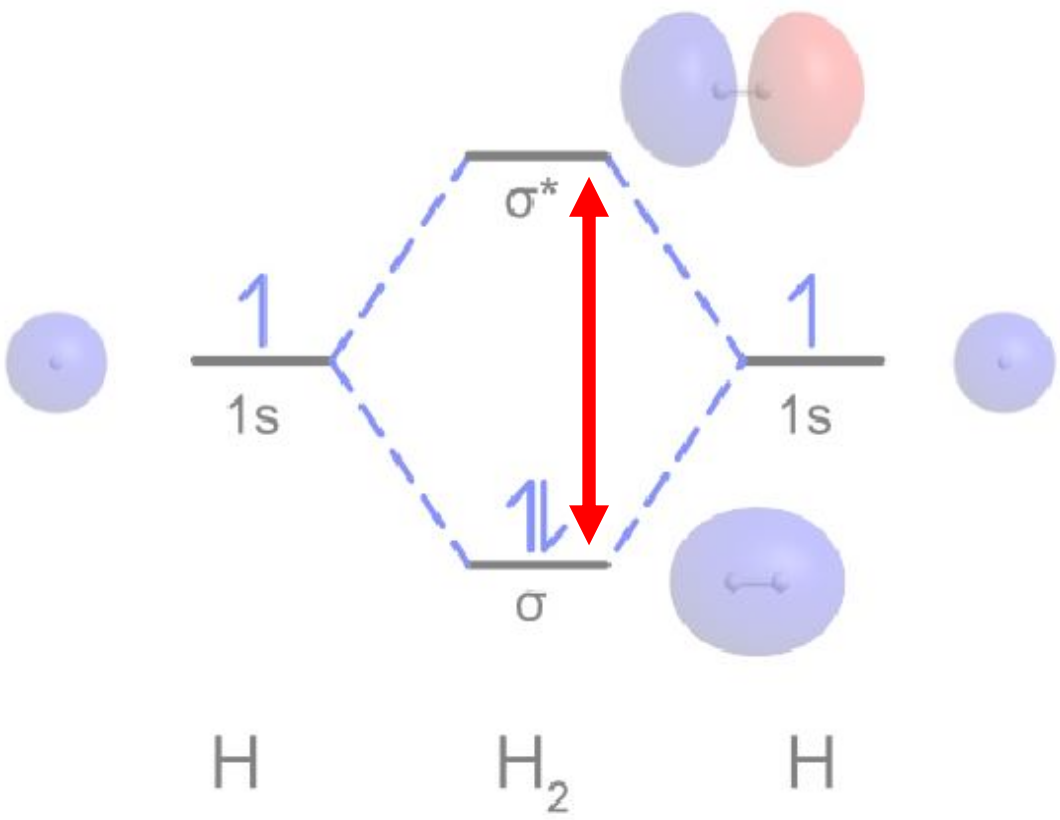
These huge differences in conductivity can be traced back to the electronic structure

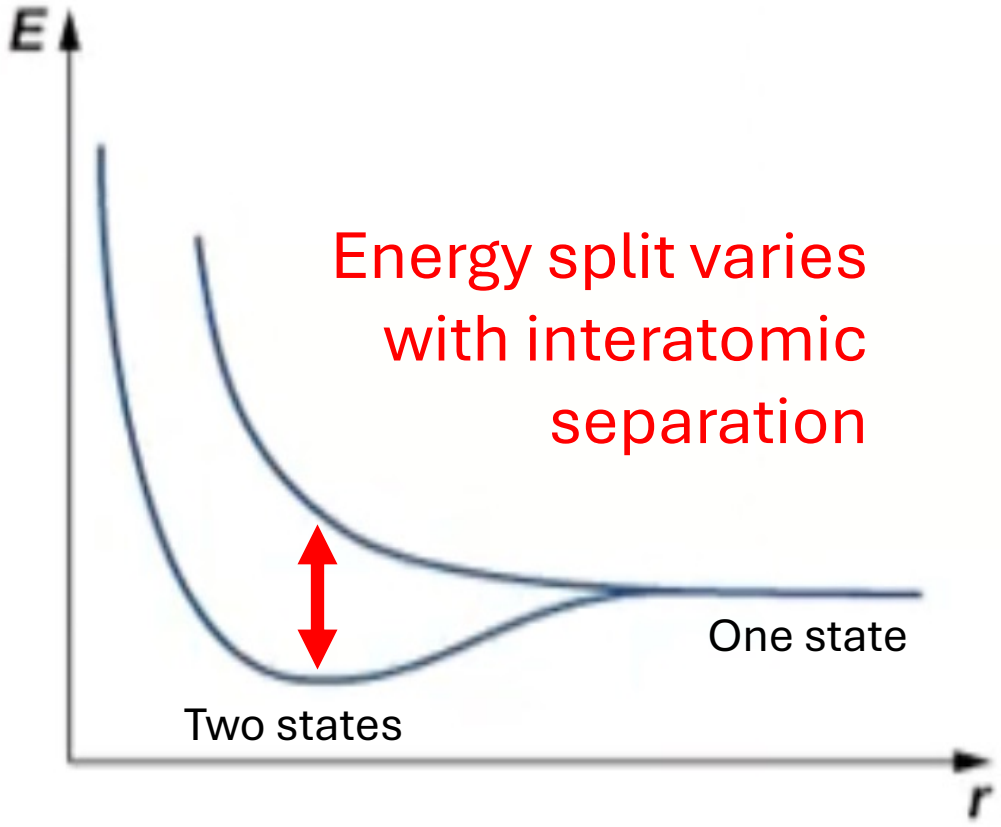


Consider two isolated hydrogen atoms. Each has a **single relevant energy level**, occupied by one electron.

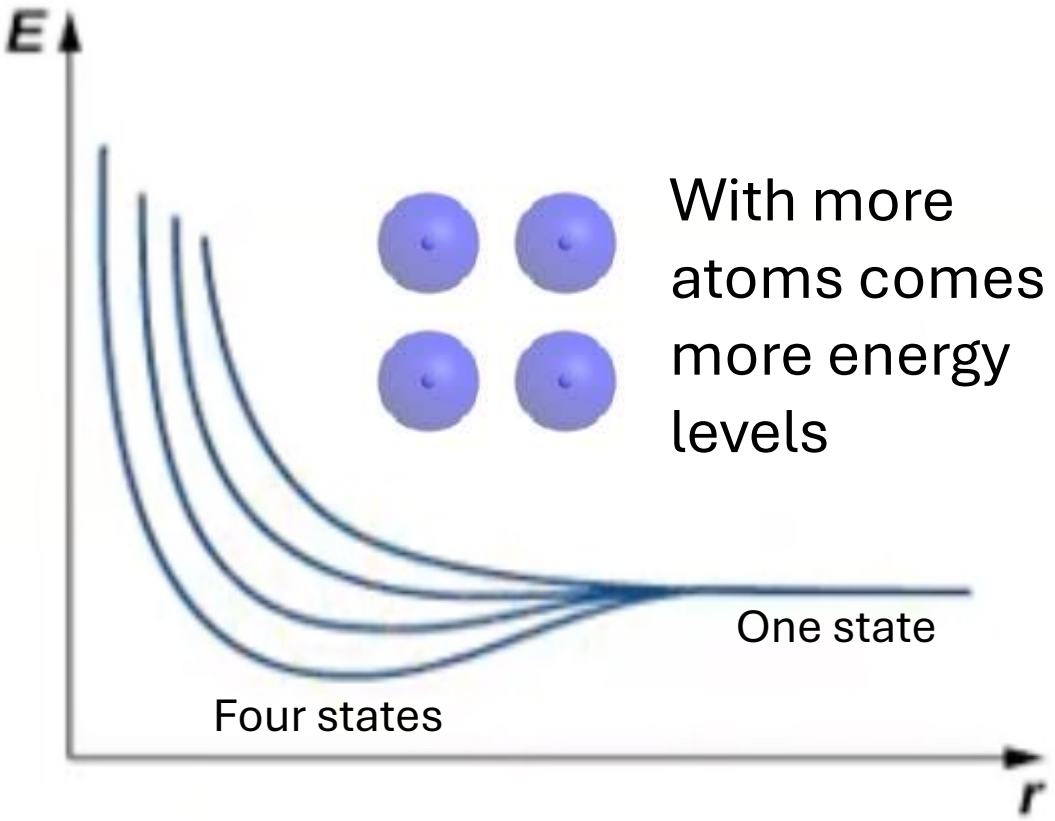
But as we bring these two atoms together, they form **two molecular orbitals** whose energy splitting is determined by the H_2 bond distance.

These huge differences in conductivity can be traced back to the electronic structure

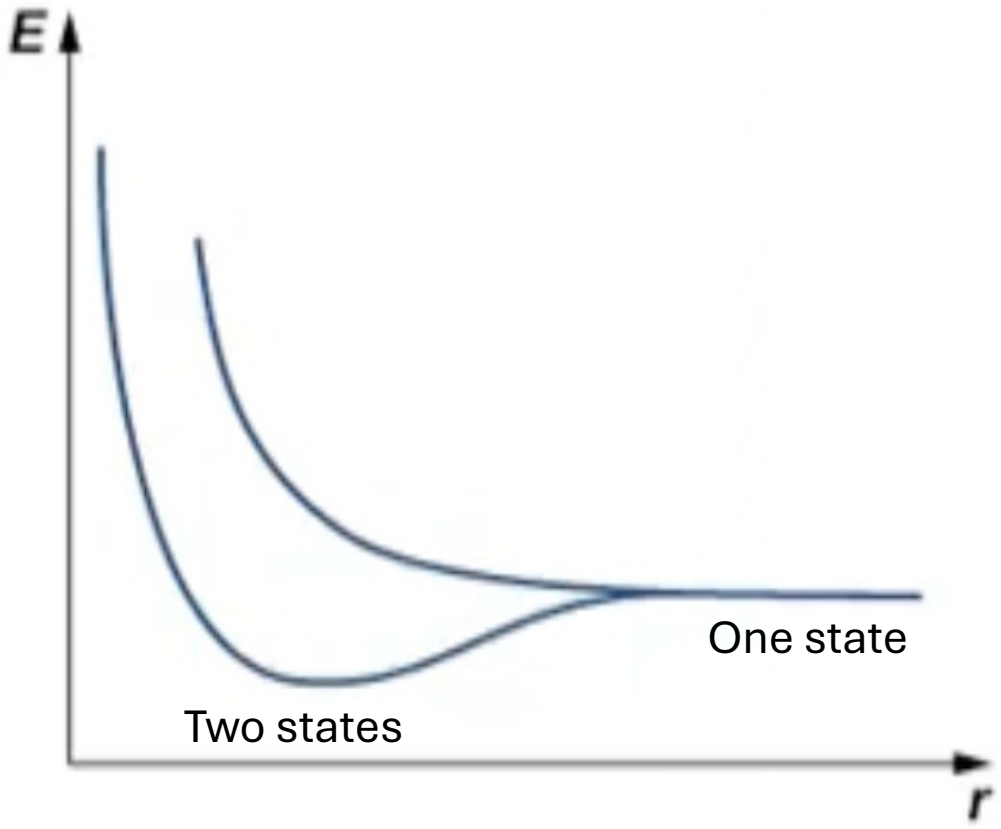




These huge differences in conductivity can be traced back to the electronic structure

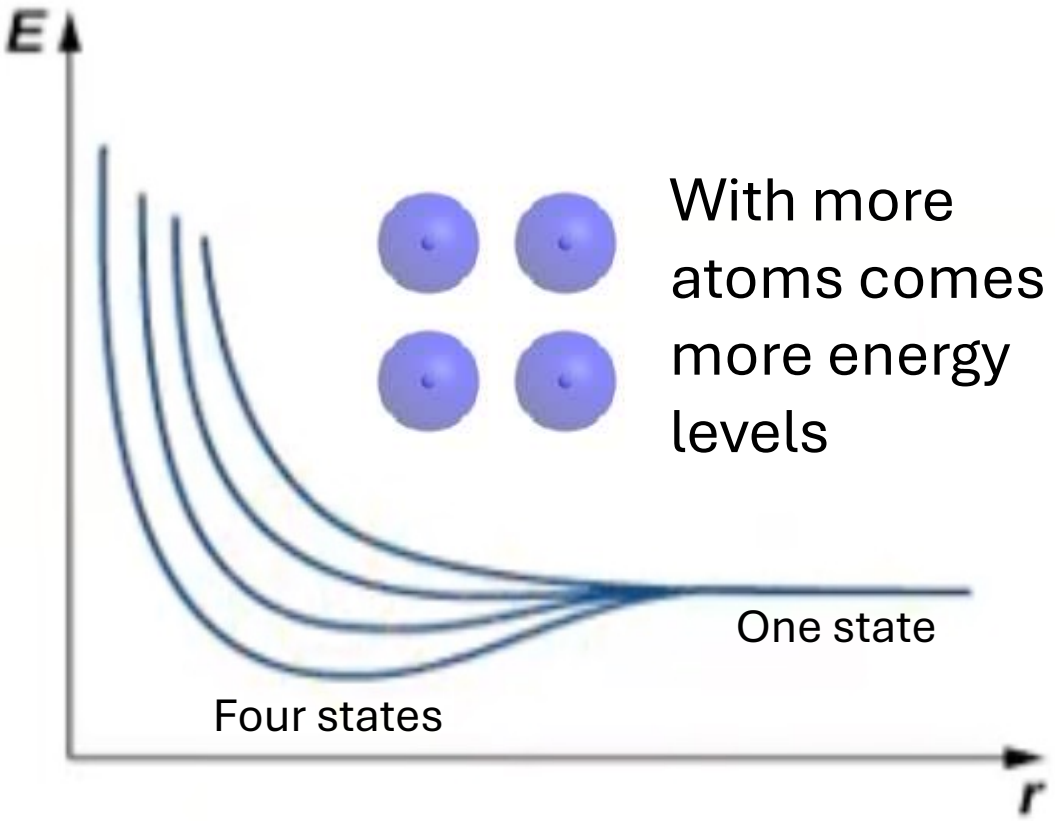


Interaction among *four* atoms

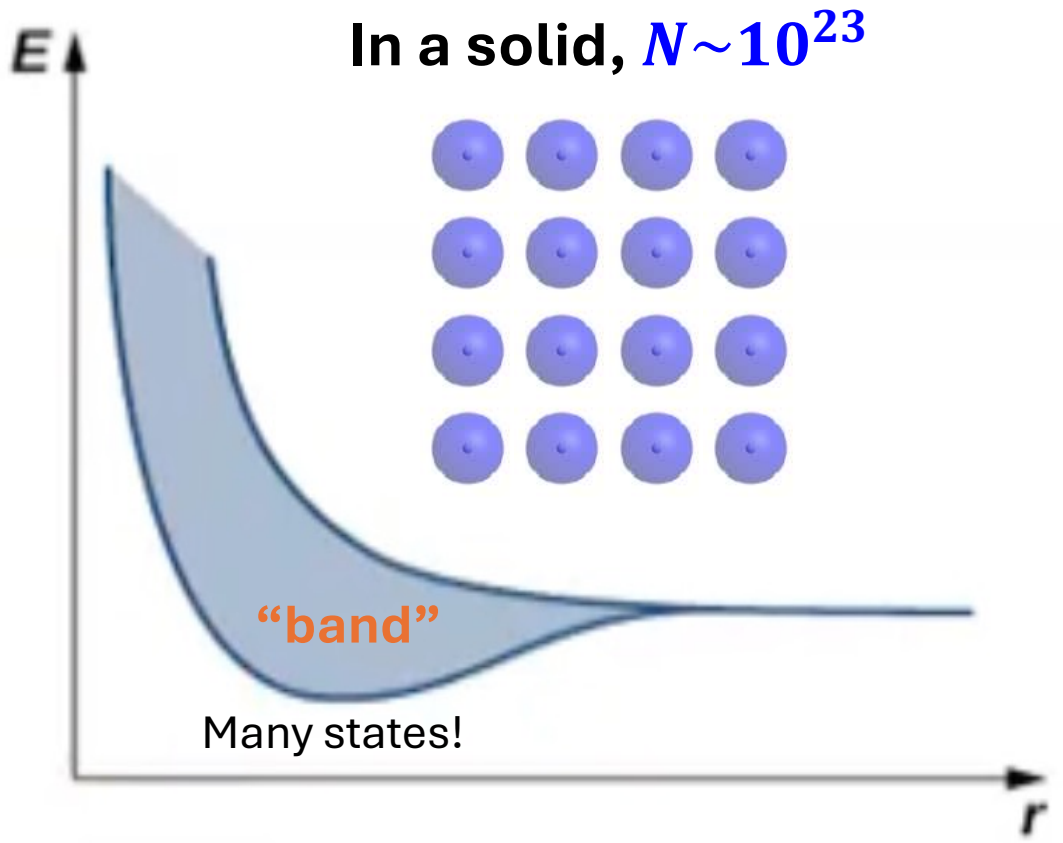


Interaction among two atoms

These huge differences in conductivity can be traced back to the electronic structure

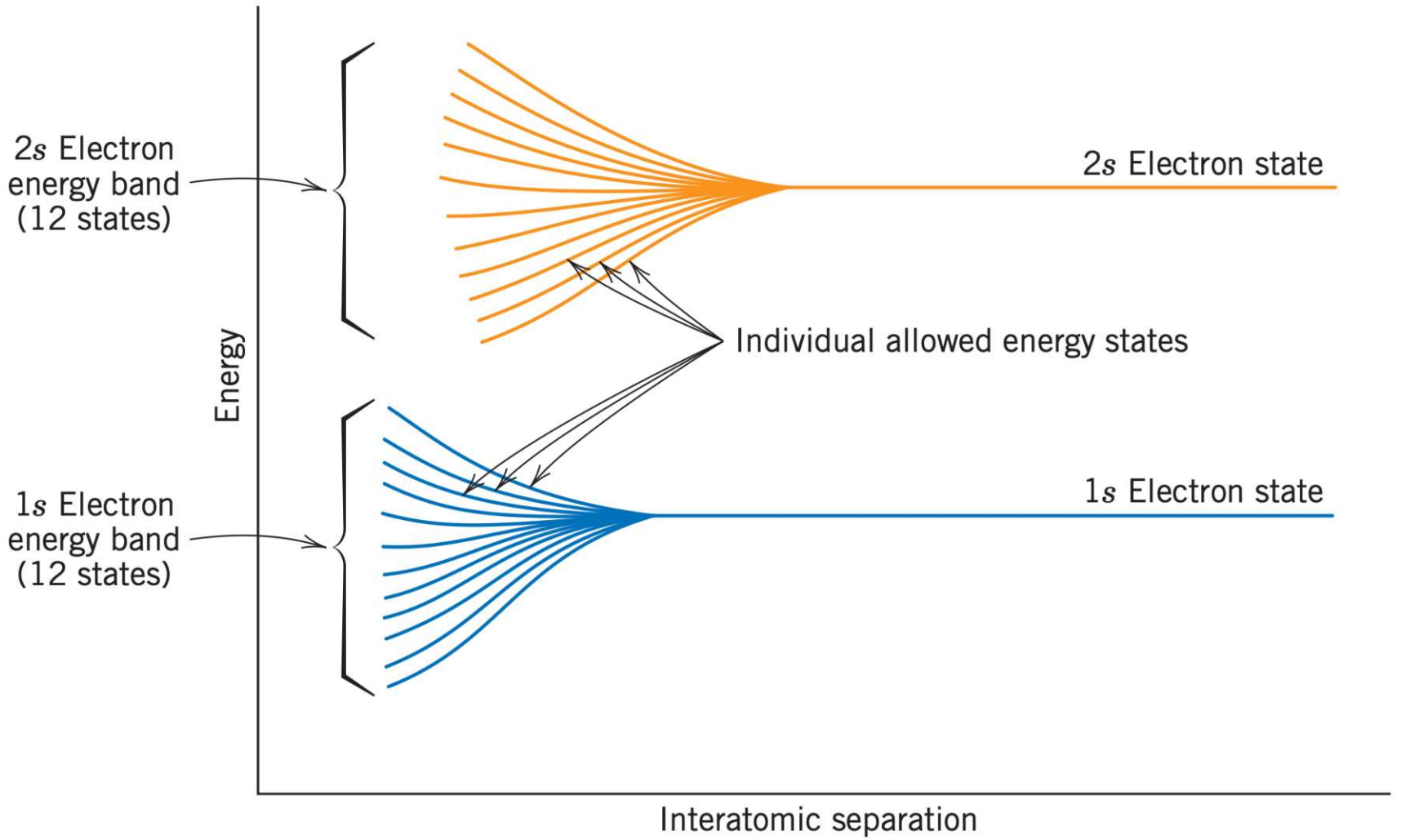


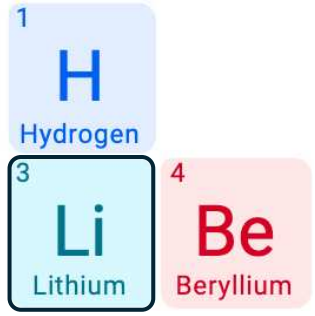
Interaction among *four* atoms



Interaction among *N* atoms

These huge differences in conductivity can be traced back to the electronic structure





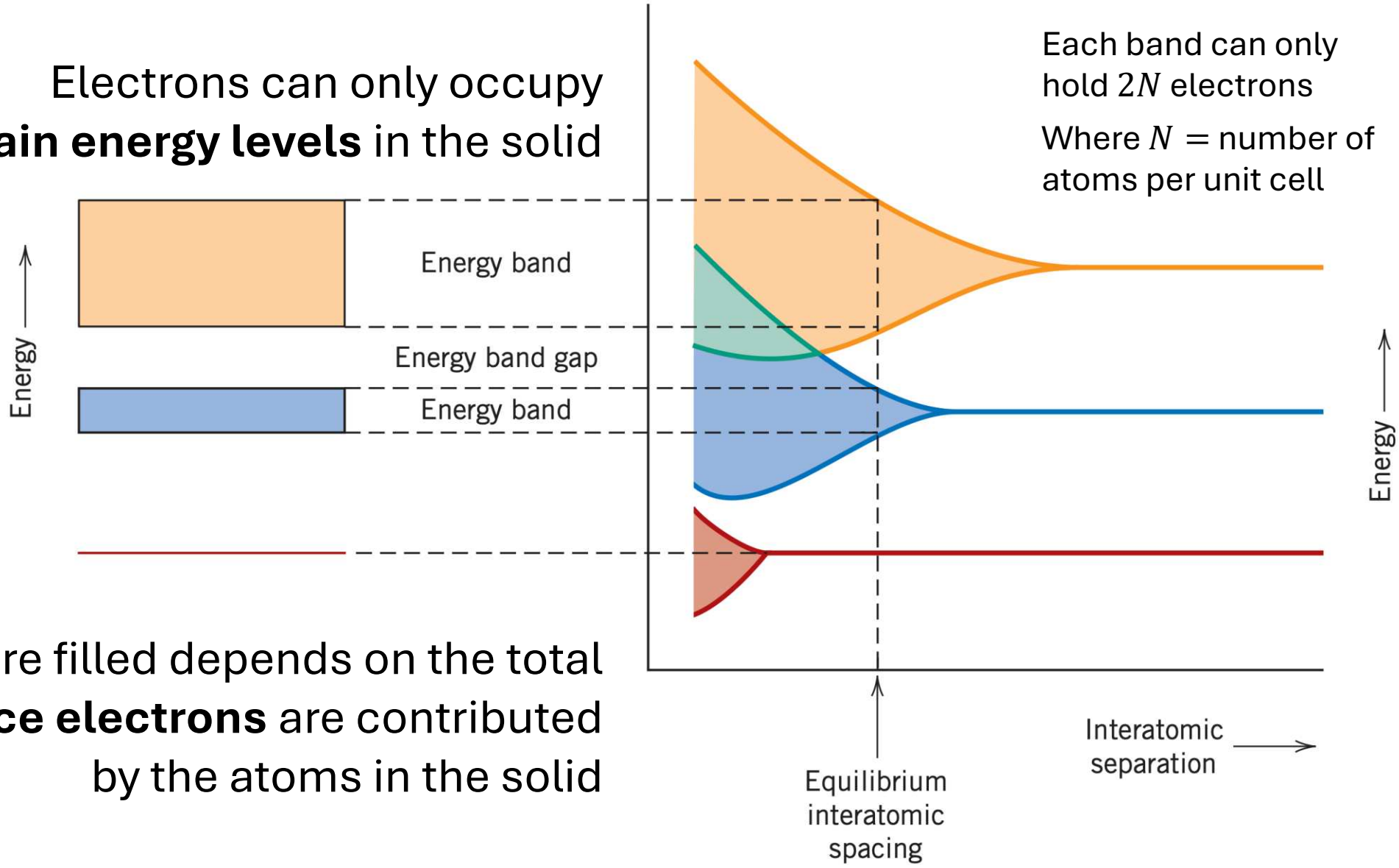
We get one band for every atomic orbital, resulting in **many bands for a solid**

Band diagrams show available energy levels

Electrons can only occupy **certain energy levels** in the solid

Each band can only hold $2N$ electrons

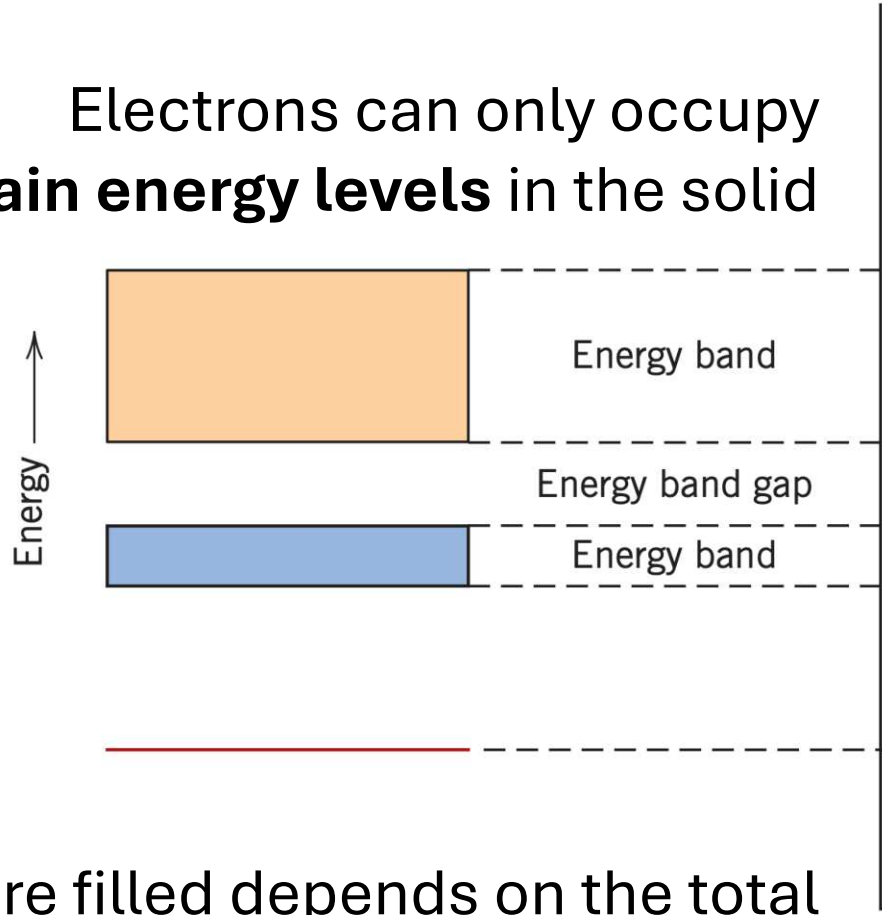
Where N = number of atoms per unit cell



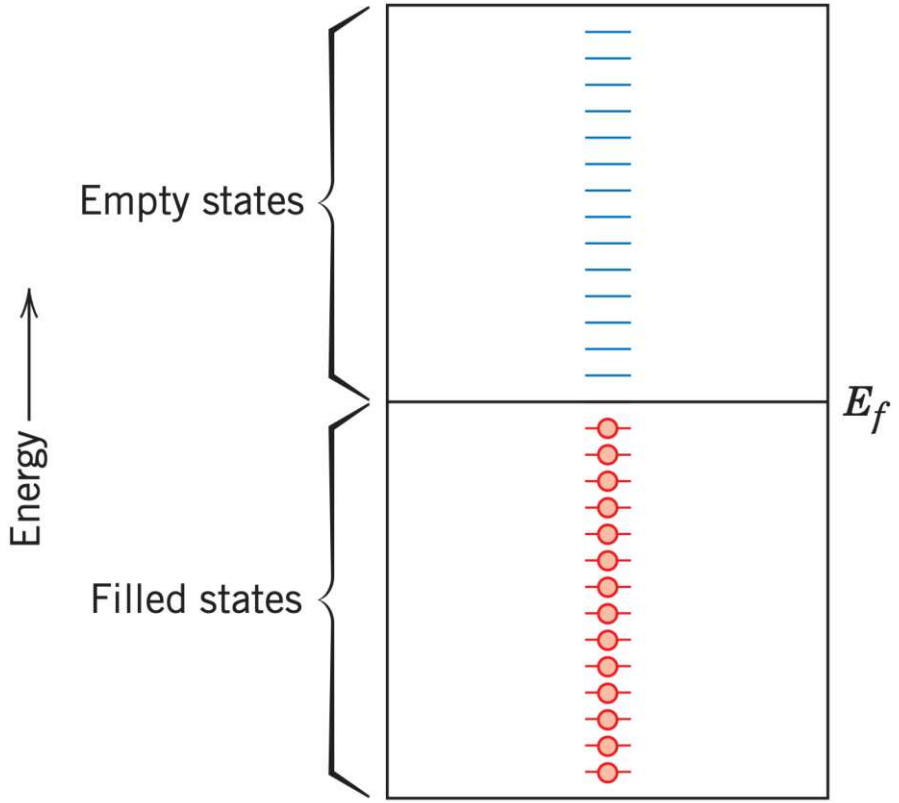
Which levels are filled depends on the total **number of valence electrons** are contributed by the atoms in the solid

Band diagrams show available energy levels

Electrons can only occupy **certain energy levels** in the solid



Which levels are filled depends on the total **number of valence electrons** are contributed by the atoms in the solid

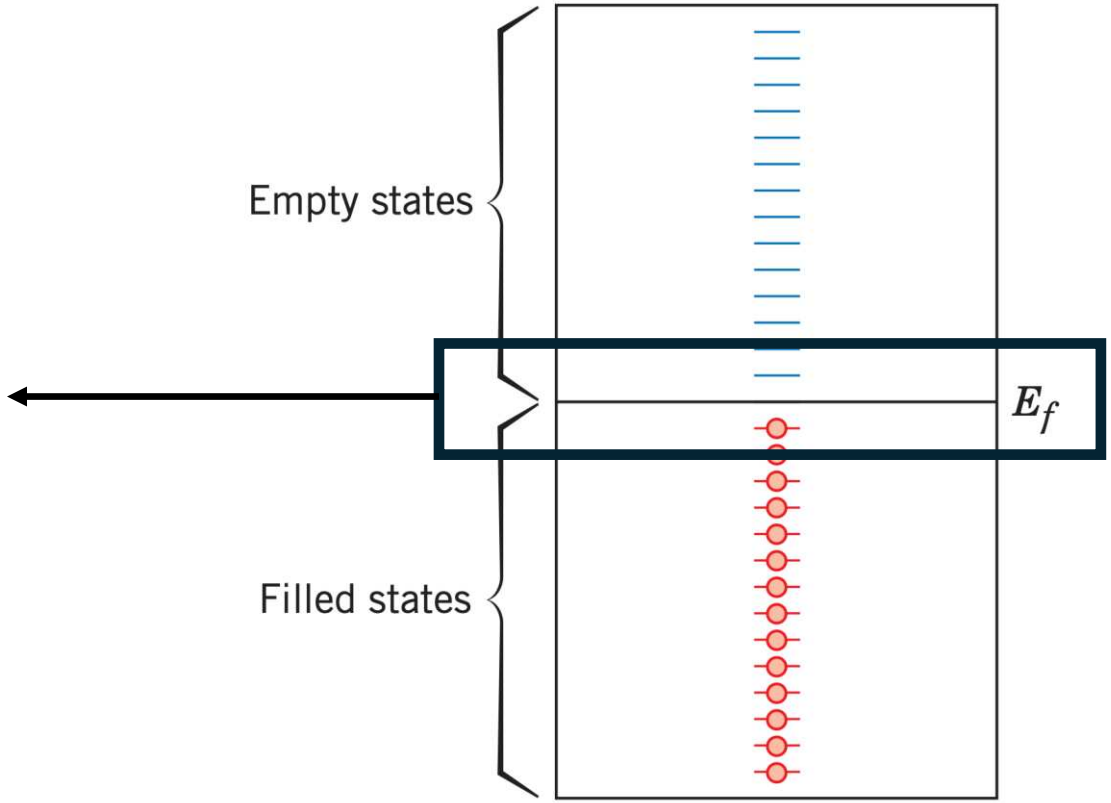


Electrons will always fill the **lowest energy levels first**, then "work their way up" (Pauli exclusion principle)

Band diagrams show available energy levels

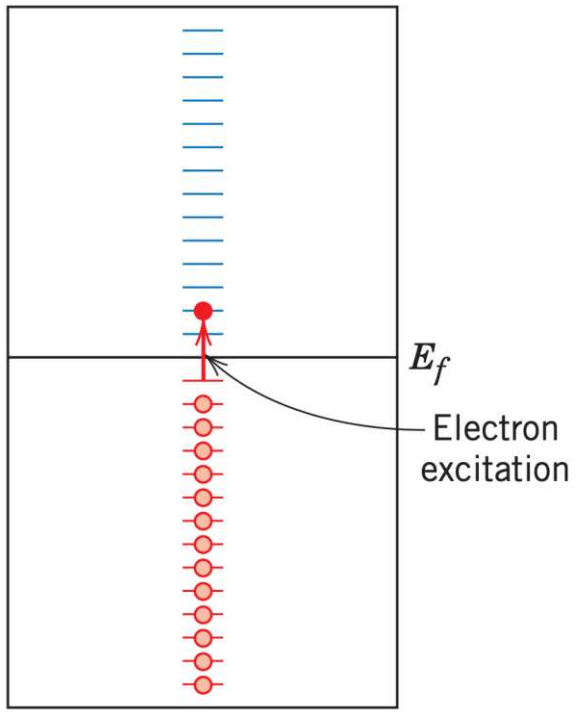
The **Fermi energy (E_f)** is the energy of the highest-filled state at 0 K

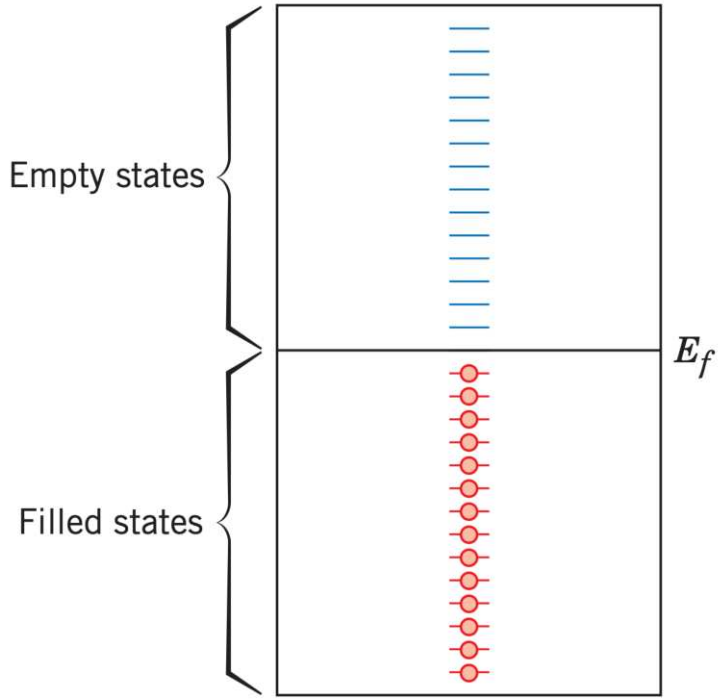
***Where E_f* falls** is very important! This is what separates a metal from an insulator.

