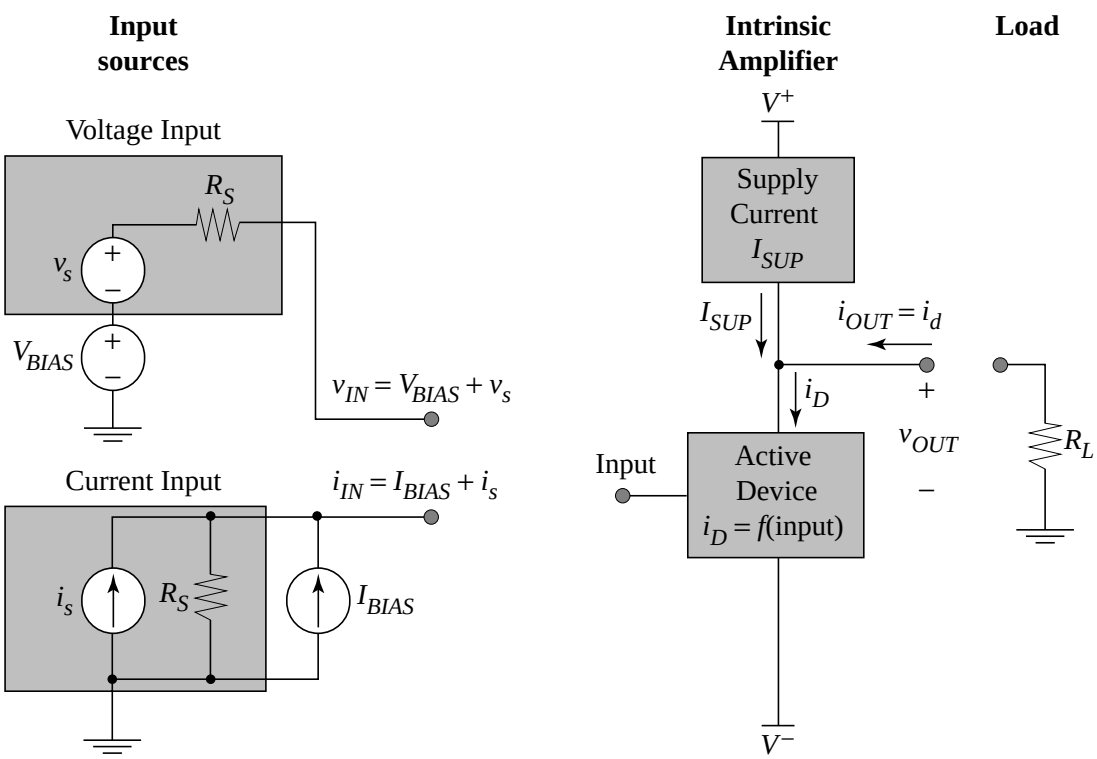
# Transistor Amplifiers

- Perspective: look at the various configurations of bipolar and MOS transistors, for which a *small-signal* voltage or current is transformed (e.g., usually *amplified* -- increased in magnitude) between the input and output ports.
- Amplifier terminology:




Abstractions:

Sources include precisely adjusted bias voltages or currents

Source resistance is associated with the small-signal source (and neglected for bias calculations)

Load resistance typically models another amplifier, speaker, actuator, etc.

# Amplifier Biasing

- Input bias voltage $V_{IN}$ sets the DC device current, $I_D$ to precisely equal the supply current $I_{SUP}$

  (note -- $D$ = "*device*" here)

- Likewise, if the input is the sum of small-signal and DC current sources, then the input bias current $I_{BIAS}$ is chosen so that it sets $I_D = I_{SUP}$

  The DC output current is $I_{OUT} = I_D - I_{SUP} = 0$ A, which implies that the DC output voltage $V_{OUT} = 0$ V also.

Note: both positive and negative DC supply voltages are used so $V_{OUT} = 0$ V does *not* mean that the DC voltage drop is zero!

