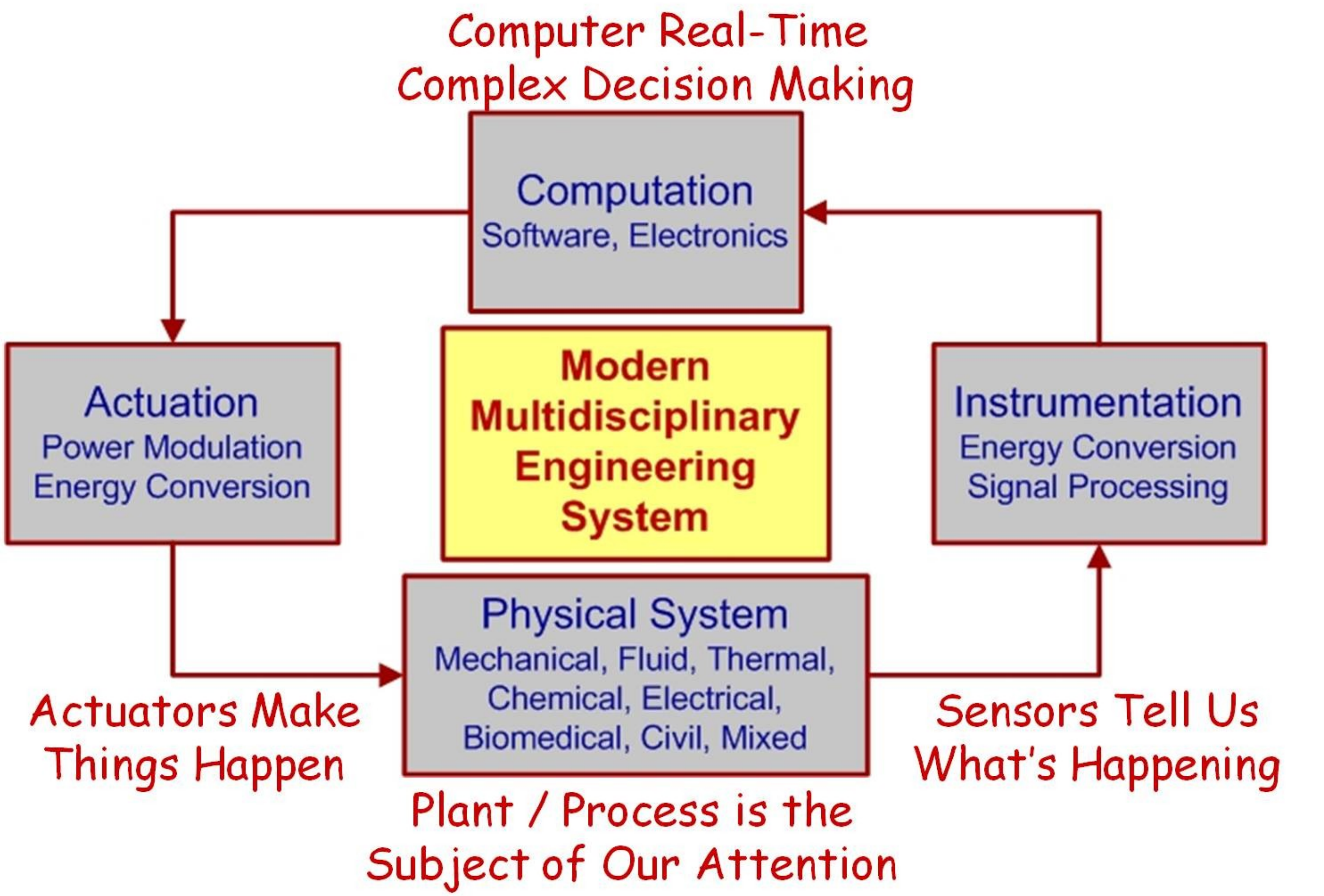
Electrical Systems:
Modeling, Analysis, Measurement, & Control



Electrical System Topics

- Part 5
  - Diodes
    - LED and Photodiode
  - Bipolar Junction Transistor (BJT)
    - Phototransistor

