Bipolar Junction Transistors

- A three terminal device that allows a small current to control a much larger one
- Essentially two junction diodes
Bipolar Junction Transistors

• What’s going on?
  • BE diode doesn’t turn on until forward biased to ~ 0.6 V
  • In the linear region \( I_C = \beta \times I_B \) (\( \beta \) is a bad design parameter!)
  • Eventually saturate and \( I_C \) depends solely on the attached load.
Bipolar Junction Transistors

• Be sure “switch side” is opposite the load side.
Circuit Dynamics

- Frequency dependence of impedance is important

- Current through an inductor cannot change instantaneously.

- What happens when the switch is closed?

  \[ KVL: \ V = L \frac{dl}{dt} + IR \rightarrow I(t) = \frac{V}{R} \left[ 1 - e^{-t/\tau} \right] \]

  where \( \tau = L/R \) is the time constant

So, as \( t \to \infty \), \( V_L \to 0 \) and the inductor behaves as a short circuit.
Junction Diodes

- Inductive kickback
  - Big problem when switching inductive loads (motors, solenoids)
  - A changing current induces a voltage across the inductor, making the potential at A greater than at B.
  - This can cost you the price of a new switch.
  - Flyback diodes protect against this.

![Diagrams](image)
Bipolar Junction Transistors

- H-Bridge motor drivers
Operational Amplifier

- Two inputs
  - inverting
  - non-inverting
- One output
- External power connections

[Diagram of an operational amplifier with labeled inputs and output.]
Operational Amplifier (w/o feedback)

• The internal op-amp formula is
  \[ V_{out} = \text{Gain} \times (V_+ - V_-) \]

• So if \( V_+ \) is greater than \( V_- \), the output goes positive
• If \( V_+ \) is less than \( V_- \), the output goes negative
• A Gain of ~200,000 (for a real op-amp) makes this device practically useless (at least as shown here...)
Operational Amplifier (negative feedback)

- Infinite gain is not generally useful unless used with negative feedback
- Imagine hooking the output to the inverting input

If the output is less than $V_{in}$, it must go positive
If the output is greater than $V_{in}$, it must go negative

The result is that the output quickly forces itself to be exactly $V_{in}$. 
Operational Amplifier (negative feedback)

• What happens under load?

• Load wants to pull output to GND

• Op-Amp will do all it can (within current limitations) to drive output to $V_{in}$
  
  • In this case, the op-amp drives (or sinks, if $V_{in}$ is negative) a current through the load until $V_{out} = V_{in}$

The result is that we have a buffer that can apply $V_{in}$ to a load without worrying about the characteristics of the source of $V_{in}$. 
Operational Amplifier (positive feedback)

• What happens under positive feedback?

• Now if the non-inverting input is more positive by even a tiny amount, the output tries to drive it still more positive

• The system will immediately “rail” at the supply voltage
  • This could be either positive or negative, depending on the initial offset
Golden Rules

• The inputs draw no current
• When wired with negative feedback the output does whatever is necessary to make the difference between the input voltages zero.

→ Only KCL, KVL, and Ohm’s Law are necessary to completely analyze op amp circuits.
Inverting Amplifier

- Resistor $R_f$ is connected to the inverting input and forms a negative feedback loop:

$$\text{No current flows into op-amp}$$

$$\frac{V_{in} - V_-}{R_1} = \frac{V_- - V_{out}}{R_f}$$

Using KCL:

$$V_{out} = G \left( V_+ - V_- \right) \quad \text{and} \quad V_+ = 0$$

$$V_{in} + \left( \frac{-V_{out}}{G} \right) = \left( \frac{-V_{out}}{G} - V_{out} \right)$$

$$\frac{V_{out}}{V_{in}} = - \frac{R_f}{R_1}$$
Non-Inverting Amplifier

- Positive input is held at $V_{in}$

$$V_{out} = G(V_+ - V_-)$$

$V_+ = V_{in}$ and $V_- = \frac{R_1}{R + R_f} V_{out}$

$$V_{out} = G \left( V_{in} - \frac{R_1}{R + R_f} V_{out} \right)$$

$\frac{V_{out}}{V_{in}} = \frac{G}{1 + \frac{GR_1}{R_1 + R_f}} \approx 1 + \frac{R_f}{R_1}$
Gain & Shift

Choose $R_f / R_1 = 1/8$

$V_{out} = \pm 1.5 \text{ V}$

Now what?

Limited to 0-3 V

Full-range is 3 V

Full-range is 24 V

Recall:

$\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$
Gain & Shift

\[ V_{\text{out}} = -\frac{R_f}{R_1} V_{\text{in}} + \left( \frac{R_3}{R_2 + R_3} + \frac{R_3}{R_2 + R_3} \frac{R_f}{R_1} \right) V_{\text{CC}} \]

Gain on input voltage

Shift on reference voltage

Vin (±12 V)

VCC

\( R_1 \)

\( R_2 \)

\( R_3 \)

\( R_f \)

\( v_{\text{out}} \) Limited to 0-3 V
Summing Amplifier

\[
\frac{V_A - V_1}{R} + \frac{V_A - V_2}{R} + \frac{V_A - V_3}{R} + \frac{V_A - V_{out}}{R_f} = 0
\]

\[
\rightarrow \quad V_{out} = -\frac{R_f}{R} (V_1 + V_2 + V_3)
\]
Differentiator

- High-Pass filter
- Tends to accentuate the effects of noise

\[ V_{\text{out}} = -RC \frac{dV_{\text{in}}}{dt} \]
Integrator

• Low-pass filter
• Tends to smooth signals over time.

\[ V_{out} = -\frac{1}{RC} \int V_{in}(t) \, dt \]