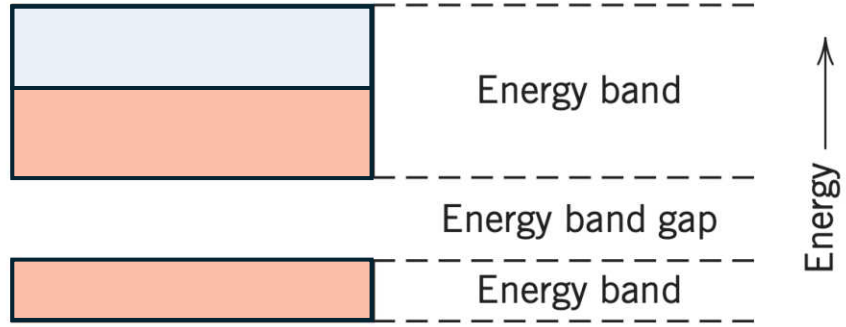


Electrons will always fill the **lowest energy levels first**, then "work their way up" (Pauli exclusion principle)

Band diagrams of metals

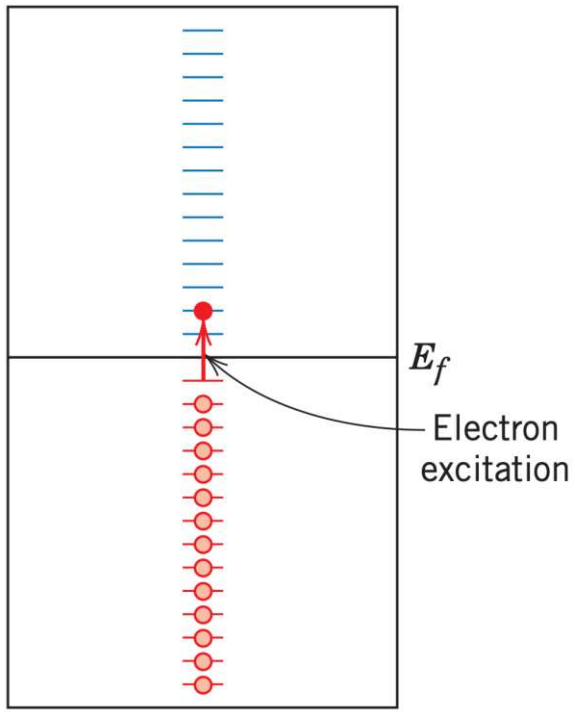


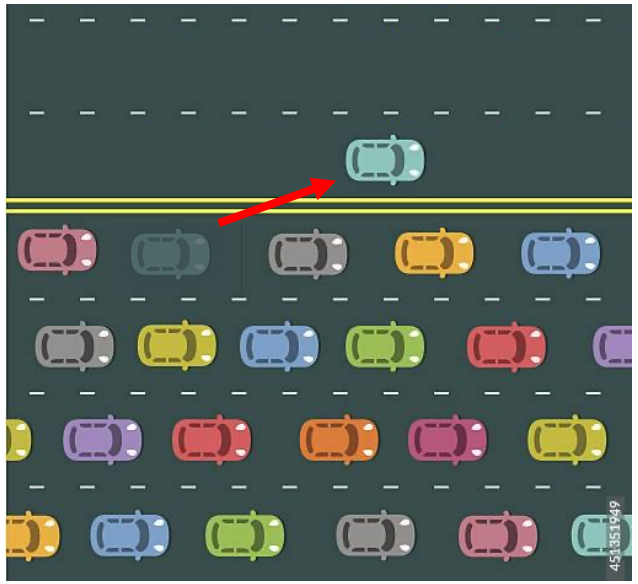




If **the Fermi energy falls in the middle of a band**, thermal excitations can easily promote electrons into unoccupied states, where they move around freely and conduct electricity → **this is a metal!**

Band diagrams of metals

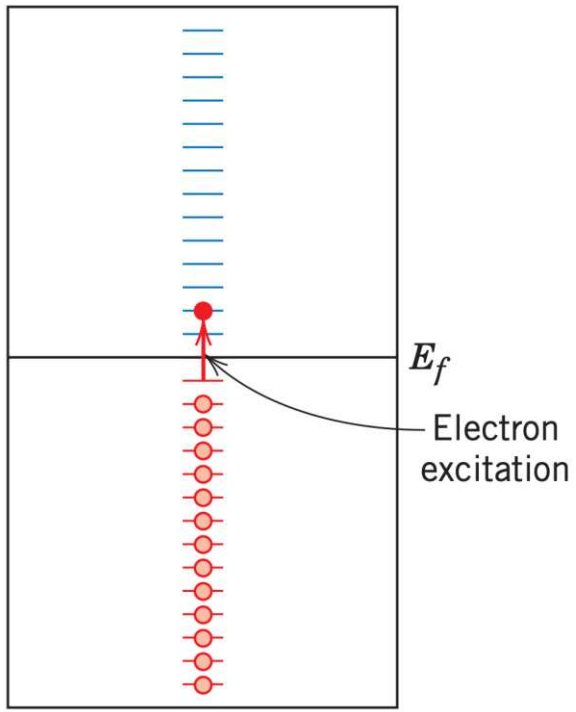


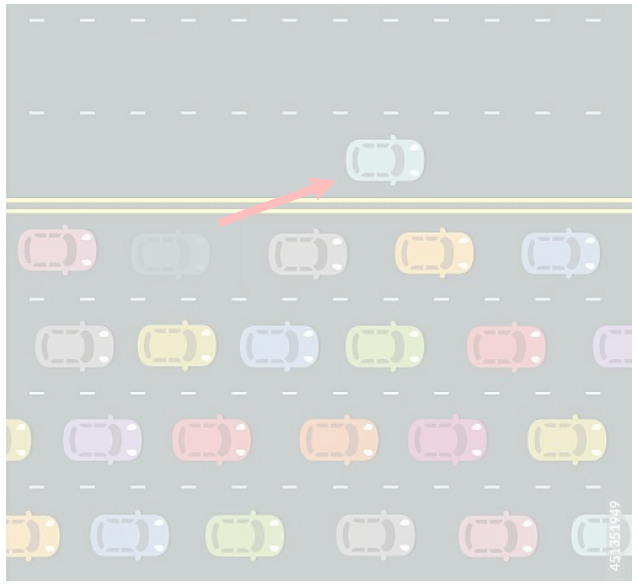


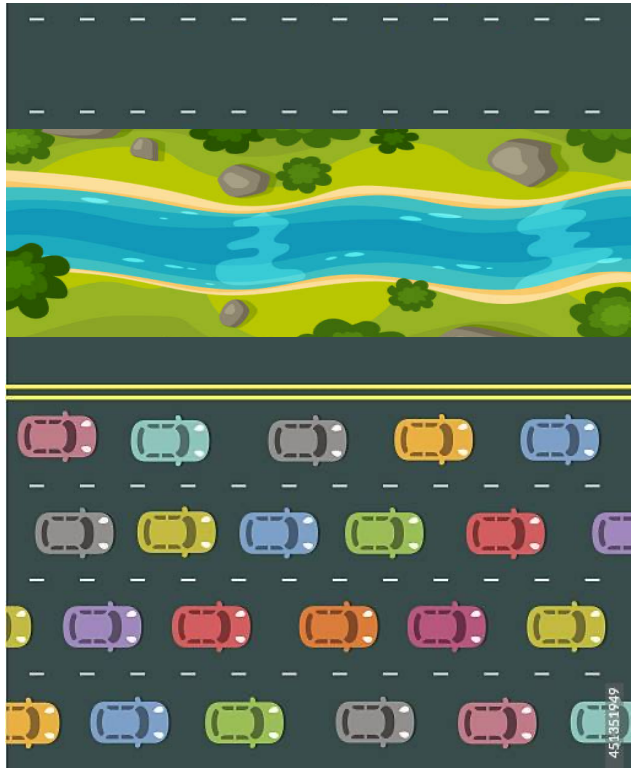
Traffic analogy:
if a nearby lane is open, you can pass freely

If **the Fermi energy falls in the middle of a band**, thermal excitations can easily promote electrons into unoccupied states, where they move around freely and conduct electricity → **this is a metal!**

Band diagrams of metals



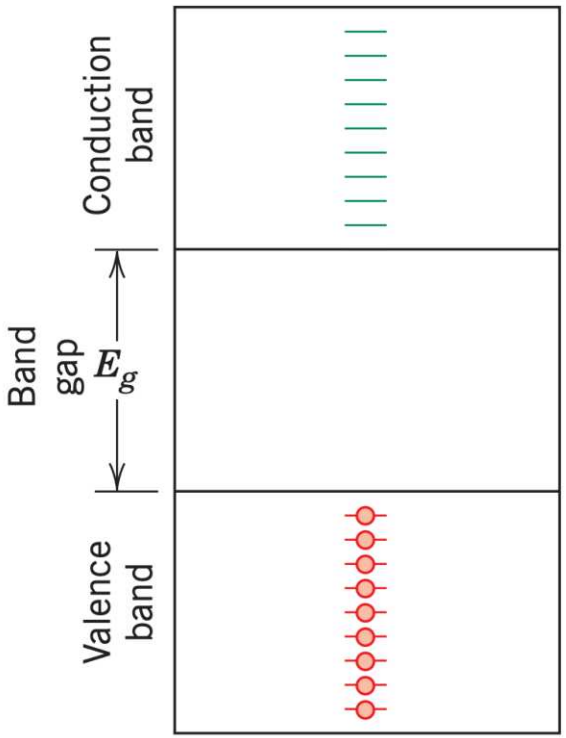


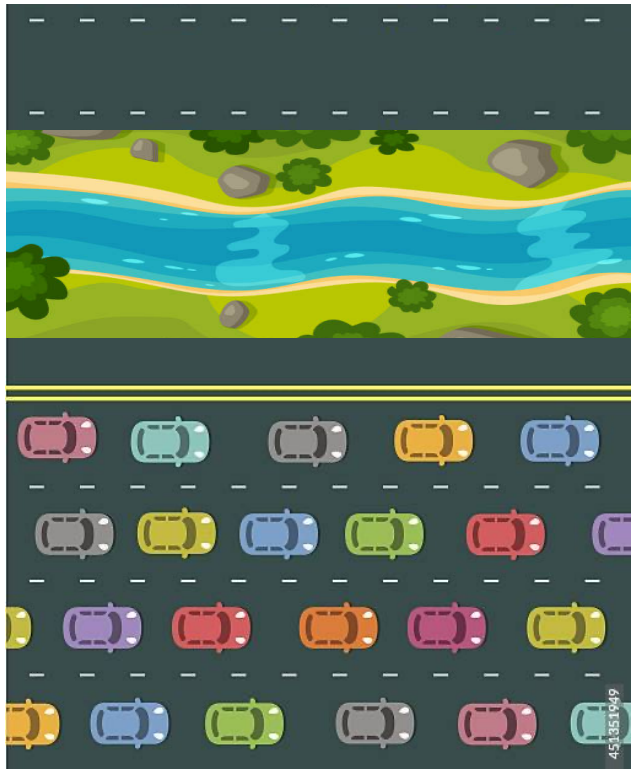


What if there is a **gap** between you and the nearest passing lane…

If **the Fermi energy falls in the middle of a band**, thermal excitations can easily promote electrons into unoccupied states, where they move around freely and conduct electricity → **this is a metal!**

Band diagrams of insulators and semiconductors

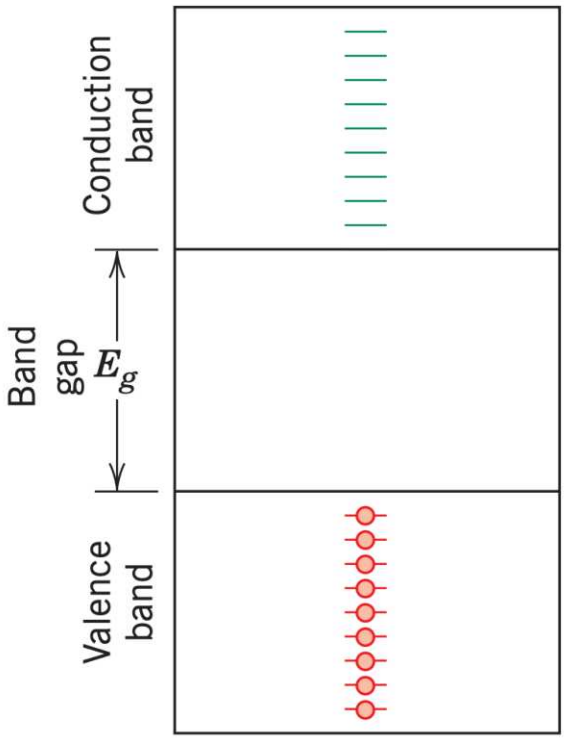


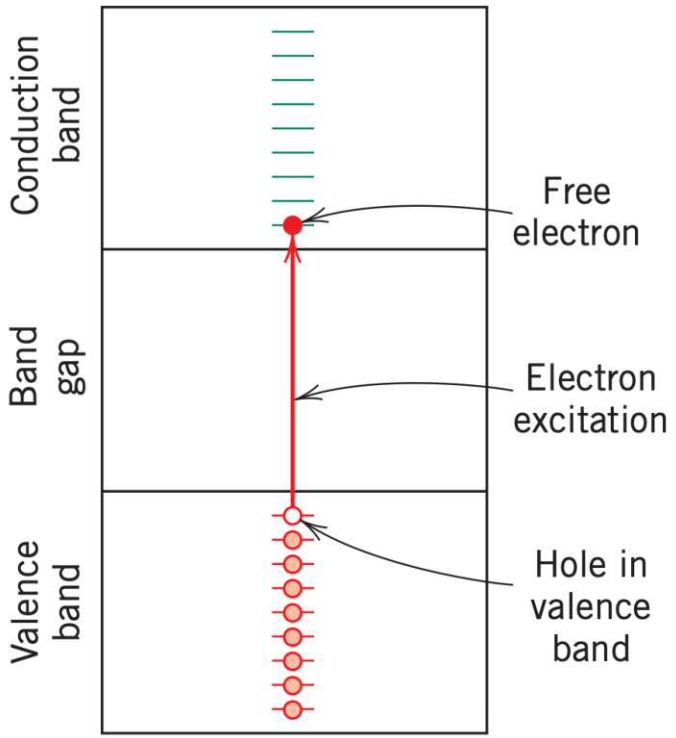


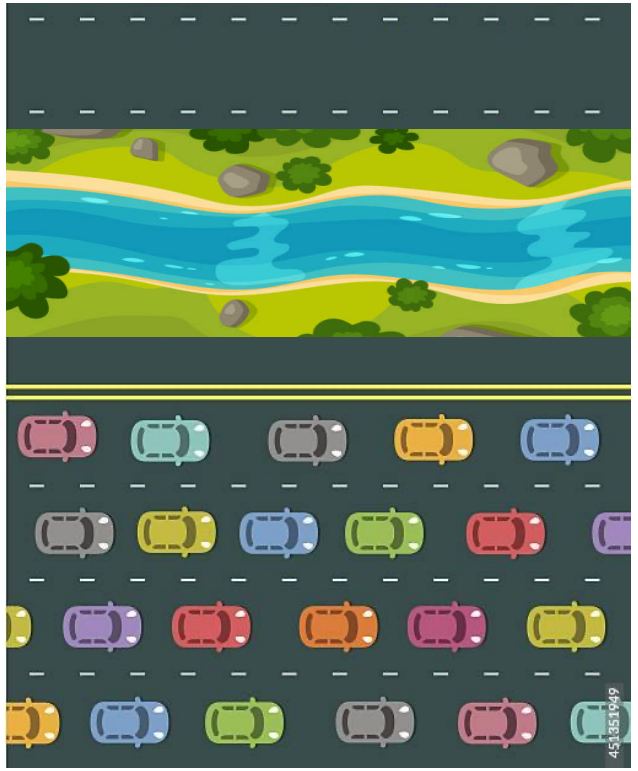
What if there is a **gap** between you and the nearest passing lane…

If **the Fermi energy falls at the top of an occupied band (below a band gap)**, thermal excitations *cannot* easily promote electrons into unoccupied states, which means all electrons are locked in place → **this is an insulator!**

Band diagrams of insulators and semiconductors







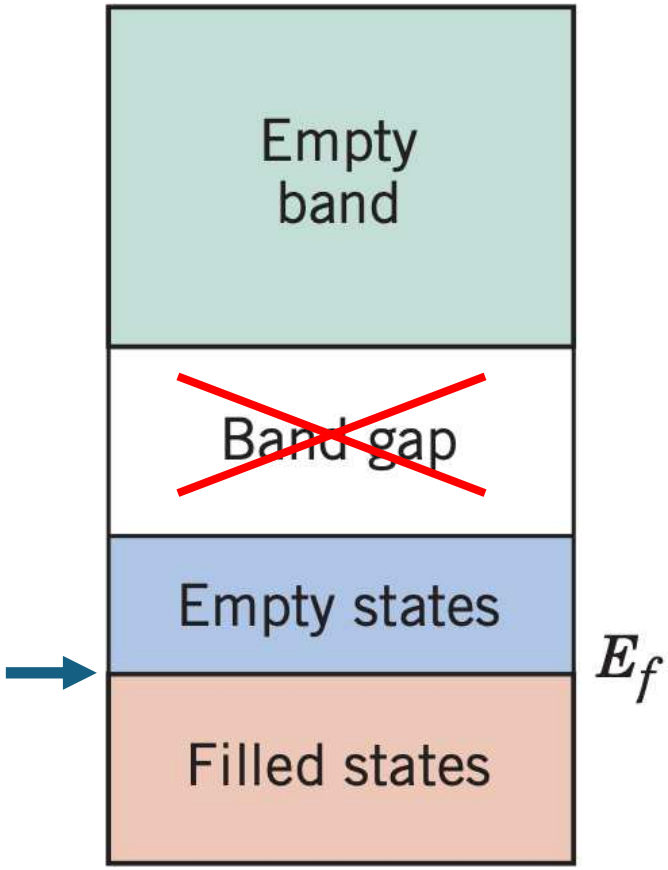
What if there is a **gap** between you and the nearest passing lane…

In principle, this “jump” to the **conduction band** can still be made if the band gap is sufficiently small (**< 2 eV, semiconductors**) and the thermal energy is high ($E \sim k_B T$ is around 25 meV at room temperature)

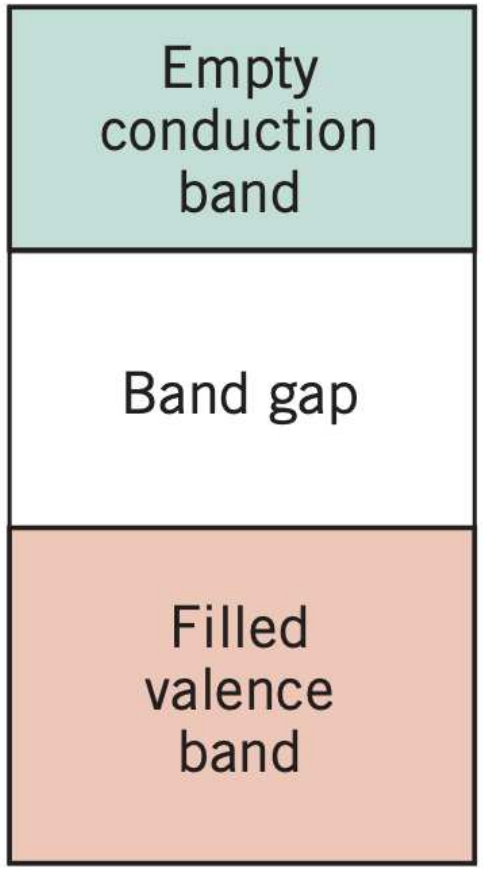
ENERGY DIAGRAMS

Questions?

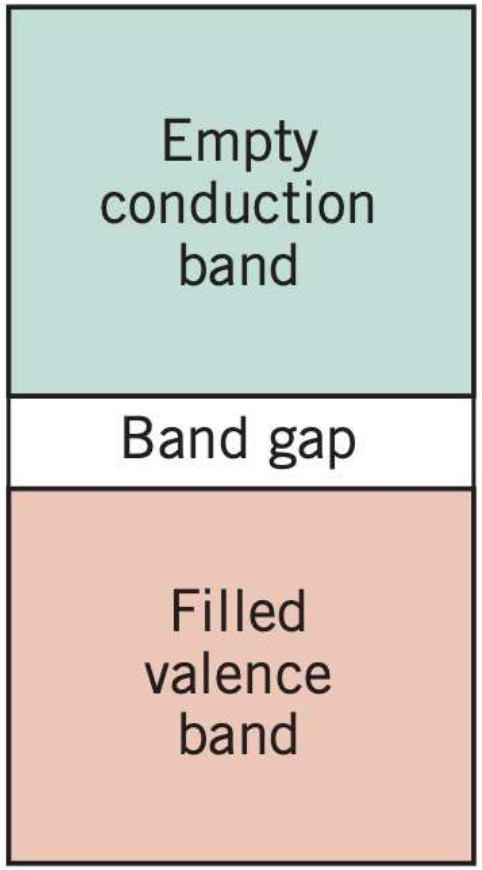
Three classes of materials:
In terms of electrical conduction



Metals

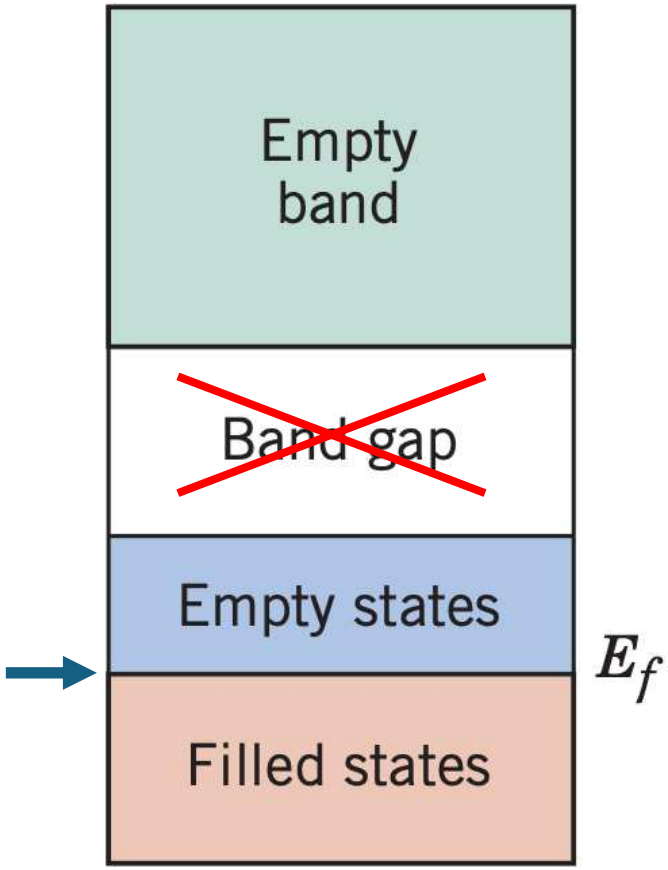


Insulators

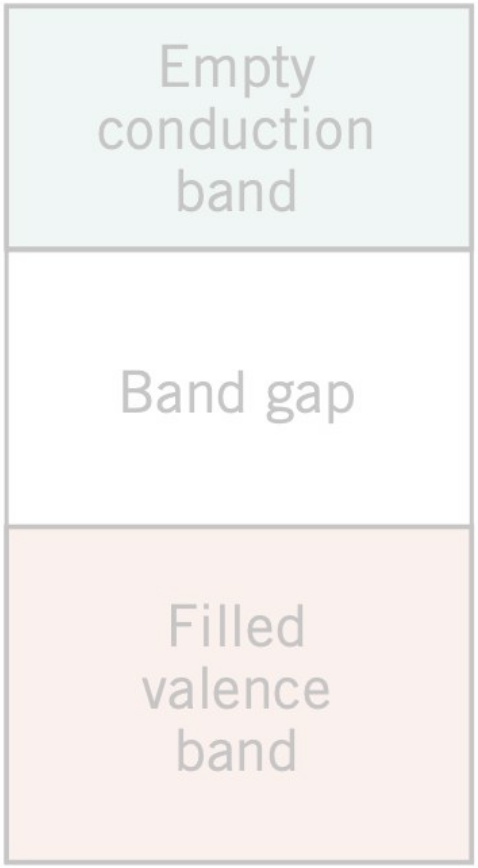


Semiconductors

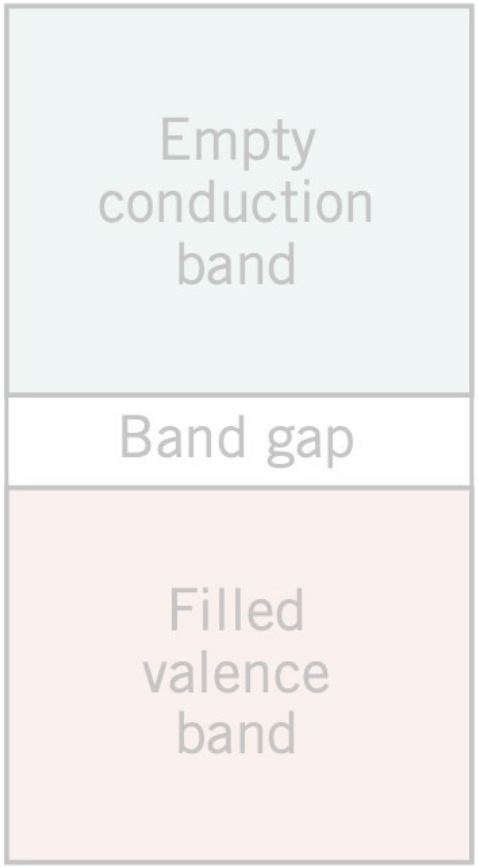
Three classes of materials:
In terms of electrical conduction



Metals

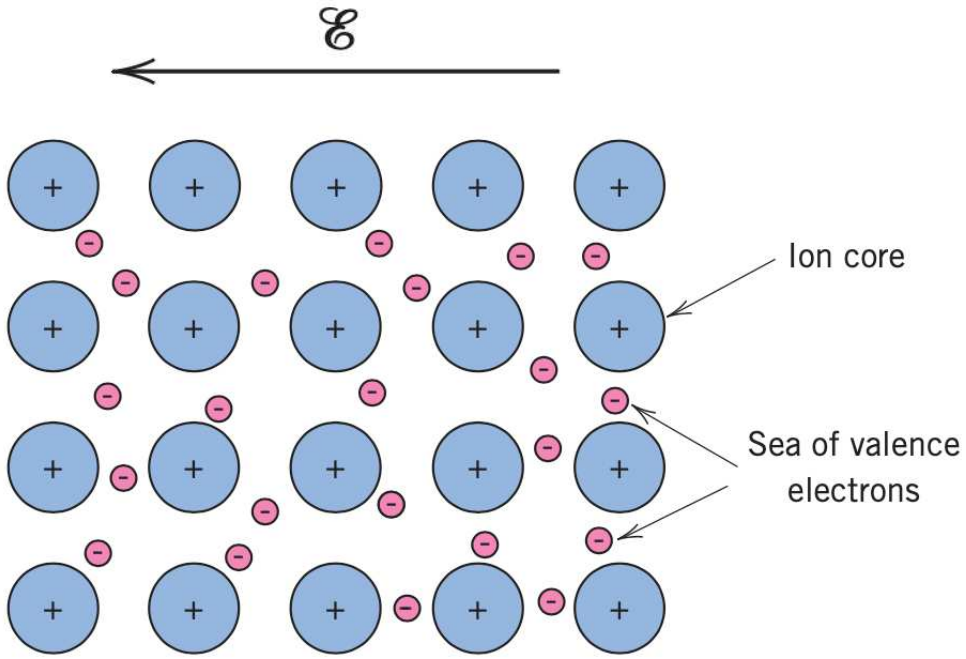


Insulators



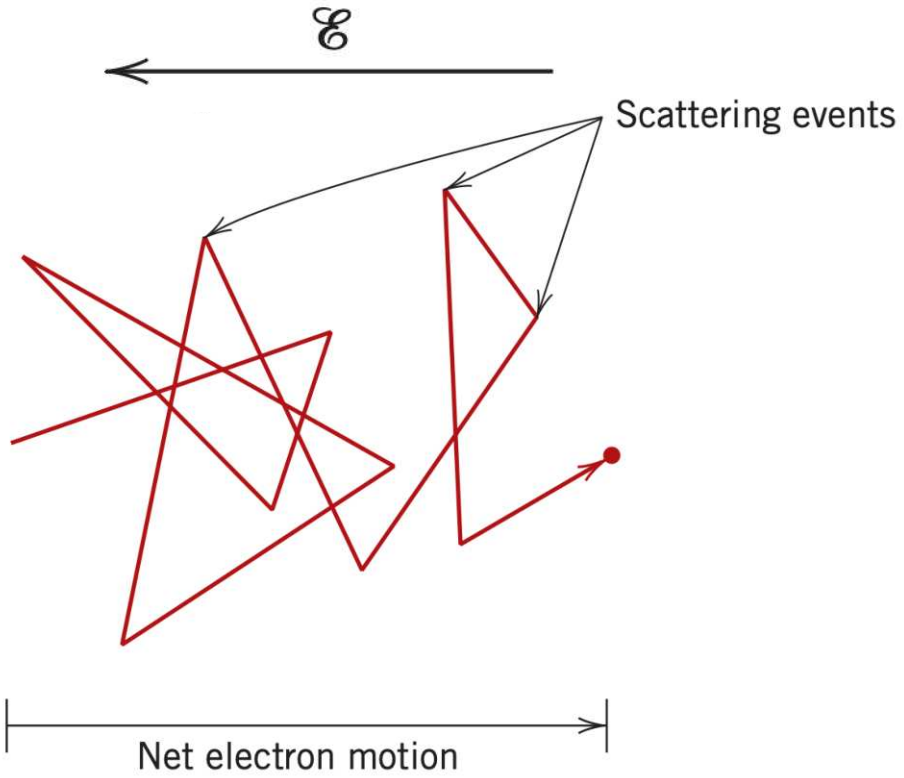
Semiconductors

Electrical conduction in metals



Recall: we can think of a metal as having a ”sea” of electrons

If we **apply an electric field, these electrons will *drift*** in the opposite direction