Diodes

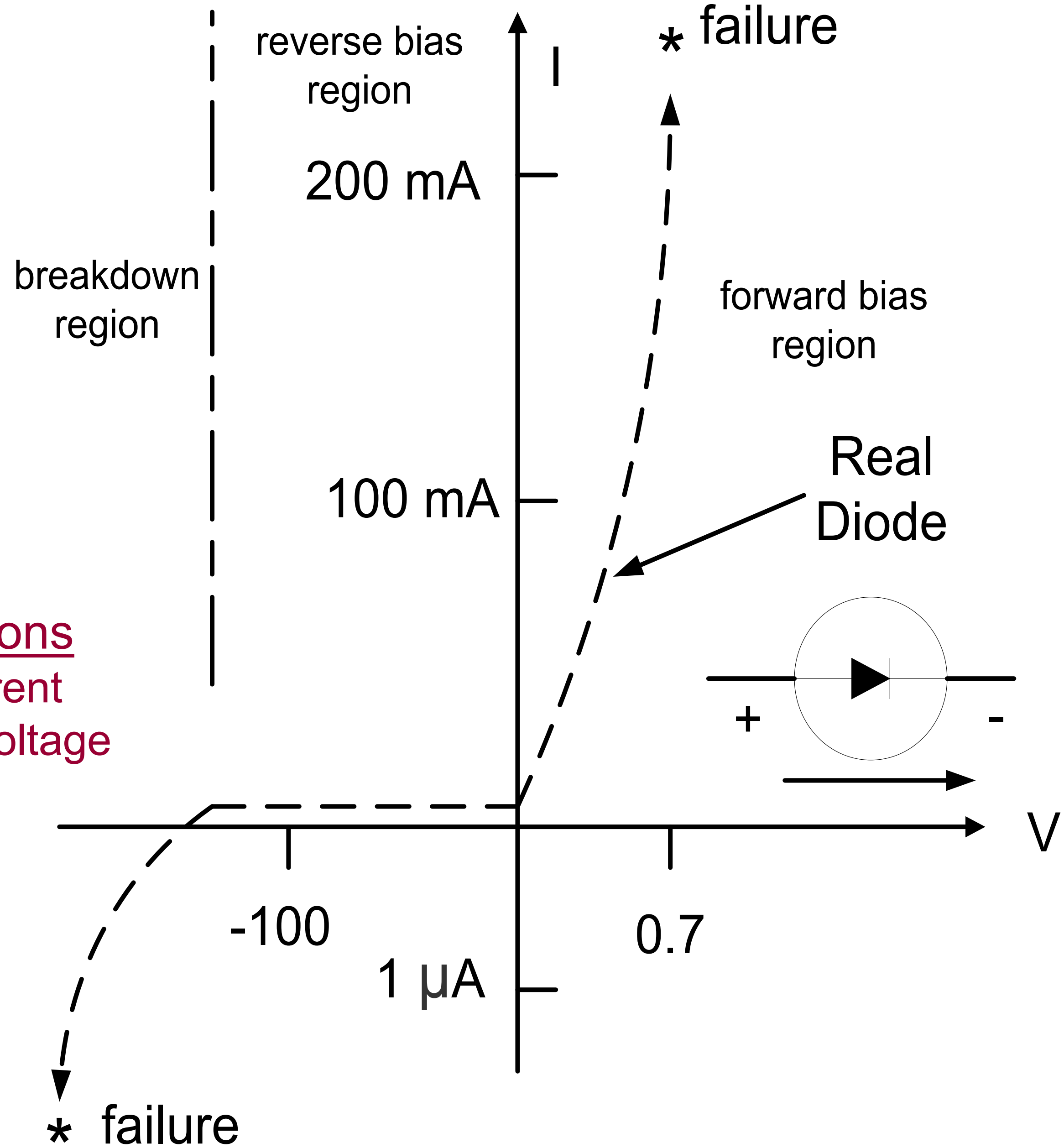
- Conductors, Insulators, & Semiconductors
  - Conductor: electrons migrate freely when an electric field is applied
  - Insulator: electrons do not move easily when an electric field is applied
  - Semiconductor: has properties somewhere between conductors and insulators
- Semiconductors
  - Silicon and Germanium (group IV of the periodic table) have current-carrying characteristics that depend on temperature or the amount of light falling on them.

- In a semiconductor crystal, a valence electron can jump to the conduction band and leave a hole in the valence band which can be filled by a valence electron from a nearby atom.
- Current can be thought of as the movement of holes in one direction or electrons in the other.
- Properties of pure semiconductor crystals can be changed by doping, i.e., adding small amounts (by diffusion or implantation) of elements (dopants) from group III (boron or gallium) or group V (arsenic or phosphorous) of the periodic table.
- Group V dopants are called donors because they enhance the electron conductivity of the semiconductor, resulting in a n-type semiconductor.

- Group III dopants are called acceptors because they cause the formation of holes, positive charge carriers, in the semiconductor, resulting in a p-type semiconductor.
- The purpose of doping a semiconductor, therefore, is to elevate and control the number of charge carriers in the semiconductor.
- n-type semiconductor: charge carriers are electrons
- p-type semiconductor: charge carriers are holes
- The interaction between n-type and p-type semiconductor materials is the basis for most semiconductor electronic devices.
- Contemporary electronic devices are produced by creating microscopic interfaces between differently doped semiconductor material.

