Today

Analog electronics

- Anatomy of insulators and semiconductors
- P and N semiconductors
- Structure of diodes and transistors
- Transistor usage

Administrivia

- Tomorrow (Friday): milestone 4 is due
- Next Thursday: homework 2 is due

Device of the Day...

Device of the Day...

- The voltage converter (often known as a **DC-to-DC converter**)
- We have two varieties in the lab:
  - Both convert to 5 V
  - 100 mA and 500 mA
- 3 pins (for our types):
  - Common
  - Input voltage
  - Output voltage

Conductors

Recall that:

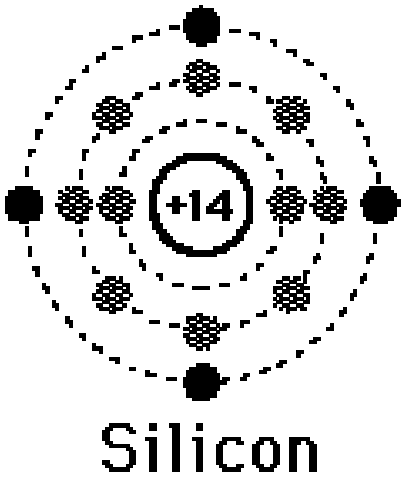
- Atoms that make up conductors easily give up electrons (from their outer shell)
- When an electron is released, it leaves a positively charged “hole” that can be filled by another electron
- In conductors, there are approximately the same number of holes as there are free electrons

Conductors (cont)

- Current flow in conductors involves:
  - The flow of electrons from negative to positive
  - The flow of holes from positive to negative
- An electron must be near a free hole in order for the electron to move
  - The electron must also be free (or relatively free)

Silicon Atoms

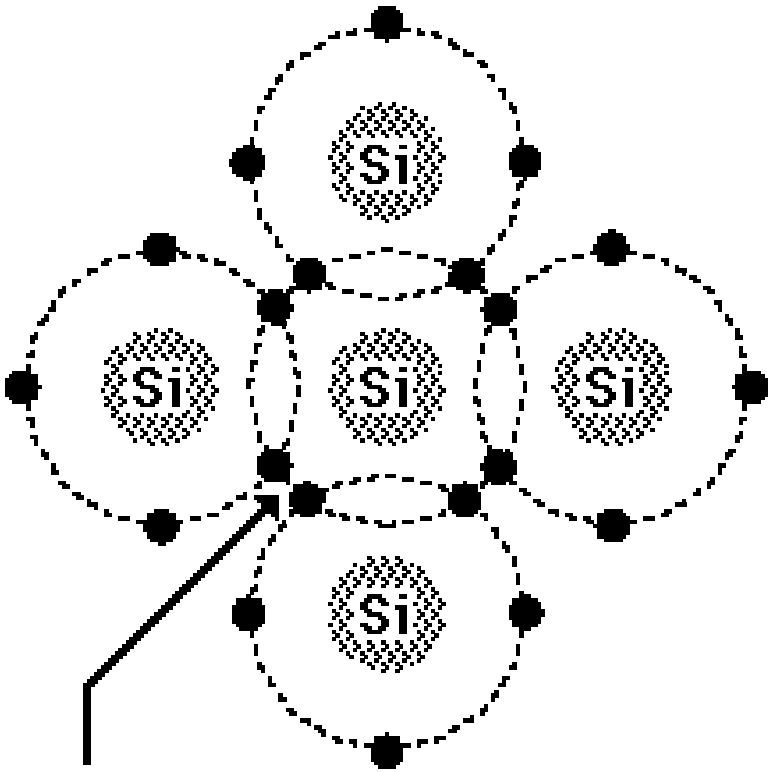
- 4 electrons in the outer shell
- These outer electrons can be shared



Figure(s) from C. R. Nave @ GSU

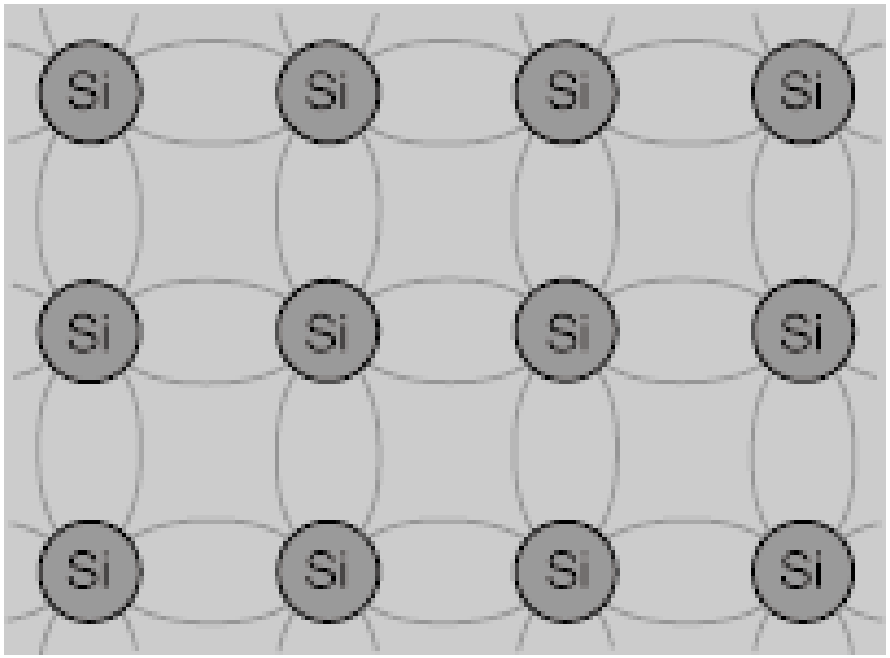
Silicon Atoms Form a Crystal

- One silicon atom can share each of its electrons with a neighboring atom
- This sharing of electrons forms a covalent bond
- The energy required to remove one of these electrons is rather high
  - Which means ...?



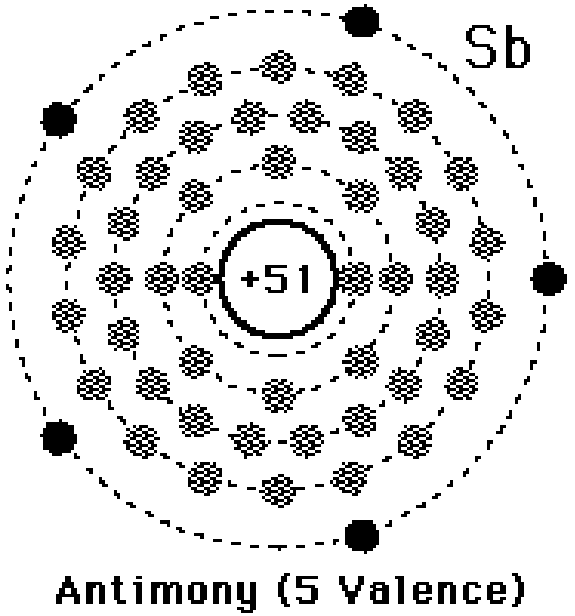
Silicon Crystals Are Good Insulators

- There are no electrons that are free to move
- ... and there are no holes to which electrons can bind
- Atoms in the crystal are actually arranged in 3D