**KEY IDEA**: the small-signal voltage or current source perturbs the amplifier bias, through $i_D$ = f (input), which results in a small-signal output current

$$i_{OUT} = i_D - i_{SUP} = (I_D + i_d) - I_{SUP} = i_d$$

since the supply current is DC ($i_{SUP} = I_{SUP}$)

A small-signal output voltage is generated

$v_{out} = - R_L\, i_{out}$ , where $R_L$ is the load resistor

# Two-Port Amplifier Models

- How do we characterize an amplifier's response to a general input signal (Thévenin or Norton source)?

  the controlled source is determined by output signal
  (voltage or current ... we select which is of interest) and by the input signal

  Therefore, there are **FOUR** types of amplifiers:

  - Voltage
  - Current
  - Transconductance (voltage in, current out)
  - Transresistance (current in, voltage out)

- From network theory, any linear two-port network can be represented by $y_{ij}$, $z_{ij}$, $h_{ij}$, $g_{ij}$ ... our amplifier models are closely related to these formal two-port equivalent circuits, but they have

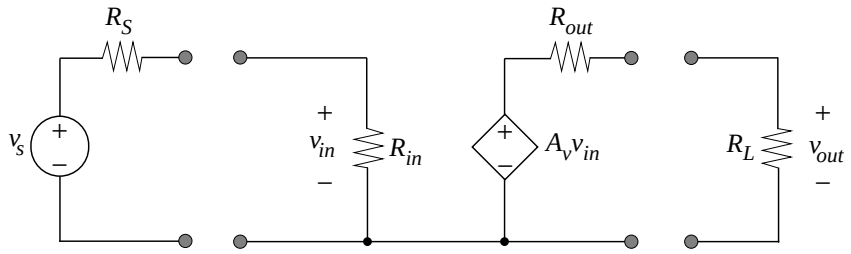
  > intuitively based elements, that can depend on $R_L$ or $R_S$

  > only numerically significant elements
  (no reverse transmission from output to input is included in any of our models)

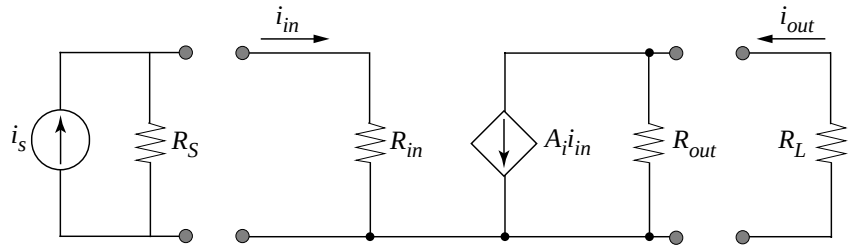
- We need methods to find the key parameters for all four models:

| | |
|---|---|
| $R_{in}$ = Input Resistance | $R_{out}$ = Output Resistance |
| $A_v$ = Voltage Gain | $A_i$ = Current Gain |
| $G_m$ = Tranconductance | $R_m$ = Transresistance |

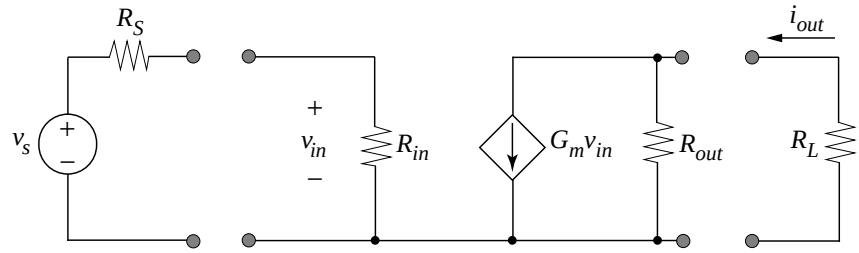
# Two-Port Small-Signal Amplifiers



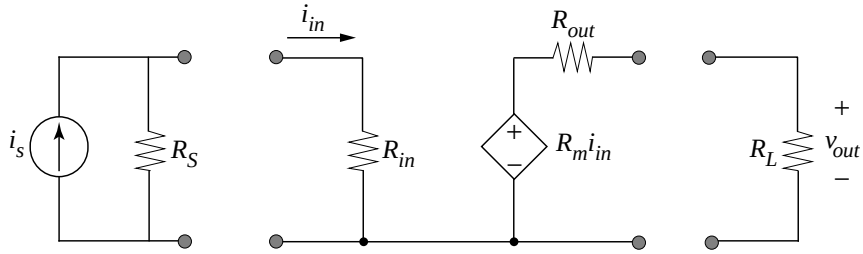

(a)