- Junction Diode
  - pn junction: p-type region adjacent to a n-type region
  - depletion region: electrons from the n-type silicon diffuse to occupy the holes in the p-type silicon creating a depletion region.
  - contact potential: A small electric field develops across this thin depletion region due to the diffusion of electrons which results in a voltage difference across the depletion region called the contact potential, 0.6-0.7 V. The positive side is the n-type region; the negative side is the p-type region.
  - forward bias or conduction: connect a voltage source to the pn junction forming a complete circuit (+ to p-type and – to n-type). Depletion region shrinks and current flows when the applied voltage is > 0.6-0.7 V.

- reverse bias: connect a voltage source to the pn junction forming a complete circuit (– to p-type and + to n-type). Depletion region is enlarged, inhibiting diffusion of electrons and thus current.
- A pn junction passes current in only one direction; it is a one-way switch. It is known as a silicon diode and it is analogous to a fluid check valve, which allows fluid to flow only in one direction.
- An ideal diode has zero resistance (short circuit) when forward biased and infinite resistance (open circuit) when reverse biased. Switching between on and off states requires nanoseconds.
- Diodes are useful in passing only the positive half or the negative half of an AC signal, a process called rectification.



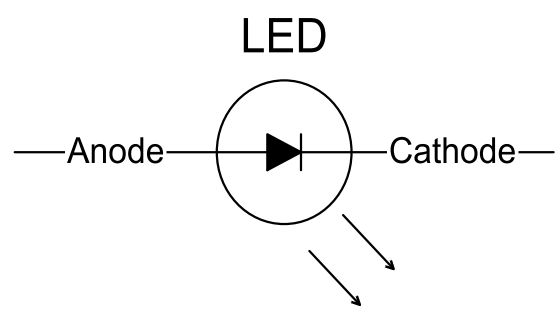
Important Specifications

maximum forward current

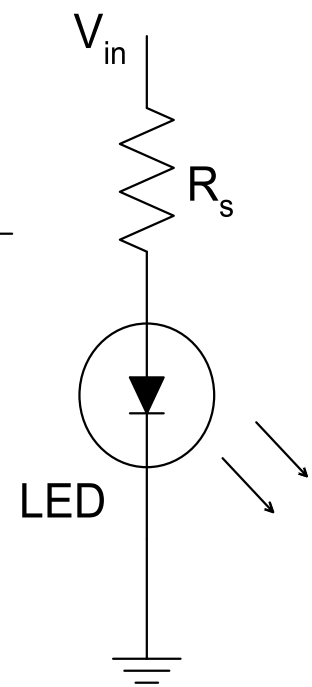
maximum reverse bias voltage

- Light-Emitting Diode (LED)
  - The Light-Emitting Diode (LED) is a semiconductor pn junction diode that emits visible light or near-infrared radiation when forward biased. Visible LEDs emit relatively narrow bands of green, yellow, orange, or red light. Infrared LEDs emit in one of several bands just beyond red light.
  - LEDs switch off and on rapidly, are very rugged and efficient, have a very long lifetime, and are easy to use. They are current-dependent sources, and their light output intensity is directly proportional to the forward current through the LED.
  - Always operate an LED within its ratings to prevent irreversible damage.

- Use a series resistor (R_s) to limit the current through the LED to a safe value. Usually a 330 Ω resistor is used in series with an LED when used with a 5V supply.
- V_{LED} is the LED voltage drop. It ranges from about 1.3 volts to about 2.5 volts.
- I_{LED} is the specified forward current.



$$R_s = \frac{V_{in} - V_{LED}}{I_{LED}}$$

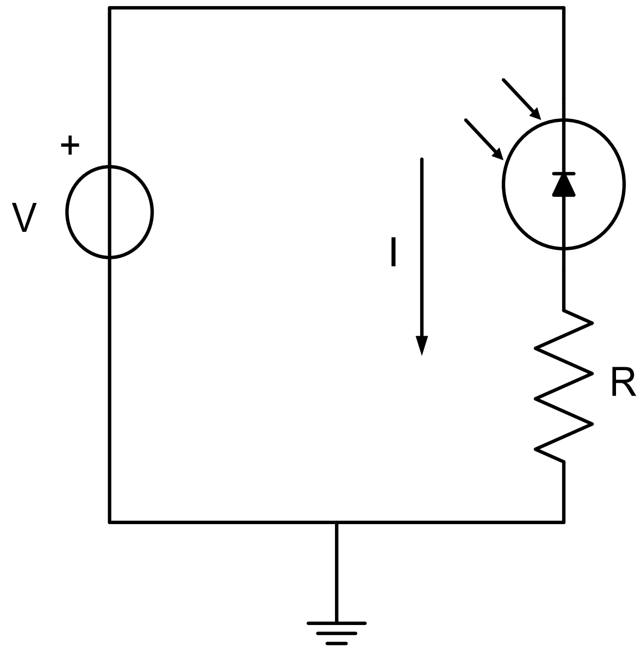


- Photodiode
  - The pn junction is sensitive to light.
  - Photodiodes are designed to detect photons and can be used in circuits to sense light.