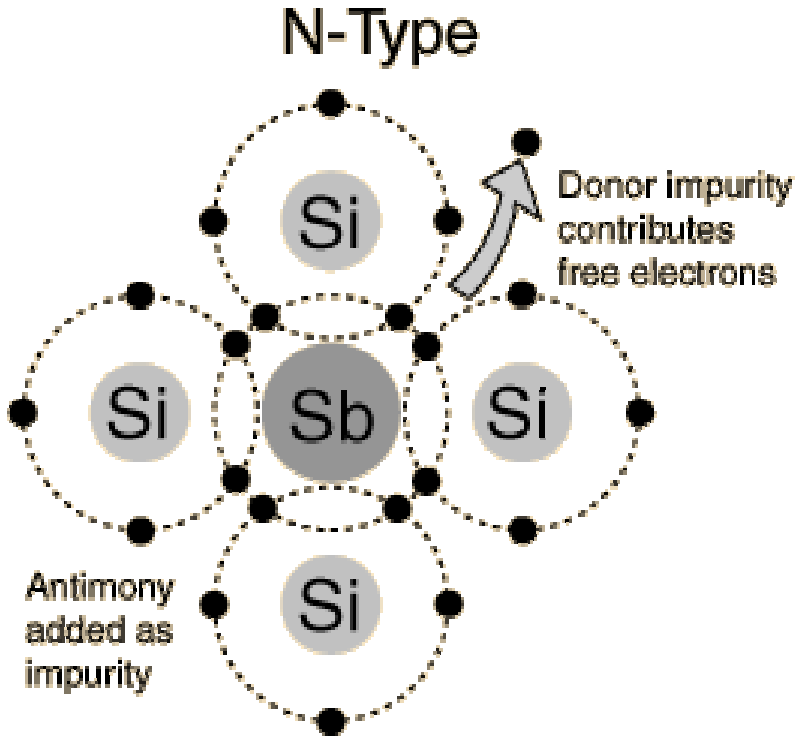
“ Doping” a Silicon Crystal with an Impurity

We can replace a silicon atom in the crystal with an atom with 5 electrons in the outer shell (e.g., arsenic, phosphorus, or antimony)



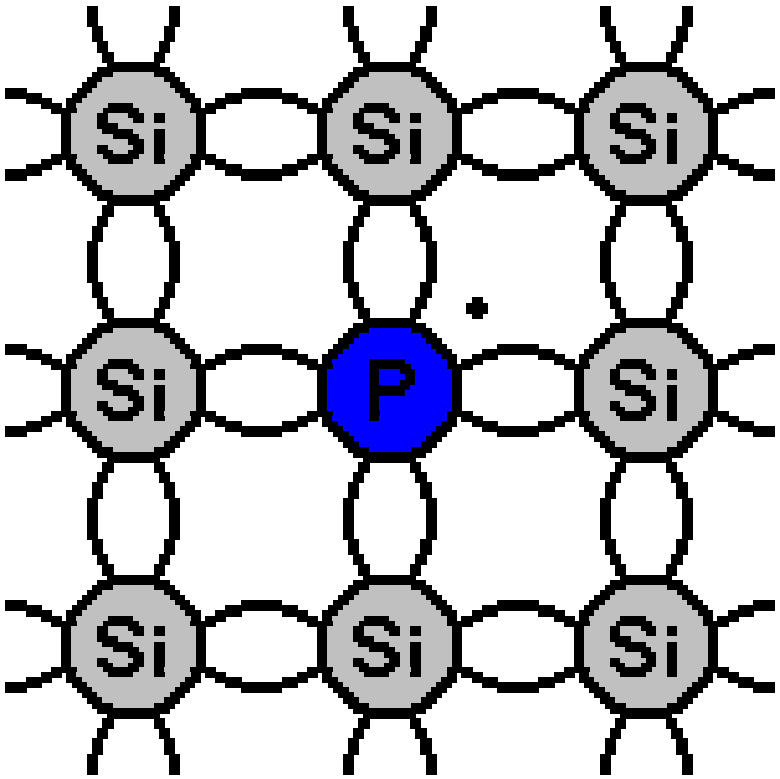
“ Doping” a Silicon Crystal with an Impurity

- This atom will bind with the four silicon atoms in the crystal with covalent bonds
- This leaves one additional electron that is not shared
- The energy required to remove this electron is very small relative to the previous case



“ Doping” a Silicon Crystal with an Impurity

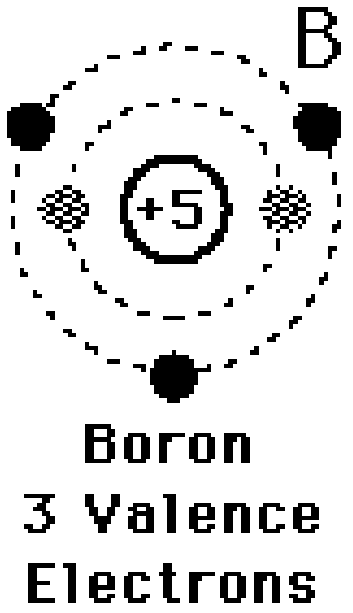
- This doped crystal has a set of free electrons with essentially no holes (the holes only have a weak attractive force)
- Thus, movement of current through this crystal involves movement of electrons, but not of holes
- We call this an **N-type semiconductor**



Figure(s) from Ken Bigelow

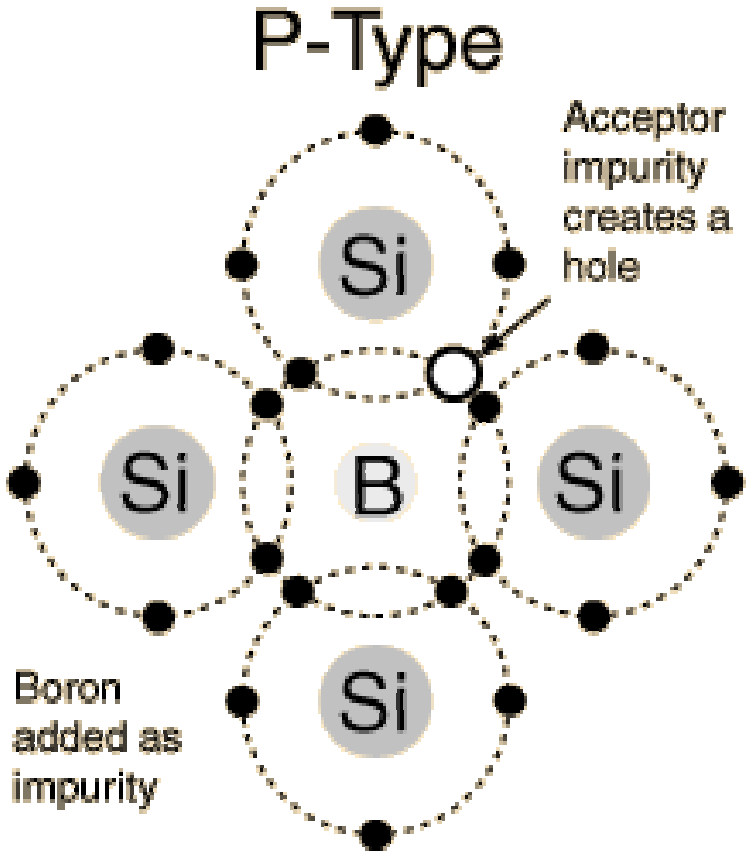
Other Types of Impurities

We can also dope the silicon crystal with atoms of valence 3 (e.g., aluminum, boron, or gallium)