But they do so imperfectly, **scattering off atoms in the solid,** which slows them down and gives rise to ***resistivity***

Matthiessen's rule for conduction in metals

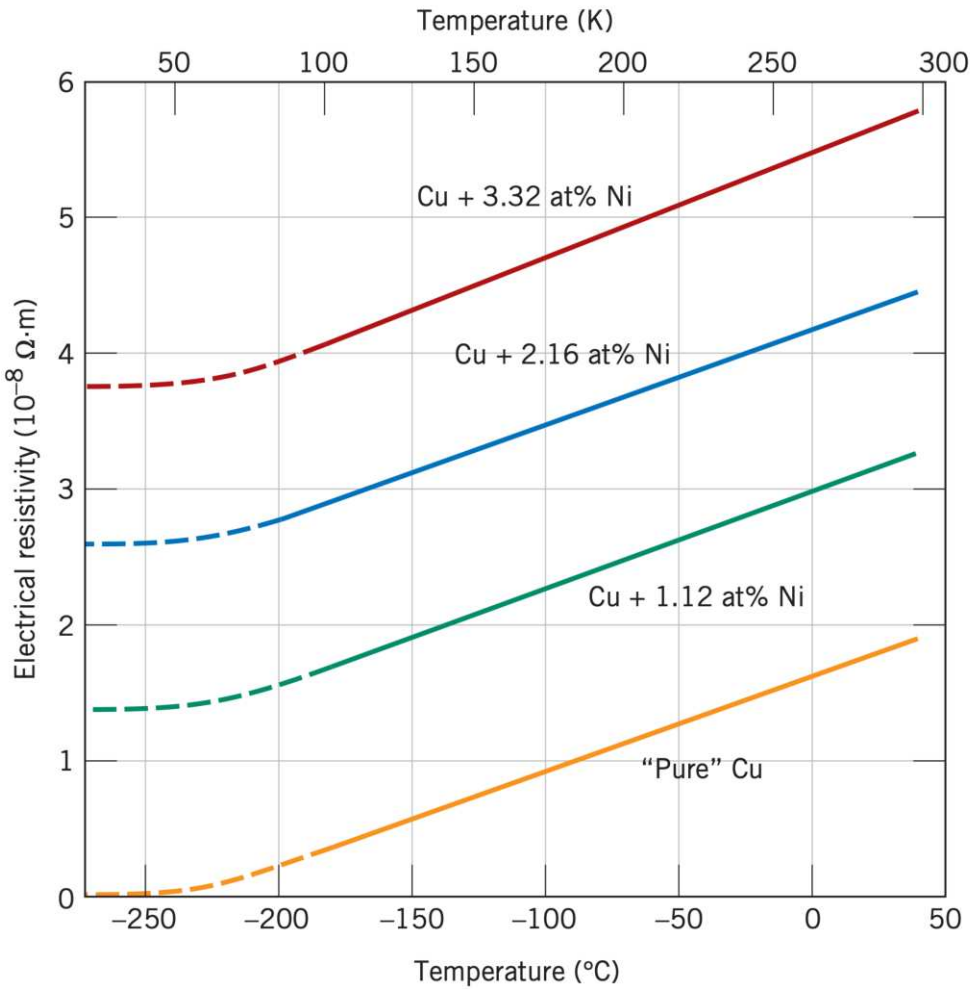
$$\rho_{\text{total}} = \rho_{\text{thermal}} + \rho_{\text{impurities}} + \rho_{\text{deformation}}$$

Matthiessen's rule for conduction in metals

$$\rho_{\text{total}} = \rho_{\text{thermal}} + \rho_{\text{impurities}} + \rho_{\text{deformation}}$$

Thermal energy causes atoms to vibrate and bump into electrons more often

$$\rho_{\text{thermal}} = \rho_0 + aT$$



Higher temperature leads to more resistance in metals

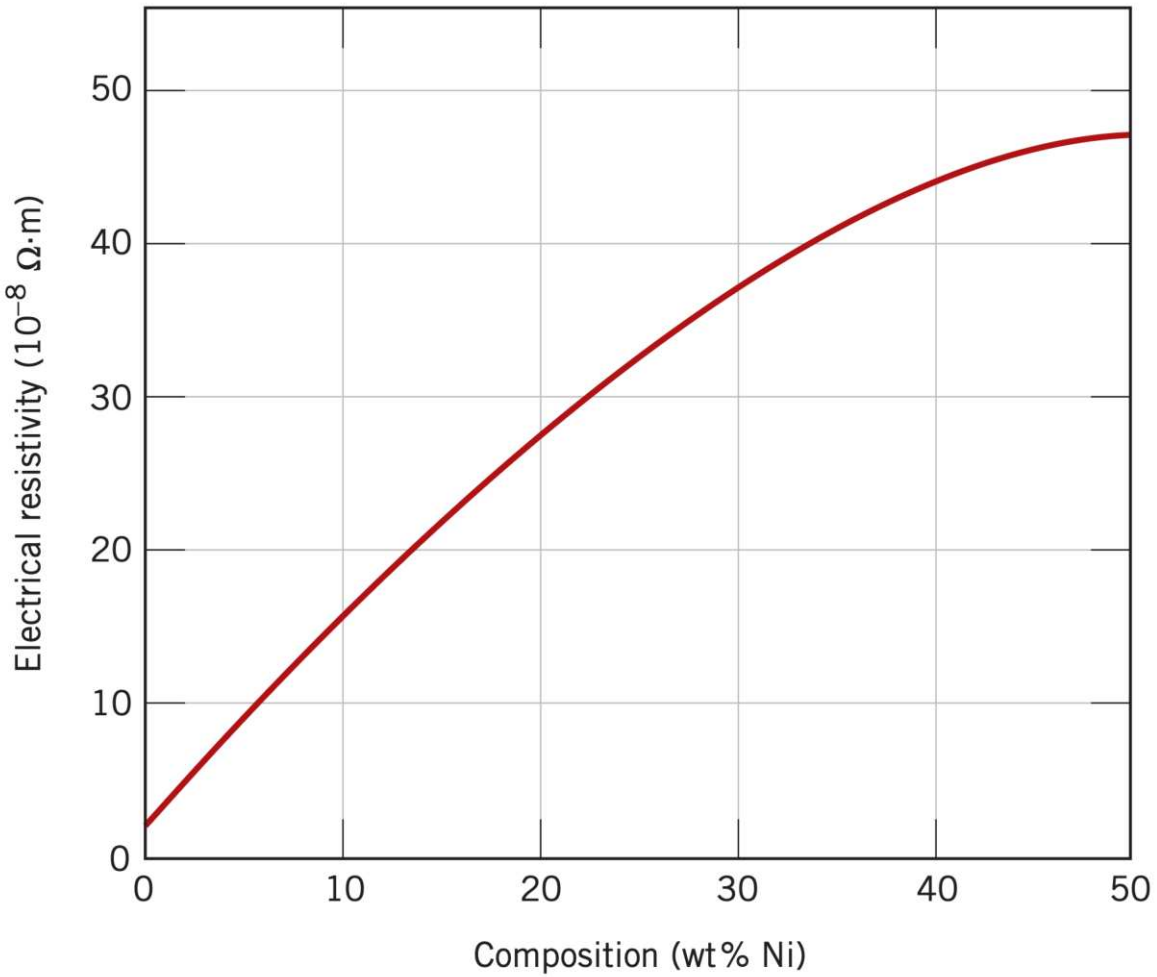
Matthiessen's rule for conduction in metals

$$\rho_{total} = \rho_{thermal} + \rho_{impurities} + \rho_{deformation}$$

Impurities are more likely to cause scattering events than regular atoms

$$\rho_{impurities} = A c_i (1 - c_i)$$

More impurities = higher resistivity (up to a point...50/50 in a binary mix)

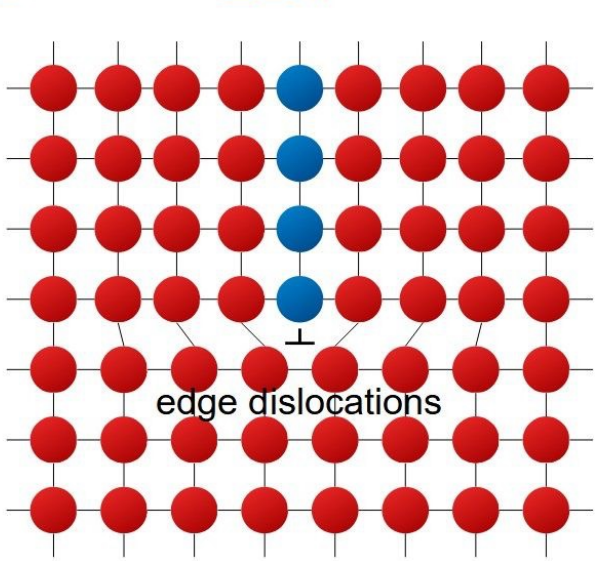


Matthiessen's rule for conduction in metals

$$\rho_{\text{total}} = \rho_{\text{thermal}} + \rho_{\text{impurities}} + \rho_{\text{deformation}}$$

Plastic deformation introduces more dislocations that tend to scatter electrons

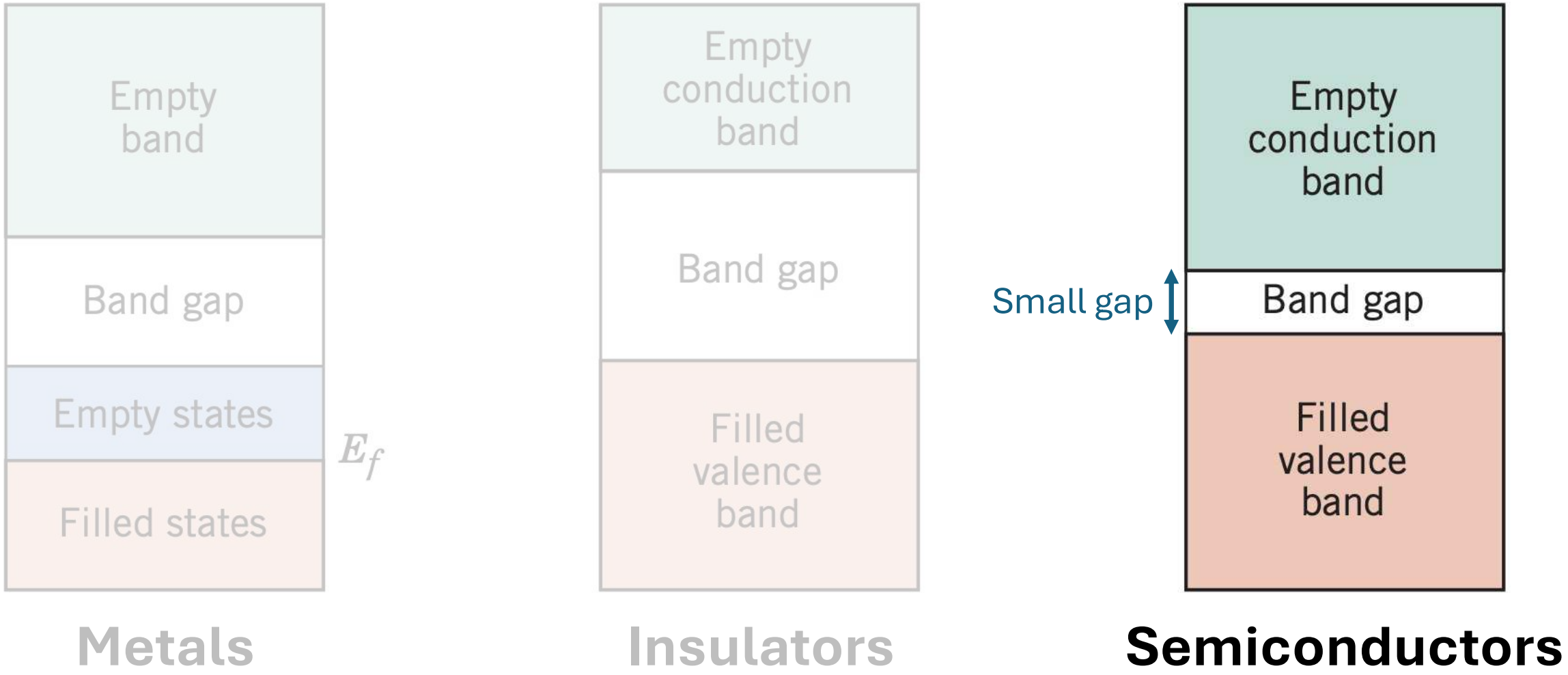
This effect is usually quite small, unless you are working with heavily cold-worked metals…



What to know:

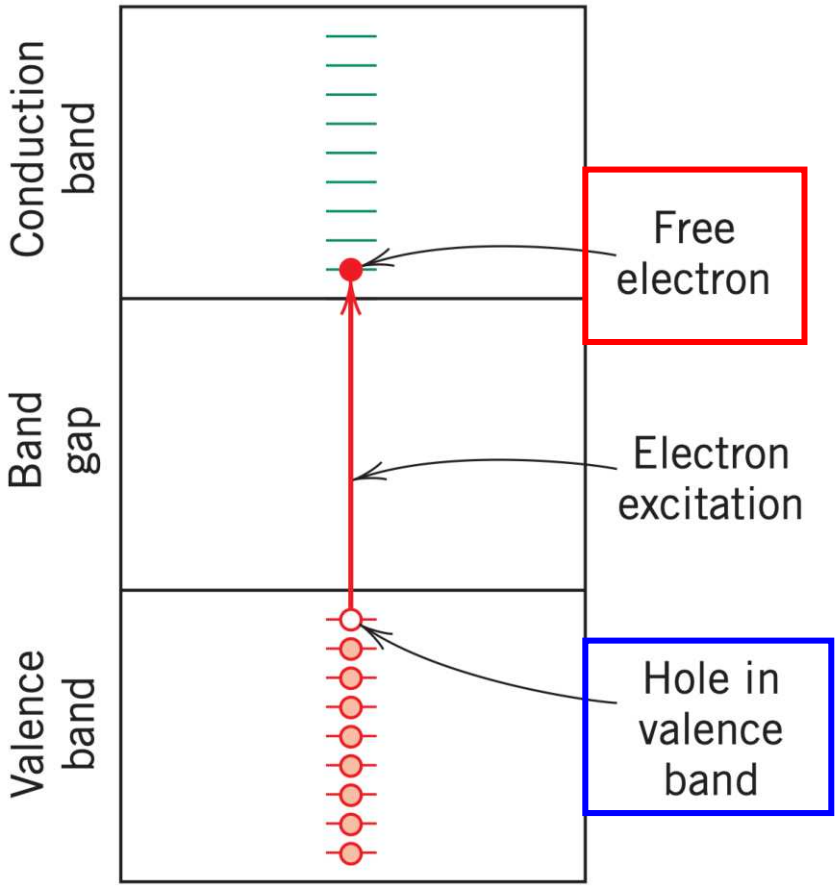
In metals, higher $T \rightarrow$ more resistance

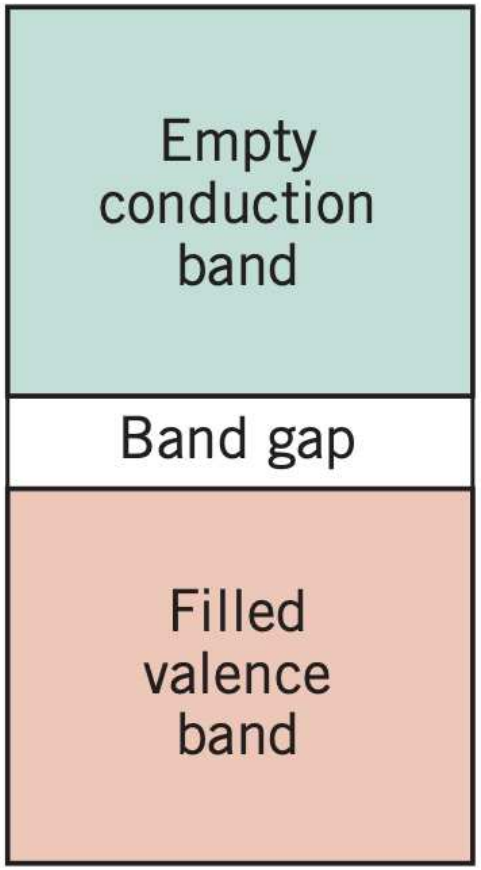
Three classes of materials:
In terms of electrical conduction



Electrical conduction in semiconductors

Conduction in semiconductors occurs through **electrons in the conduction band** *and* **holes in the valence band**

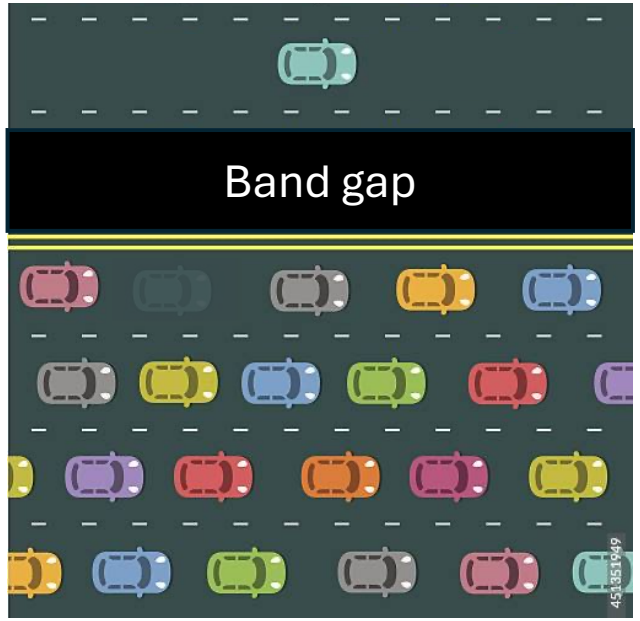


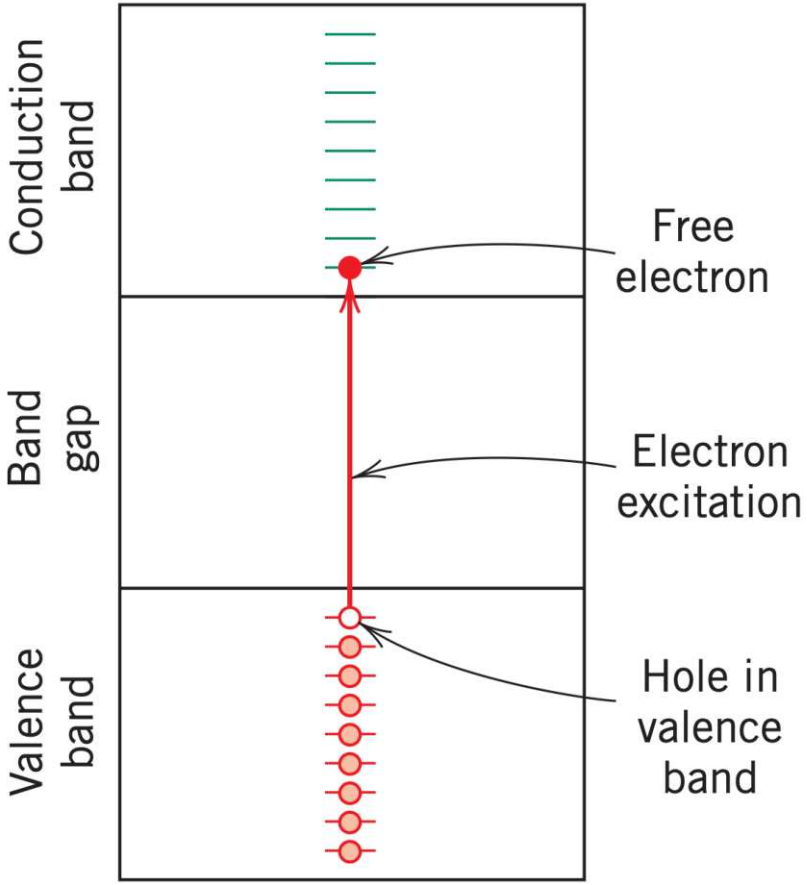


Semiconductors

Electrical conduction in semiconductors

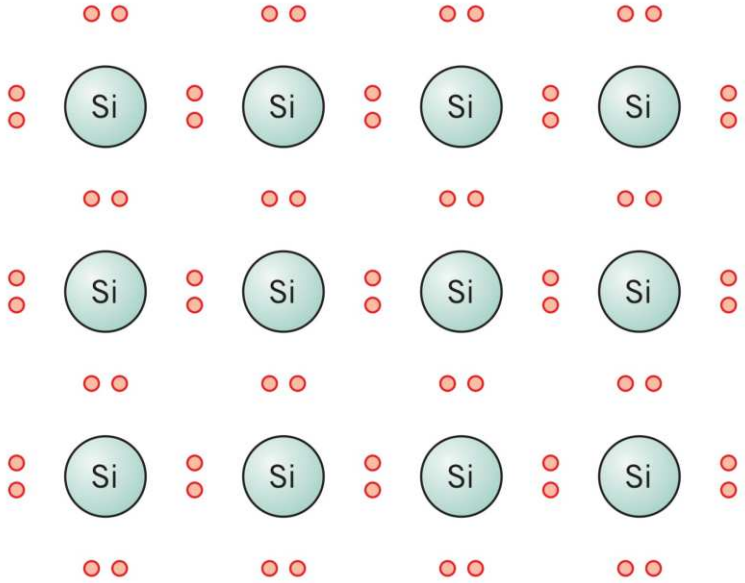
If this car moves into the passing lane, it leaves a space (the hole) for cars to move up a spot. As the cars move right, the hole moves left.





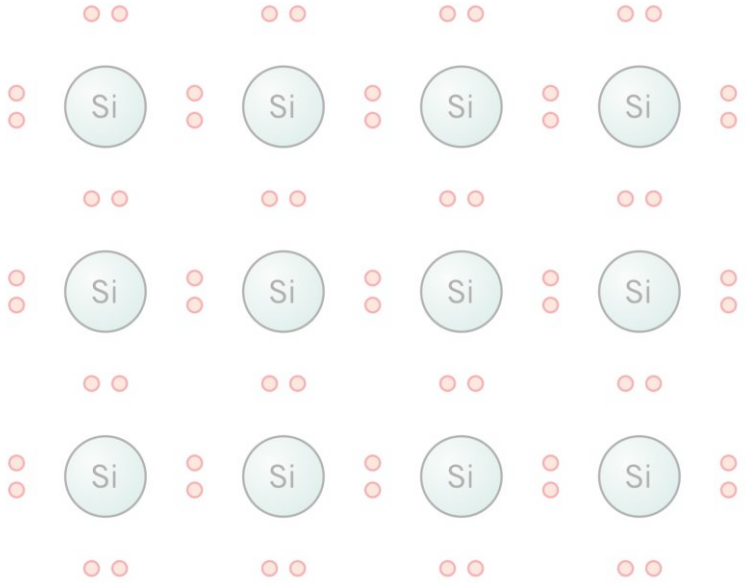
Electrical conduction in semiconductors

An atomistic picture

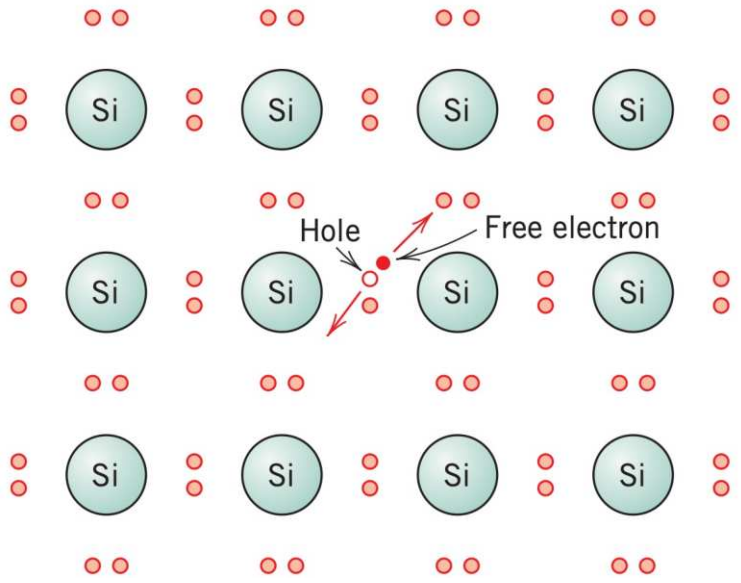


Consider the most common semiconductor: **silicon (Si).**
At 0 K, all valence electrons are trapped in bonds
→ **no conduction.**

Electrical conduction in semiconductors

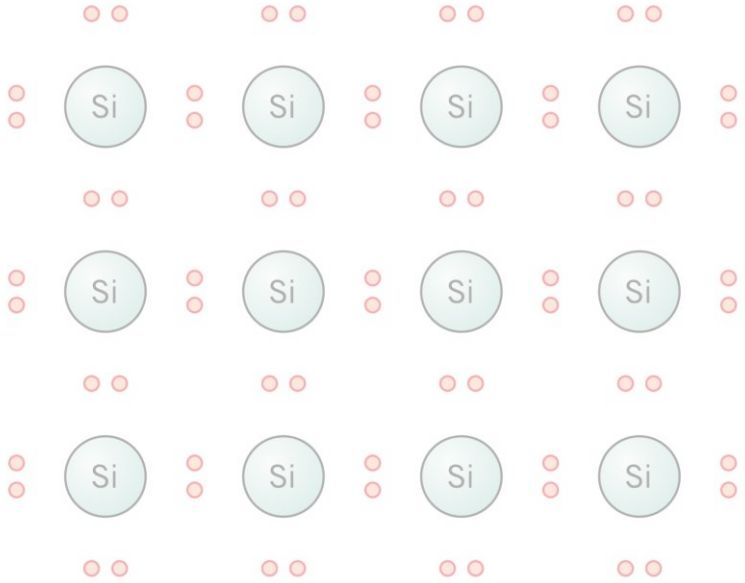


Consider the most common semiconductor: **silicon (Si).** **At 0 K**, all valence electrons are trapped in bonds → **no conduction.**

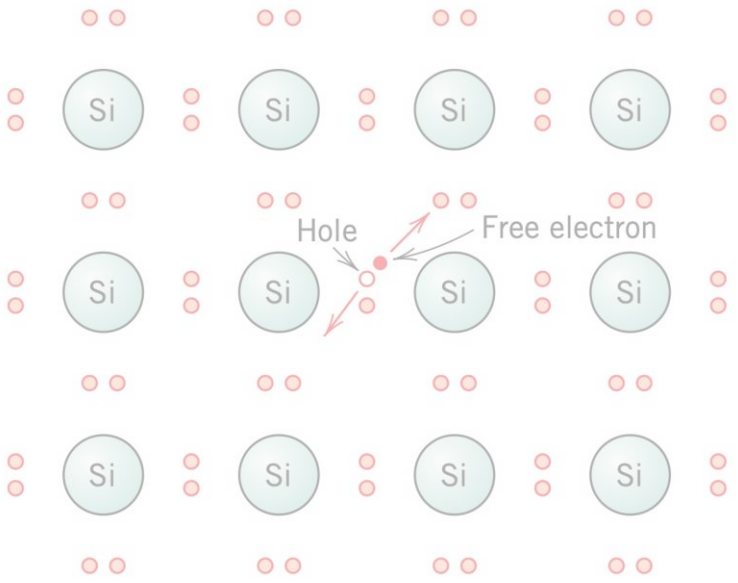


But if we give the system enough **thermal energy**, some electrons will be kicked off from their bonds, leaving behind a **hole.**

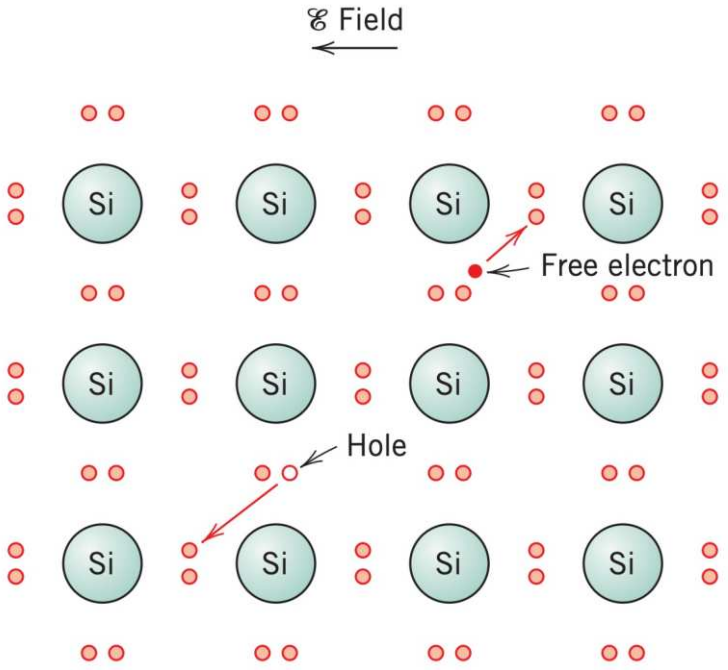
Electrical conduction in semiconductors



Consider the most common semiconductor: **silicon (Si).** **At 0 K**, all valence electrons are trapped in bonds → **no conduction.**



But if we give the system enough **thermal energy**, some electrons will be kicked off from their bonds, leaving behind a **hole.**



This electron/hole pair can then be separated by an electric field, leading to **electrical current.**

Electrical conduction in semiconductors

Both electrons and hole contribute to the conductivity:

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

Electrical conduction in semiconductors

Both electrons and hole contribute to the conductivity:

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

Concentration of electrons in the conduction band

Mobility of those electrons – how easily they move

Electrical conduction in semiconductors

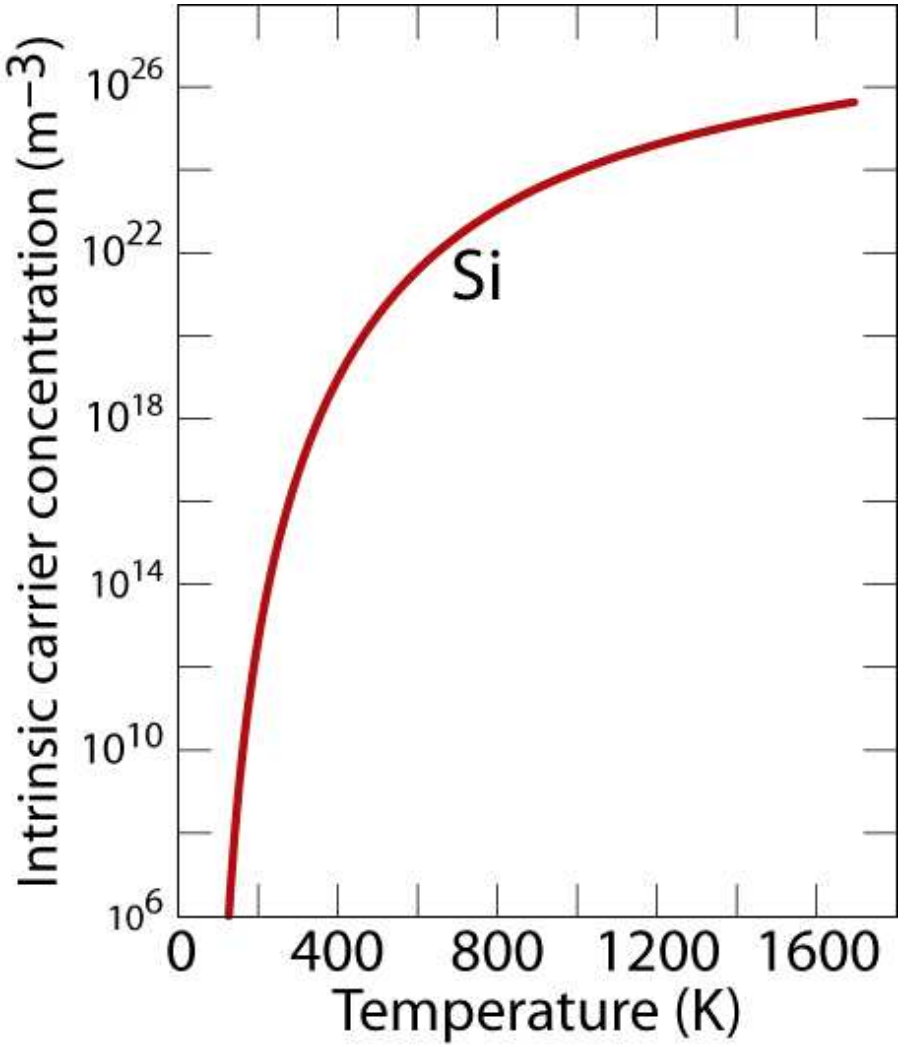
Both electrons and hole contribute to the conductivity:

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

Concentration of holes in the valence band

Mobility of those holes

Electrical conduction in semiconductors



Both electrons and hole contribute to the conductivity:

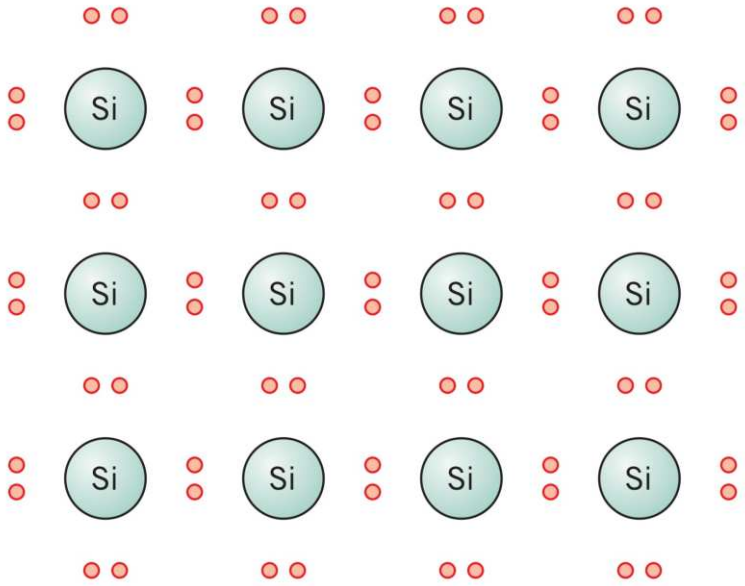
$$\sigma = n|e|\mu_e + p|e|\mu_p$$

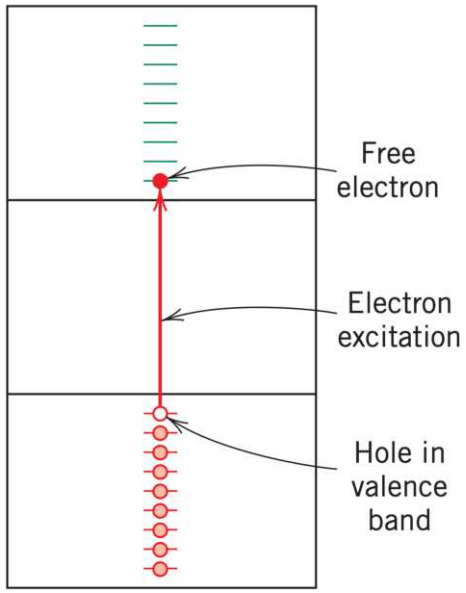
For ***intrinsic*** semiconductors (negligible impurities): $n = p$

$$n = p = e^{-E_{\text{gap}}/k_B T}$$

Higher temperature → better electrical conductivity (opposite of metals!)