Note:

Reverse current flows through the photodiode when it is sensing light.
If photons excite carriers in a reverse-biased pn junction, a very small current proportional to the light intensity flows.
The sensitivity depends on the wavelength of light.

Photodiode Light-detector Circuit



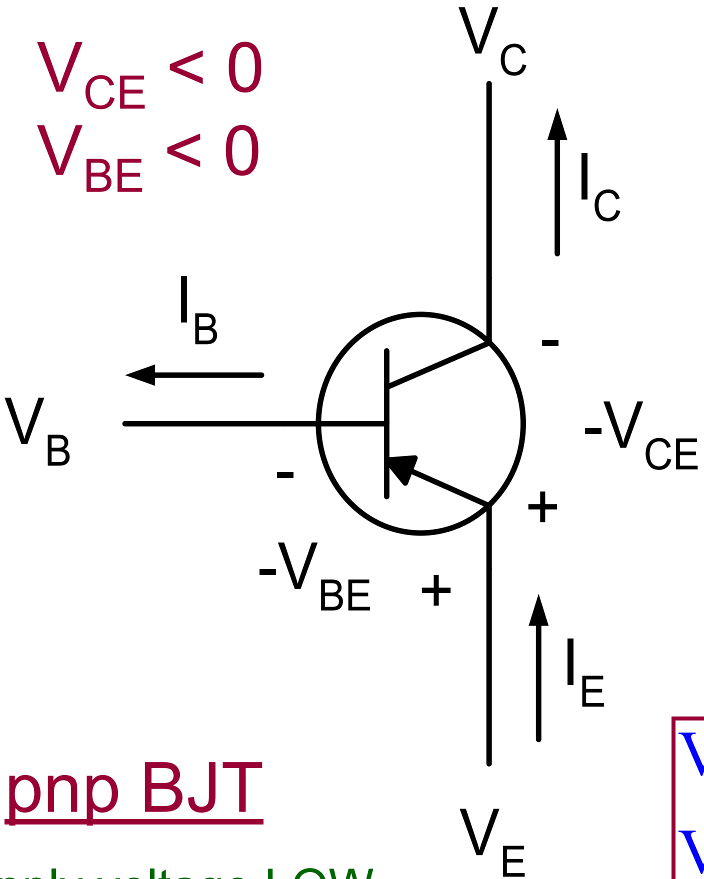
BJT and Phototransistor

- The bipolar junction transistor (BJT) is the salient invention that led to the electronic age, integrated circuits, and ultimately the entire digital world. The transistor is the principal active device in electrical circuits.
- When inputs are kept relatively small, the transistor serves as an amplifier. When the transistor is overdriven, it acts as a switch, a mode most useful in digital electronics.
- A BJT consists of three adjacent regions of doped silicon, each of which is connected to an external lead. The base, a very thin slice of one type, is sandwiched by the complimentary pair of the other type, hence the name bipolar.

- There are two types of BJTs, npn and pnp, and the three layers are called collector (C), base (B), and emitter (E).
- In the npn transistor, the base is a p-type silicon, and the collector and emitter are n-type silicon, with the emitter more heavily doped than the collector.
- In the pnp transistor, the base is a n-type silicon, and the collector and emitter are p-type silicon, with the emitter more heavily doped than the collector.
- Each type has three different ways the load can be wired across the collector and emitter, in regard to position and current direction. They are common emitter, common collector, and common base.
- All current directions are reversed from the npn-type to the pnp-type.