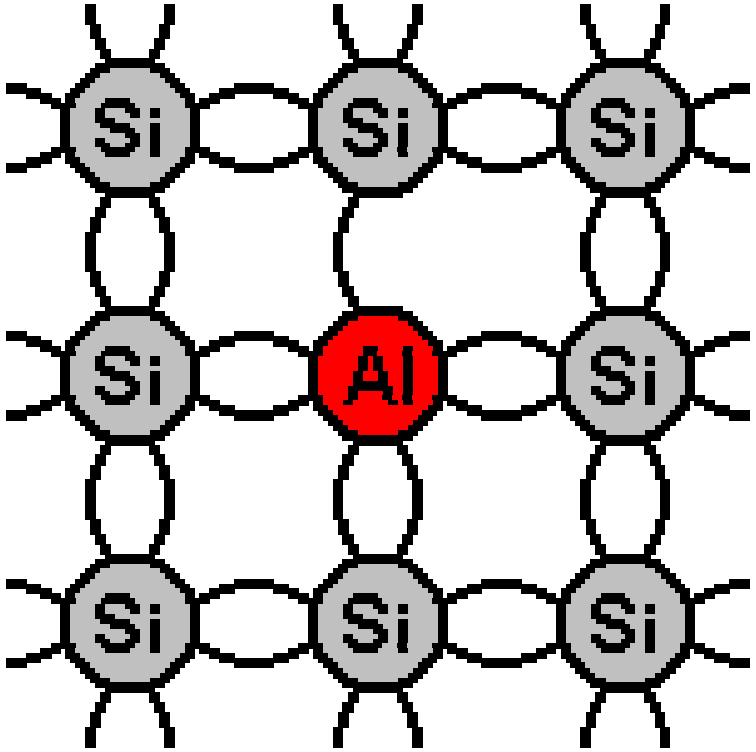
Impurities with a Valance of Three

- This type of atom will form three covalent bonds, leaving one bond incomplete
- This leaves a hole in the crystal that can be bound to a free electron
- Once bound, only a small amount of energy is required to free it



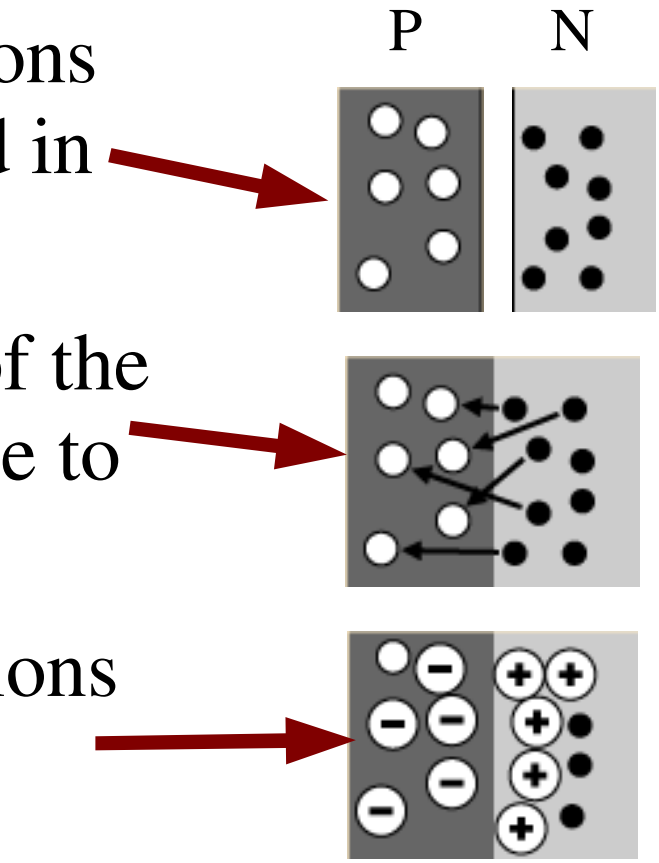
Impurities with a Valance of Three

- This type of crystal forms a **P-type semiconductor**
- Movement of current through this type of semiconductor primarily involves the movement of holes



Bringing Together P- and N-type Semiconductors

- When not connected, the electrons and holes are evenly distributed in their respective crystals
- When brought together, some of the electrons near the junction move to fill the holes
- This leaves positively charged ions in the N-region and negatively charged ions in the P-region

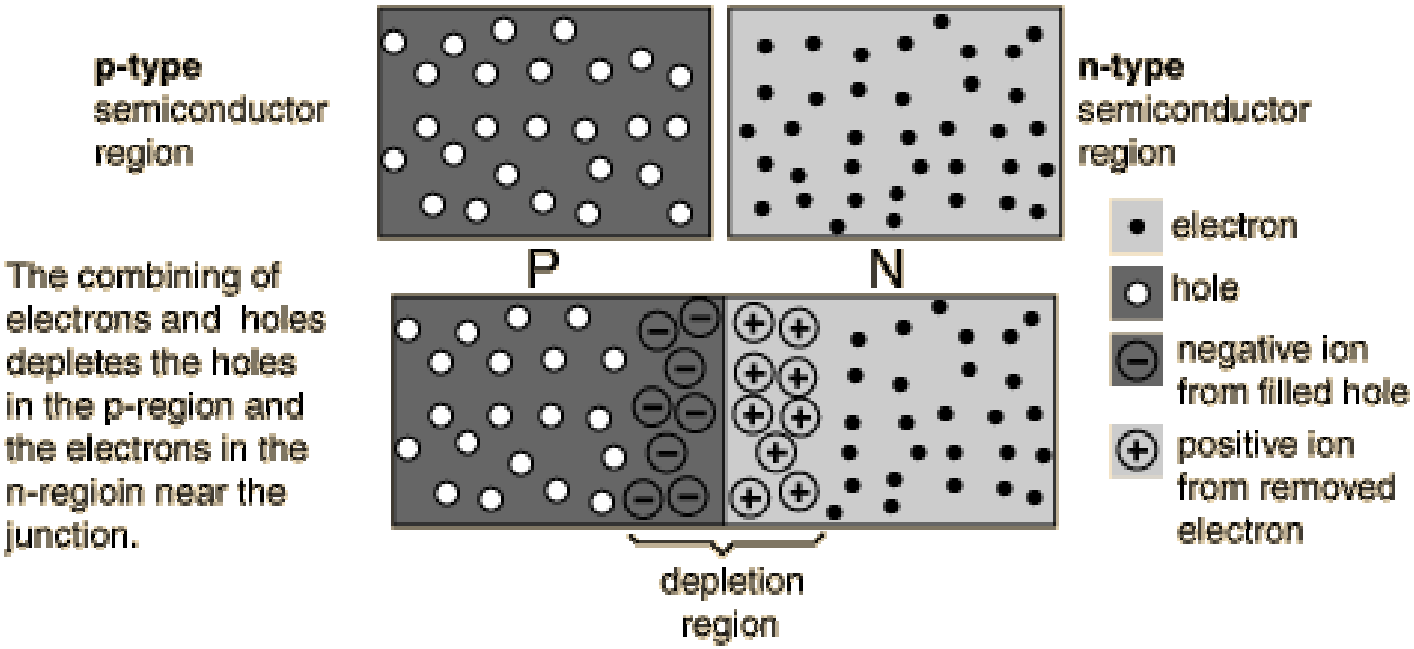


Electron Hole Negative ion from filling of p-type vacancy. Positive ion from removal of electron from n-type impurity.