Intrinsic *vs.* Extrinsic semiconductors



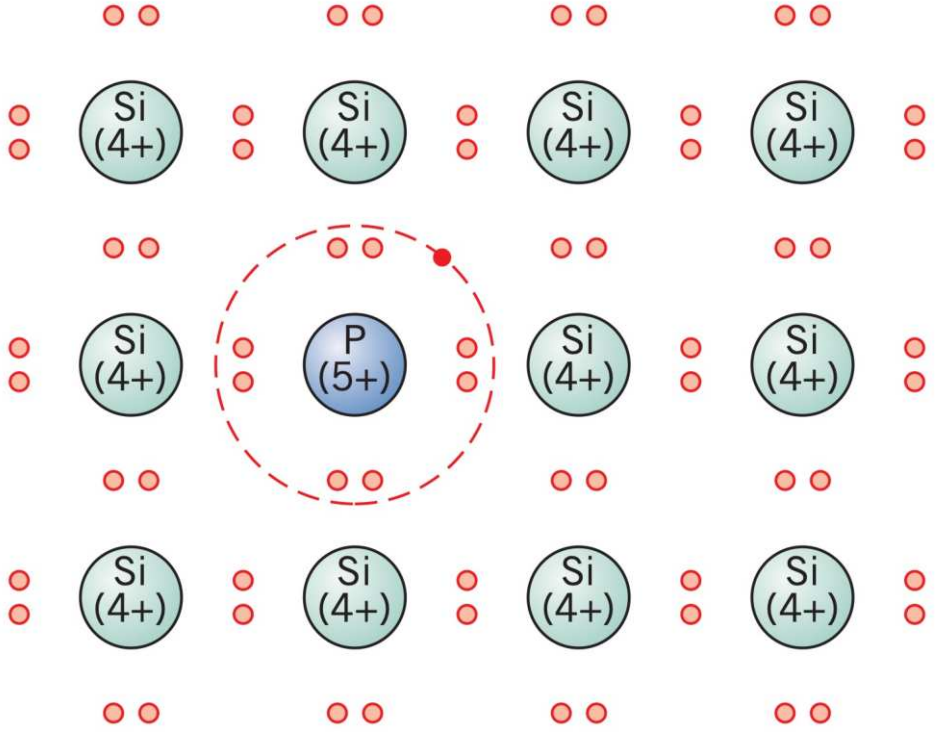


Intrinsic semiconductor: electrical conductivity is based on **pure material**

EX: pure silicon

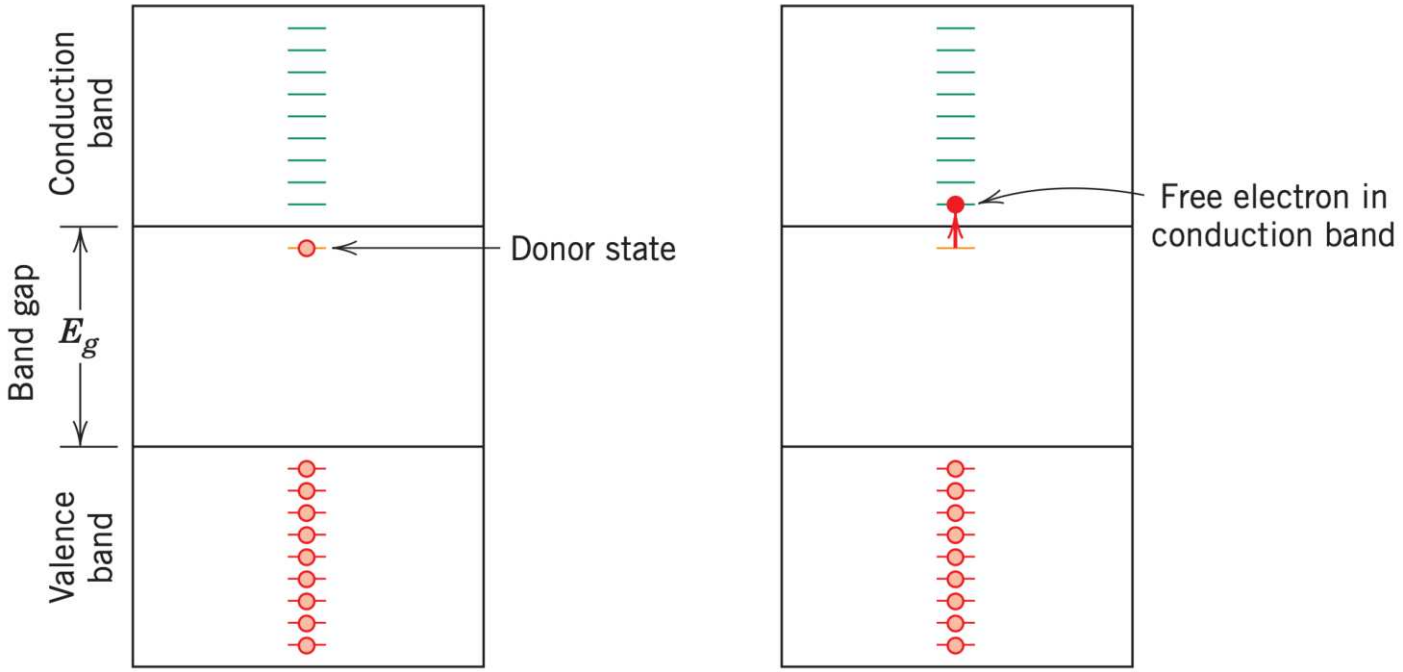


Extrinsic semiconductor: electrical conductivity is based on **impurities (*dopants*)**

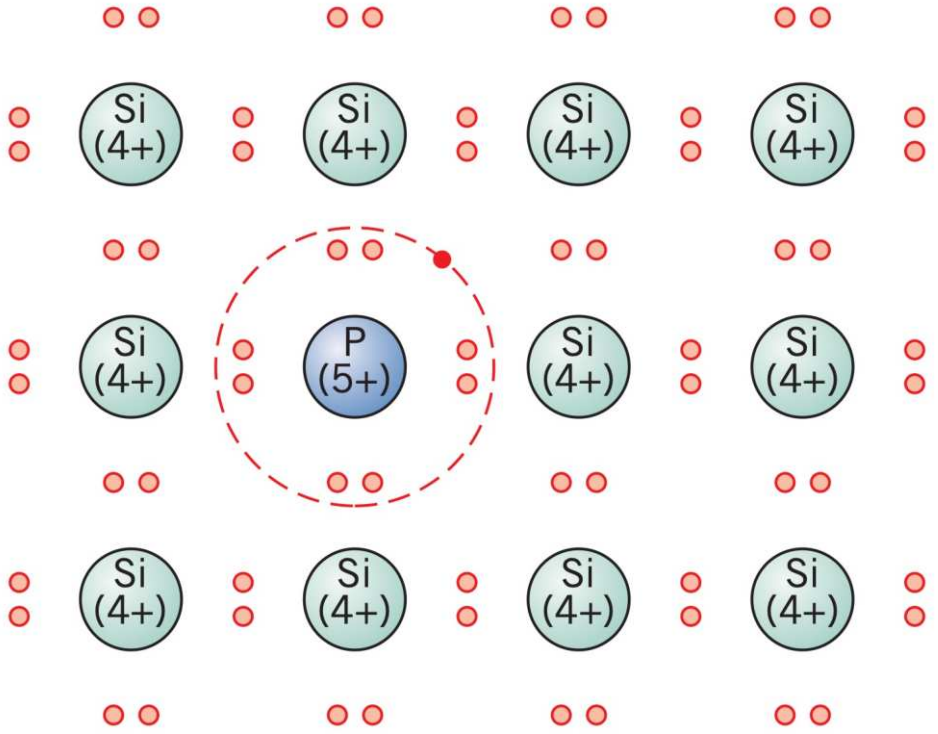


EX: silicon with **P dopants**

Intrinsic *vs.* Extrinsic semiconductors



Extrinsic semiconductor: electrical conductivity is based on **impurities (*dopants*)**



EX: silicon with **P dopants**

P^{5+} has an extra electron that is loosely bound. It can be easily **excited to the conduction band** (away from P^{5+}) by thermal energy.
→ ***n*-type conductivity**



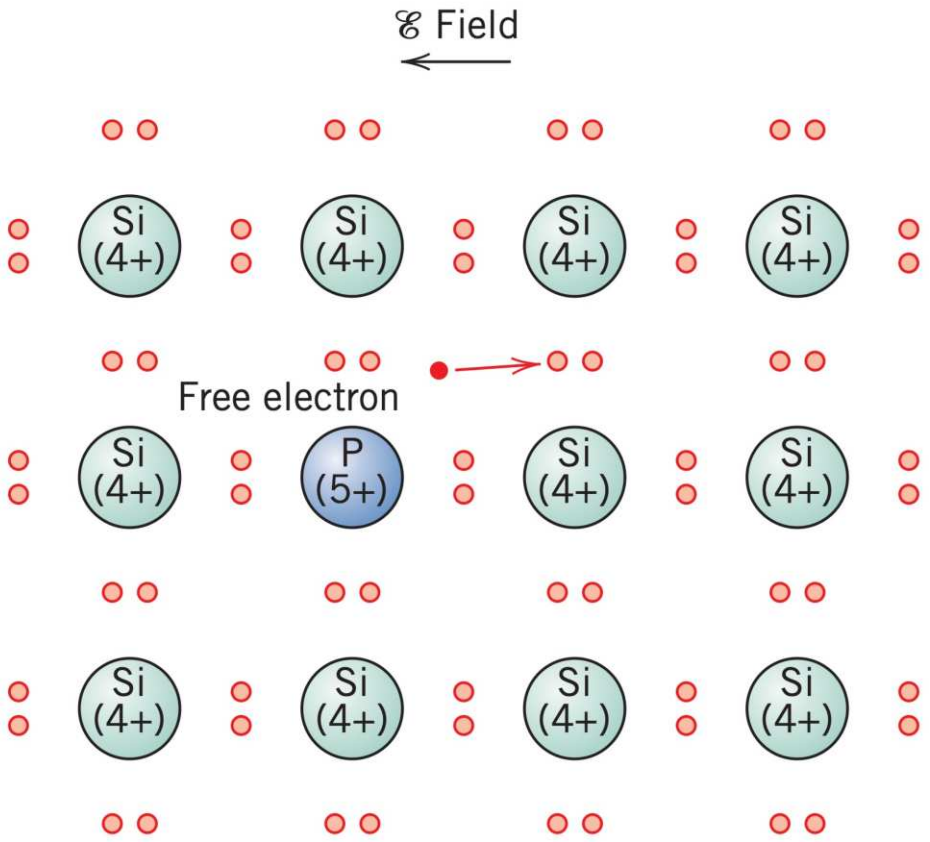
Intrinsic *vs.* Extrinsic semiconductors

n-type conductivity:

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

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

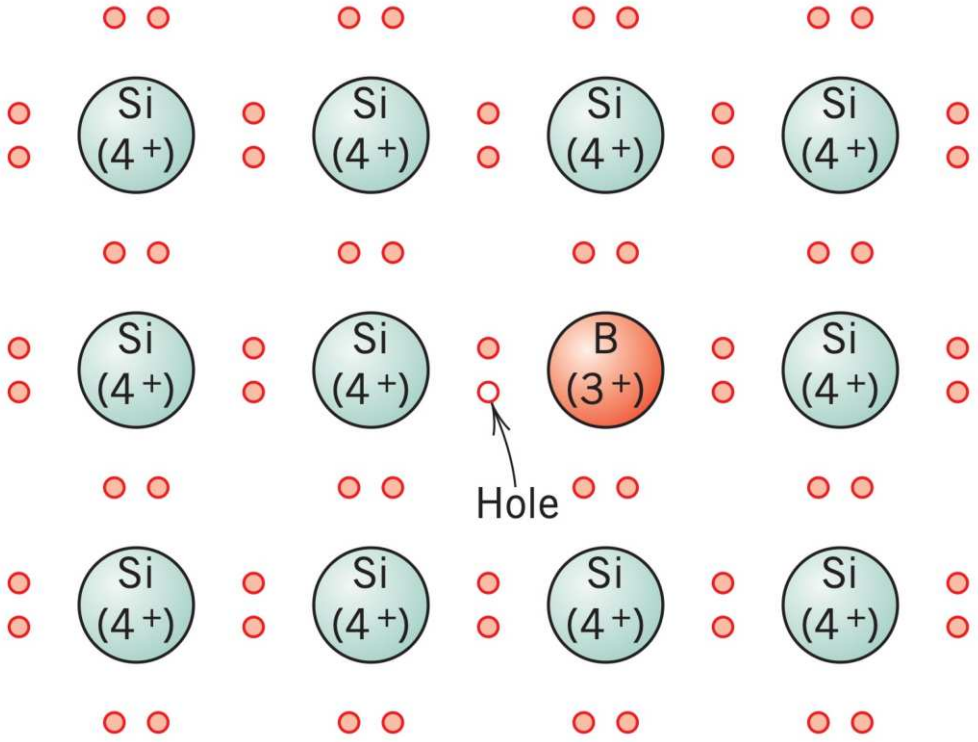
Free electrons from the donor atoms (n-type dopants) are the primary charge carriers

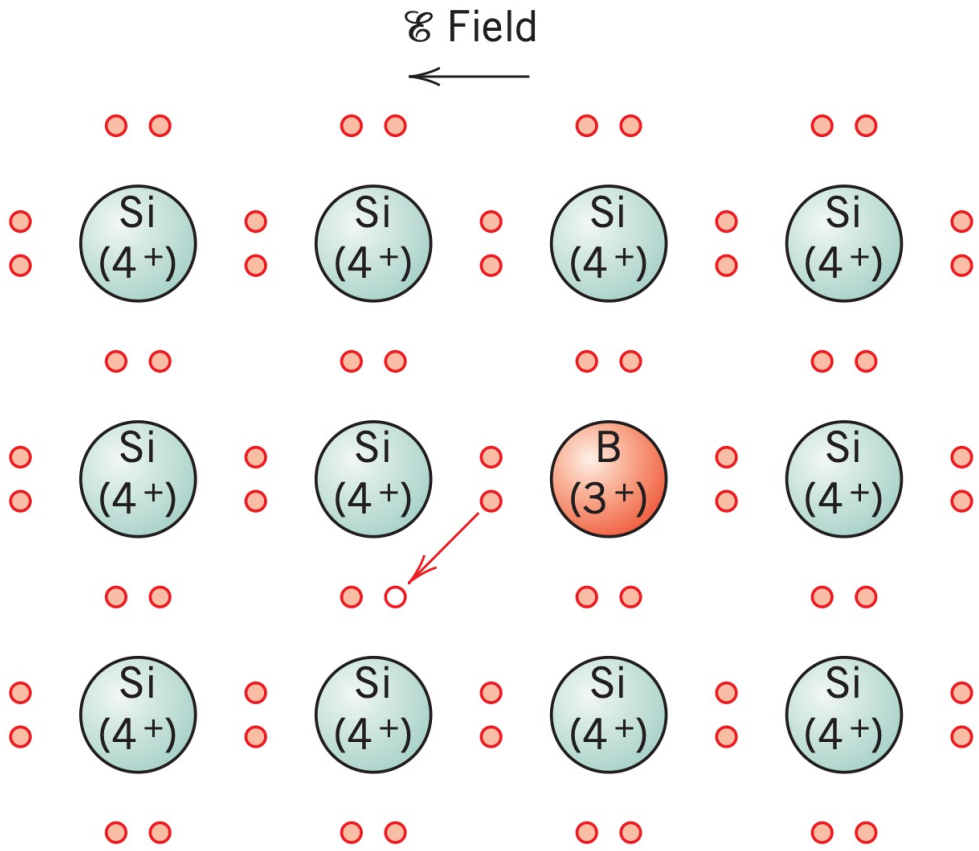


Note that we can also have the opposite case..

p-type conductivity (holes)

Intrinsic *vs.* Extrinsic semiconductors

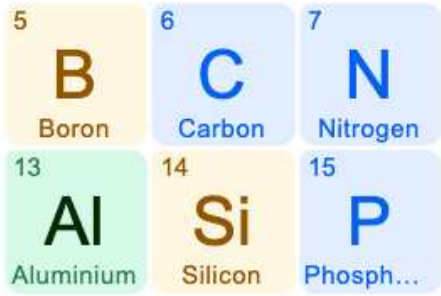




Note that we can also have the opposite case..

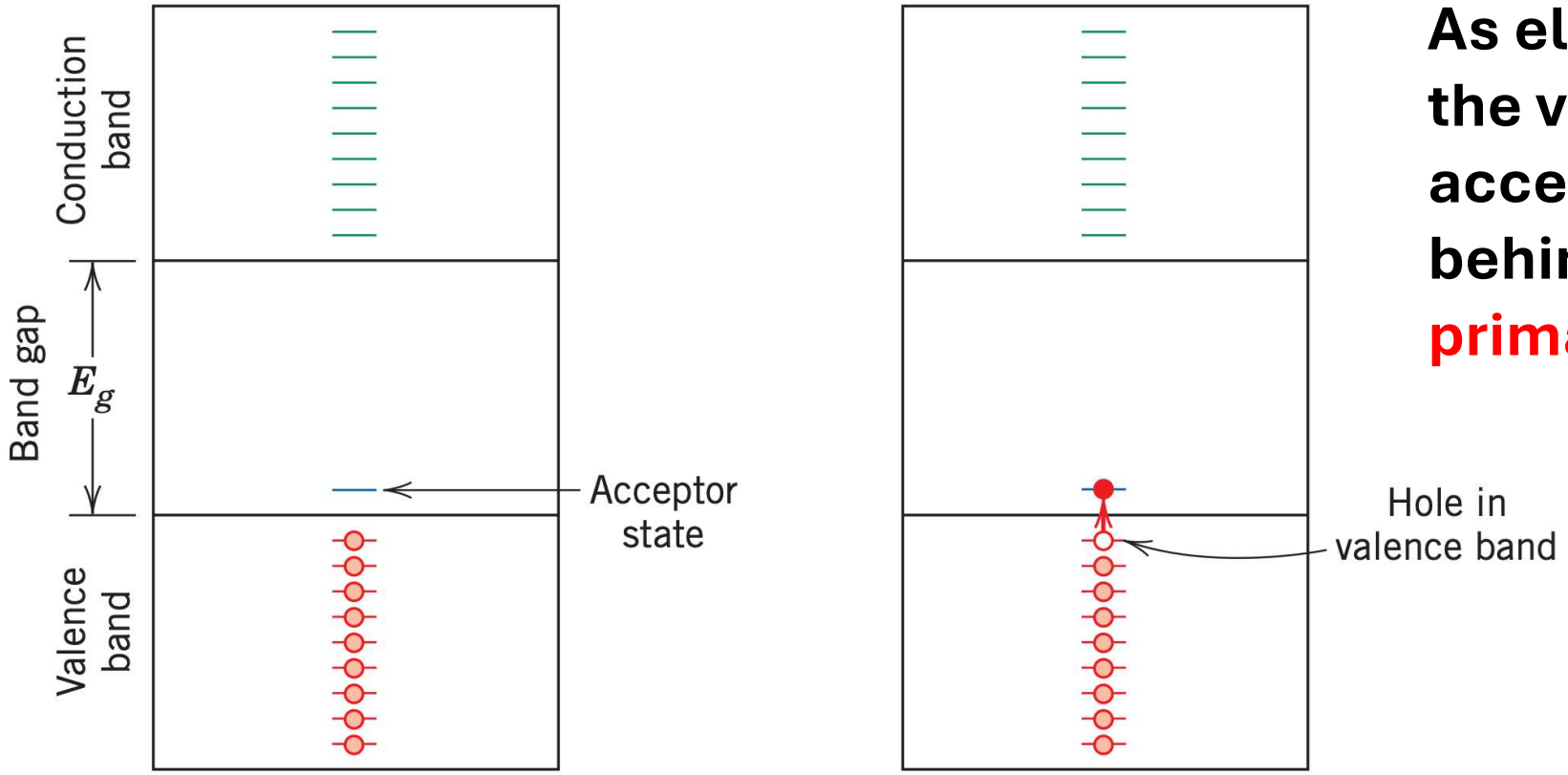
***p*-type conductivity (holes)**

EX: silicon with **B dopants**

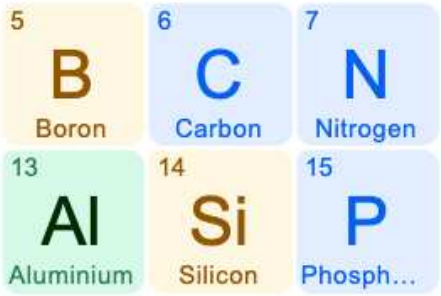


Intrinsic *vs.* Extrinsic semiconductors

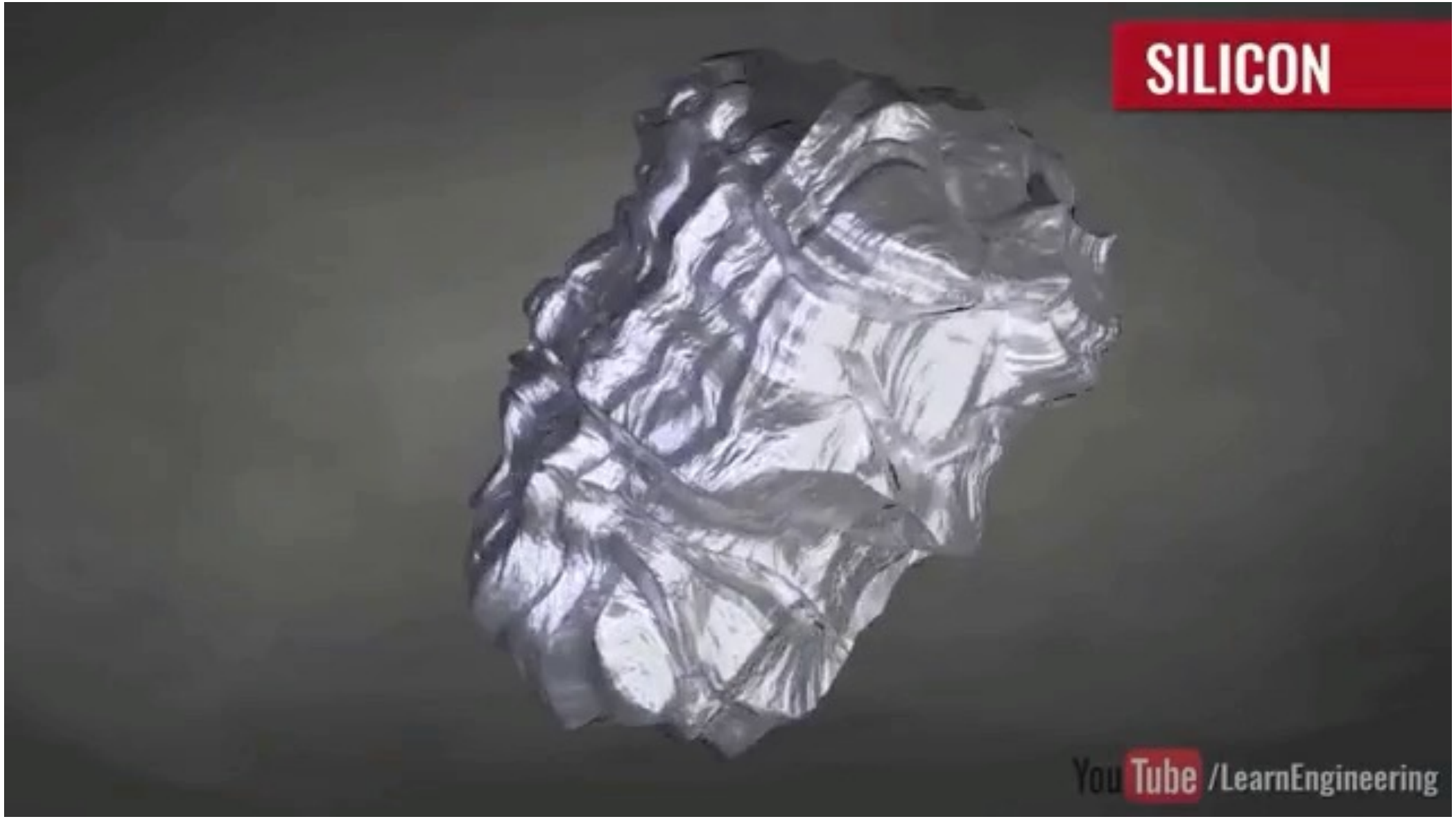
p-type conductivity: $\sigma = n|e|\mu_e + p|e|\mu_p$ $\quad\quad$ $\sigma \approx p|e|\mu_p$



As electrons are excited from the valence band into the acceptor states, they leave behind holes that become the primary charge carriers

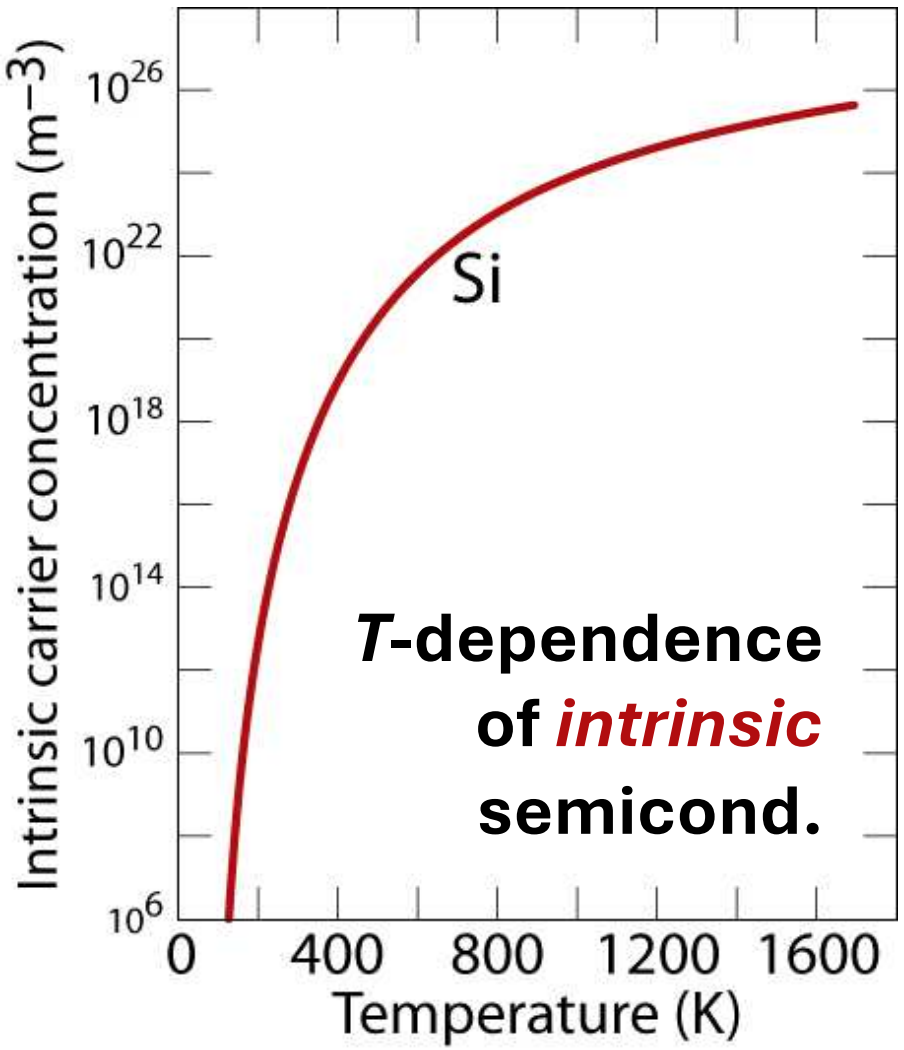


Intrinsic *vs.* Extrinsic semiconductors



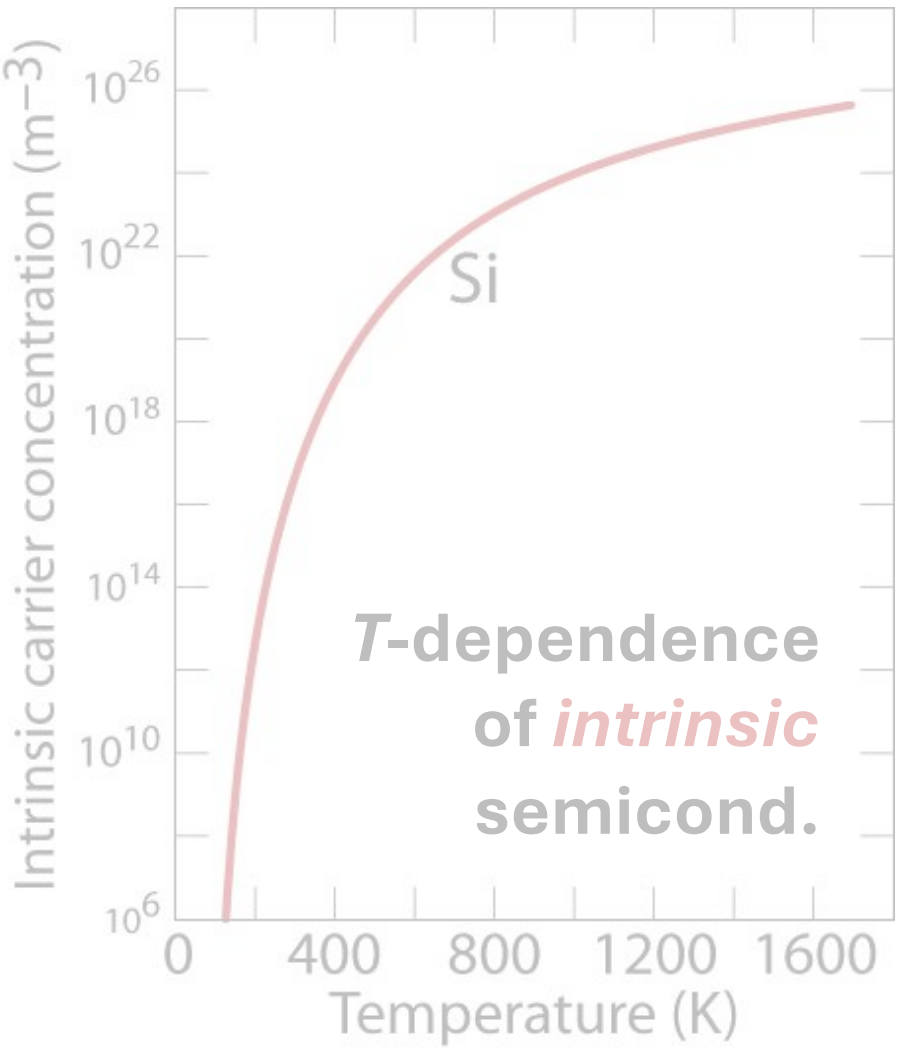
Questions?