• Bipolar Junction Transistors

$V_{CE} < 0$
$V_{BE} < 0$

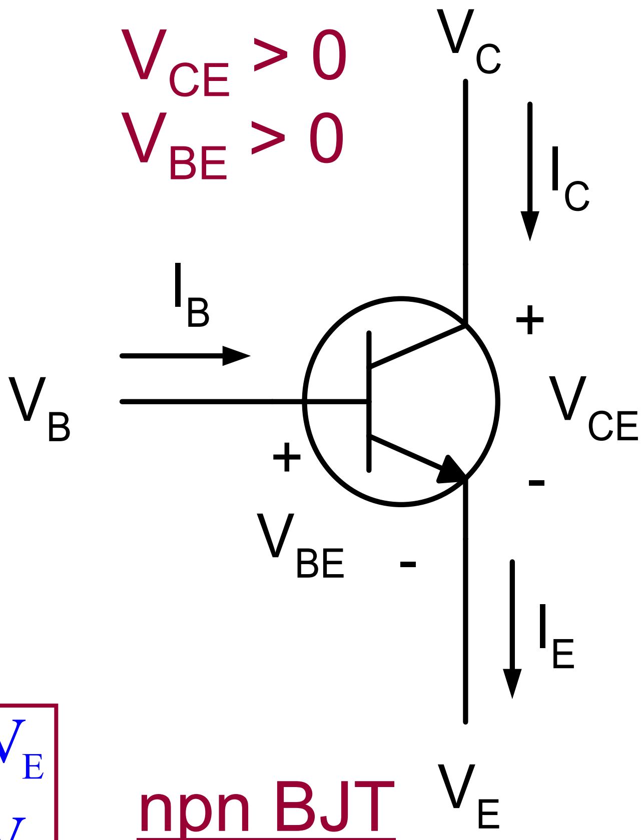


pnp BJT

Apply voltage LOW
to base to turn ON

$$\boxed{\begin{aligned} V_{CE} &= V_C - V_E \\ V_{BE} &= V_B - V_E \\ I_E &= I_C + I_B \end{aligned}}$$