Bringing Together P- and N-type Semiconductors

This transfer of electrons into the P-region only happens in the vicinity of the junction between the two

This **depletion region** is essentially devoid of free electrons and holes



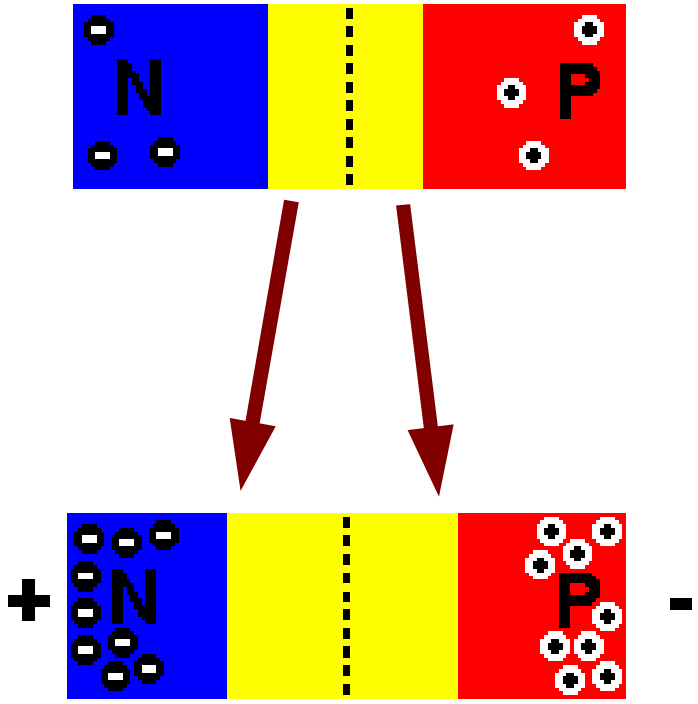
Current Across the Depletion Region

- Because there are few free electrons and few holes, the flow of current through the depletion region is restricted

- Suppose we connect leads to the polar ends of the P- and N-type semiconductors
- What happens when the potential difference from P to N is positive?

Applying a Potential Difference

- The electrons gather at the positive terminal
- The holes gather at the negative terminal
- We see a widening of the depletion region

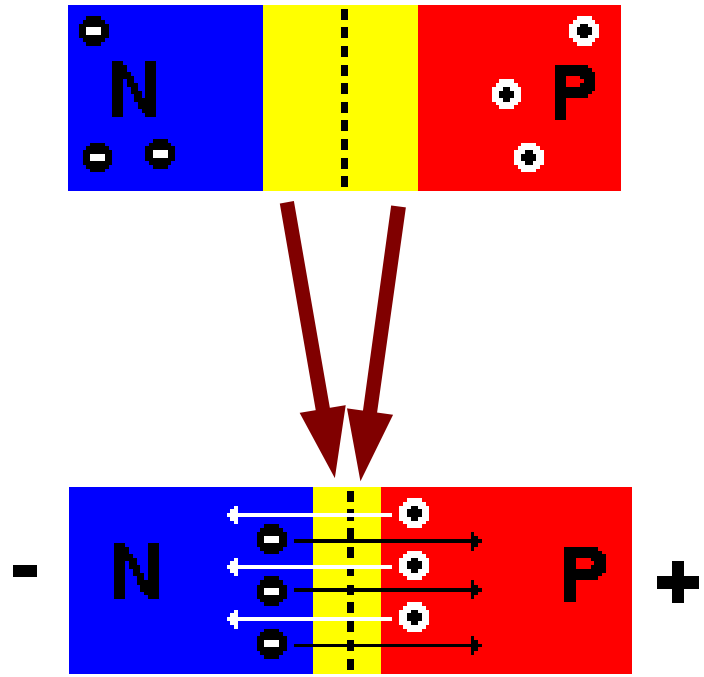


Current is even less likely to flow through the depletion region

What Happens if We Reverse the Potential?

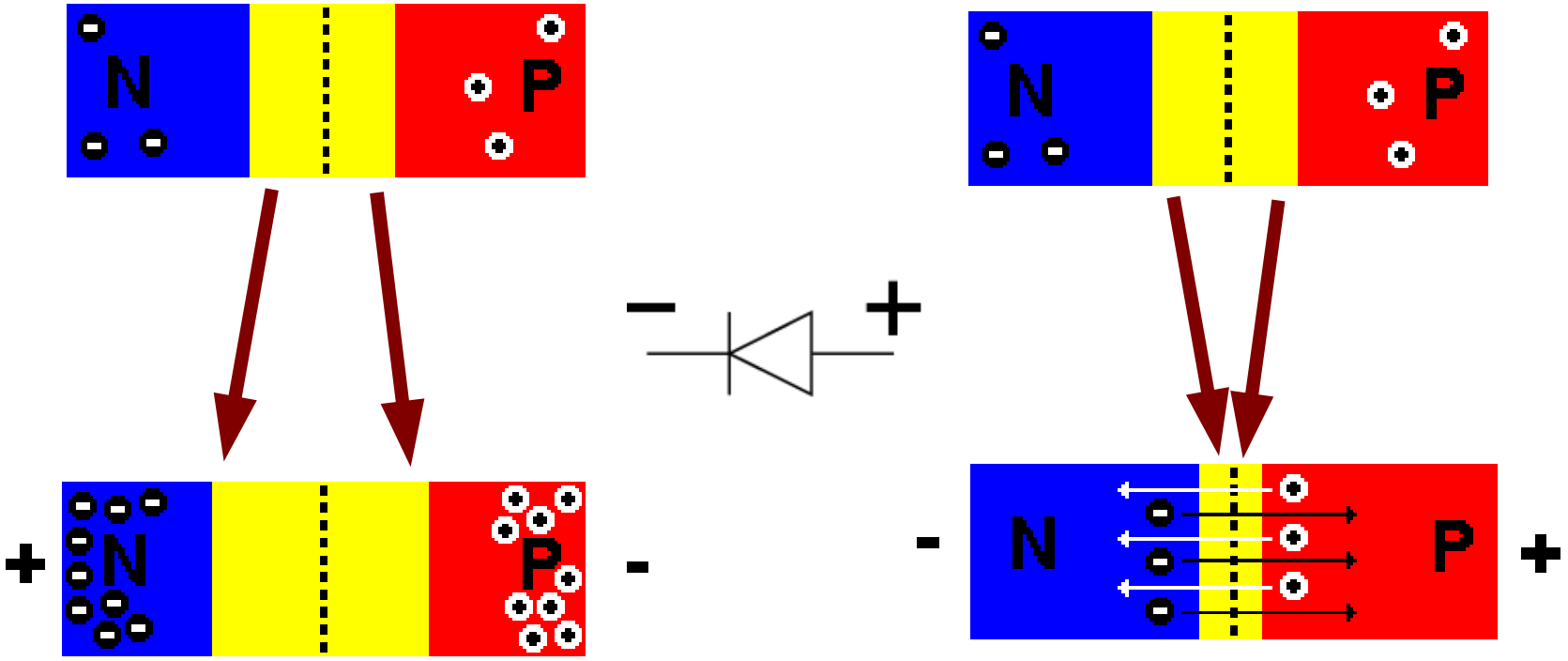
What Happens if We Reverse the Potential?

- The depletion region shrinks
- This brings the region of free electrons closer to the region of available holes
- This allows current to flow between the leads



What type of device do we have?