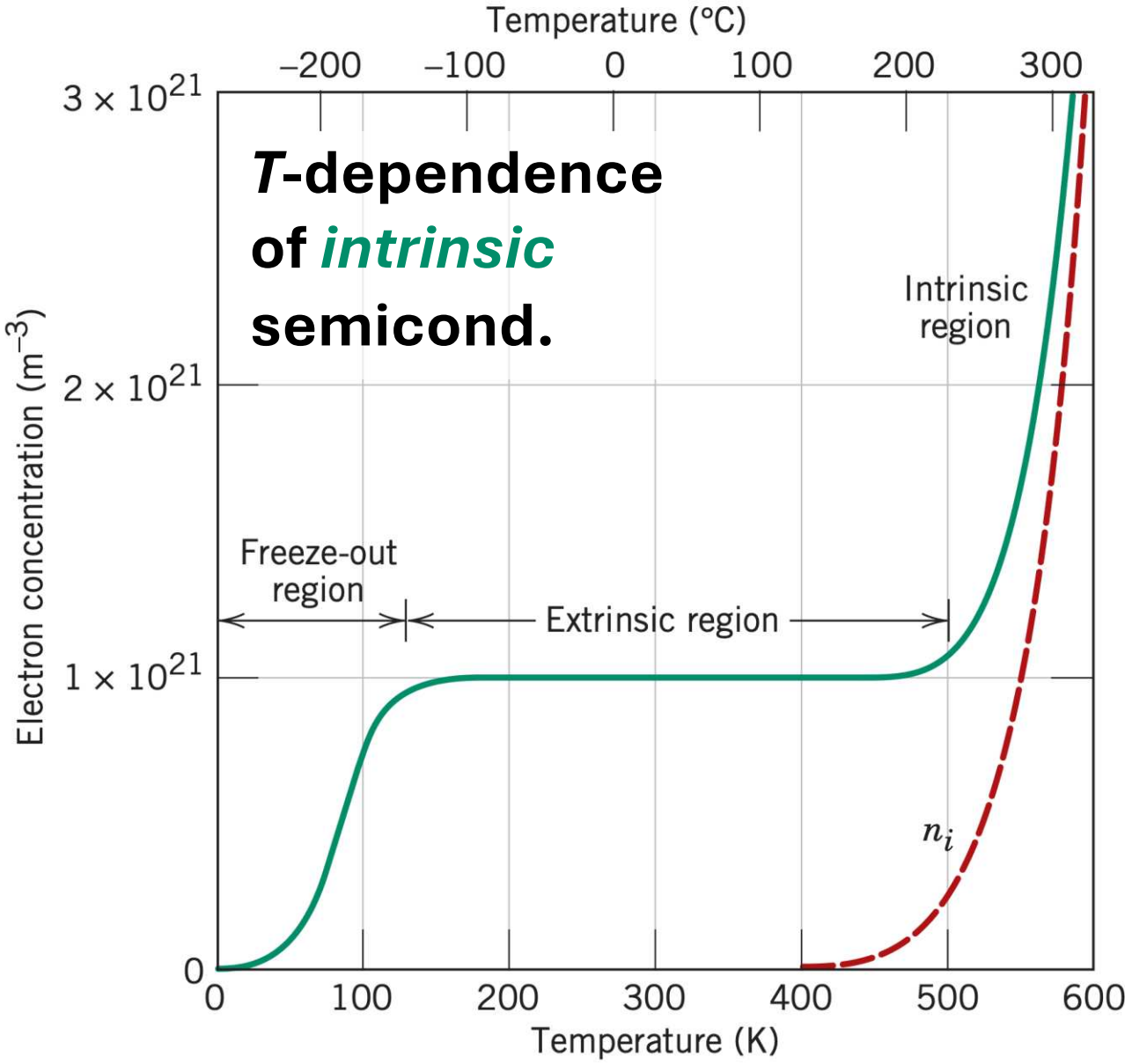
Intrinsic *vs.* Extrinsic semiconductors



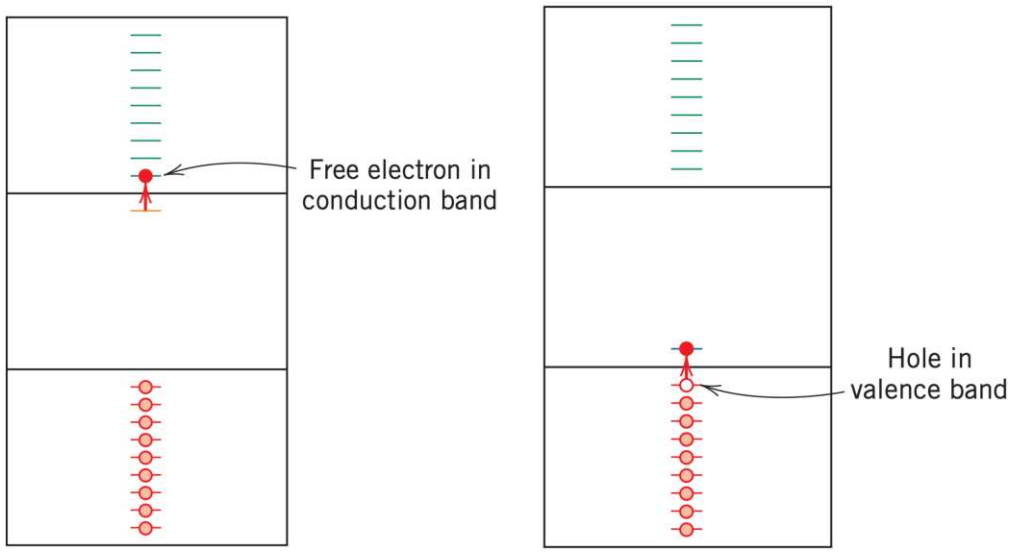
***T*-dependence of *intrinsic* semicond.**

Intrinsic *vs.* Extrinsic semiconductors

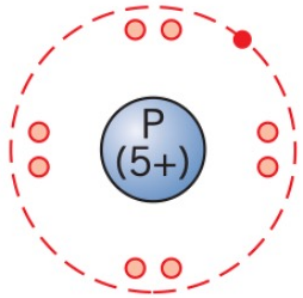




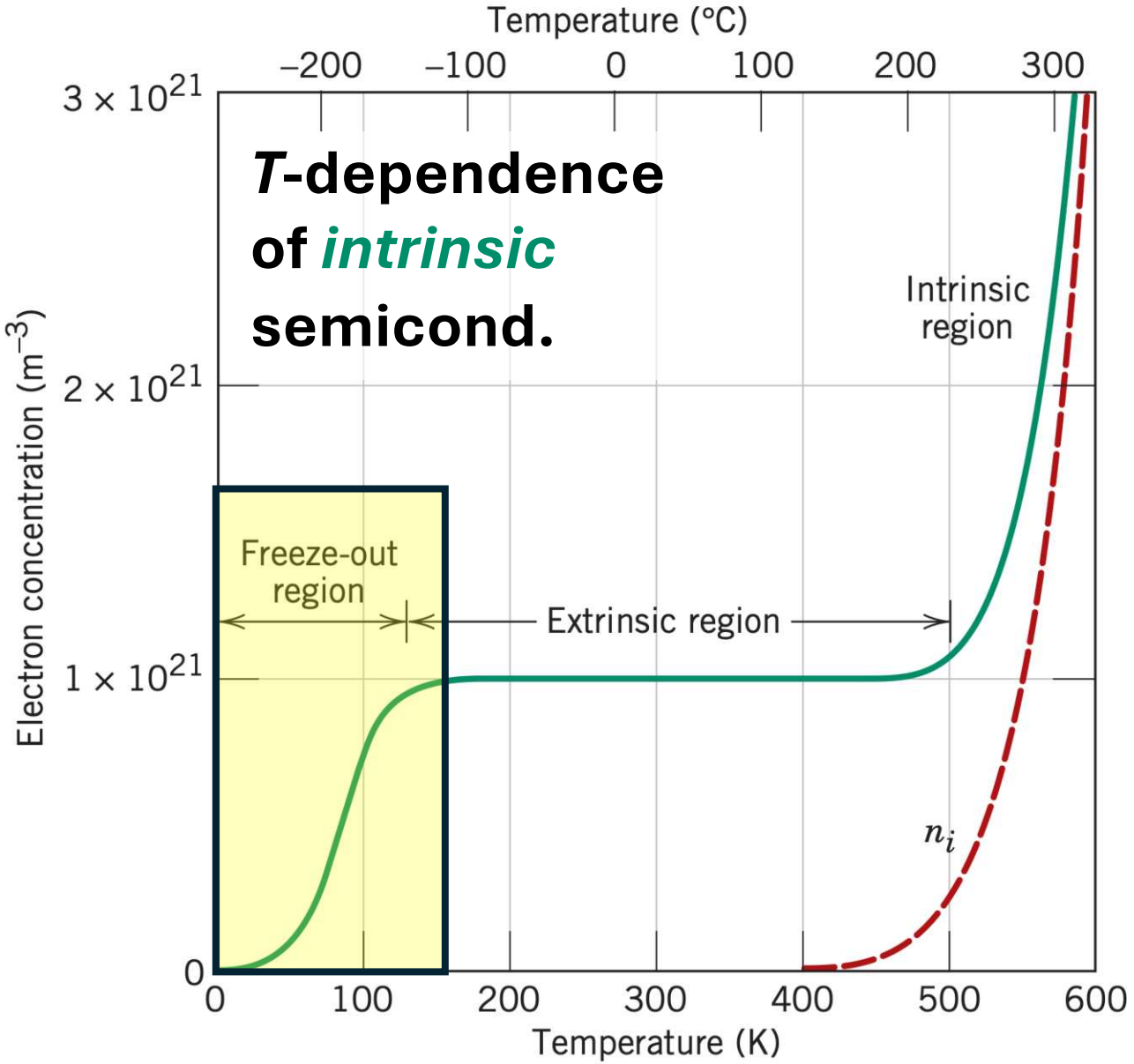
Intrinsic *vs.* Extrinsic semiconductors



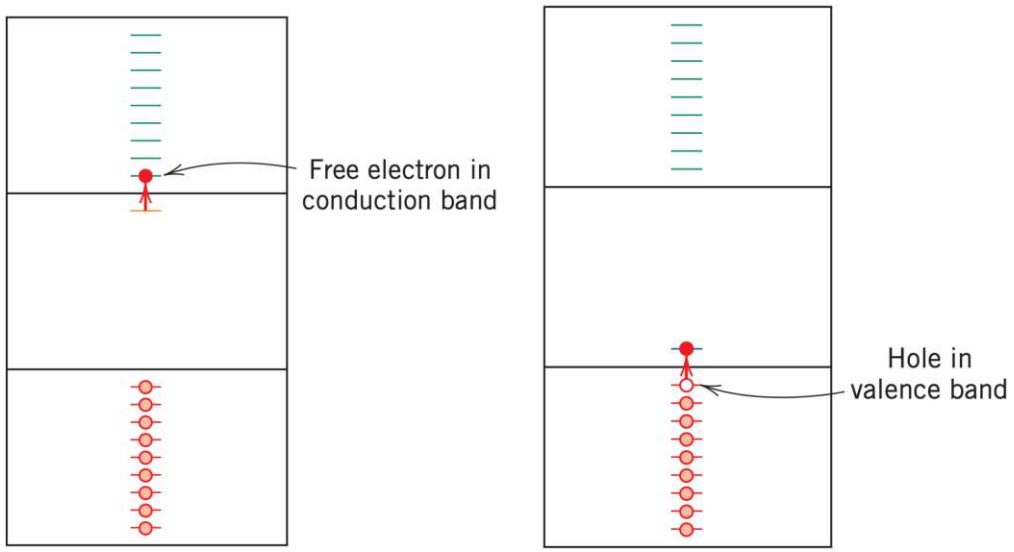
- **Donor/acceptor excitations happen at low temperature**



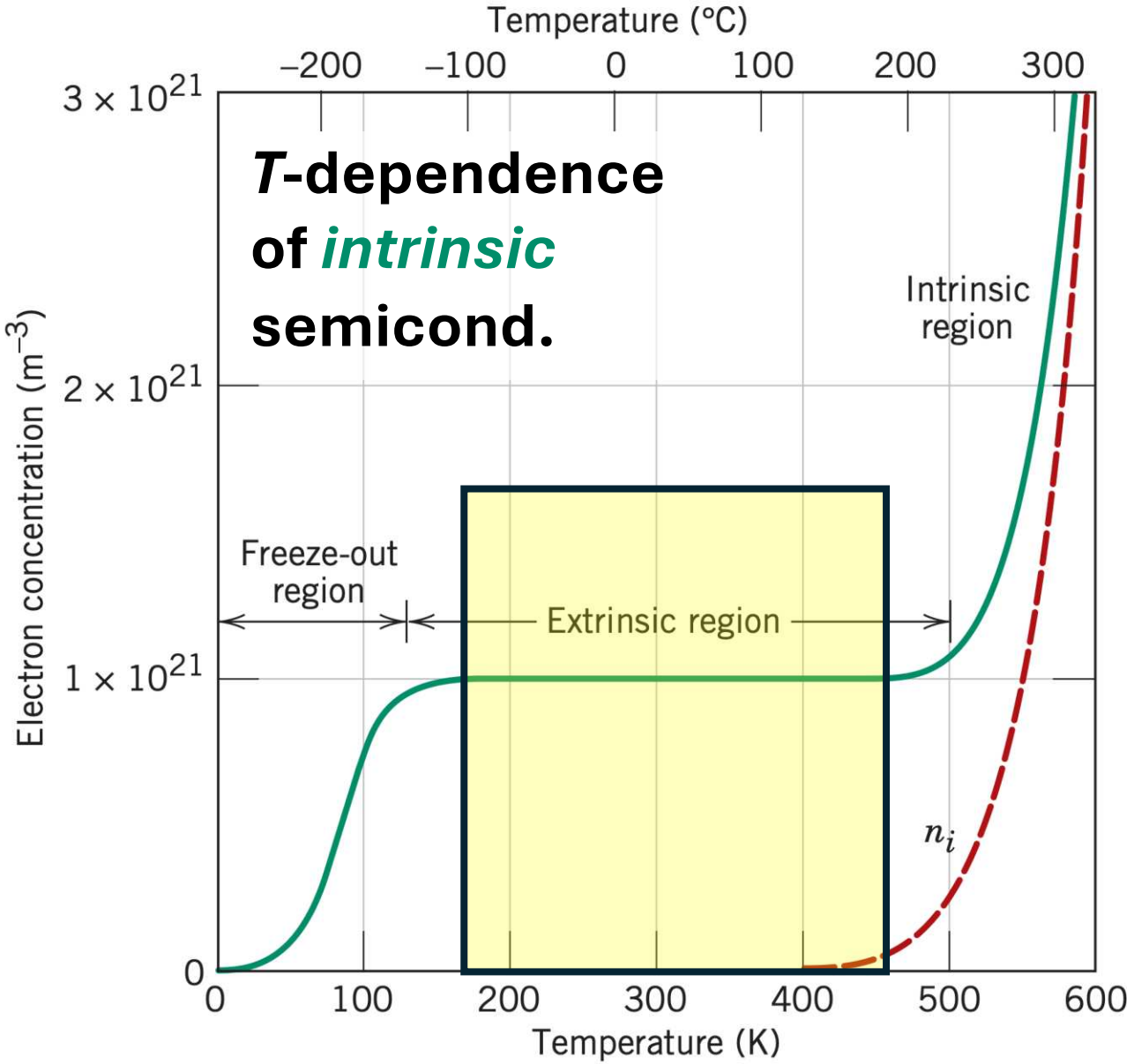
Extra electron (or hole) is loosely bound to dopant atom



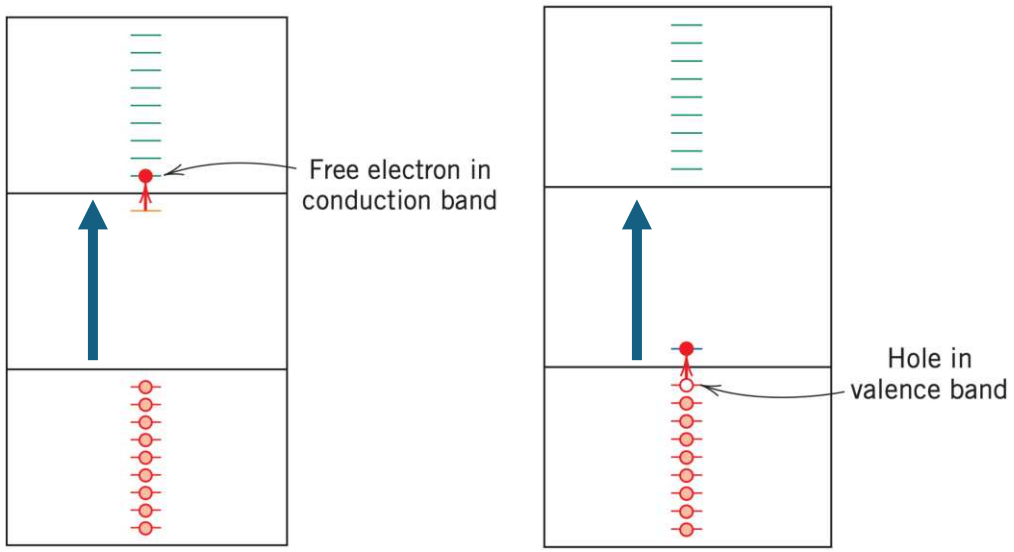
Intrinsic *vs.* Extrinsic semiconductors



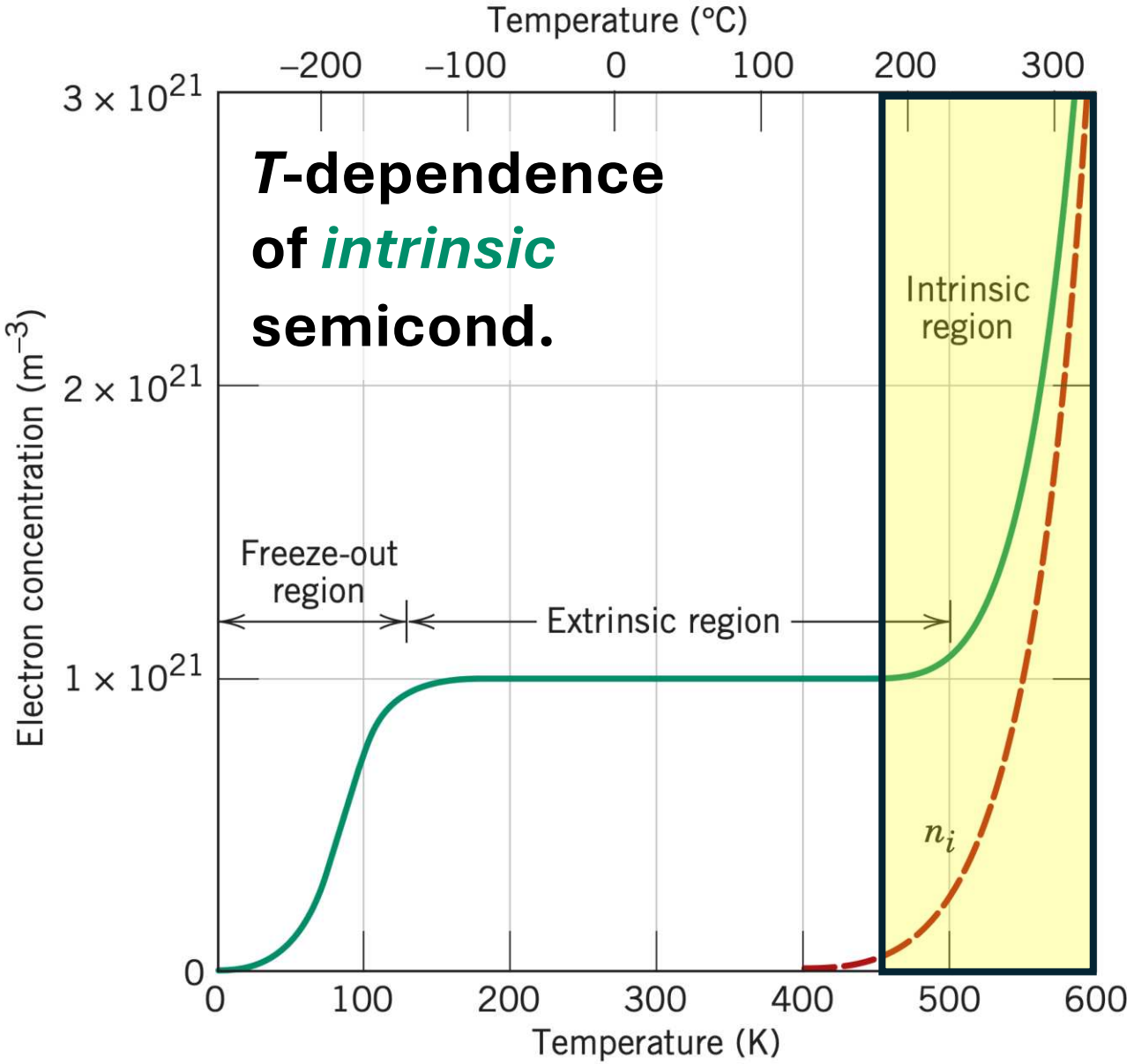
- Donor/acceptor excitations happen at low temperature
- **Then nothing happens for a while – constant conductivity**



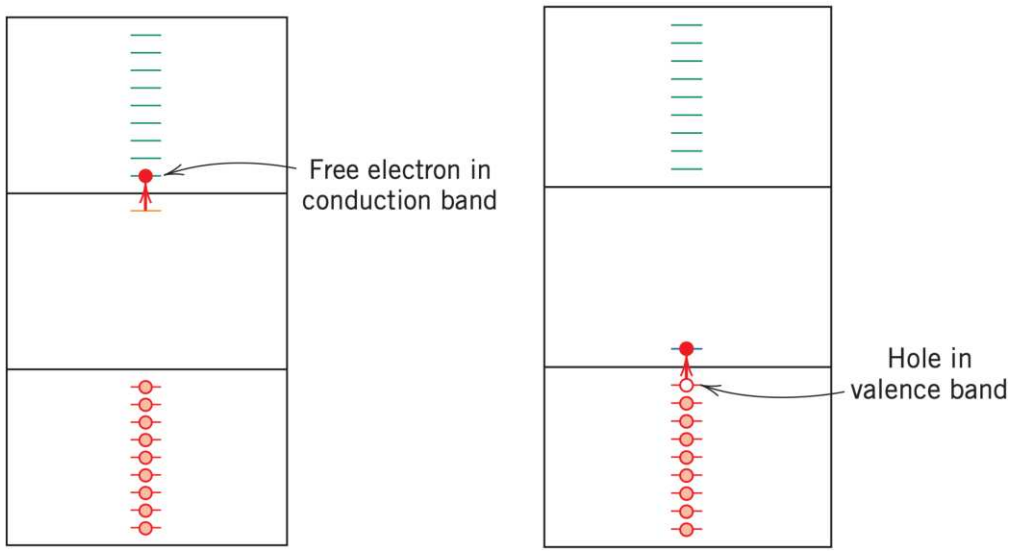
Intrinsic *vs.* Extrinsic semiconductors



- Donor/acceptor excitations happen at low temperature
- Then nothing happens for a while – constant conductivity
- **At very high temperature, electrons are excited from valence to conduction band**

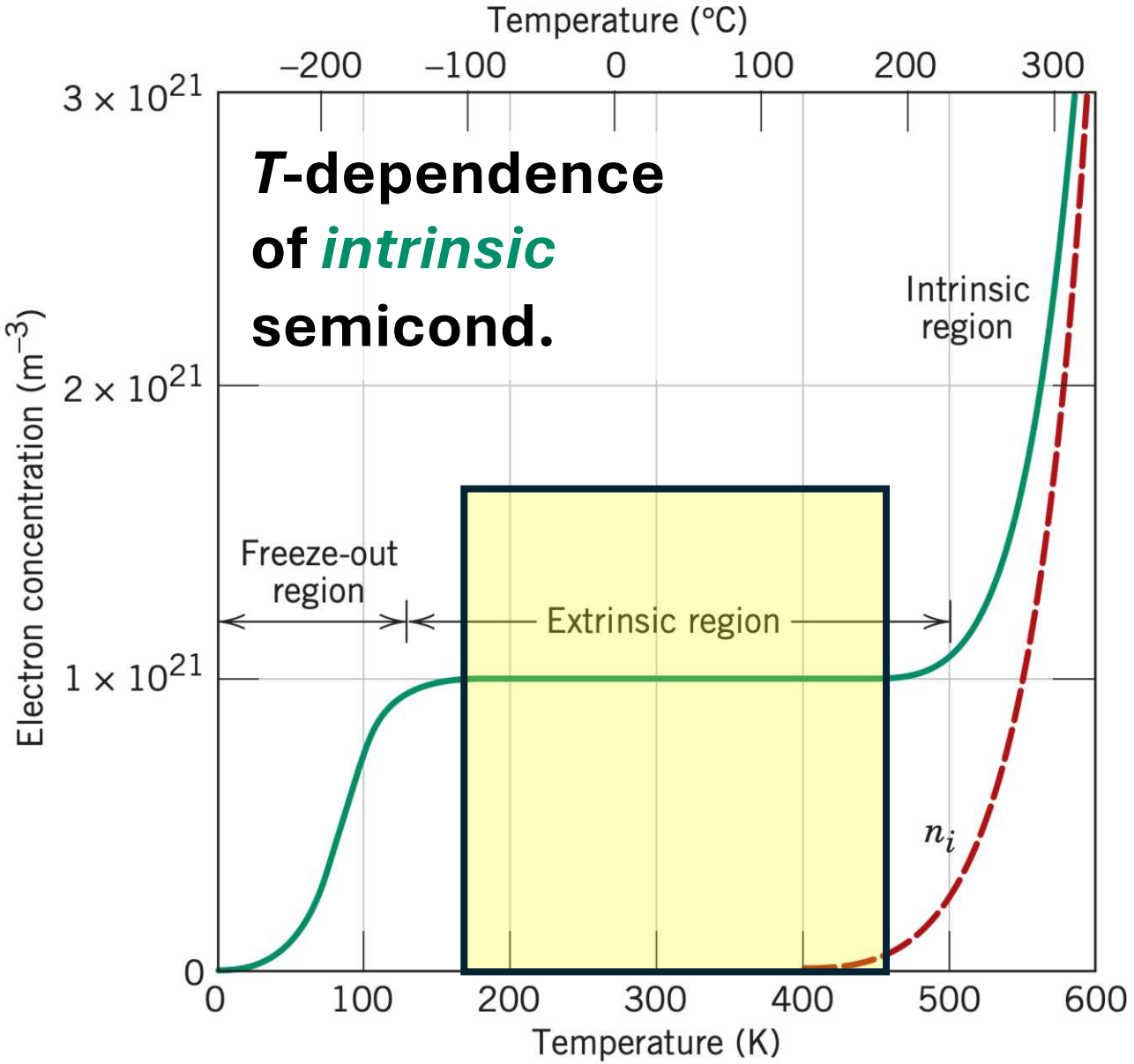


Intrinsic *vs.* Extrinsic semiconductors

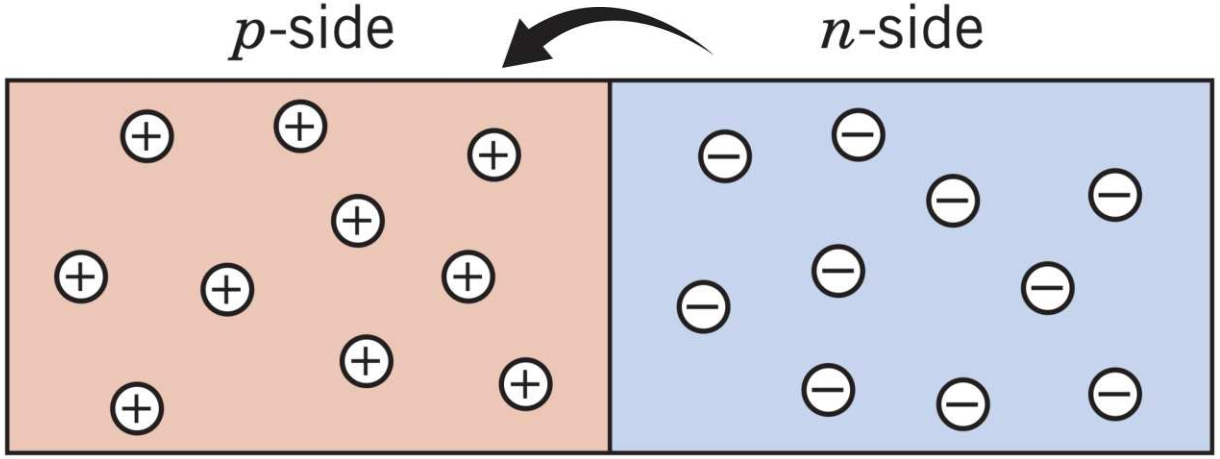


The extrinsic region is where most semiconductors are used. Conductivity is set by dopant concentration (we control it!)