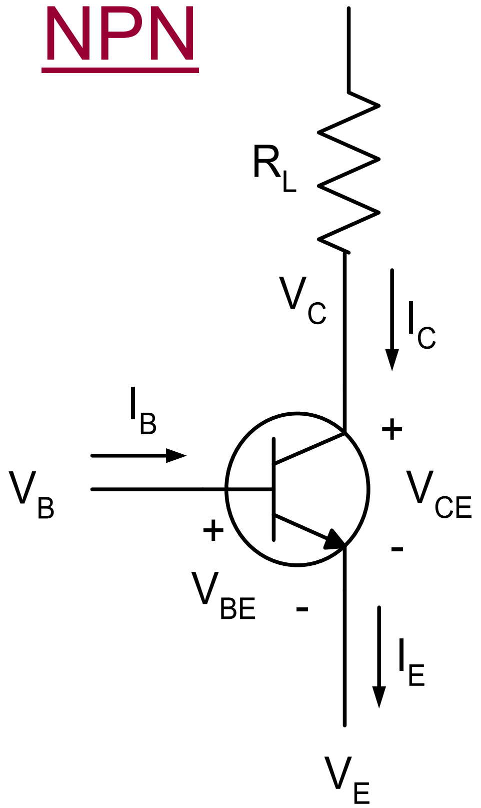
$V_{CE} > 0$
$V_{BE} > 0$

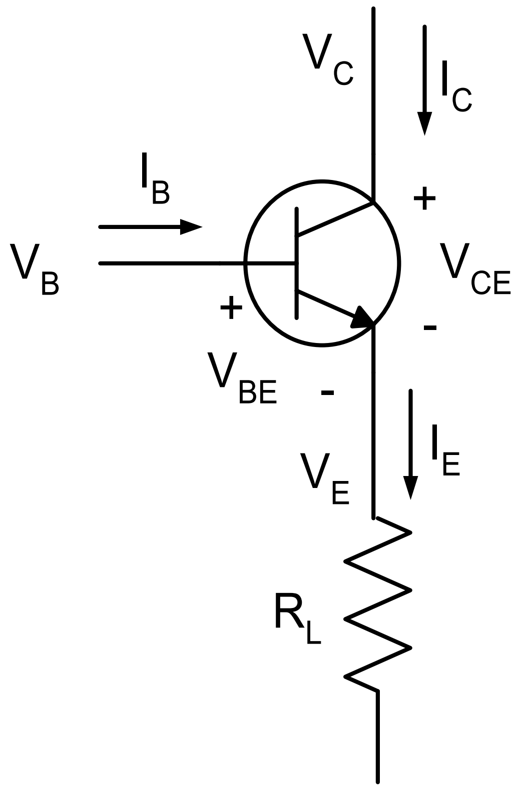


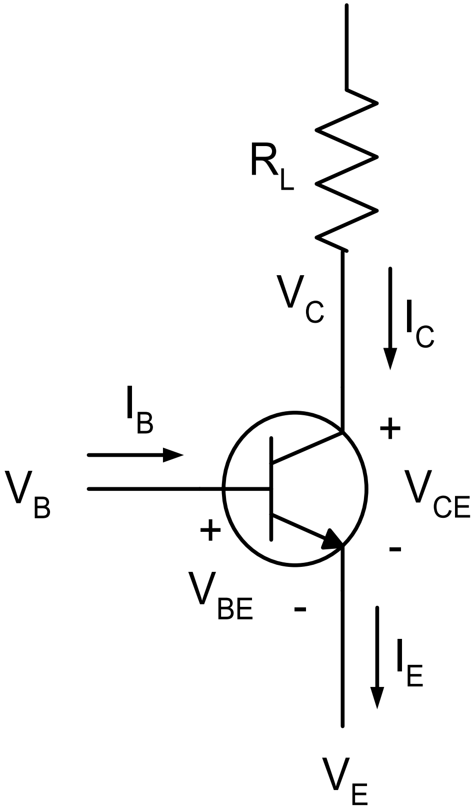
npn BJT

Apply voltage HIGH
to base to turn ON

NPN







Common Emitter

Highest Power Gain

Common Collector

Highest Input Resistance
Lowest Output Resistance

Common Base

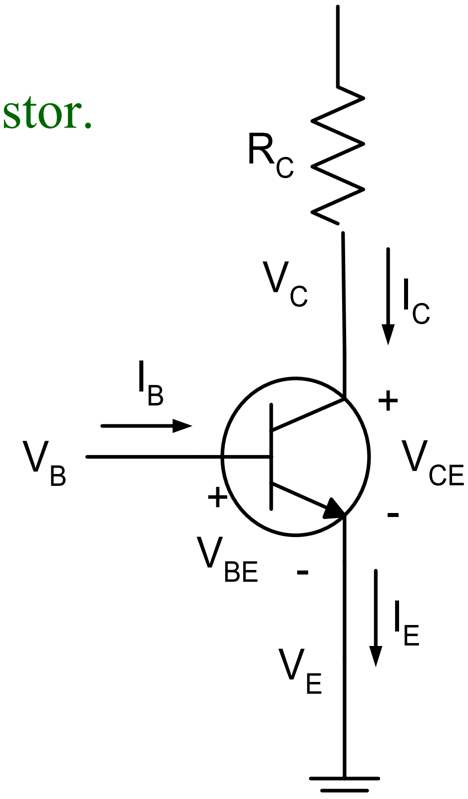
Lowest Input Resistance
Highest Output Resistance

Note: All current directions are reversed from the npn-type to the pnp-type. The npn-type is the more popular; it is faster and costs less.

- Let's understand how the npn BJT functions
  - The base-to-emitter junction is normally forward biased ($V_B > V_E$).
  - Electrons diffuse from the emitter n-type region to the base p-type region.