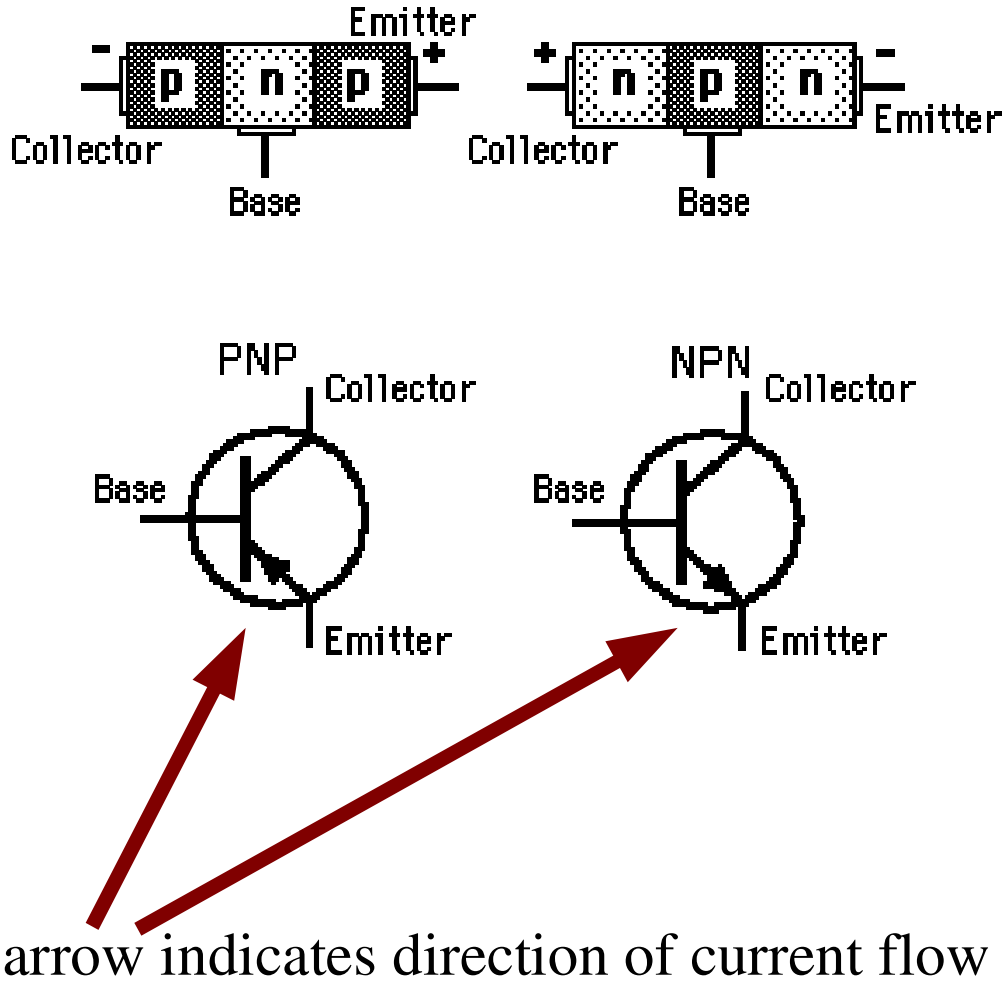
What Type of Device Do We Have?



A diode!

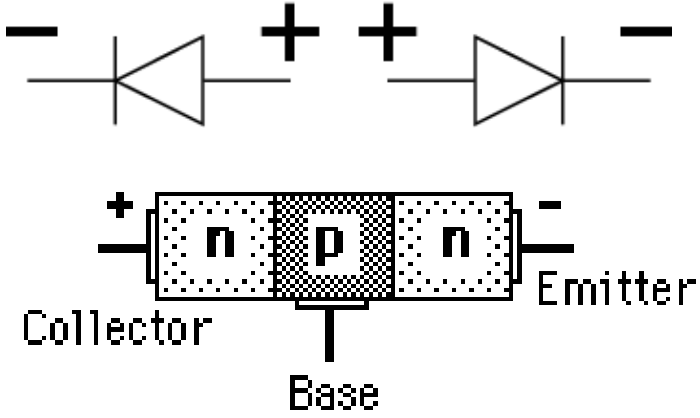
More Complicated Combinations of P- and N-type Semiconductors

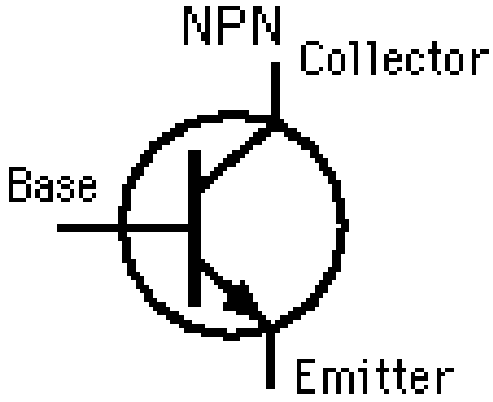
- Transistors are three lead devices
- Two forms: NPN and PNP
- The central region is generally very narrow relative to the poles



NPN Transistors

- One view: two diodes arranged back-to-back
- What do we expect to happen when we apply a voltage to the base (relative to the emitter)?

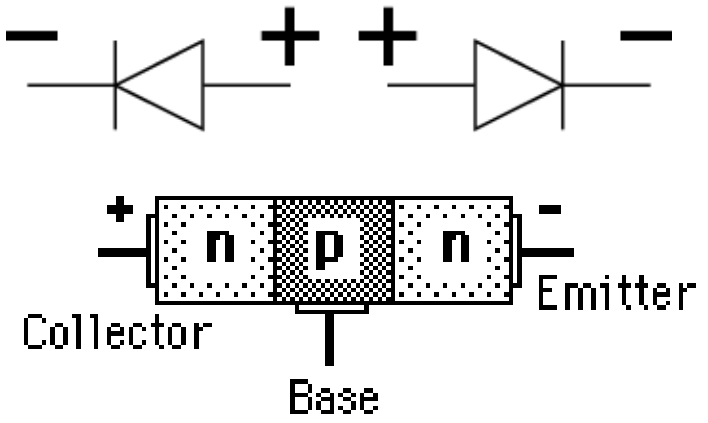


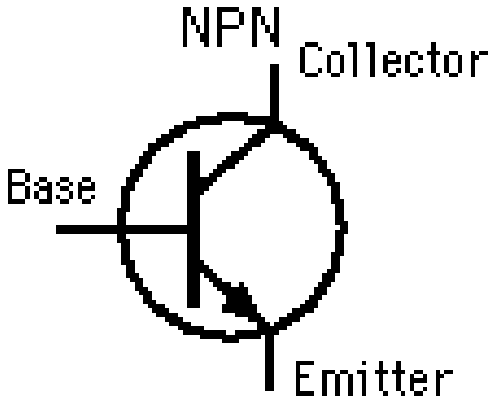


NPN Transistors

What do we expect to happen when we apply a voltage to the base (relative to the emitter)?

- We expect a current flow from the base to the emitter
- ... but not a flow from the collector to the base

