Vacuum Tube

- Evacuated tubes used in PhotoElectric Effect and early X-ray work circa 1890.
- Vacuum tube invented circa 1903 for radio by Marconi group. Diode action!
- Triode allowed modulation of anode current by small change in grid voltage.
Solid State Transistors

- Lilienfeld, Heil (Germany)
- Shockley and Pearson (Bell Labs Patent) circa 1930.
- Current modulation and gain
  \[ I_{CE} = \beta I_{BE} \quad (\beta \approx 100) \]
BiPolar Transistor Operation

Quiescent State: Open (diode action)
No current flow.

Conducting State: Closed (Forward Bias)
Internal Electric Fields $E$ are cancelled.

$I_E = I_C + I_B$
$I_B \sim 0$ small
$\alpha = \frac{I_C}{I_E} \sim 1$
$\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$
$B = h_{FE}$ transistor gain

Holes injected into base lower barrier potential.
$V_{CE} > 2V$ to allow electrons to flow across barrier.
(They can be captured by injected holes!)
Cross Section of an NPN Bipolar Device

Figure 3.13
Transistor Curves

- $I_C$ the current through the collector is almost constant when the transistor is operated in its linear range. $I_C = \beta I_B$

Transistor Curves

- The base current $I_B$ will begin to flow freely when $V_{BE} > 0.7V$.
- We say the transistor has turned on at this point.

$$I_C = \beta I_B$$
Amplification and Zin

Amplification

1) \( I_E = I_b + I_C \) \[\rightarrow\] \( \delta I_E = \delta I_C \)

2) \( \beta = I_C / I_b \sim I_E / I_b \) (\( I_b \sim 0 \) = few \( \mu A \))

2) \( V_E = V_b + 0.7V \) \[\rightarrow\] \( \delta V_b = \delta V_E = \delta I_E R_E \)

2) \( V_{cc} = V_C + V_E + 0.7V \) \[\rightarrow\] \( \delta V_E = -\delta V_C = \delta I_C R_C \)

\[
A_V = \frac{\delta V_C}{\delta V_b} = -\frac{\delta I_C R_C}{\delta I_E R_E} = -\frac{\delta I_C R_C}{\delta I_C R_E} = -\frac{R_C}{R_E}
\]

\[
A_V = -\frac{R_C}{R_E}
\]

Input Impedance (Impedance looking in to base)

\( Z_{IN} = V_b / I_b \approx V_E / I_b = I_E R_E / I_b = (I_E / I_b) R_E = \beta R_E \)

\[
Z_{IN} = \beta R_E
\]
Temperature Dependence

The base-emitter voltage of the silicon pn junction in a transistor is written as a function of temperature $T$, reference temp $T_0$, bandgap gap voltage $V_g$, collector current $I_C$ and current $I_{C0}$ at $T_0$.

$$I_C = I_{C0} \cdot e^{\frac{qV_g}{kT}(1-T/T_0)} \cdot e^{\frac{qV_{BE0}}{kT} \left(\frac{T}{T_0}\right)} \times e^{\frac{qV_{BE}}{kT}}$$

This temperature dependence will make any transistor amplifier gain drift up or down. Differential pairs of transistors are commonly used to cancel common mode drifts.

$$I_C \sim I_{C0} \cdot e^{\frac{qV_{BE}}{kT}}$$
Differential Pair

• In order to cancel transistor temperature drifts and some \textit{common mode noise} we commonly see a differential pair used.
• Temperature dependent leakage currents in the two transistors tend to cancel when Q1 and Q2 are located near each other.
• When the input is grounded Q1 and Q2 cancel each others signal so the output is clamped to zero also.

\begin{center}
\textbf{Fig. 5-3. Amplifier with single-ended input.}
\end{center}
Frequency Response

- We can think of the amplifier as a combination of low and high pass filters in the circuit below.
- \( f_{lo} \) = mainly due to the input capacitor \( C_{IN} \) and input impedance \( R_{IN} = Z_{IN} \).
- \( f_{hi} \) = The stray capacitances \( C_S \) is internal to the every circuit and represents small capacitances due to connection leads and internal fabrication. \( R_{OUT} = Z_{OUT} \)

\[
\begin{align*}
  f_{lo} & \sim \frac{1}{2\pi R_{IN} C_{IN}} \\
  f_{hi} & \sim \frac{1}{2\pi R_{OUT} C_S}
\end{align*}
\]

\( C_{IN} = 1\mu F \)
\( R_{IN} = 10K\Omega \)
\( R_{OUT} \)
\( C_S = 1nF \)

high pass  
low pass
Common Emitter Amplifier

• Emitter is grounded ➔ “Common Emitter”
  (Signal Source and load share the ground at E)

• NPN Transistor with positive +Vcc forward biases
  the base-emitter junction.
• The transistor acts as a “Constant Current Source” when
  forward biased correctly.
• The resistance across the base-emitter junction is about
  \( r_E = 25 \text{mv} / I_E \)

