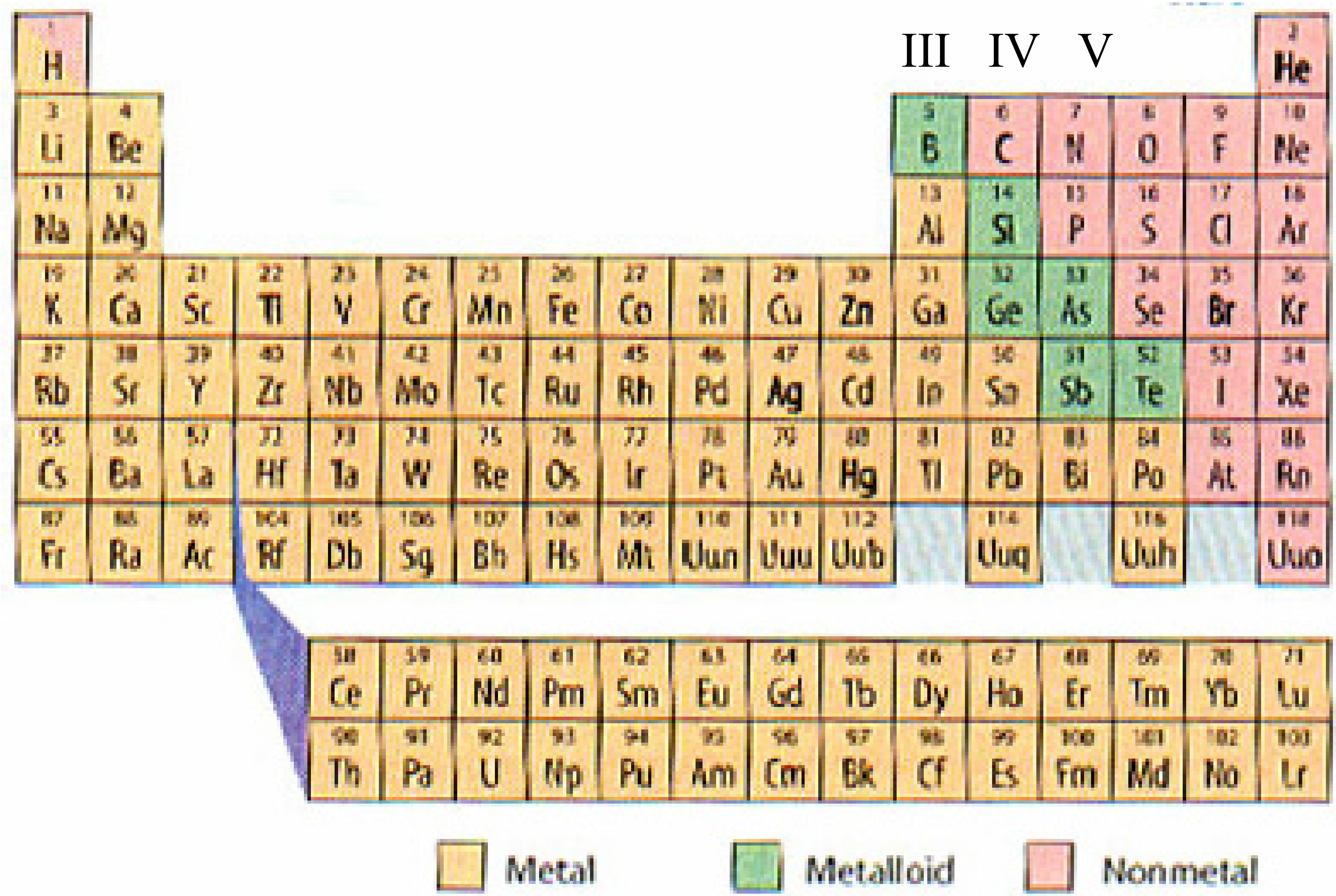
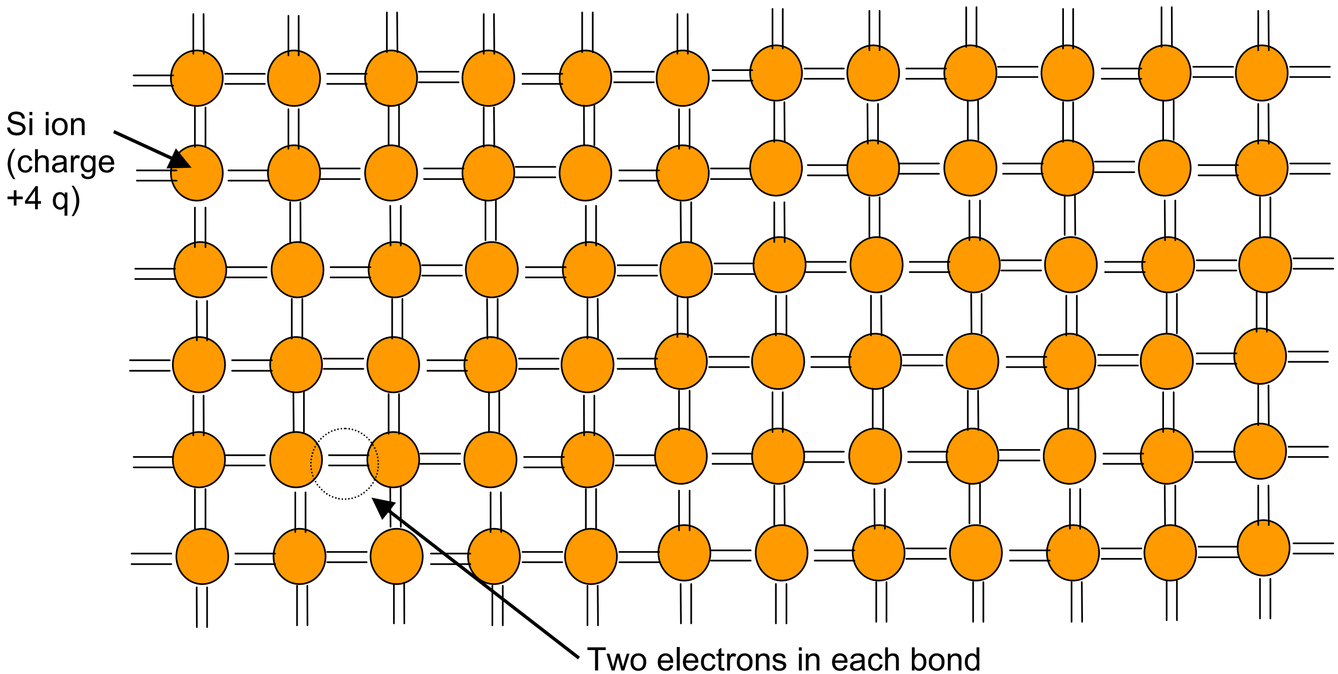
The Periodic Table