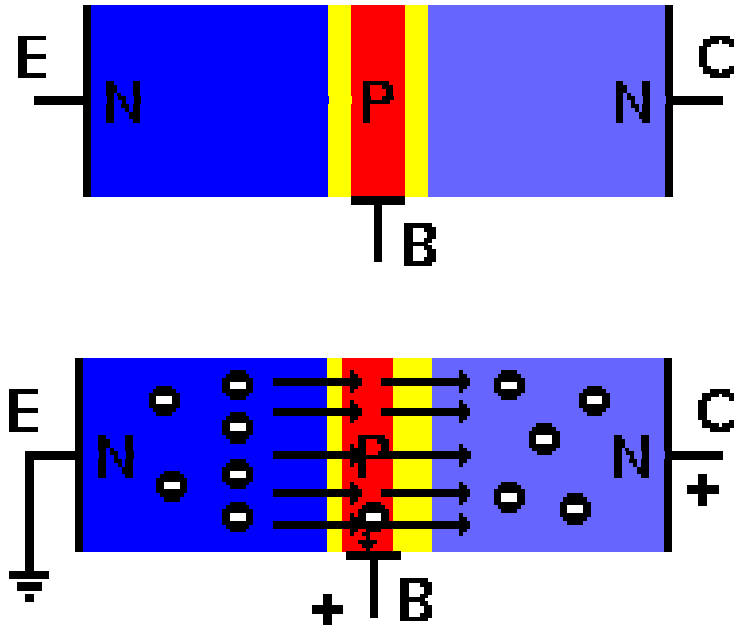




NPN Transistors

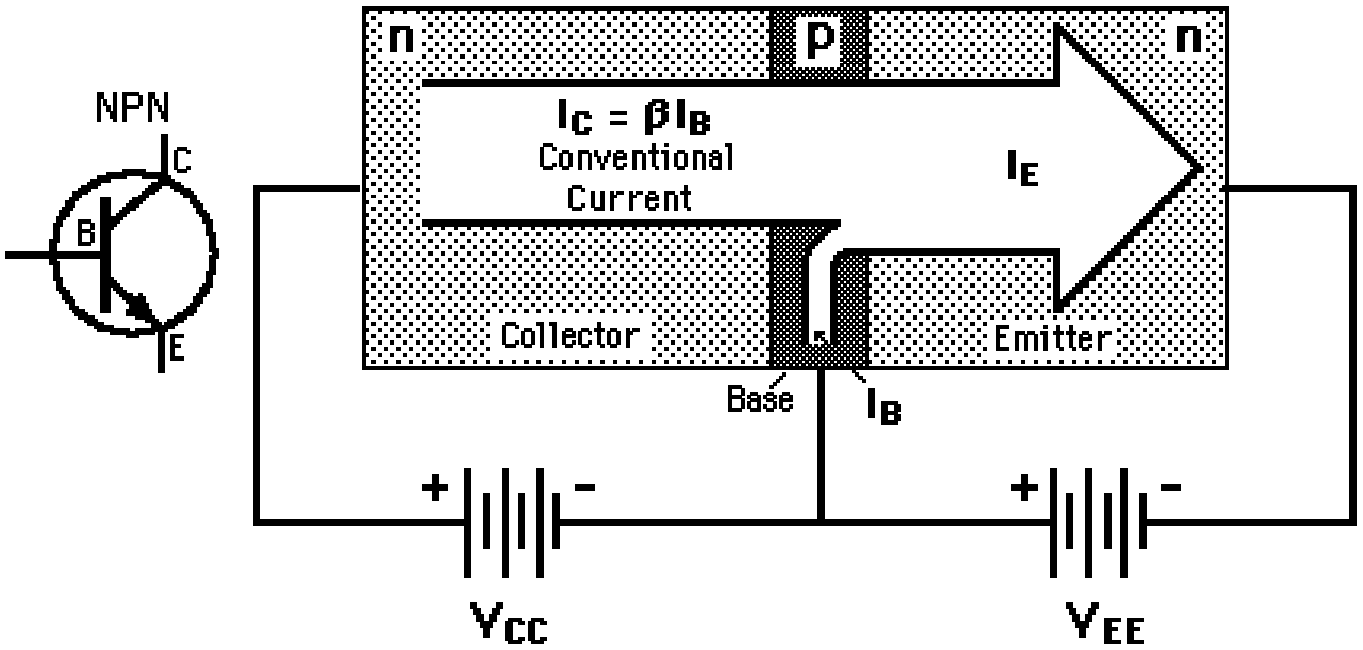
But: the two halves interact

- Electrons flow from emitter to base
- The momentum of the electrons carries many of them through the P-region of the transistor
- The higher potential of the collector (over the base) captures these electrons



NPN Transistors

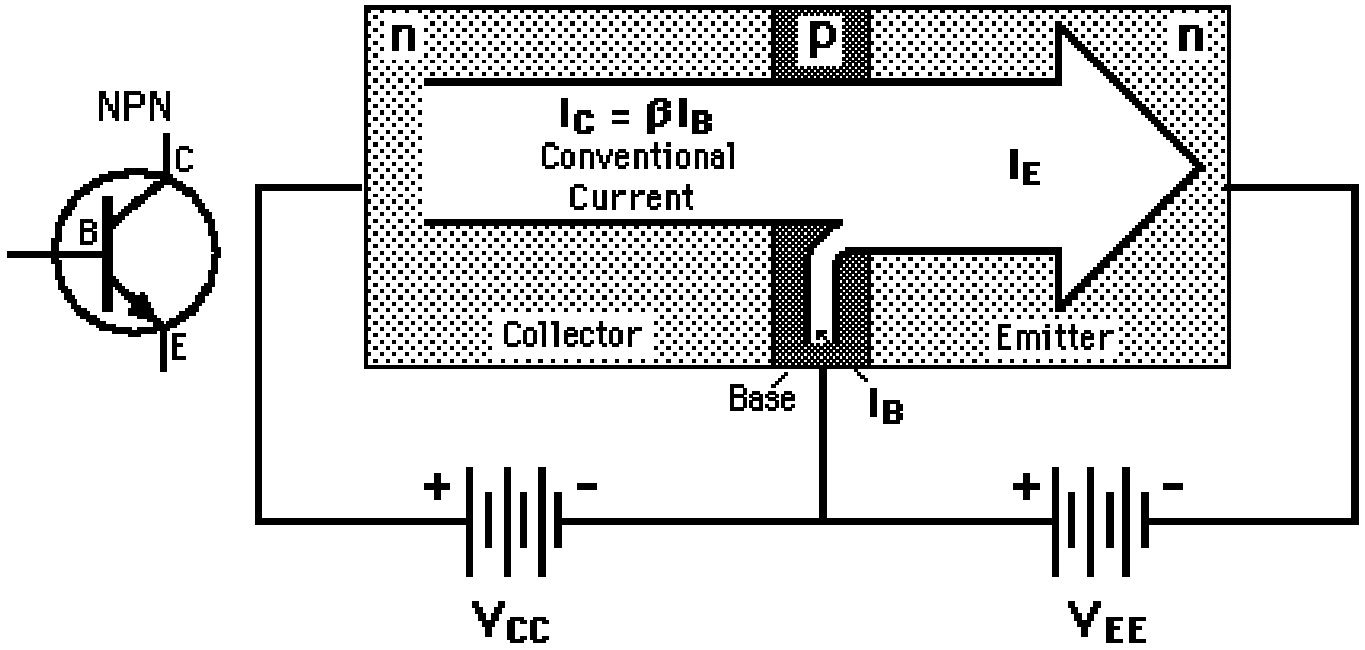
- Within a certain range, the current from collector to emitter is proportional to the current from base to emitter
- The transistor operates as an amplifier of base current!



NPN Transistors

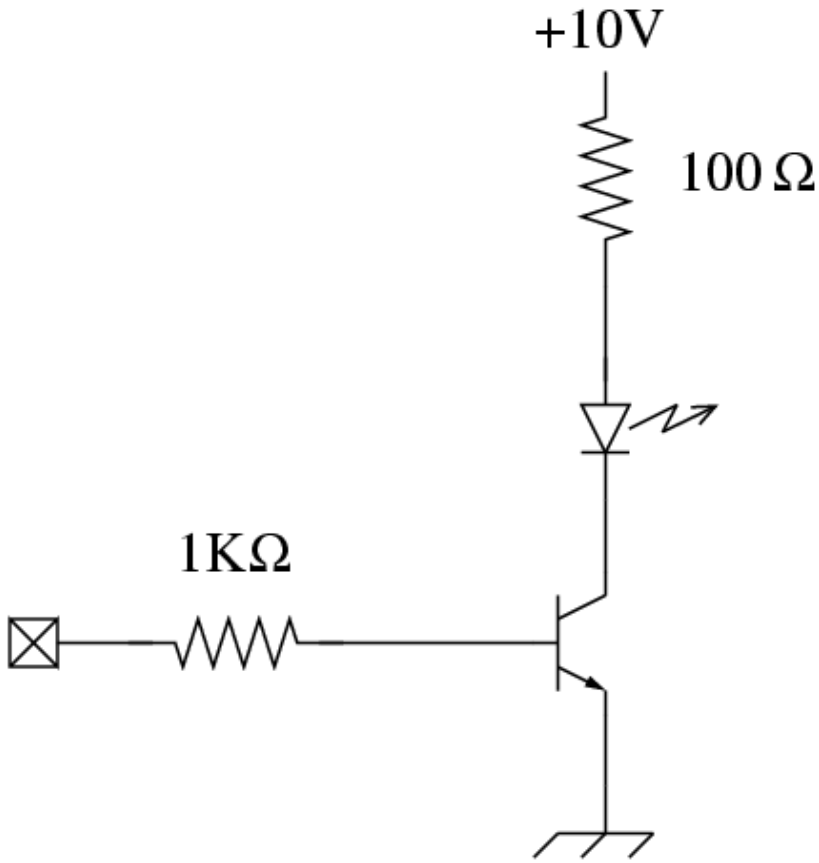
Caveats

- The base voltage must exceed the forward voltage of the base-emitter “diode” (~ 0.5 V)
- The collector current will saturate at some point