  - The base-to-collector is normally reverse biased ($V_C > V_B$) and there is a depletion region that would normally prevent the flow of electrons from the base to the collector.
  - The base, however, is very thin and the emitter is more heavily doped than the base. Most of the electrons from the emitter accelerate through the base region with enough momentum to cross the depletion region into the collector without recombining with holes in the base.
  - The result is that a small base current I_B flows from the base to the emitter and a larger current I_C flows from the collector to the emitter.
  - The small base current controls a larger collector current and the BJT functions as a current amplifier.

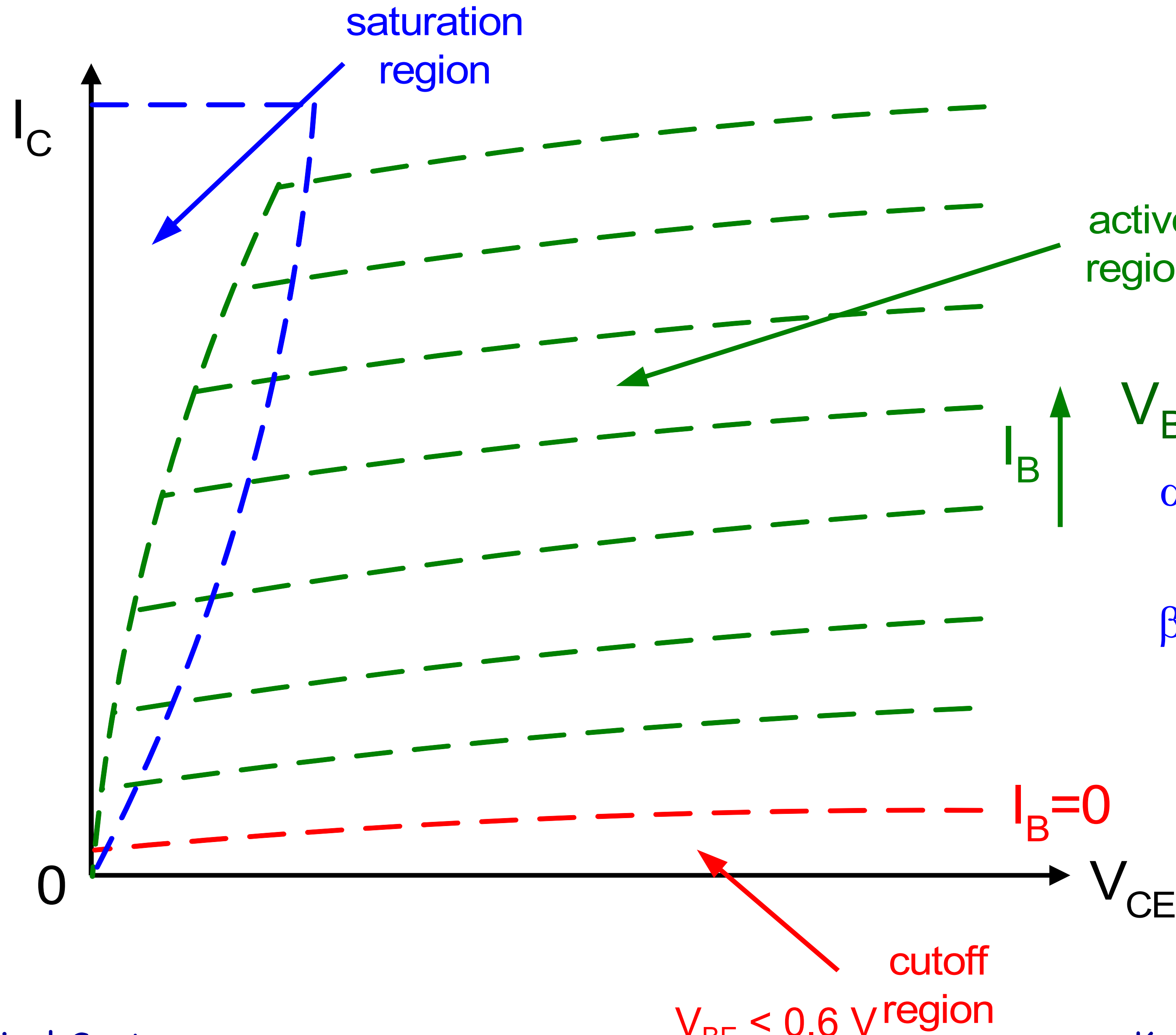
$$I_C = \beta I_B \qquad 10 < \beta < 1000$$