Electronic Bonds in Silicon

2-D picture of perfect crystal of pure silicon; double line is a Si-Si bond with each line representing an electron



Actual structure is 3-dimensional tetrahedral- just like carbon bonding in organic and inorganic materials.

Very few conduction electrons: semiconductor →

How to get conduction in Si?

We must either:

1) Chemically modify the Si to produce free carriers (permanent) or

2) Electrically "induce" them by the field effect (switchable)

For the first approach controlled impurities, "dopants", are added to Si:

Add group V elements (5 bonding electrons vs four for Si), such as phosphorus or arsenic

(Extra electrons produce "free electrons" for conduction.)

or

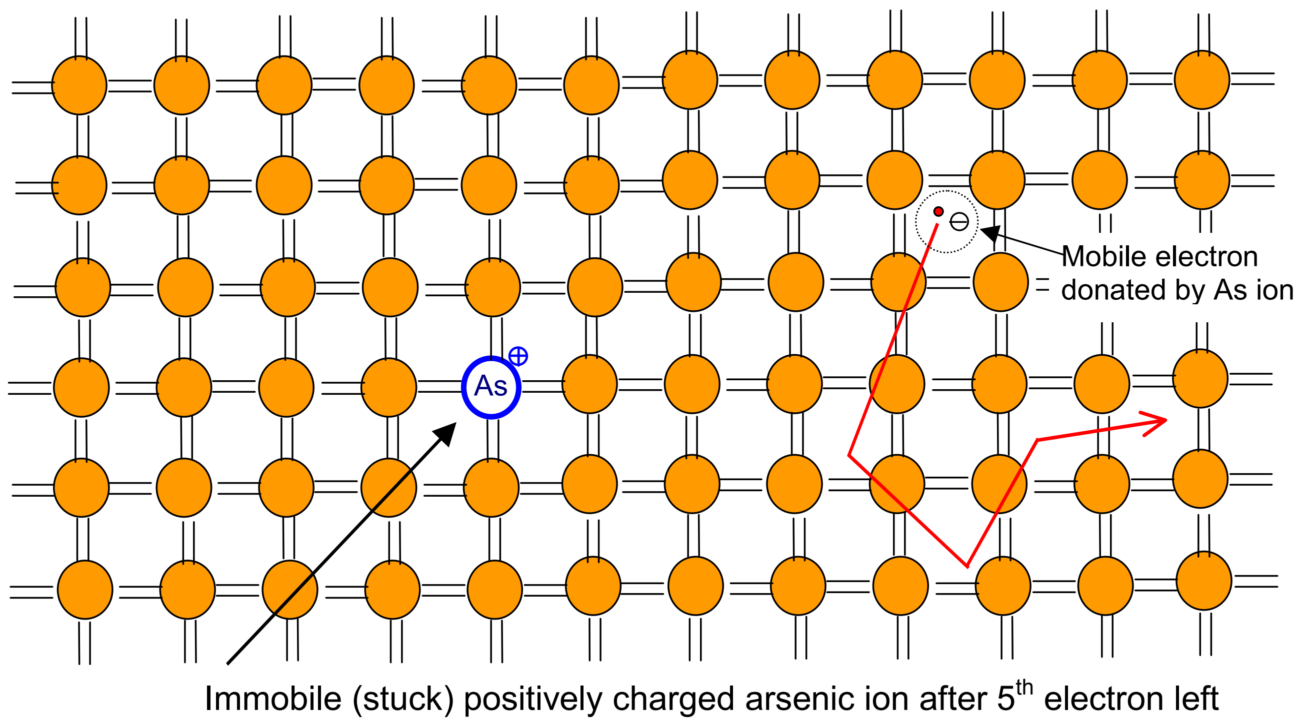
Add group III elements (3 bonding electrons), such as boron

Deficiency of electrons results in "free holes"

Doping Silicon with Donors (n-type)

Donors donate mobile electrons (and thus "n-type" silicon)

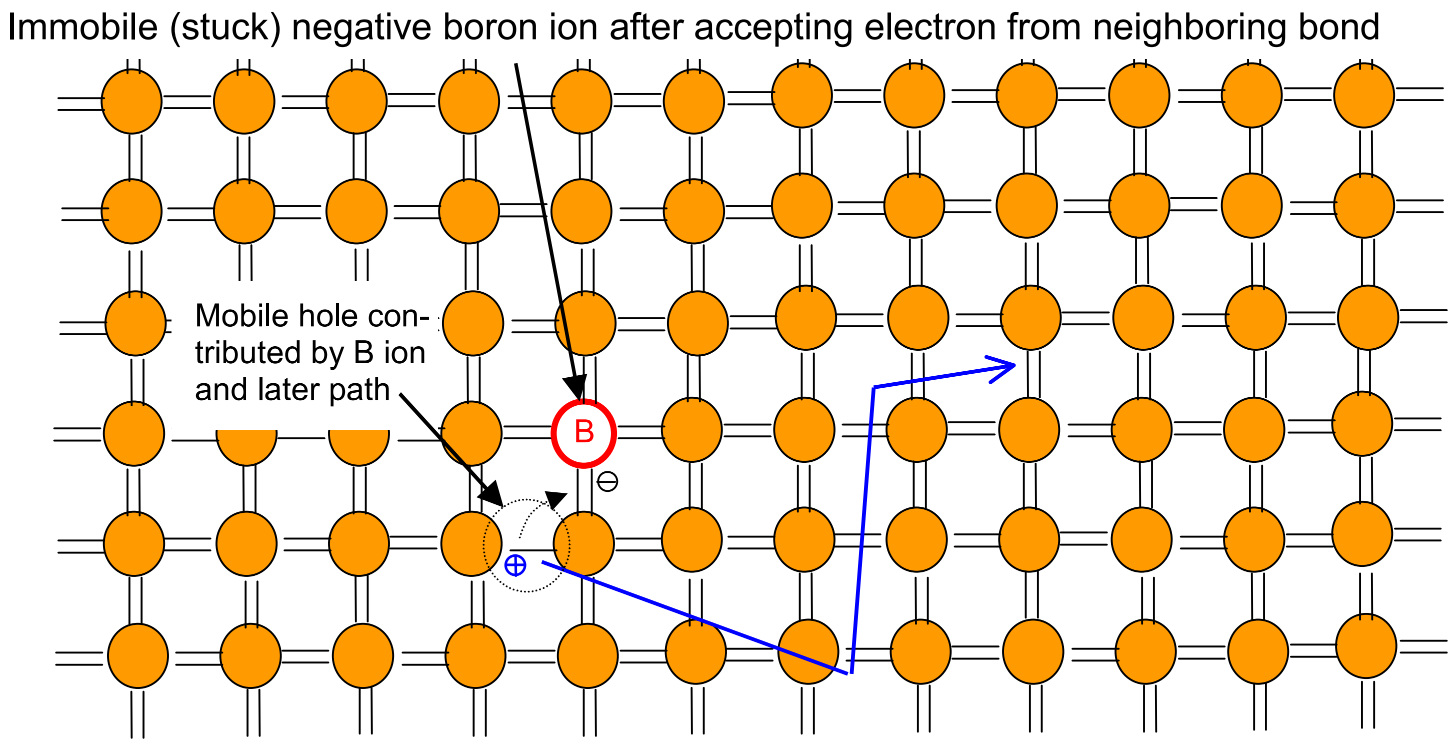
Example: add arsenic (As) to the silicon crystal:



The extra electron with As, "breaks free" and becomes a free electron for conduction

Doping with Acceptors (p-type)

Group III element (boron, typically) is added to the crystal



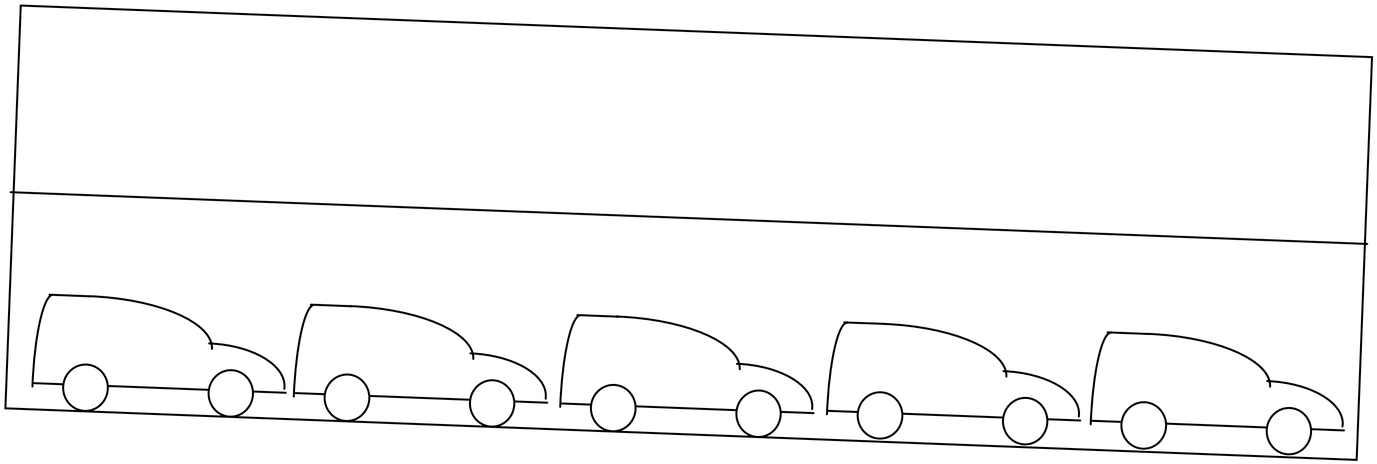
The “hole” which is a missing bonding electron, breaks free from the B acceptor and becomes a roaming positive charge, free to carry current in the semiconductor. It is positively charged.

Doping

- Typical doping densities: $10^{16} \sim 10^{19}$ cm^{-3}
- Atomic density for Si: 5×10^{22} atoms/cm^3
- 10^{18} cm^{-3} is 1 in 50,000
  - two persons in all of Berkeley wearing green hats