NPN Transistors in Action

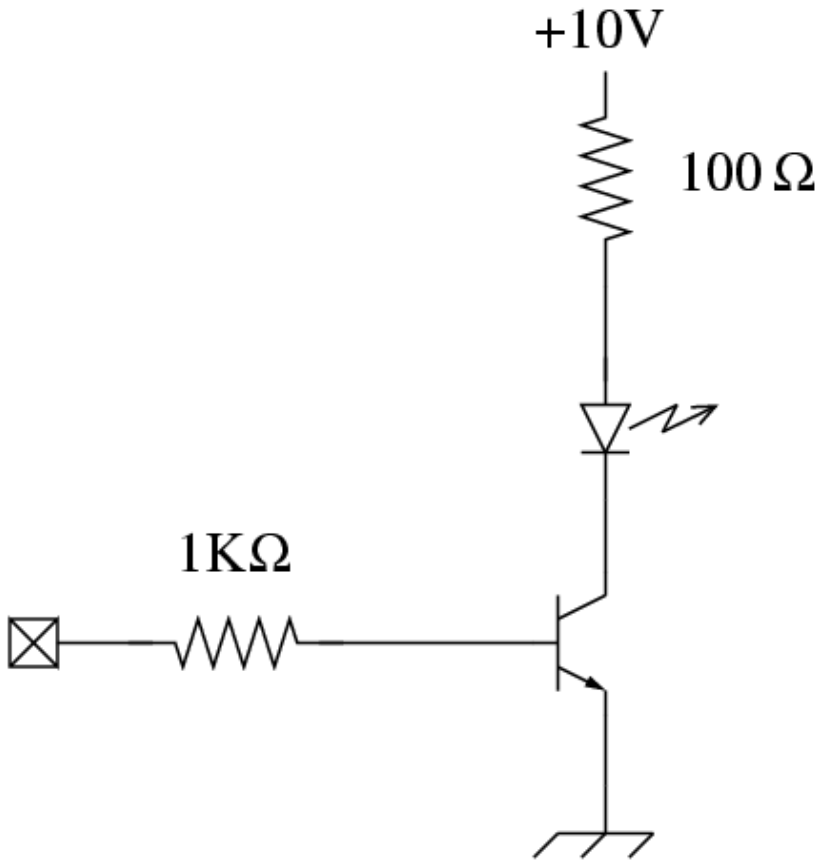
- This allows us to get around the 25 mA limit on PIC outputs
- In this case, the transistor is being used as a switch (as it is used in many situations)



What happens if we vary the pin voltage?

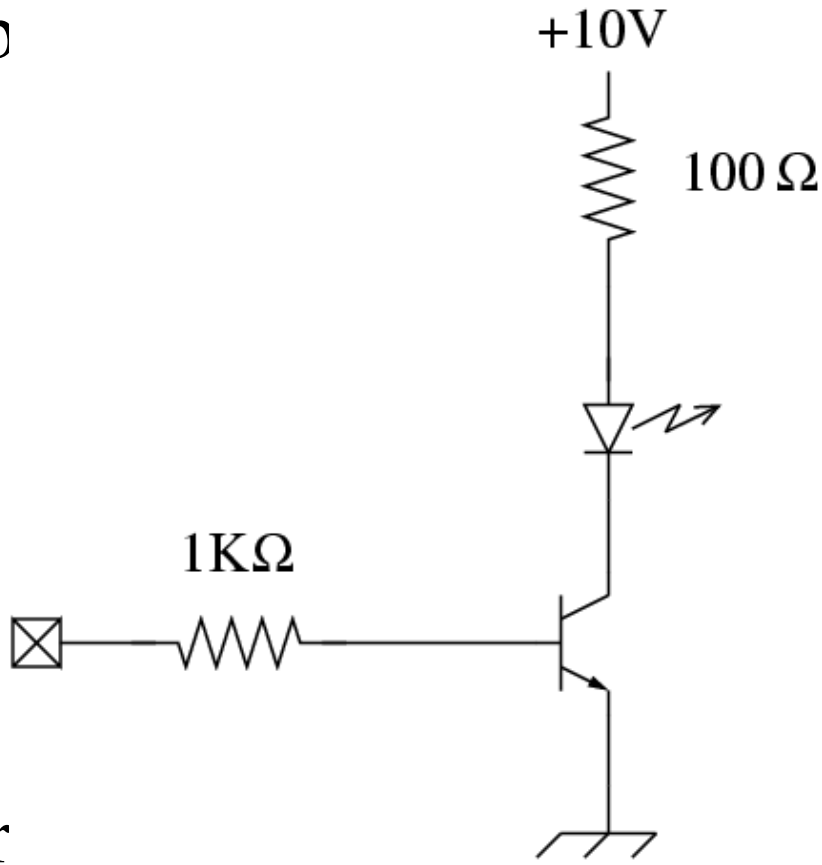
What Happens When We Vary the Pin Voltage?

- Assume that we are in the **dynamic range** of the transistor
- Cutting the pin voltage by half:
  - (assuming a forward voltage of 0): Reduces the base voltage by half
  - We reduce the base current by half



What Happens When We Vary the Pin Voltage?

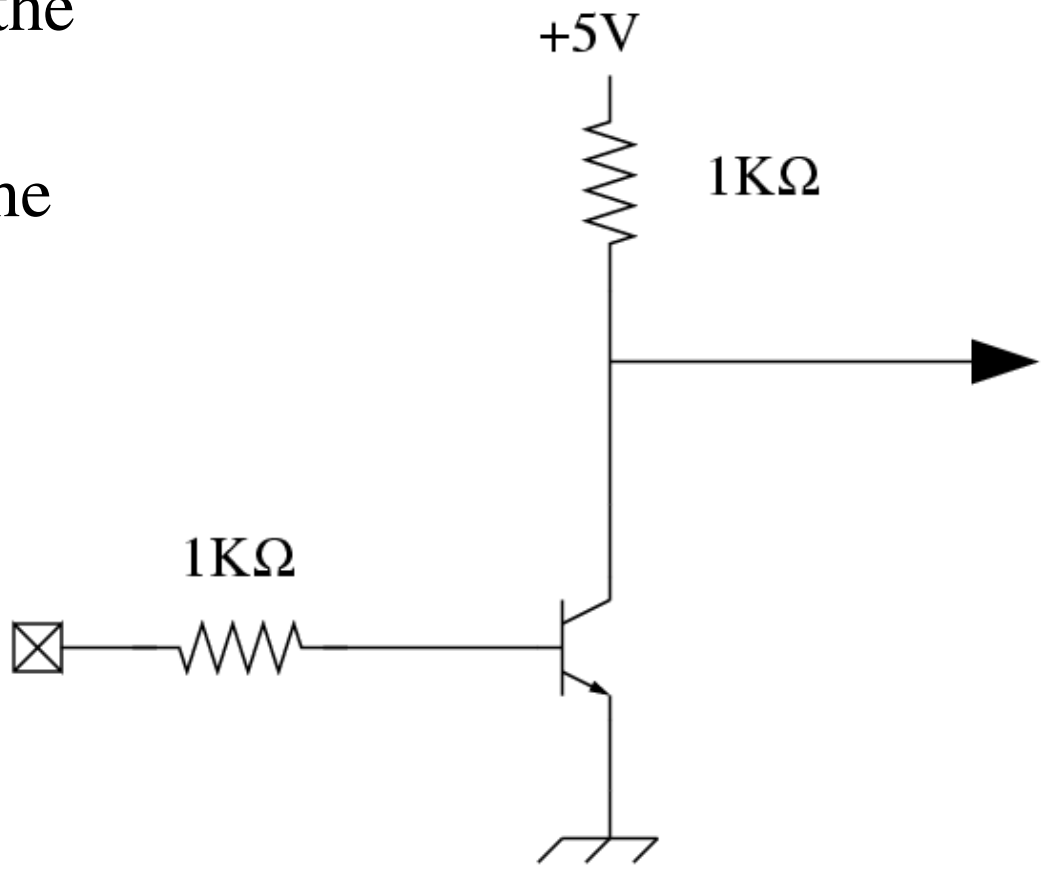
- We reduce the base current b half:
  - Reduces the collector current by half
  - ... which reduces the LED brightness by ~half