- The amplification factor β for the transistor is temperature and voltage dependent and so a design should not depend on a precise value for β.
- The BJT can be used as a current amplifier or simply to switch current on and off. The on-off switching is the basis for most digital computers as it allows easy implementation of a two-state binary representation.
- Consider the common emitter circuit shown.
- The family of curves (next page) describes the common emitter characteristics for the transistor.



Gradually increase I_B.
When $V_{BE} > 0.6$ V, I_C flows and $I_C = \beta I_B$.
As I_B is further increased, V_{BE} slowly rises to 0.7 V, but I_C rises exponentially.
As I_C rises, the voltage drop across R_C increases and V_{CE} drops toward ground.
The transistor is in saturation; I_C is determined by R_C and the linear relation $I_C = \beta I_B$ no longer holds.

npn Common Emitter Characteristics



$I_C = \beta I_B$

$V_{BE} = 0.7$ V

$$\alpha = \frac{I_C}{I_E}$$

$$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$$

$$0.9 < \alpha < 0.999$$

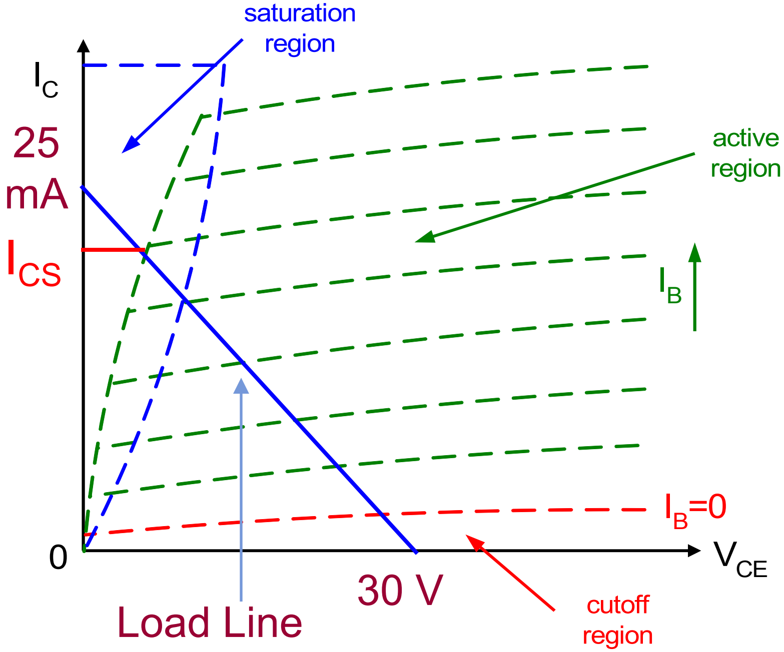
$$10 < \beta < 1000$$

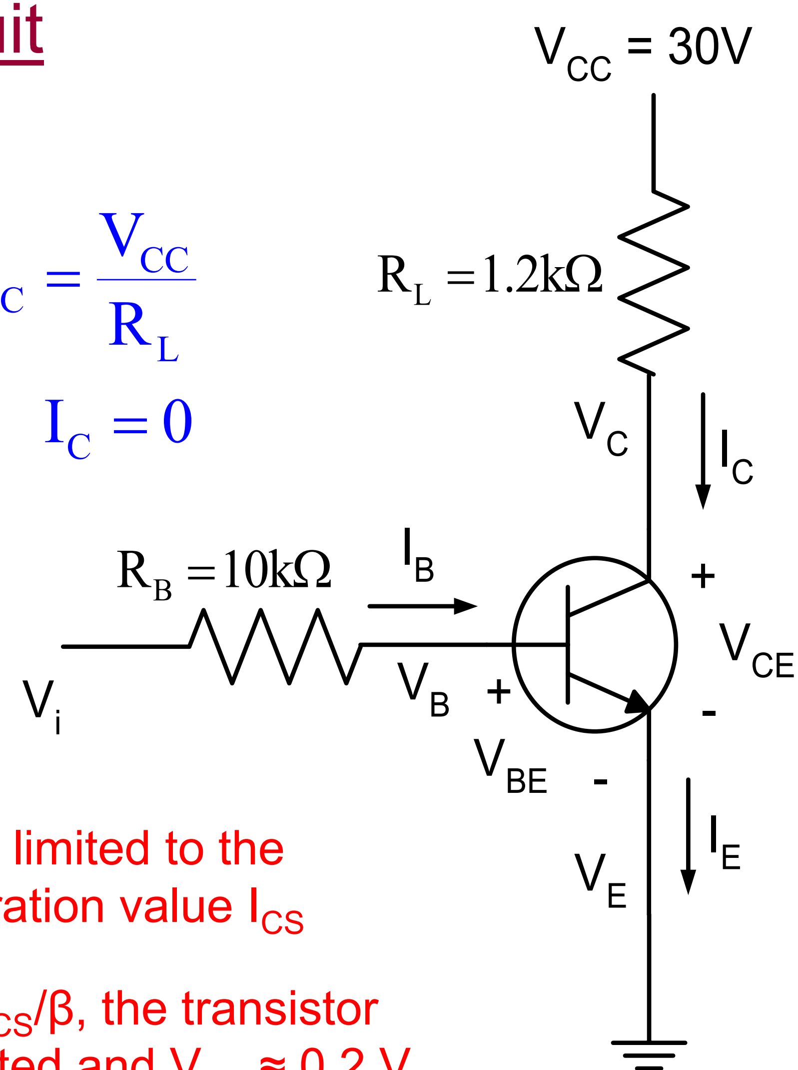
npn BJT Common Emitter Circuit

$$V_L = I_C R_L$$

$$V_{CE} = V_{CC} - V_L$$

V_{CE} can vary from: $\begin{cases} V_{CE} = 0 \;\rightarrow\; I_C = \dfrac{V_{CC}}{R_L} \\ V_{CE} = V_{CC} \;\rightarrow\; I_C = 0 \end{cases}$





I_C is limited to the saturation value I_{CS}

If $I_B \geq I_{CS}/\beta$, the transistor is saturated and $V_{CE} \approx 0.2$ V

Let V_i = 0.1 V, 1.0 V, 5 V
Describe the situations

- A transistor can be operating in only one of three states: linear or active, saturated, or cut off.
  - Cutoff region: no collector current flows
  - Active region: collector current is proportional to base current
  - Saturation region: collector current is strictly controlled by the collector circuit, assuming sufficient base current. In full saturation, V_{CE} is at its minimum (about 0.2 V). The power dissipated by the transistor ($I_C V_{CE}$) is smallest, for a given collector current, when it is fully saturated.
- For each of these states there is a set of relationships between the voltages and currents at the three terminals of the transistor.
- Saturated State – transistor acts as if the base, emitter, and collector are all connected together. The currents are determined by Kirchhoff's Laws and the external components.

$$V_E \approx V_B \approx V_C$$

- Cutoff State – no current is flowing in any of the leads. The voltages of the various terminals are unrelated and are determined by the external components in the circuit, but they must satisfy the inequalities below or else the transistor will not be cut off.

$$i_B \approx i_C \approx i_E \approx 0$$

$$\text{npn:} \quad V_B < V_C \quad \text{and} \quad V_B < V_E$$

$$\text{pnp:} \quad V_B > V_C \quad \text{and} \quad V_B > V_E$$

- Active State
  - $I_C \neq 0$ and is not a strong function of V_{CB}.
  - I_B is small and V_{BE} is small and relatively constant ≈ 0.6 V
  - $I_C \approx I_E$
  - npn transistor (finite β): all currents are > 0; $V_{CB} > 0$; $V_{CE} > 0$
  - pnp transistor (finite β): all currents are > 0; $V_{CB} < 0$; $V_{CE} < 0$

- <u>Phototransistor</u>
  - When a phototransistor is connected in series to a resistor, it functions as a photoconductive detector.
  - The junction between the base and emitter acts as a photodiode.

LED's and phototransistors are often found in pairs used to detect the presence of an object that may partially or completely interrupt the light beam between the LED and phototransistor.

An opto-isolator is composed of a LED and a phototransistor separated by a small gap; it creates a state of electrical isolation between the input and output circuits.