Shockley's Parking Garage Analogy for Conduction in Si

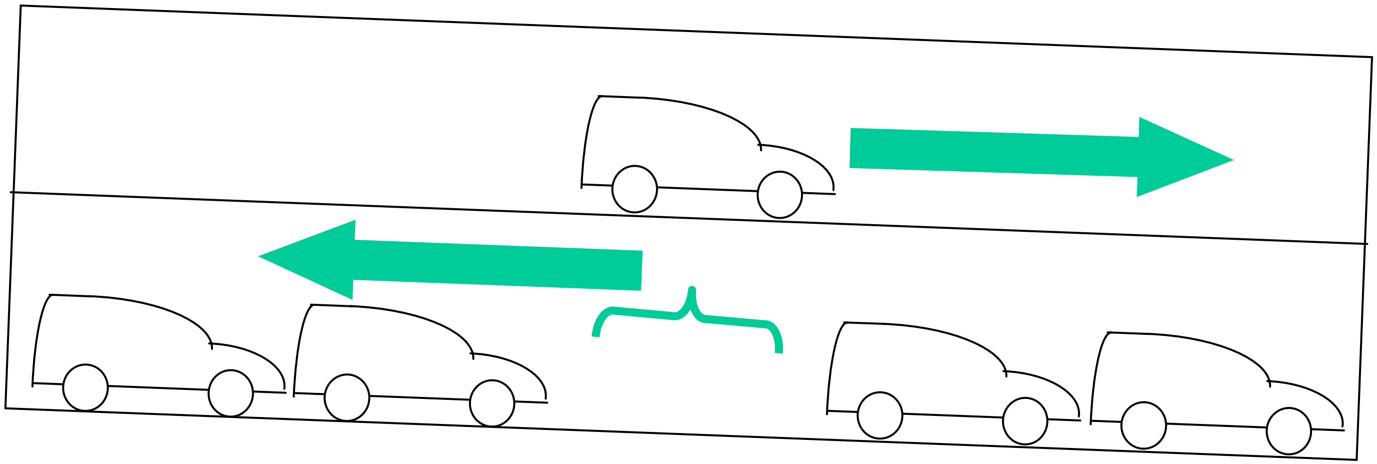
Two-story parking garage on a hill:



If the lower floor is full and top one is empty, no traffic is possible. Analog of an insulator. All electrons are locked up.

Shockley's Parking Garage Analogy for Conduction in Si

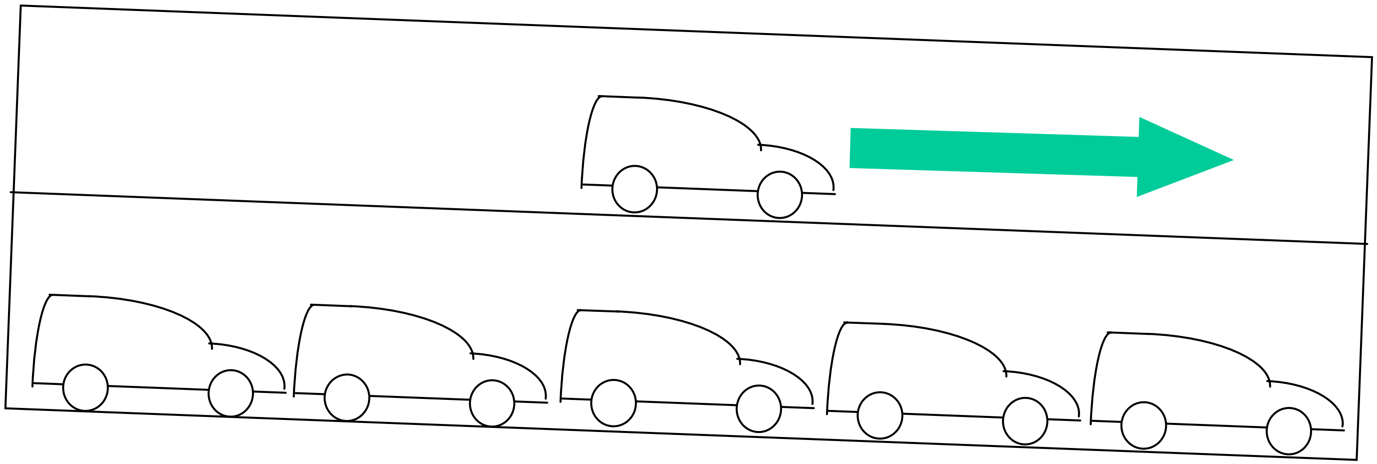
Two-story parking garage on a hill:



If one car is moved upstairs, it can move AND THE HOLE ON THE LOWER FLOOR CAN MOVE. Conduction is possible. Analog to warmed-up semiconductor. Some electrons get free (and leave "holes" behind).