How would we use a transistor to implement a **not gate**?

NPN Transistors in Action: Implementing a NOT Gate

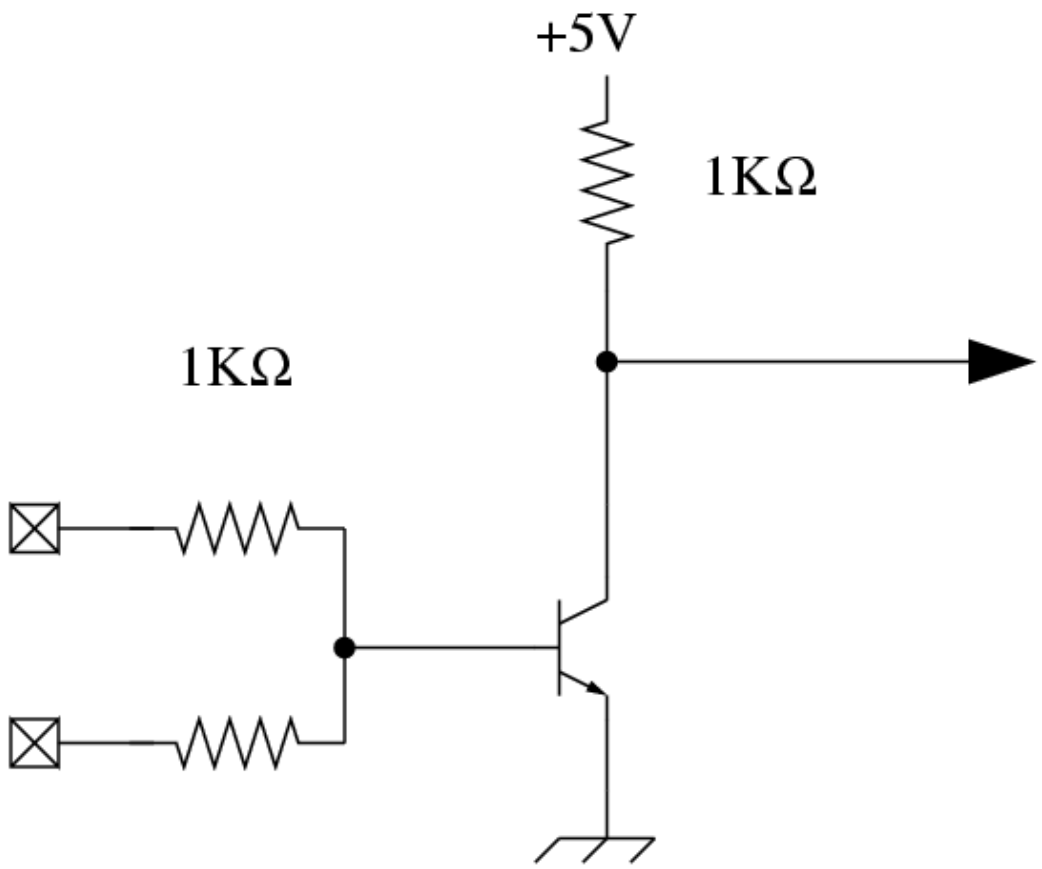
- Input: 0 V
  - No current flow through the transistor
  - Output is dominated by the pull-up resistor
- Output: 5 V
  - ~Saturate the transistor
  - Output is “effectively” connected to ground



How about a NOR gate?

Implementing a NOR Gate?

- 0 Volts on both inputs:
  - No current flow through the transistor
  - Output: 5 V
- +5 Volts on either input:
  - Saturate the transistor
  - Output is near 0 Volts



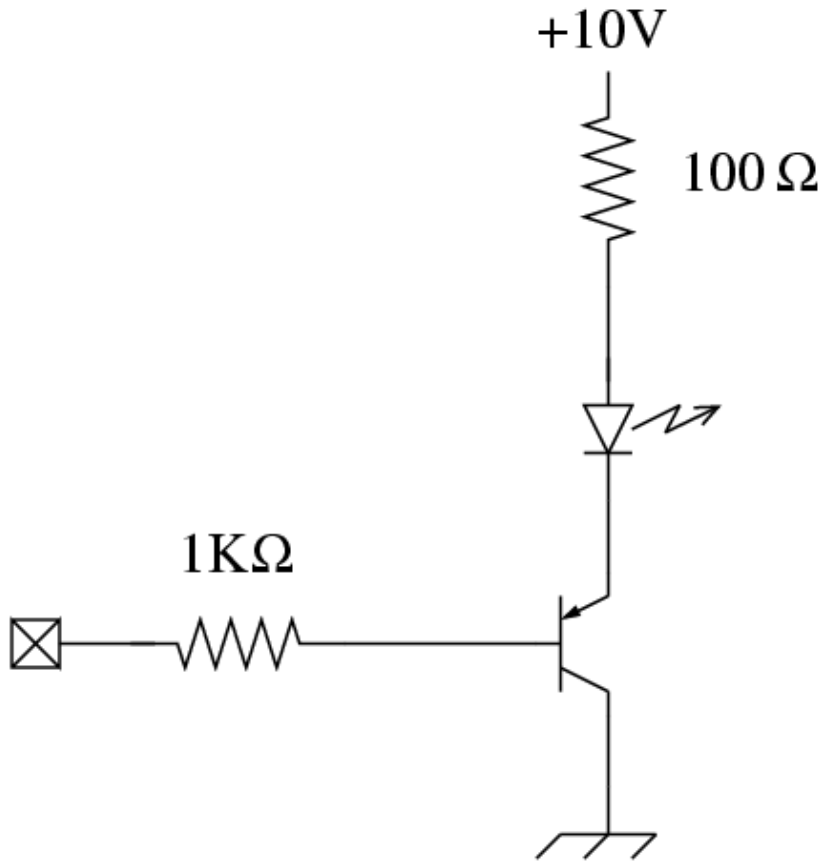
Transistor Limitations

- Must account for base-emitter forward voltage
- Response is not linear over the entire dynamic range
- Current gain can vary quite dramatically (even across the same type of transistor)

PNP Transistors

Operation is similar to NPN. But:

- Driving the base low will cause current to flow from the emitter to collector
- Note that driving the line low is different from not connecting the line to high!



Next Time

- Lab:
  - No current
- Lecture:
  - Operational Amplifiers
  - Digital-to-Analog Conversion
  - Analog-to-Digital Conversion
  - Inductive Devices
  - Make sure you have read: DEH Ch 12 (pp. 252-274) and DwPICM Ch 10