Also common is to use *both* types of semiconductors (*n* + *p*) in a single device…

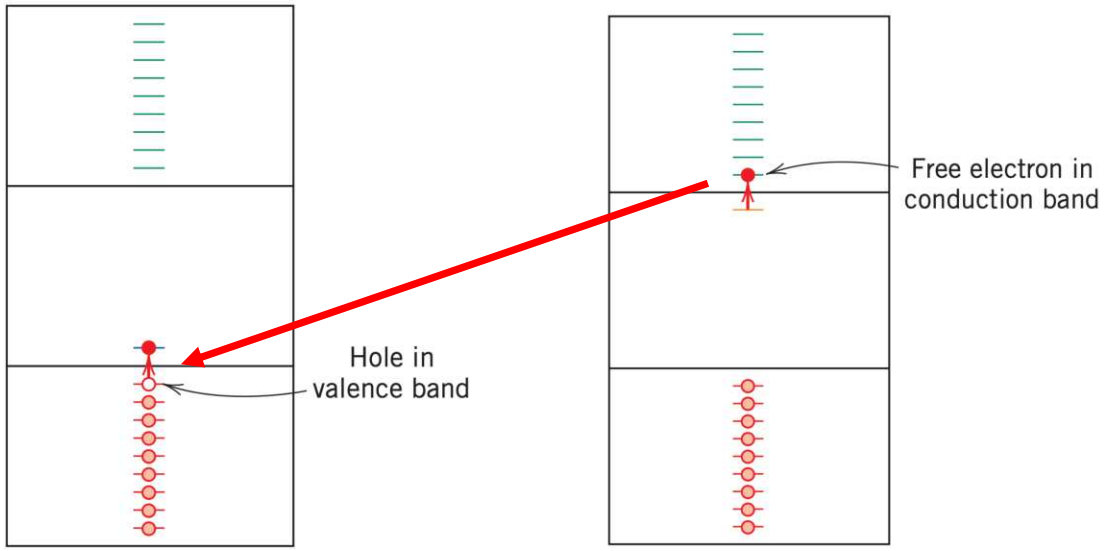


Semiconductor devices: the p-n junction



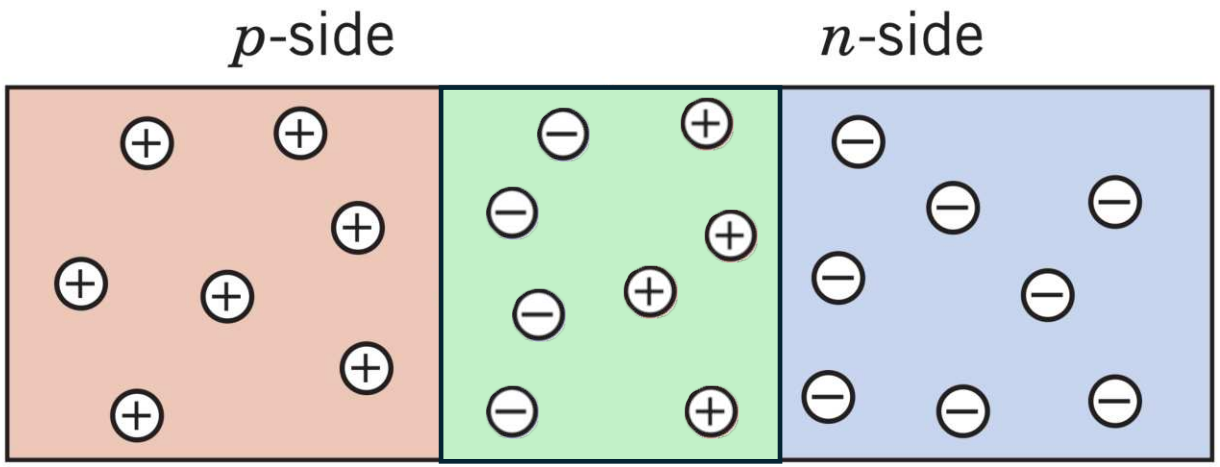
B^{3+}-doped Si (extra holes)

P^{5+}-doped Si (extra electrons)



As we put these two materials together, the electrons from the n-type side will want to move to the left and fill some of the holes on the p-type side → **recombination**

Semiconductor devices: the p-n junction



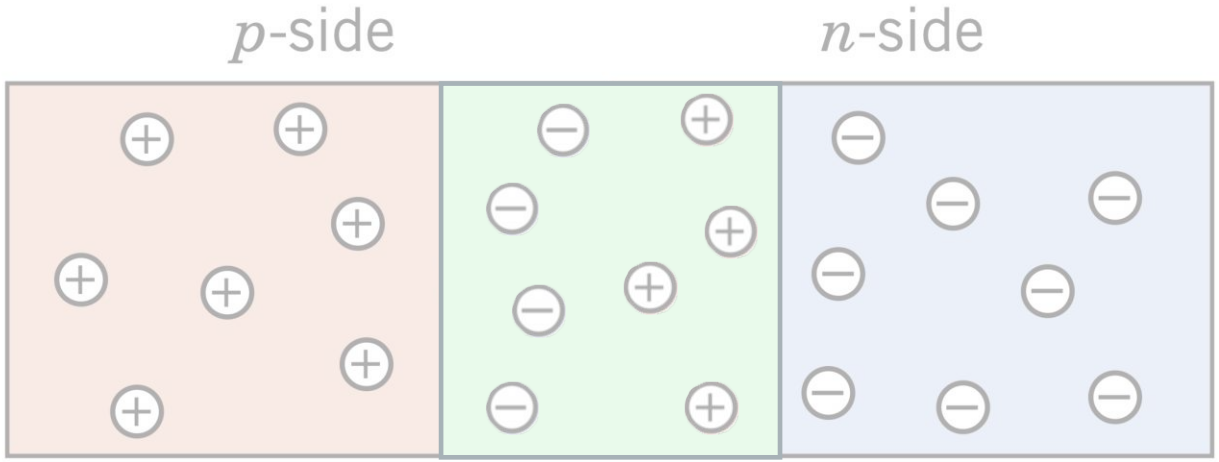
Depletion region



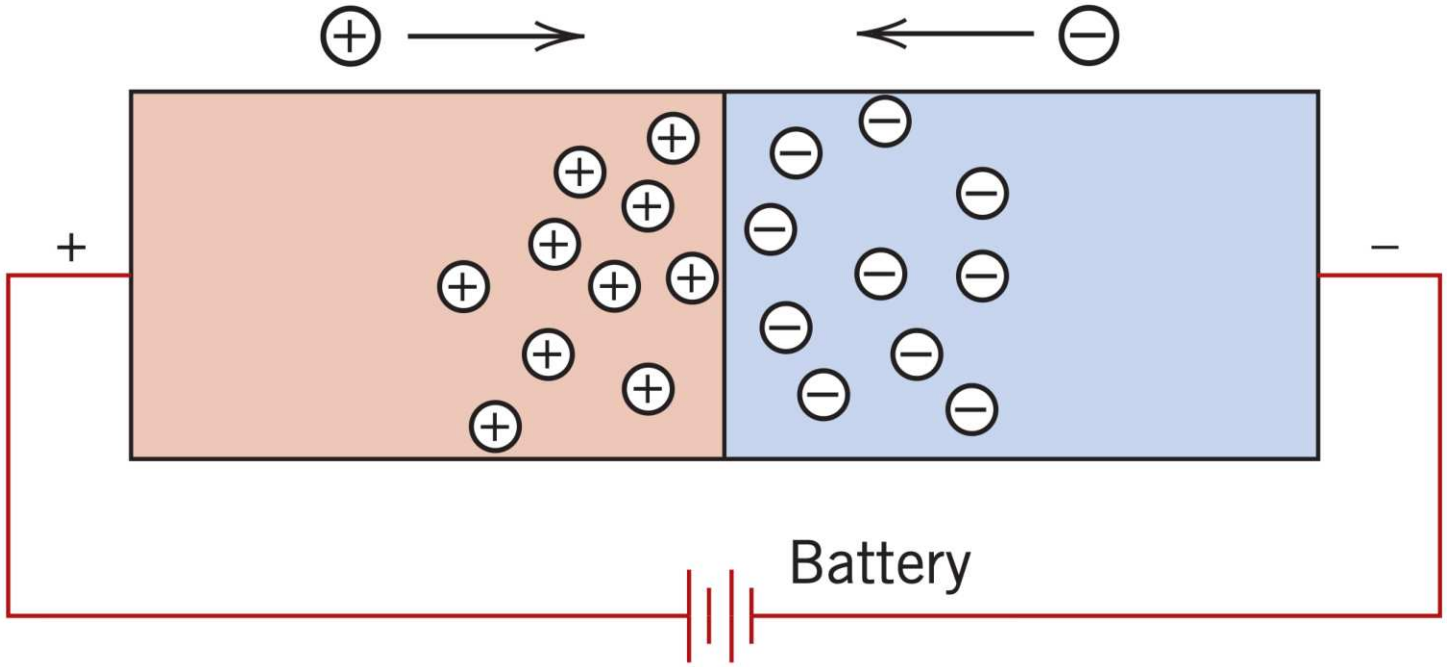
As this happens, **an electric field is established**, preventing further recombination *unless* some additional bias is applied.

As we put these two materials together, the electrons from the n-type side will want to move to the left and fill some of the holes on the p-type side → **recombination**

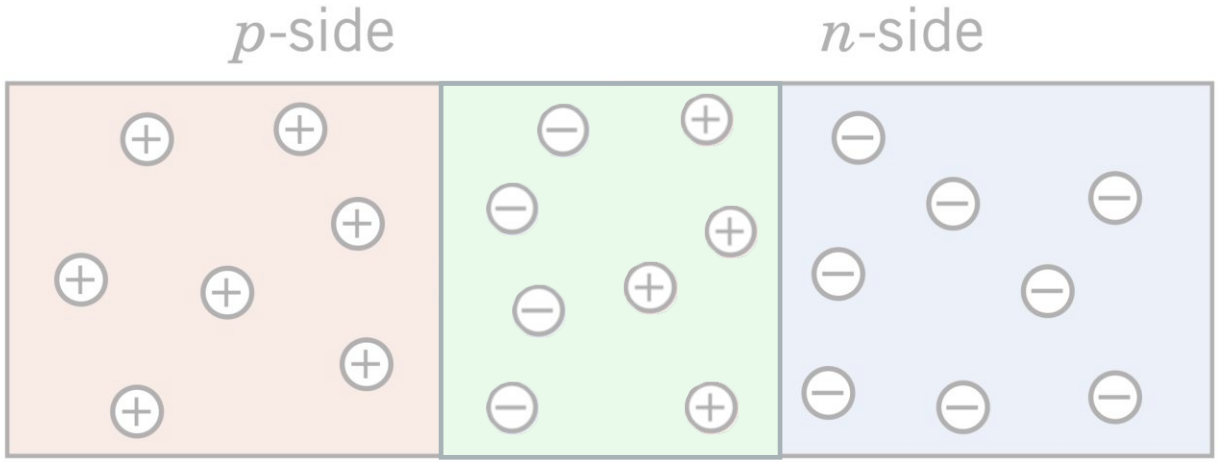
Semiconductor devices: the p-n junction



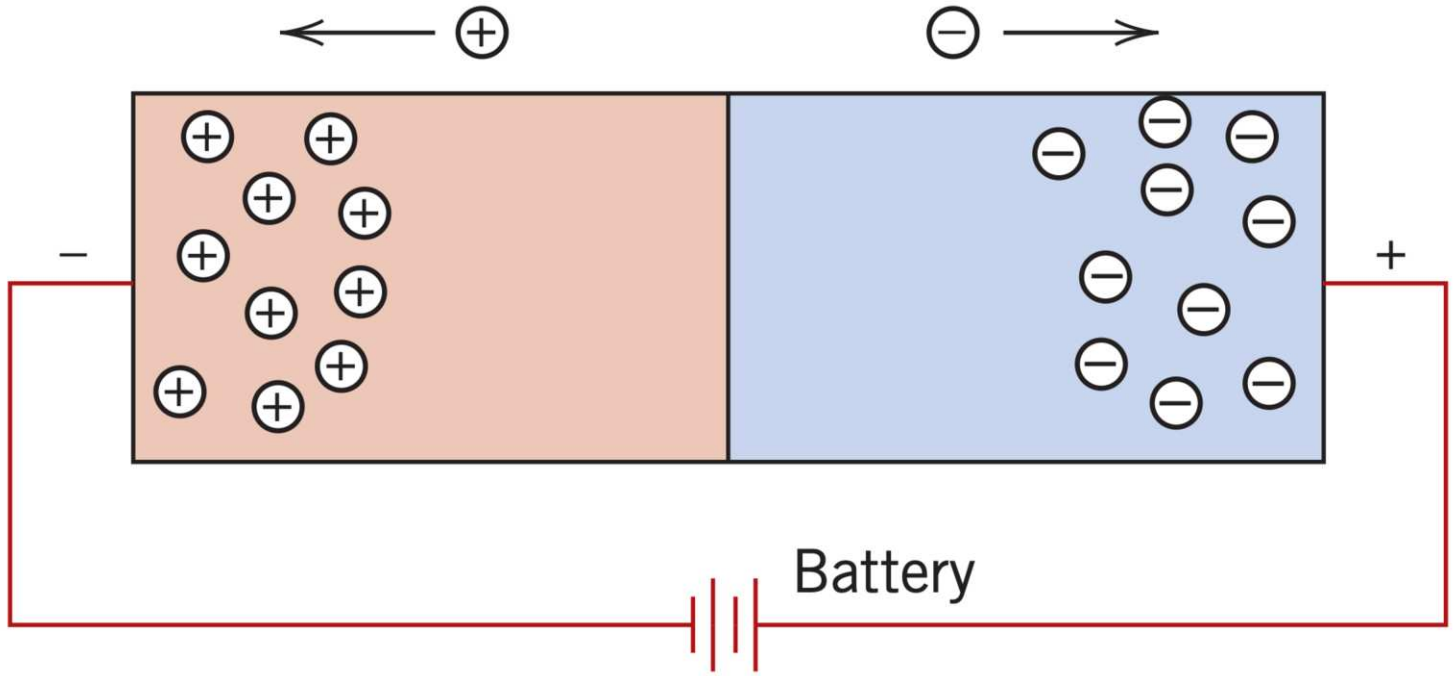
Forward bias: connect a positive voltage to the p-type material, shrinking the depletion region and **driving current**



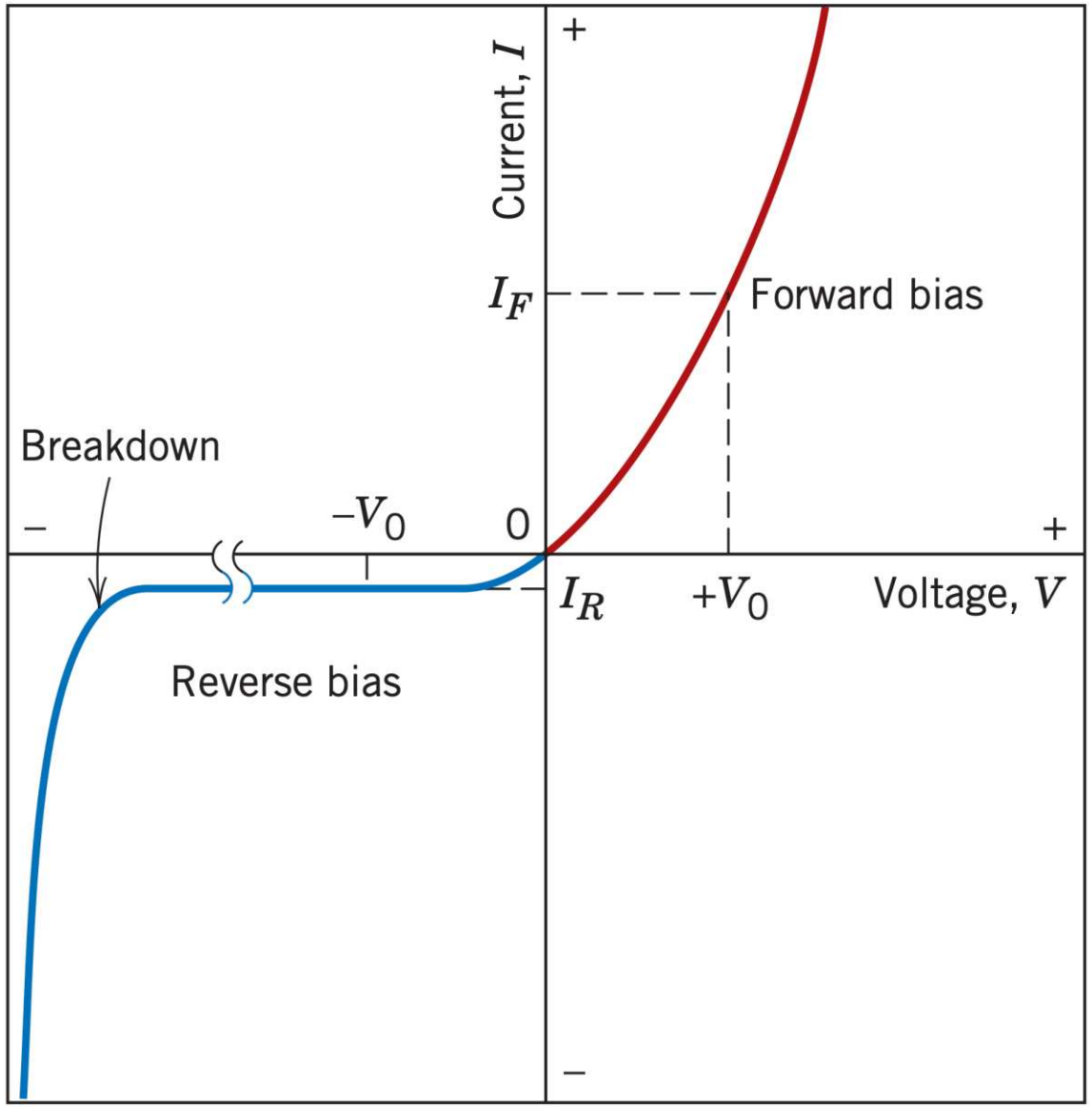
Semiconductor devices: the p-n junction



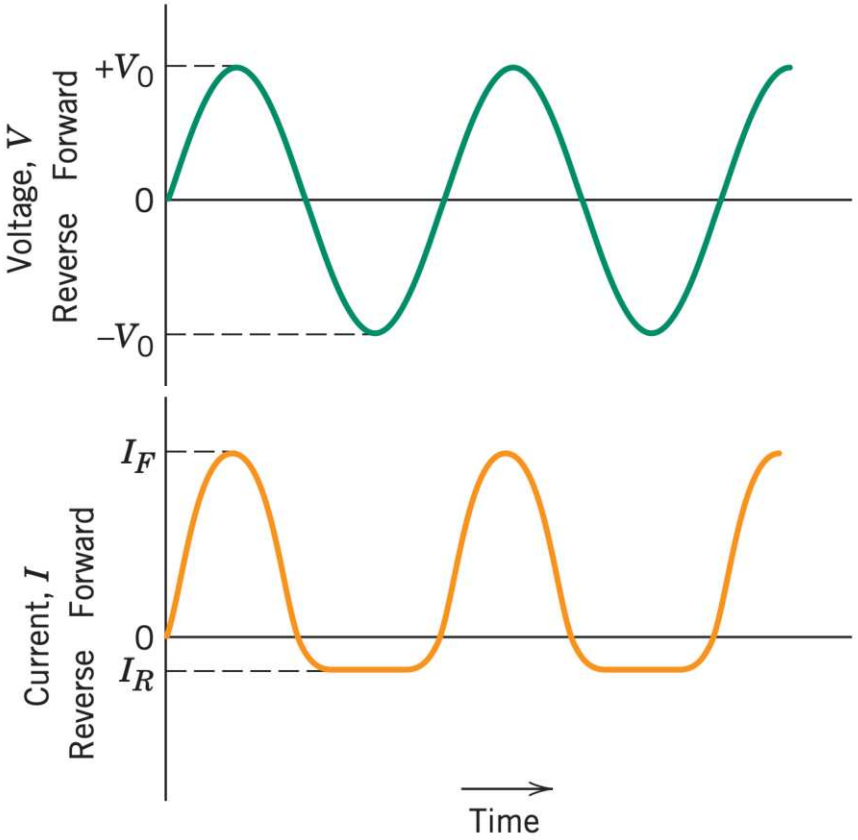
Reverse bias: connect a *negative* voltage to the p-type material, expanding the depletion region **leading to almost no current**



Semiconductor devices: the p-n junction



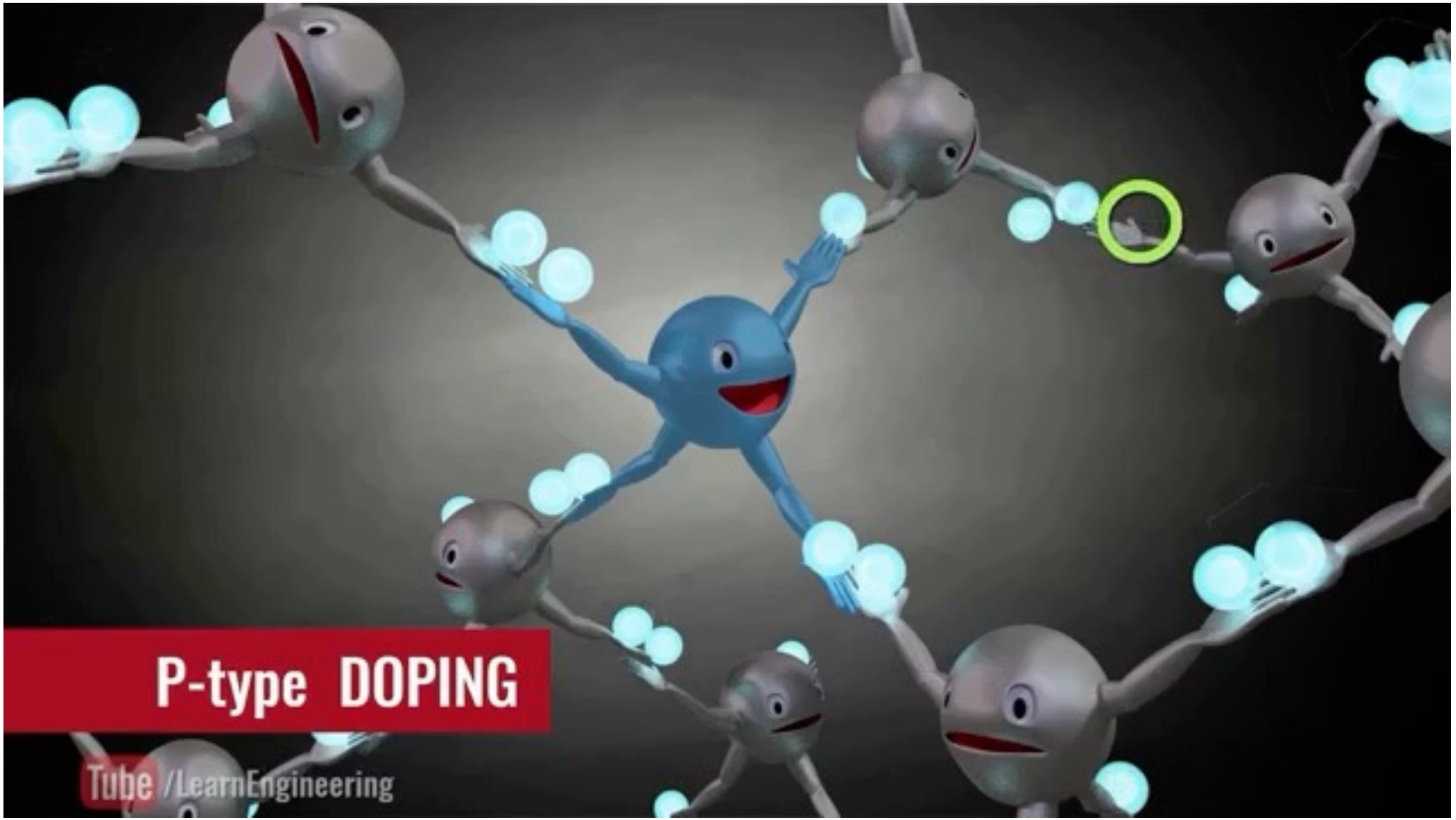
The p-n junction is useful because it lets current flow in one direction, but not the other



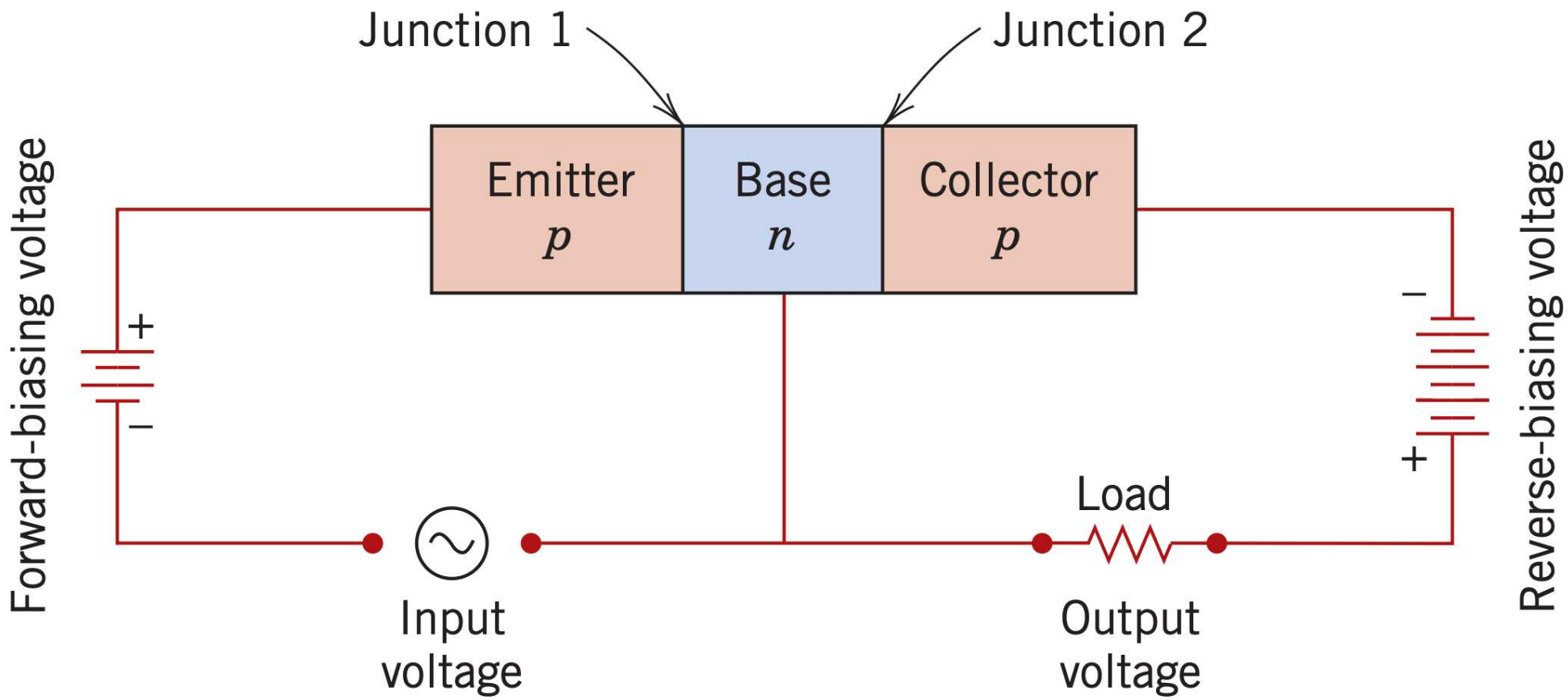
Acts as a **rectifying junction or *diode***

AC ↔ DC (sort of)