Shockley's Parking Garage Analogy for Conduction in Si

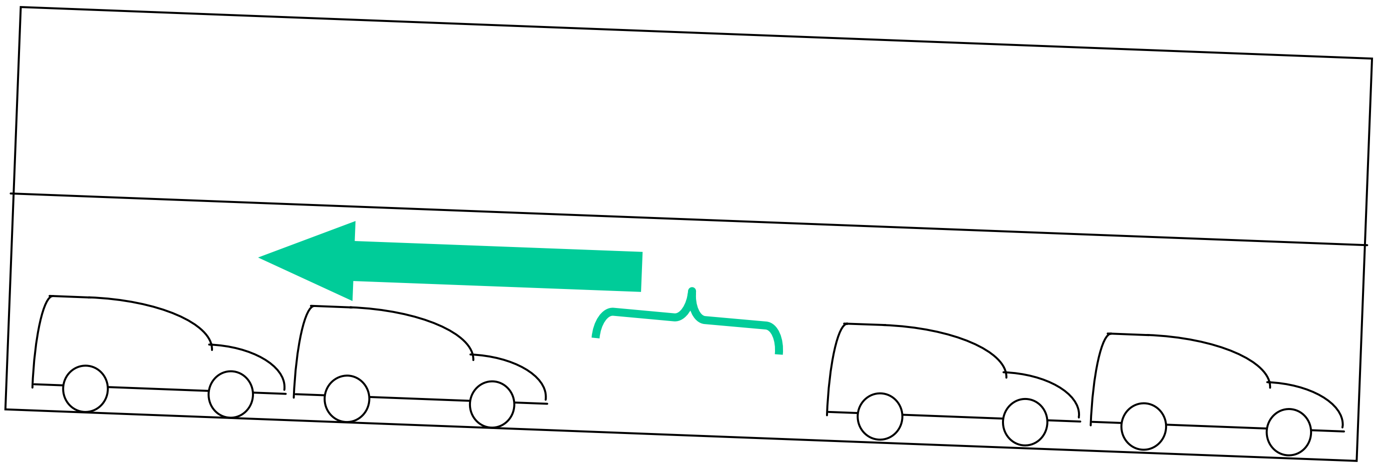
Two-story parking garage on a hill:



If an extra car is "donated" to the upper floor, it can move. Conduction is possible. *Analog to N-type semiconductor.* (An electron donor is added to the crystal, creating free electrons).

Shockley's Parking Garage Analogy for Conduction in Si

Two-story parking garage on a hill:



If a car is removed from the lower floor, it leaves a HOLE which can move. Conduction is possible. *Analog to P-type semiconductor.* (Acceptors are added to the crystal, "consuming" bonding electrons,creating free holes).

Summary of n- and p-type silicon

Pure silicon is an insulator. At high temperatures it conducts weakly.

If we add an impurity with extra electrons (e.g. arsenic, phosphorus) these extra electrons are set free and we have a pretty good conductor (n-type silicon).

If we add an impurity with a deficit of electrons (e.g. boron) then bonding electrons are missing (holes), and the resulting holes can move around … again a pretty good conductor (p-type silicon)

Now what is really interesting is when we join n-type and p-type silicon, that is make a pn junction. It has interesting electrical properties.

1

Consider a sample of material of cross section A with an electric field E applied in the x-direction. Conduction electrons (and holes) can move under the influence of an electric field. Electrons move in a direction opposite to that of the applied field, while holes move in the same direction as the field. In either case, the resulting current is in the direction of the field. Because the electrons (and holes) collide with and scatter off the ions in the lattice, impurities, and other crystal defects, the force they are subject to due to the electric field can be thought of as working only during the free flight of the electrons (or holes) between collisions, which is of the order of 10^{-13} seconds. [1] The effect of the electric field is therefore to produce a net *drift* of electrons (or holes), which results in a current, in the same direction as the electric field, called the *drift current*. This is written as

$$J_n^{dr} = qn\mu_n E \tag{1}$$

in the case of electrons, and

$$J_p^{dr} = qp\mu_p E$$

in the case of holes. Here q denotes the charge of the proton (roughly 1.6×10^{-19} coulombs), E the applied electric field in Volts/m, n the density of conduction electrons in m^{-3} and p the density of holes in the valence band in m^{-3}. μ_n and μ_p are coefficients called the *mobility* of electrons and the mobility of holes respectively; these relate to the details of the scattering process and are measured in m^2/Volt-sec. J_n^{dr} is the current density of electrons, measured in amps/m^2, and likewise J_p^{dr} is the current density of holes. The mobilities depend strongly on temperature and on the doping concentration; at room temperature and moderate doping levels ballpark figures are 1000 cm^2/Volt-sec for μ_n and 400 cm^2/Volt-sec for μ_p.

[1] The electrons (and holes) themselves move at about 10^5 m/sec at room temperature, in a random fashion so that there is no net velocity on the average. The mean distance between collisions is therefore about 10^{-8} m.