• Rule of Thumb ➔ \( I_C \sim I_E \sim 1 \text{ma} \)

• Usually the input is “AC coupled” by inputing Vin through
  capacitor C. Only the AC component of a signal is passes!
• GAIN = \( \text{Vout}/\text{Vin} = -R_C / R_E \) and Vout is 180° inverted.
• Input impedance \( r_{IN} = (1/R_1 + 1/R_2 + 1/\beta R_E)^{-1} \)
  if \( R1 \) and \( R2>>R_E \) \( r_{IN} \sim \beta R_E \)
• \( r_{OUT} \sim (1/R_C + 1/R_E)^{-1} \sim R_C \) looking into the output.
• \( V_E \sim \text{Vin} - 0.7 \text{V} \) indicating small voltage drop across
  base-emitter junction.
• \( \text{Vout} = \text{Vcc} - I_C R_C = V_C \)

• Vout maximum ~ Vcc (power supply voltage)
Transistor Switch

• A transistor can be used as a robust switch to turn currents on and off.
• A small base current can control a large voltage supply current.
• When the switch is closed the transistor is driven into saturation and acts as a short circuit.
• Transistors are useful switches when driving loads from high impedance sources (small current) such as microcomputers etc.
• Proper choice of $R_B$ important to transistor life.

\[
\begin{align*}
V_{OUT} &= \begin{cases} 
V_{cc} & \text{transistor OFF / OPEN (} I_C = 0 \text{ and } V_{out} = V_{cc}) \\
0 & \text{transistor ON / CLOSED} 
\end{cases} \\
& \text{Vout } \sim I_C \rightarrow I_{transistor} = 0
\end{align*}
\]

### Biasing Resistors

\[
\begin{align*}
I_B &= \frac{V_{cc}}{R_B} \\
I_C &= \beta I_B = \beta \left( \frac{V_{cc}}{R_B} \right) \\
V_C &= I_C R_C = \beta \left( \frac{V_{cc}}{R_B} \right) R_C \\
\frac{V_C}{V_{CC}} &= \beta \left( \frac{R_C}{R_B} \right) \leq 1 \quad (Saturation!) \\
R_B &\approx \beta R_C
\end{align*}
\]
Common Collector - Emitter Follower

• A emitter follower is a power booster circuit with unity gain.
• It is sometimes called a repeater or buffer amplifier.
• A small base current can be boosted to a large base current while preserving the signal shape, but significantly increasing the output power.
• The output is taken from the emitter.
• The emitter follower can be used to match a high impedance input to low impedance output.

![Diagram of Common Collector - Emitter Follower]

Output
1) \( V_E = V_B - 0.6V \)  \( V_E \approx V_B \)  \( V_{OUT} = V_{IN} \)

Input Impedance
(Im pedance − to − ground seen looking in to base)
1) \( V_E / R_E \sim V_B / R_E = I_E = I_B + I_C = (1 + \beta)I_B \)
   \( V_B / R = (1 + \beta)I_B \)
2) \( Z_{IN} = V_B / I_B = (1 + \beta)R_E \sim \beta R_E \)  \( Z_{IN} = \beta R_E \)

Output Impedance
(Effective series impedance at transistor output)

\[ Z_{OUT} = Z_{SOURCE} / \beta \]
Cascading Amplifiers

- To achieve higher gain or input impedance we can cascade amplifiers output-to-input.

\[ Av = \beta^2 \frac{RC}{RE} \]

\[ Rin = \beta^2 R_E \]

\[ Av = 1 \]

\[ Rin = \beta^2 R_E \]

\[ Rout = \frac{R_{sources}}{\beta^2} \]
Feedback

• An amplifier may become more stable if a fraction of the output signal is fed back into the input. ($\beta$=feedback fraction +/-)
• Positive feedback will enhance oscillatory behavior.
• Negative feedback will tend to cancel unwanted oscillatory behavior.

$Vo = A_V Vs$
$Vs = Vi + \beta Vo$
$Vo = A_V(Vi + \beta Vo) = A_V Vi + \beta A_V Vo$
$Vo (1- \beta A_V ) = Vi A_V$
$A'_V = Vo / Vi = A_V/(1- \beta A_V)$
Basic Transistor Amp

\[ I_E = I_B + I_C \]
\[ V_{CC} = V_C + V_E + 0.7V \]
\[ \Delta V_C + \Delta V_E = 0 \]
Transistor Amp Design

- Set $R_E$ by the input impedance. $Z_{in} = \beta R_E$

- Set the $R_C$ by the desired voltage gain. $|Av| = R_C / R_E$

- Set $R_2$ by the criteria that $R_2 = 10\%$ $Z_{in} = \beta R_E / 10$
  ( $R_2$ diverts most current away from the transistor )

- Set $R_1$ by the amplifier gain $Av$ and dynamic range of the power supply $V_{cc}$.
  
  $V_b = 0.7V + (1/Av) V_{cc} / 2$
  
  $V_b = \frac{R_2}{(R_1+R_2)} V_{cc}$
  
  Solve for $R_1$