Semiconductor devices: the p-n junction



Semiconductor devices: the p-n-p junction

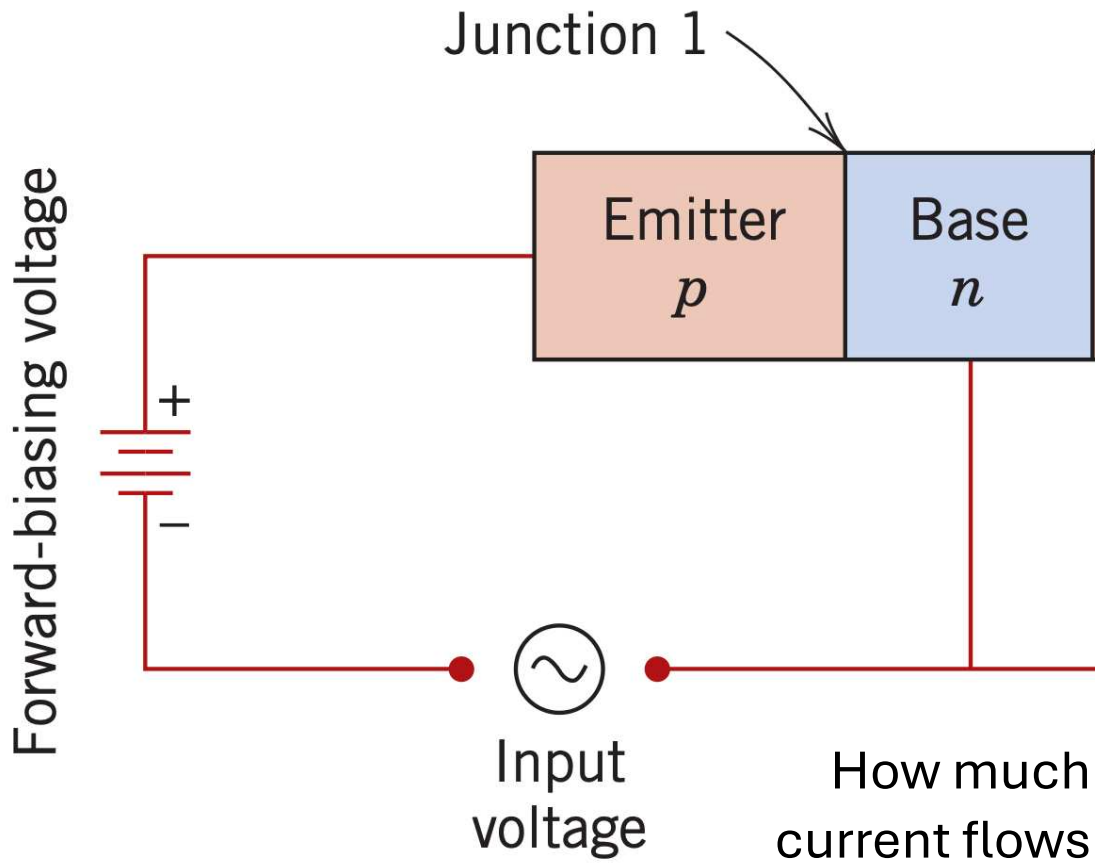


Junction 1 is placed in **forward bias**

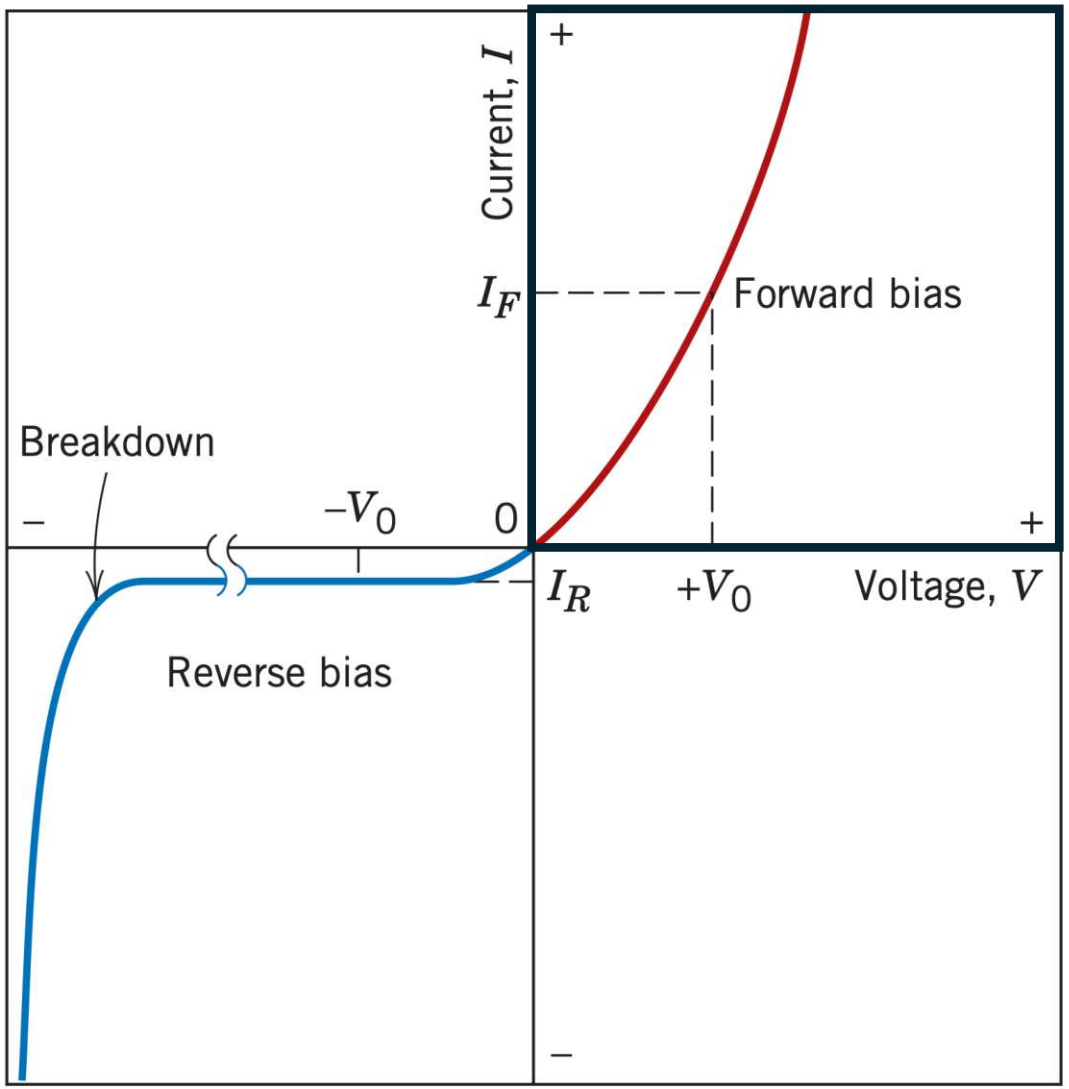
The middle (n-type) layer is very thin

Junction 2 is placed in **reverse bias**

Semiconductor devices: the p-n-p junction

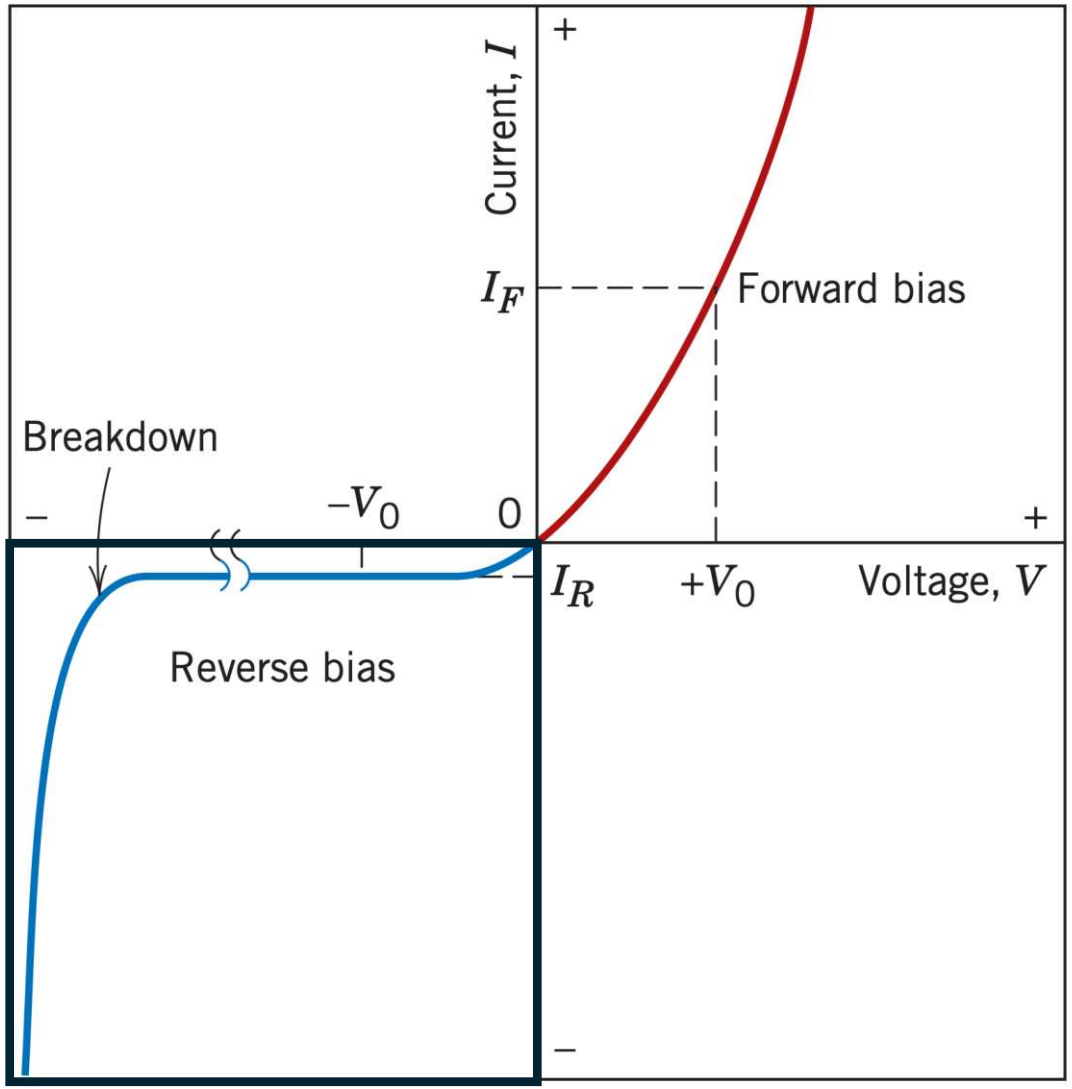


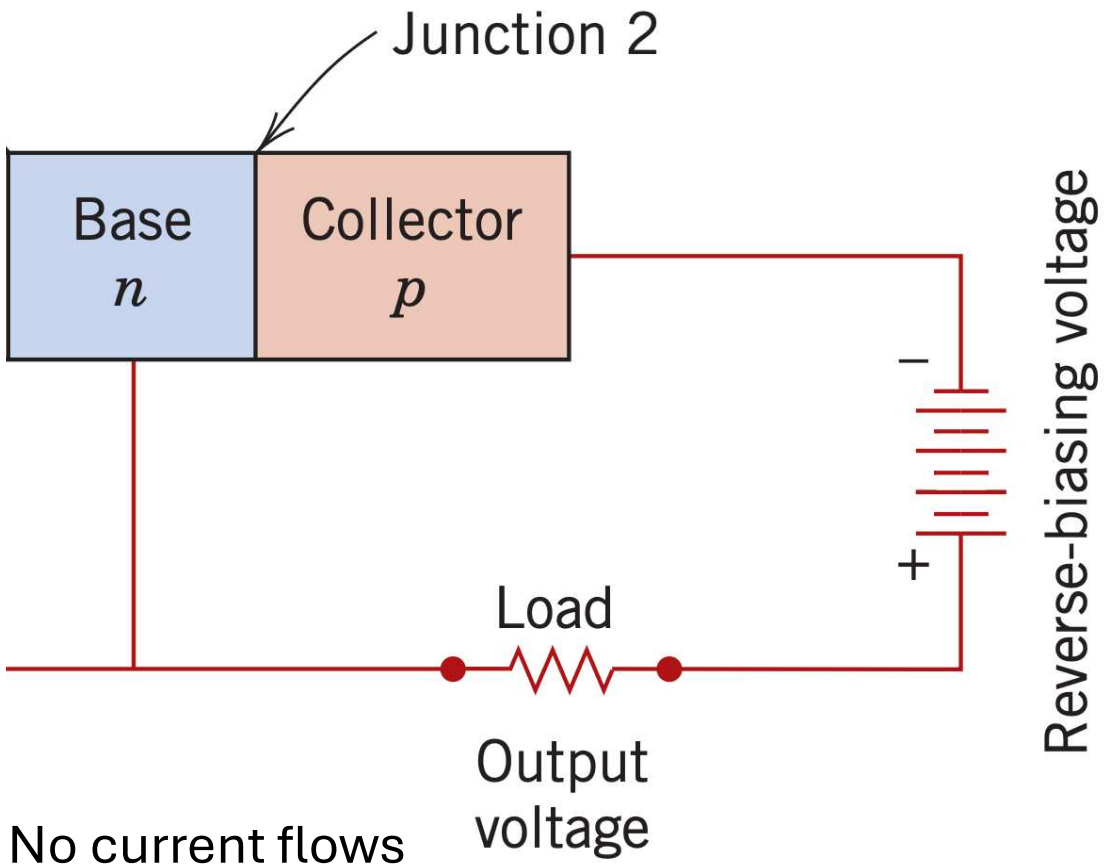
How much current flows depends on what voltage we apply



Junction 1 is placed in **forward bias**

Semiconductor devices: the p-n-p junction



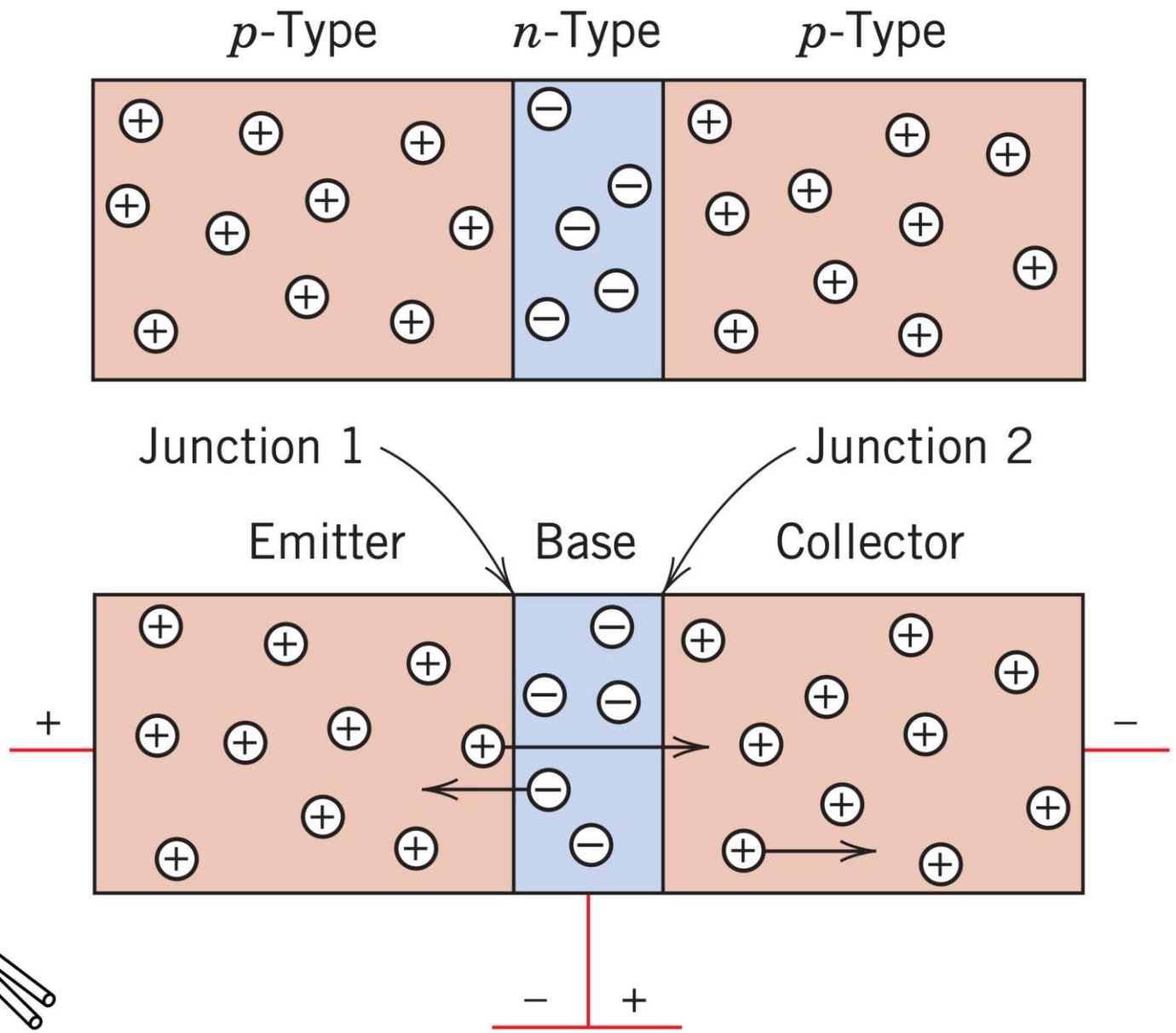


No current flows *unless* we provide holes from the first junction*

Junction 2 is placed in **reverse bias**

*We can essentially turn the base from *n*-type into *p*-type

Semiconductor devices: the p-n-p junction



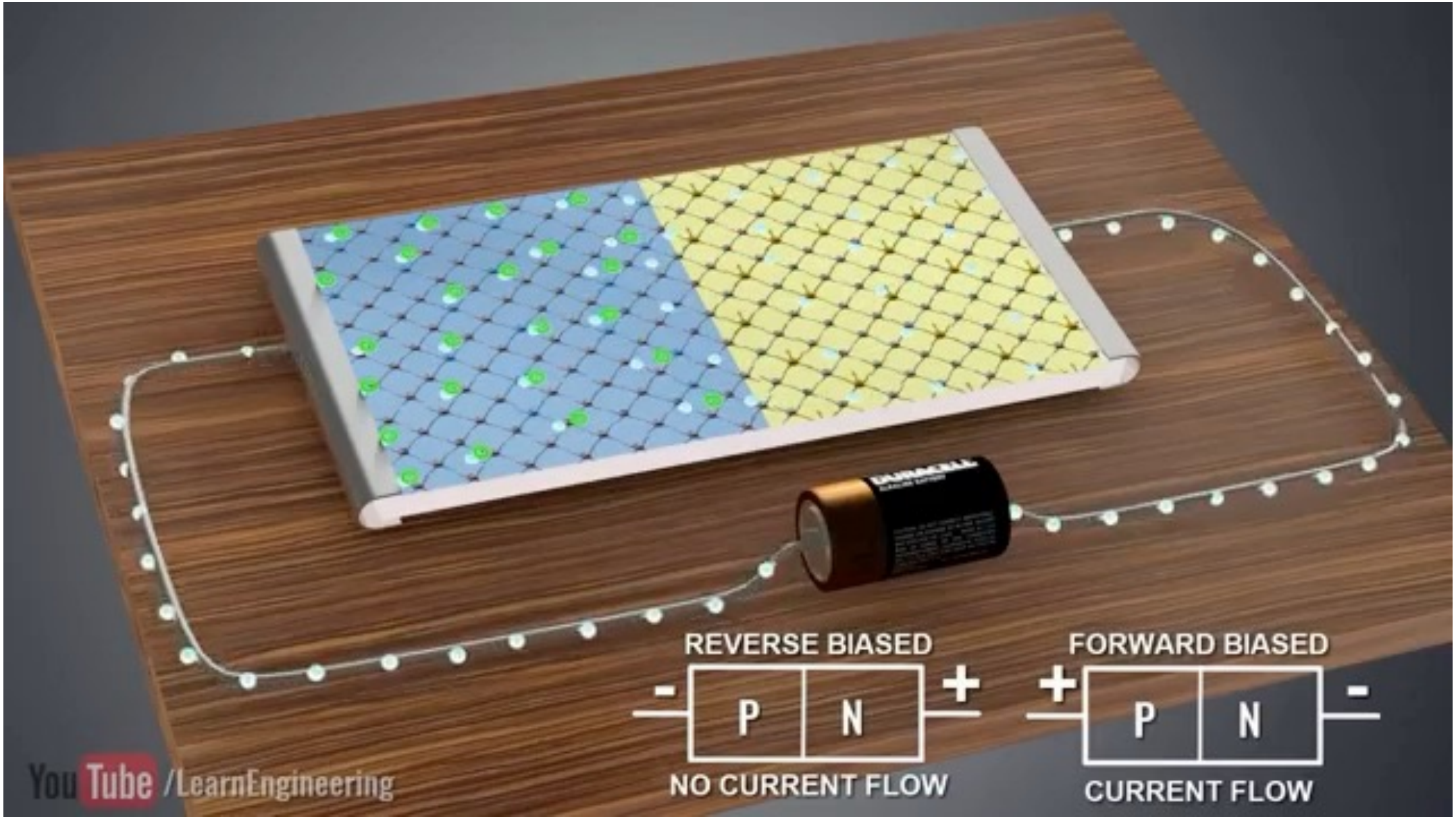
Holes get pushed from the emitter (left) to the base (middle) and cause recombination

The more we shrink the depletion region, the more current flows through the 2nd circuit into the collector (right)

Small changes to the input (left) lead to *large* changes in the output current (right)

→ **amplification!**

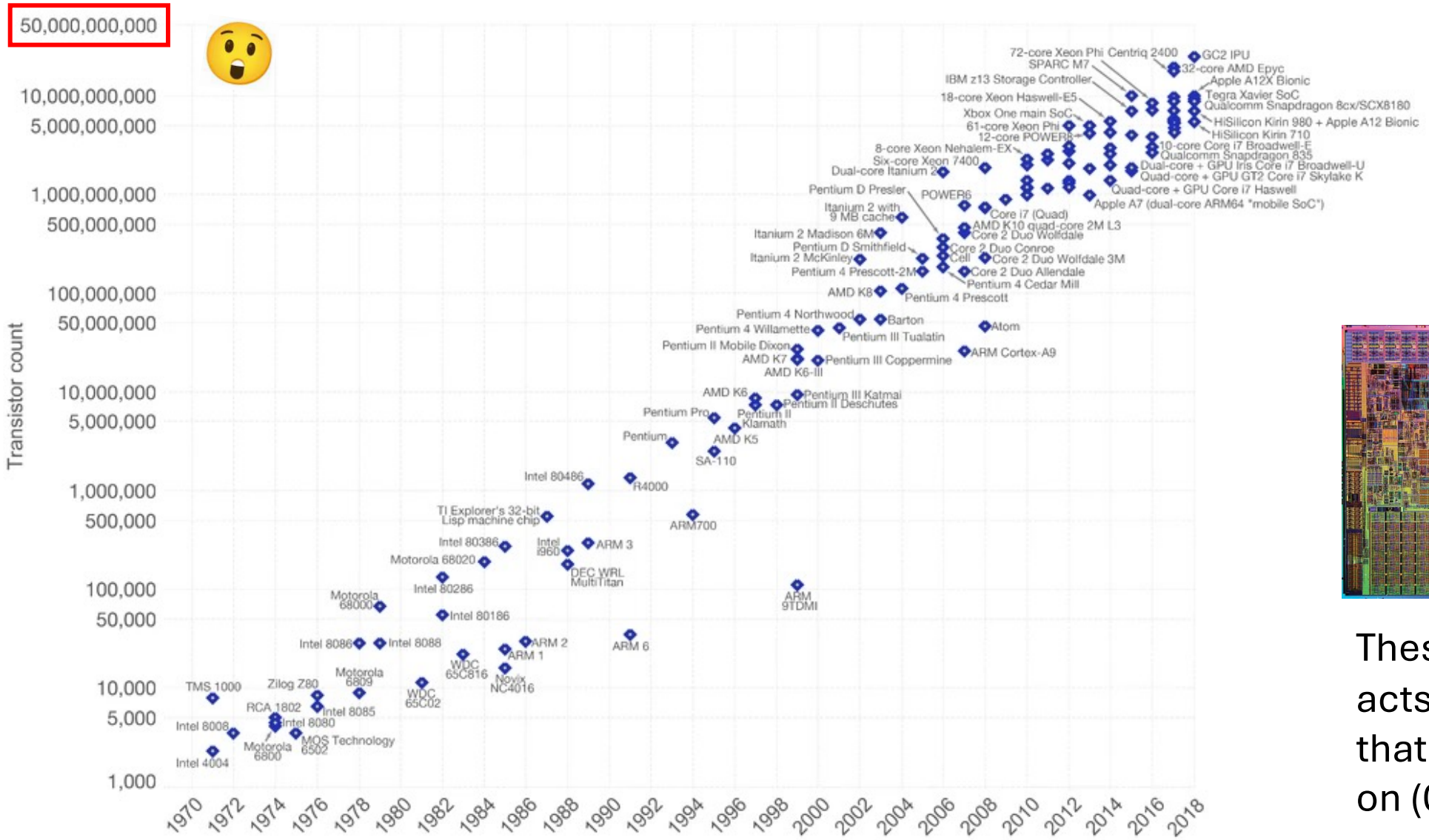
This is more commonly known as a *transistor*

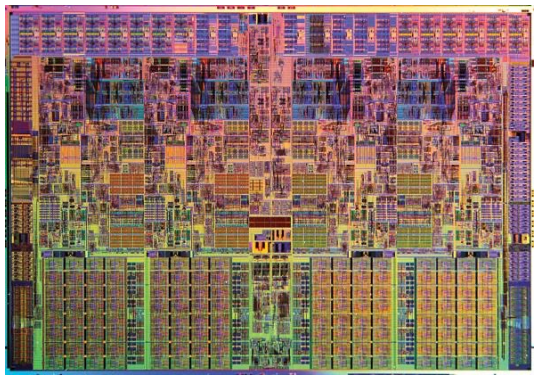


Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.

Our World in Data

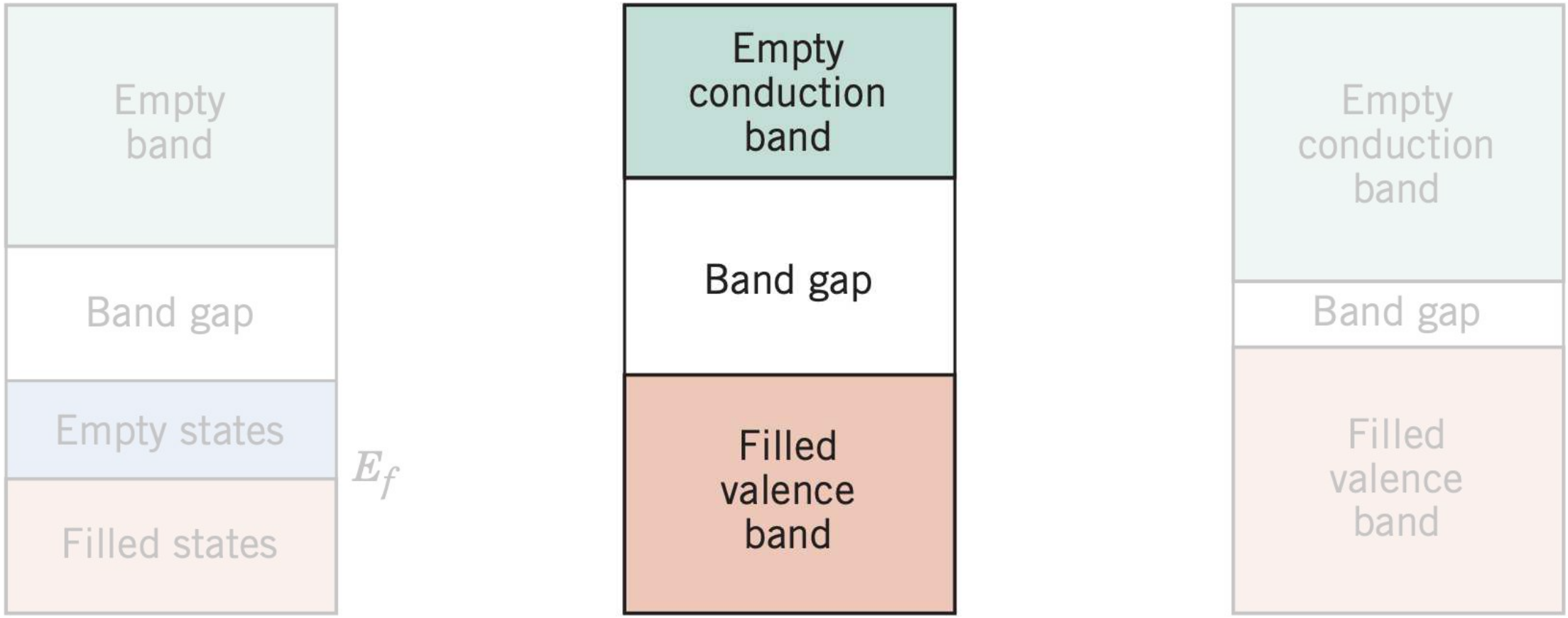




These transistors acts as "switches" that can be turned on (0) or off (1)

Questions?

Three classes of materials:
In terms of electrical conduction

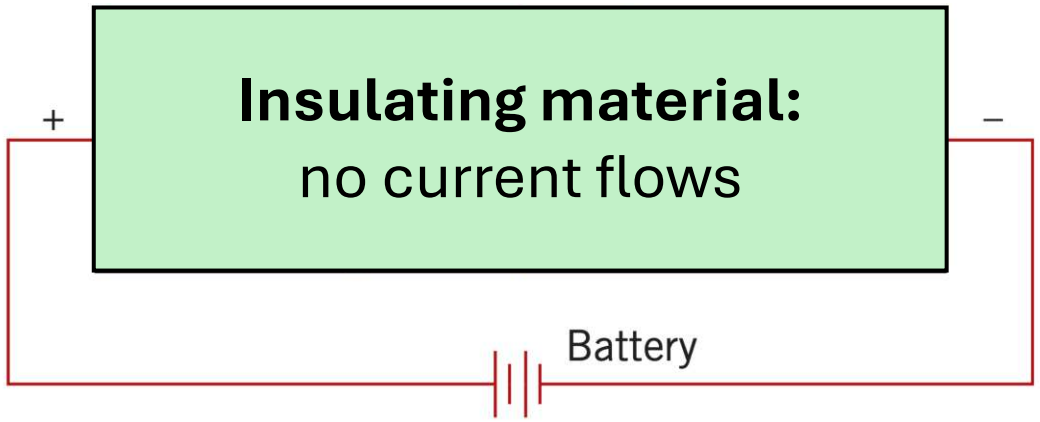


Metals

Insulators

Semiconductors

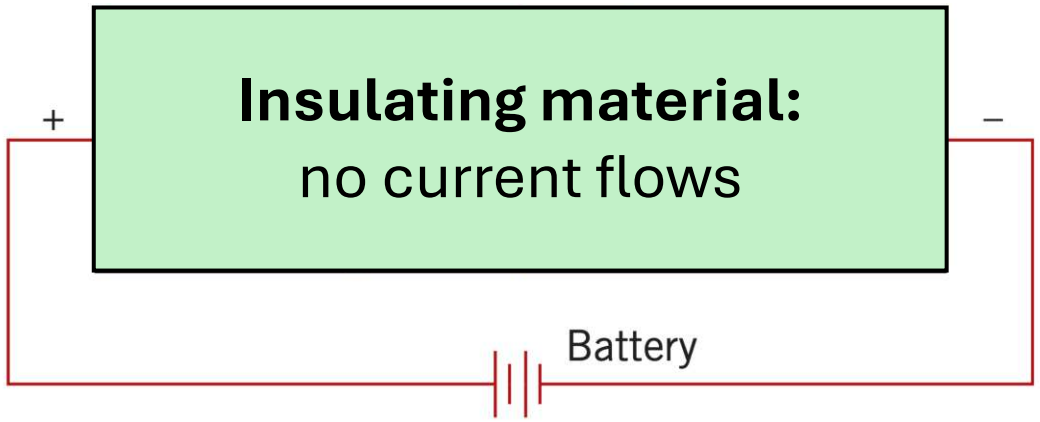
Dielectric materials



Insulators have virtually zero conductivity: $\sigma < 10^{-10}$ **S/m**

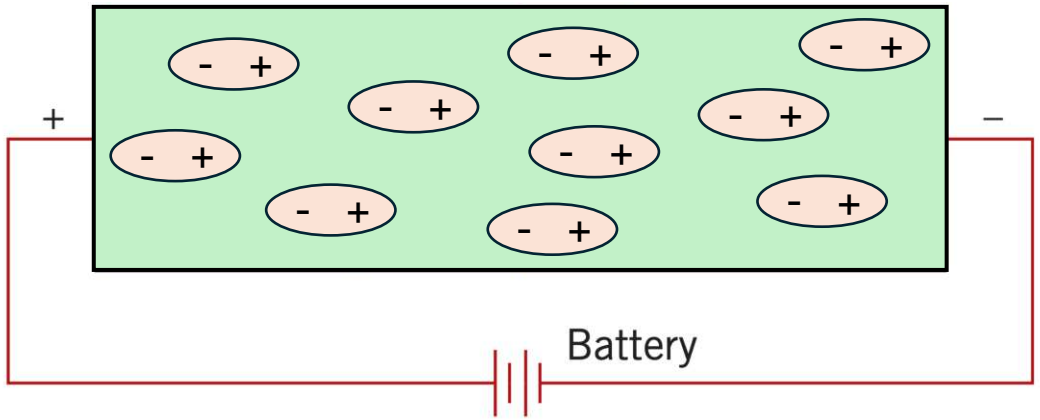
They don't *conduct* charge. But some insulators known as **dielectrics can *store* quite a bit of charge through polarization.**

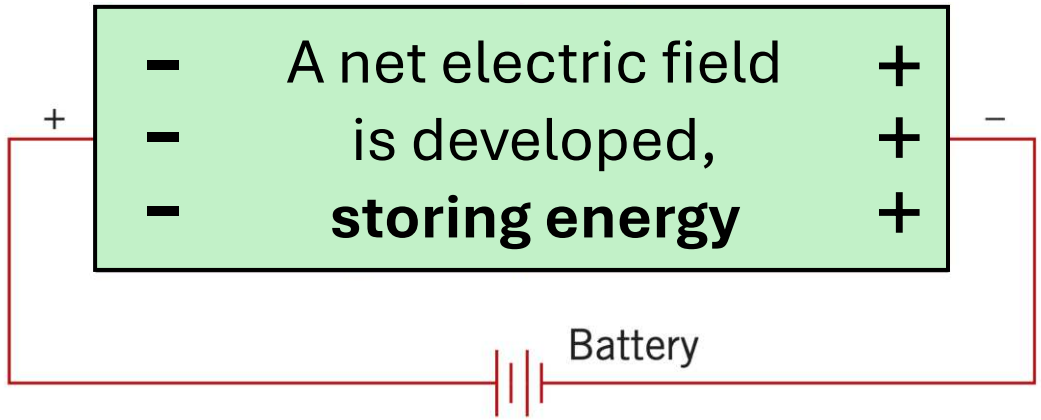
Dielectric materials



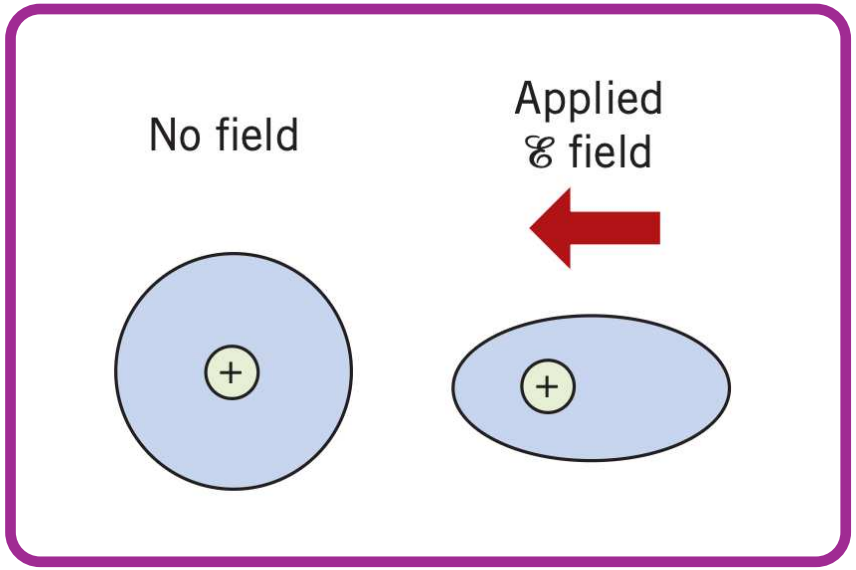
Insulators have virtually zero conductivity: $\sigma < 10^{-10}\ (\Omega \cdot \mathrm{m})^{-1}$

They don't *conduct* charge. But some insulators known as **dielectrics can *store* quite a bit of charge through polarization.**

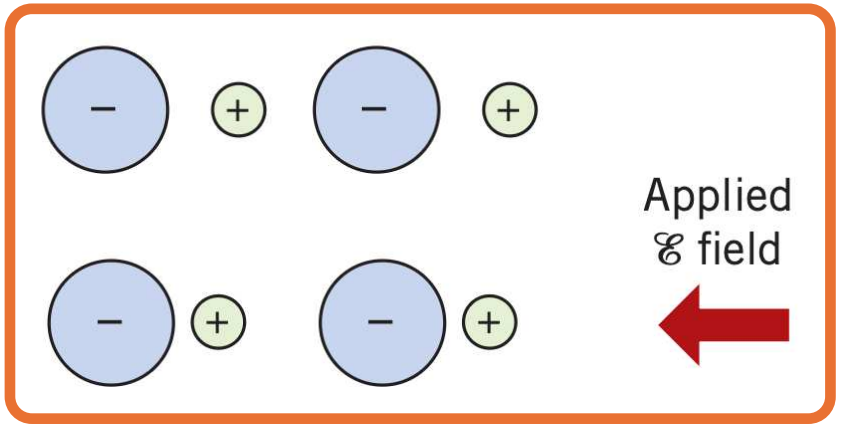


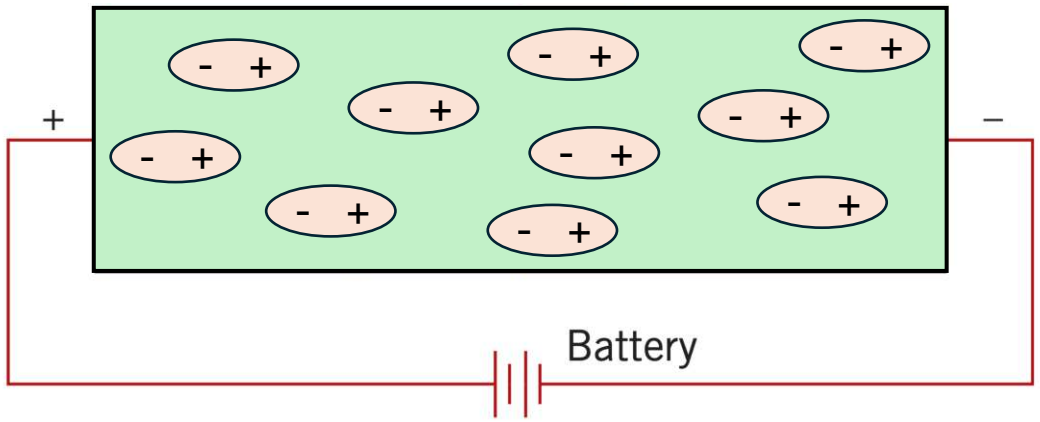


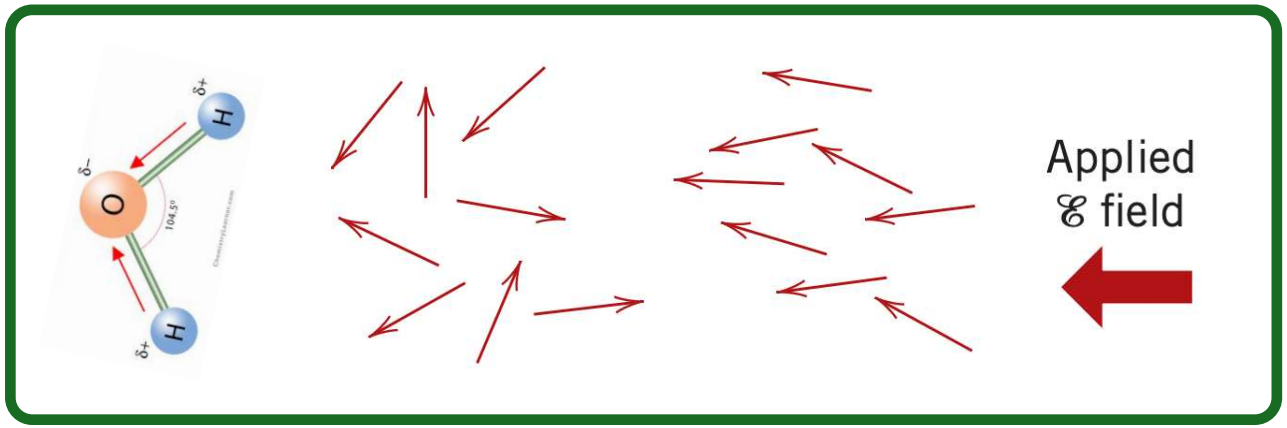
Dielectric materials: types of polarization



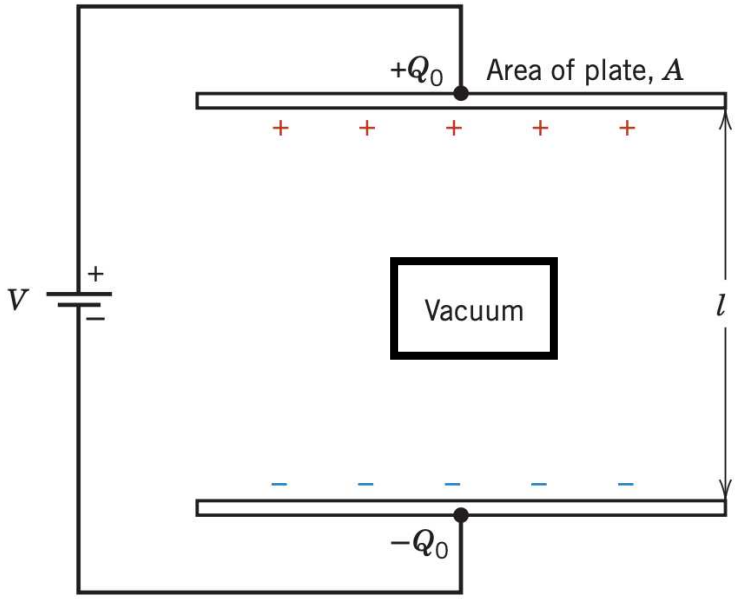
There are a few different **types of polarization** that dielectrics may exhibit: **electronic**, **ionic**, and **orientational**





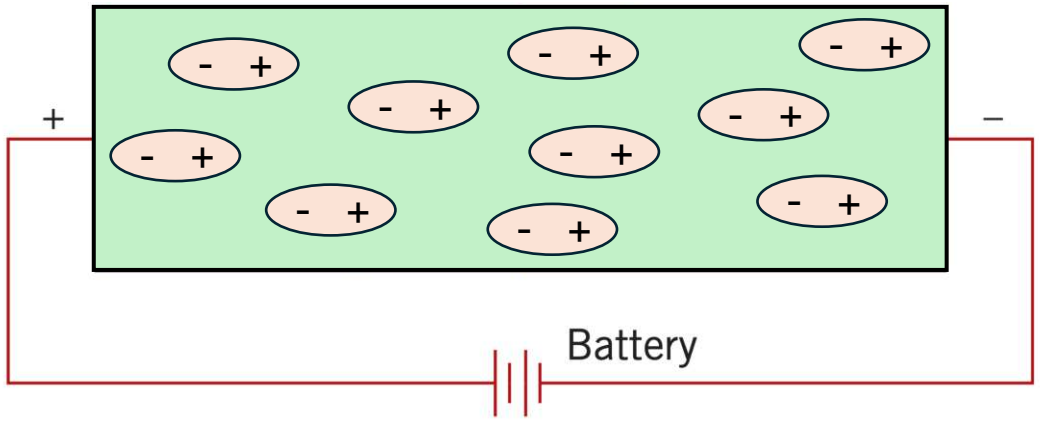


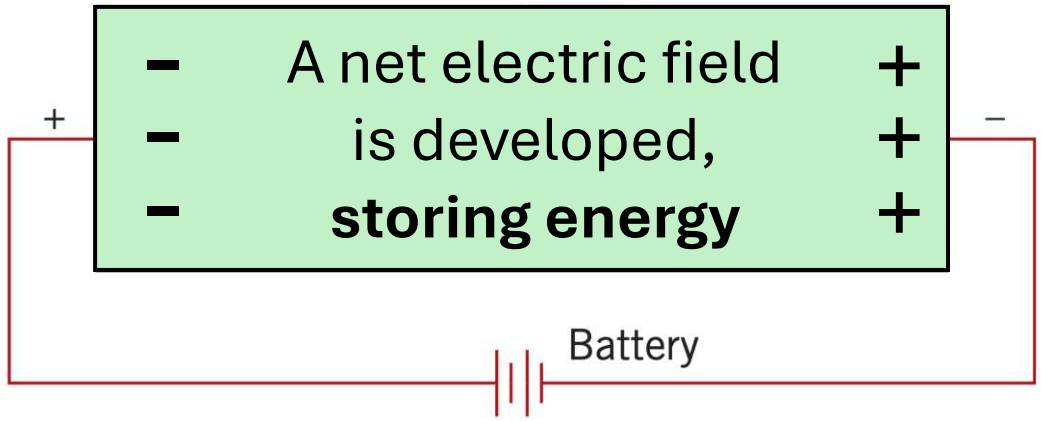
Dielectric materials: capacitance



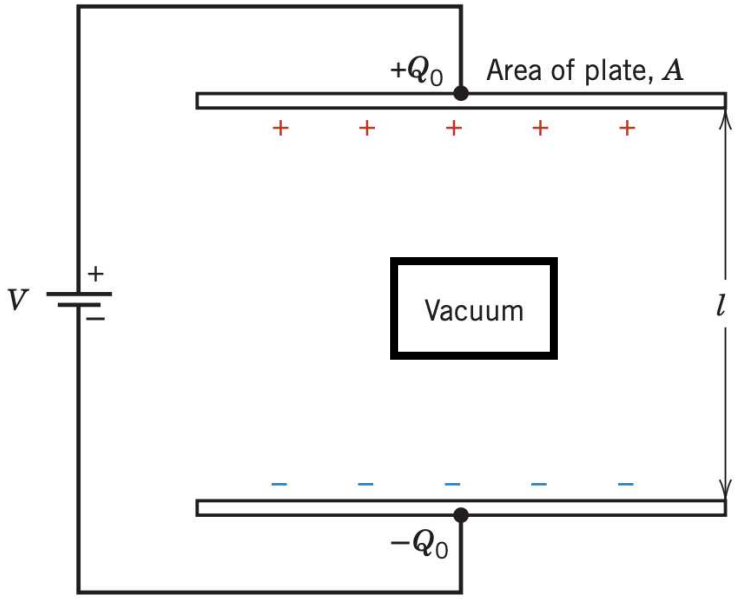
Consider two plates connected to a circuit but with a thin layer of vacuum between them.

Some charge will accumulate on either plate. **Capacitance** measures how much charge is stored at a given voltage: $\boldsymbol{C = Q/V = \varepsilon_0(A/l)}$





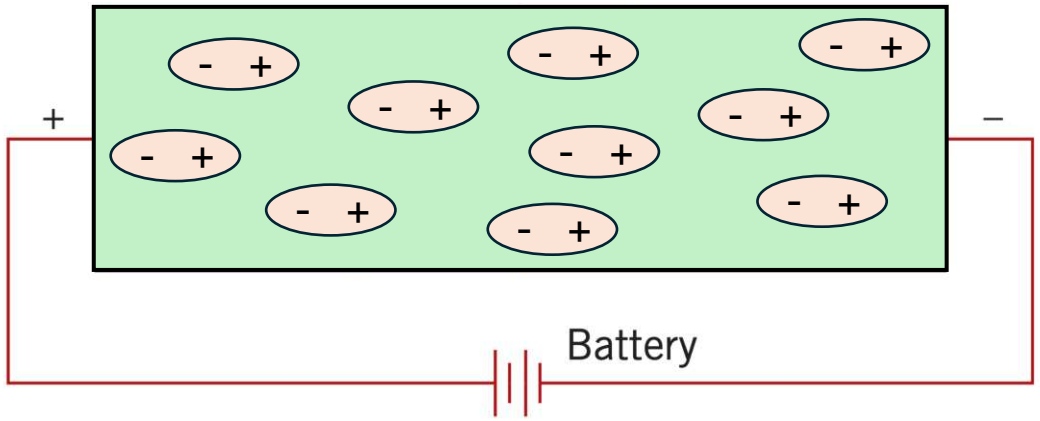
Dielectric materials: capacitance



Consider two plates connected to a circuit but with a thin layer of vacuum between them.

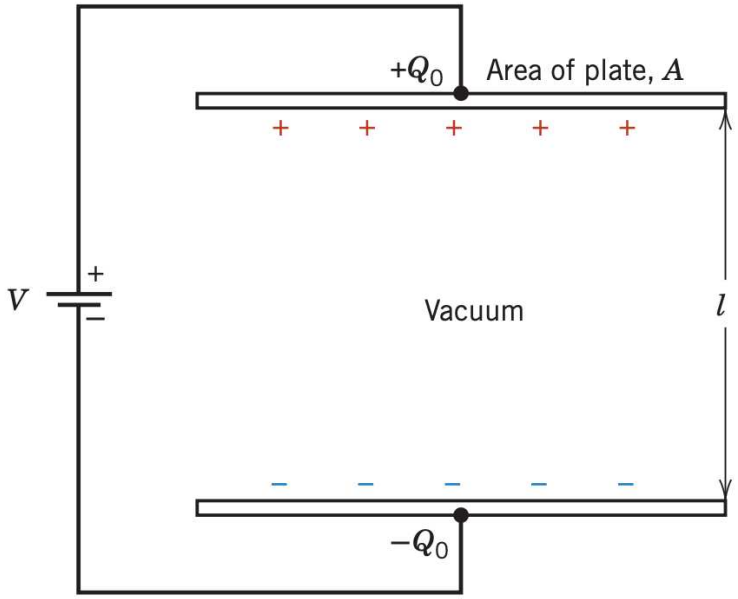
Some charge will accumulate on either plate. **Capacitance** measures how much charge is stored at a given voltage: $\boldsymbol{C = Q/V = \varepsilon_0(A/l)}$

This is the **permittivity** of the vacuum (a fixed constant).

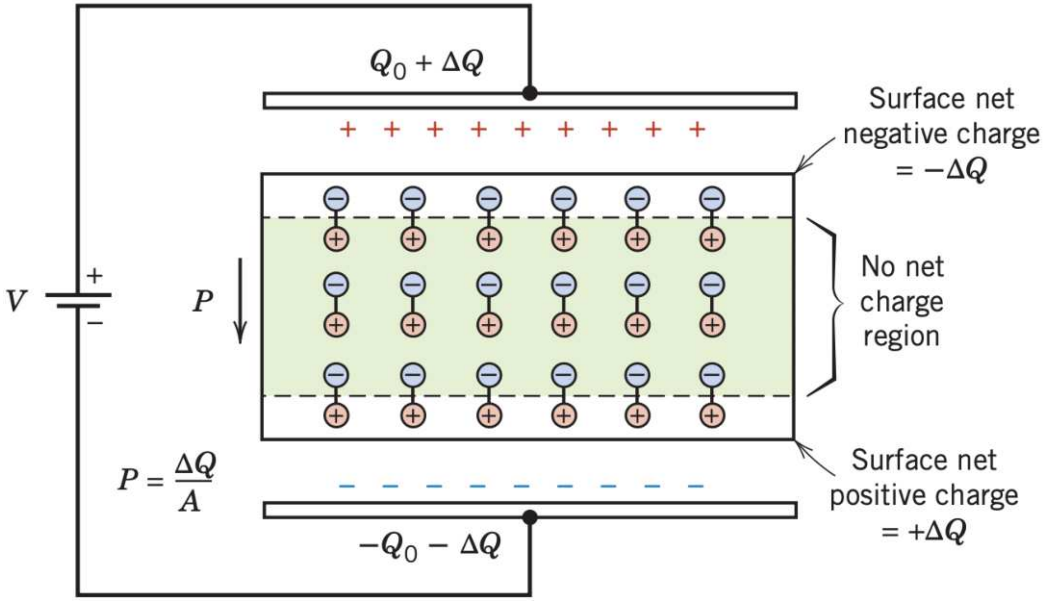


But what if we replaced the vacuum by a dielectric material?

Dielectric materials: capacitance



Vacuum replaced by dielectric that can help store charge.

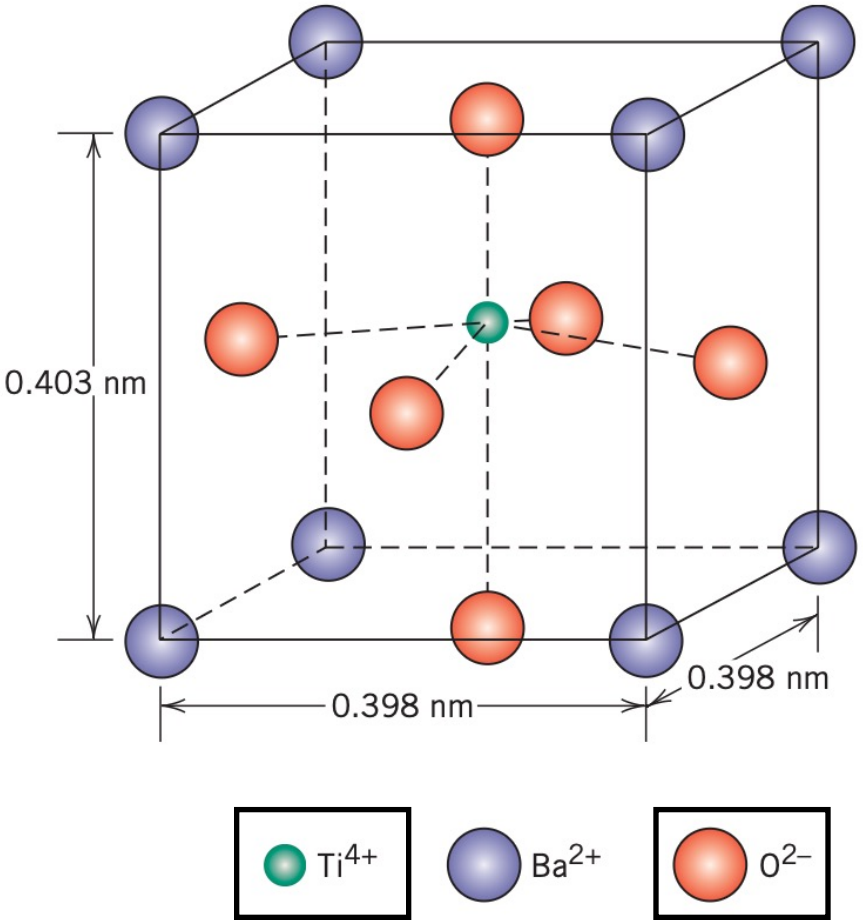


The capacitance will be increased: $\boldsymbol{C = Q/V = \varepsilon\,(A/l)}$

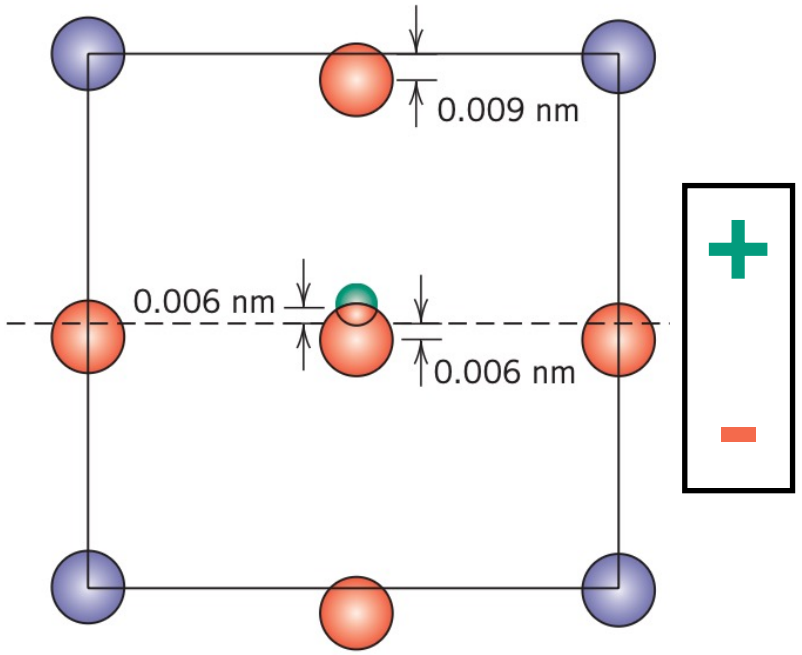
$\boldsymbol{\varepsilon > \varepsilon_0}$

$\boldsymbol{\varepsilon_r = \varepsilon/\varepsilon_0}$ is known as the dielectric constant. We want it to be high to store lots of charge and energy.

Another interesting class of insulators: ferroelectrics



These are materials that exhibit a **spontaneous ionic polarization**



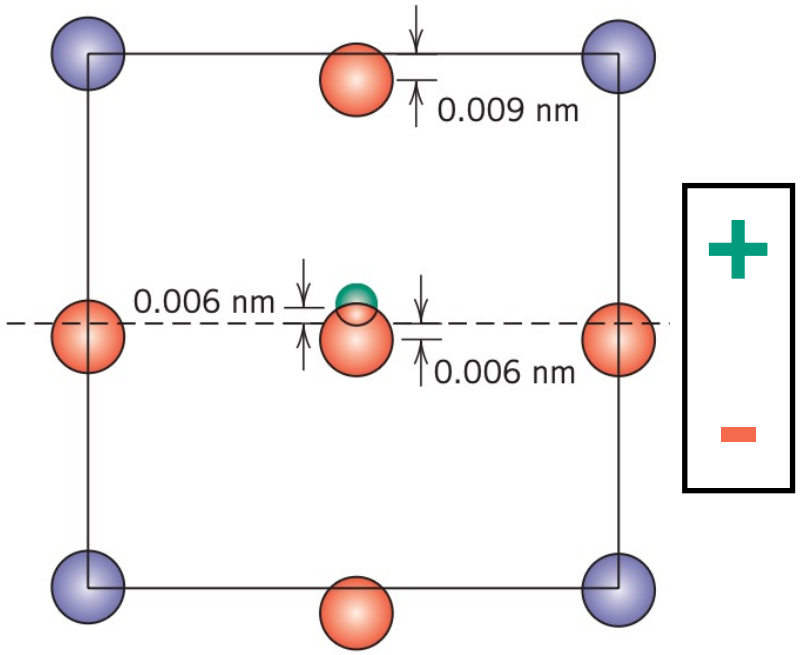
Asymmetry of ions in the unit cell leads to a **permanent dipole**

Another interesting class of insulators: ferroelectrics

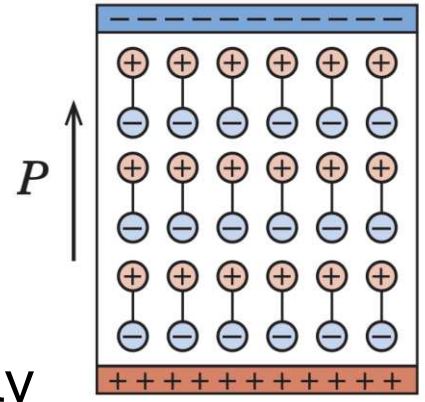


Ferroelectric RAM

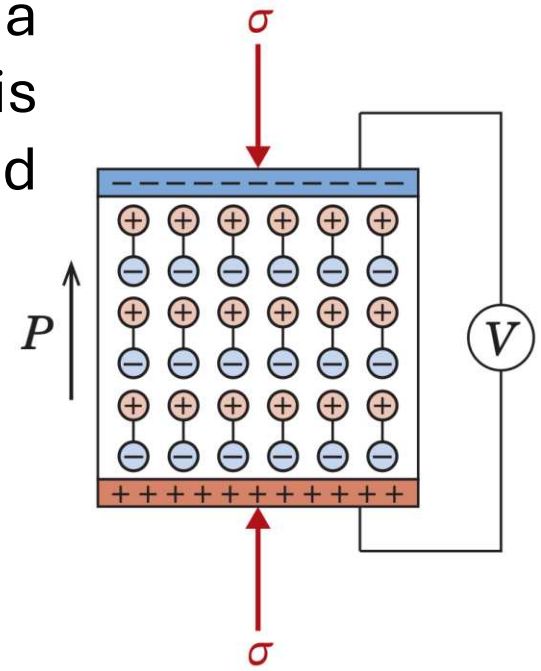
This dipole moment can be “flipped” through application of an electric field → **memory/storage**



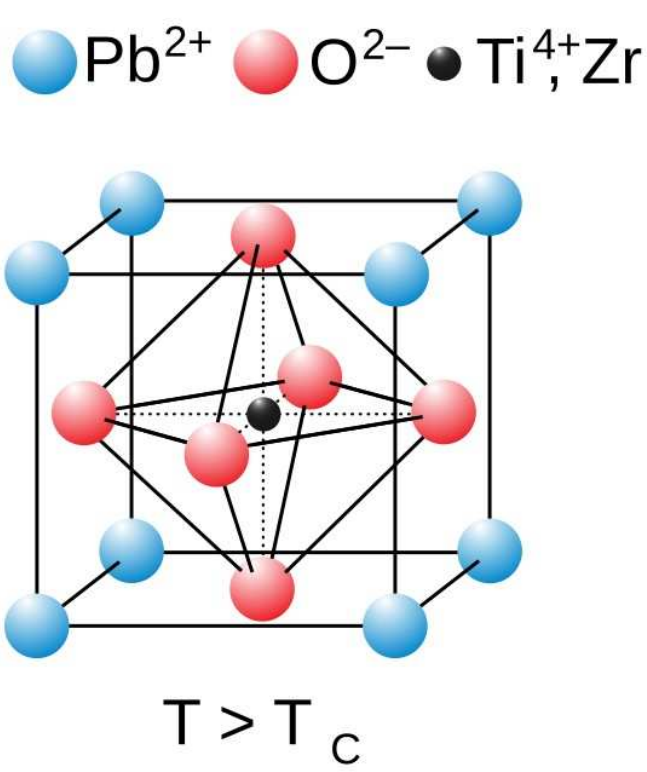
Another interesting class of insulators: piezoelectrics

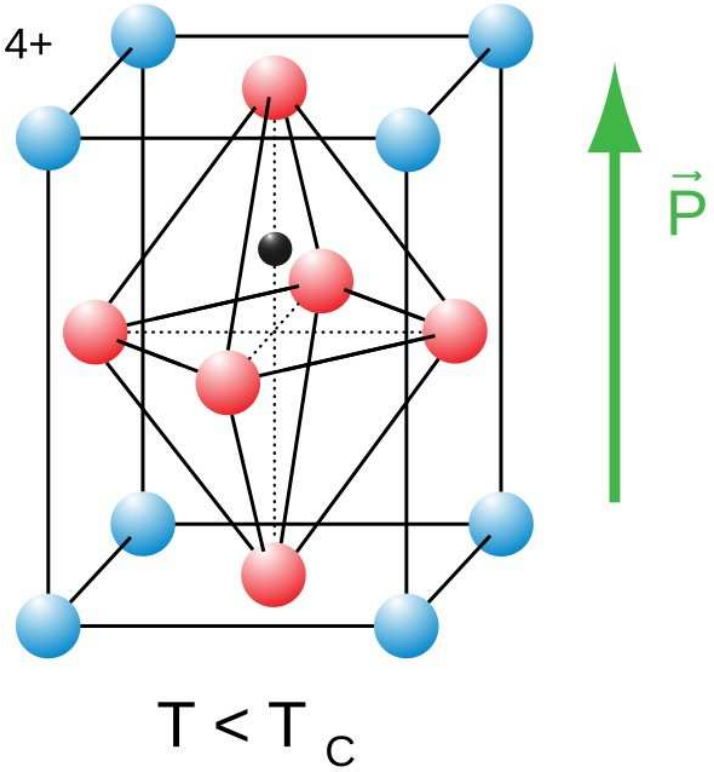


As we apply stress, a current is generated

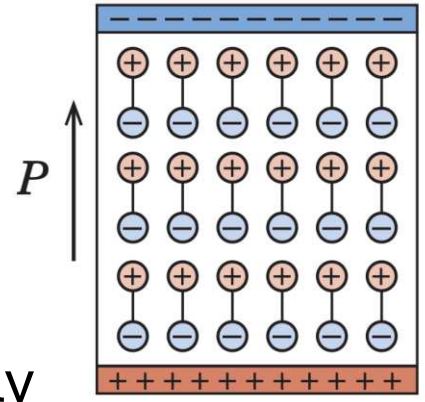


These are materials whose **polarization changes with applied stress/strain**

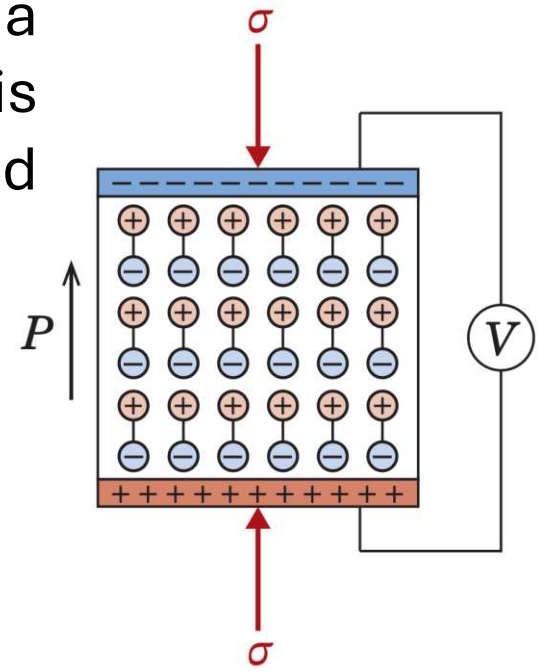


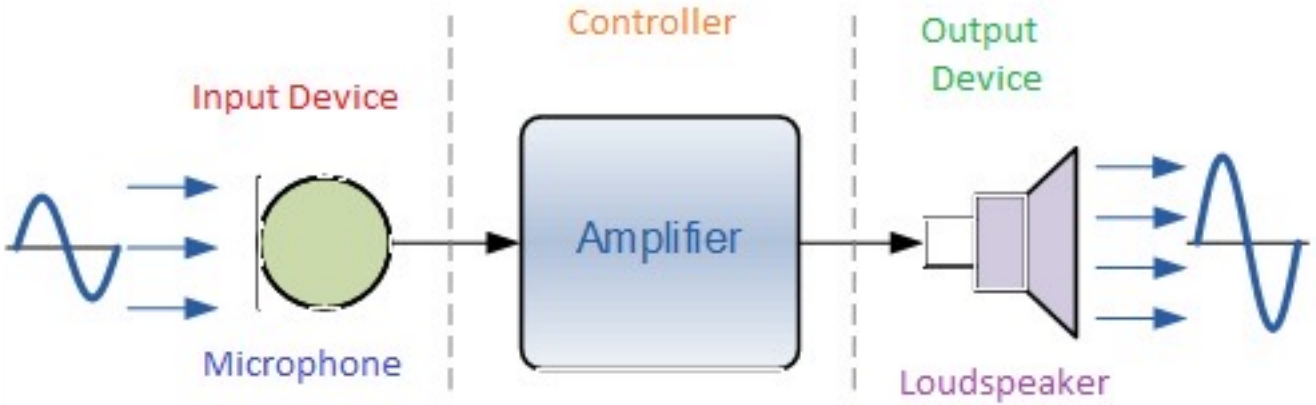


Another interesting class of insulators: piezoelectrics



As we apply stress, a current is generated





These are used to convert mechanical input (pressure/sound) into electrical signal → **transducers**

Summary of things to know

- What distinguishes a metal from an insulator (in terms of band diagram)
- How does conductivity vary with temperature for different materials
- What makes a semiconductor intrinsic versus extrinsic
- Electron and hole conduction in n-type versus p-type semiconductors

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