(b)




(c)

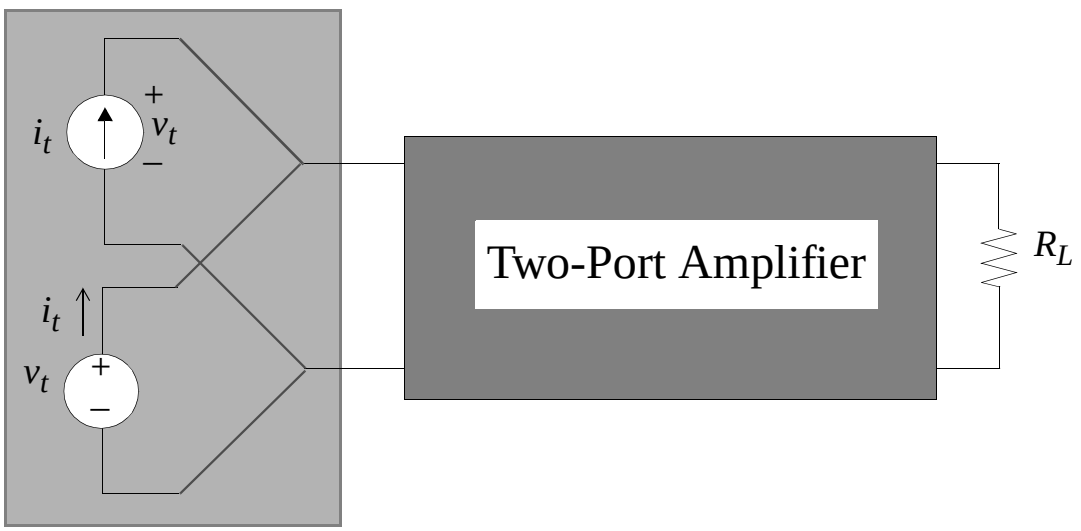



(d)

# Input Resistance $R_{in}$

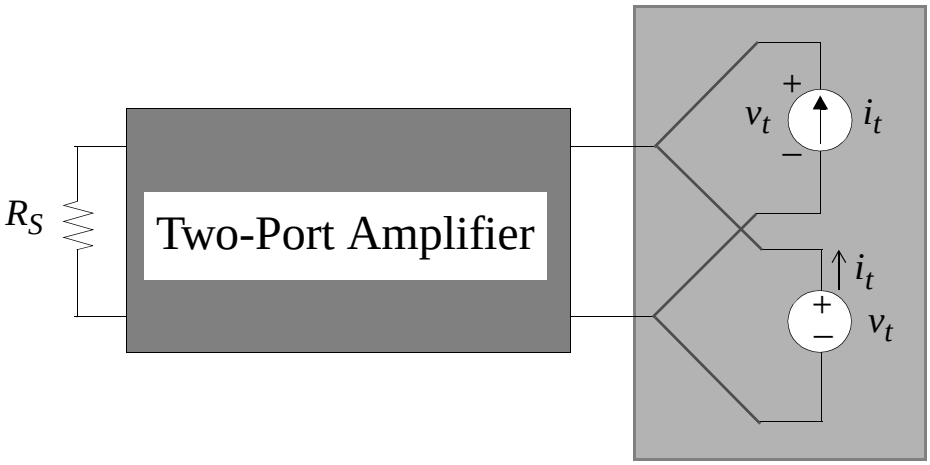
- Define systematic procedures to find the two-port parameters
- **Key idea**: leave the *load* resistance $R_L$ attached when finding $R_{in}$
- Apply a small-signal *test source* (voltage source **or** current source) and compute (using KVL, KCL, or inspection) the resulting current or voltage:

$$\boxed{R_{in} = \frac{v_t}{i_t}}$$



# Output Resistance $R_{out}$

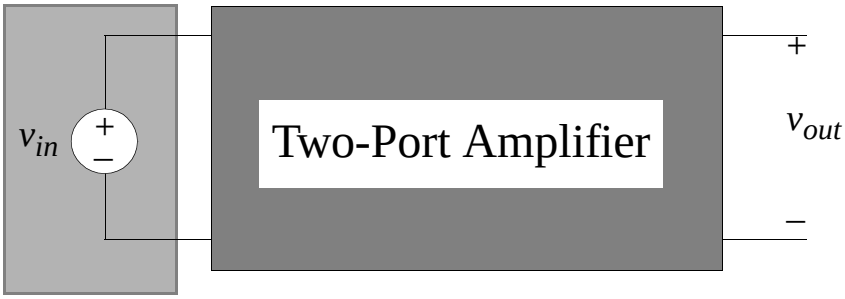
- Remove $R_L$; leave the source resistance attached when finding $R_{out}$




$$R_{out} = \frac{v_t}{i_t}$$

# Voltage Gain $A_v$ and Current Gain $A_i$

- **Voltage gain**: open-circuit the output port ($R_L$ --> infinity) and short the source resistance ($R_S$ --> 0 Ω) to find the unloaded voltage gain $A_v$:



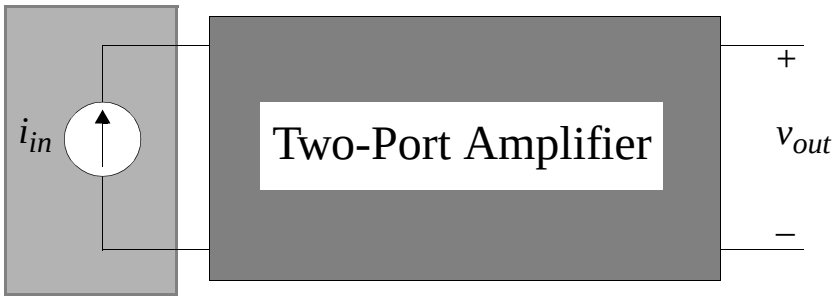

$$A_v = \left.\frac{v_{out}}{v_{in}}\right|_{R_S = 0,\ R_L \to \infty}$$

- Current gain: short-circuit the output port ($R_L$ --> 0 Ω) and open-circuit the source resistance ($R_S$ --> infinity) to find the short-circuit current gain $A_i$:


$$A_v = \left.\frac{i_{out}}{i_{in}}\right|_{R_S \to \infty,\ R_L = 0}$$

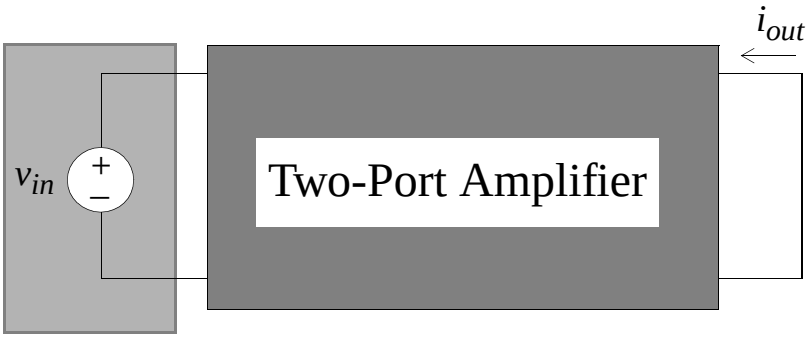
# Transresistance $R_m$ and Transconductance $G_m$

- Open-circuit the source resistance ($R_S$ --> infinity)and open-circuit the output port ($R_L$ --> infinity) to find the transresistance $R_m$:




$$R_m = \left.\frac{v_{out}}{i_{in}}\right|_{R_S \to \infty,\ R_L \to \infty}$$

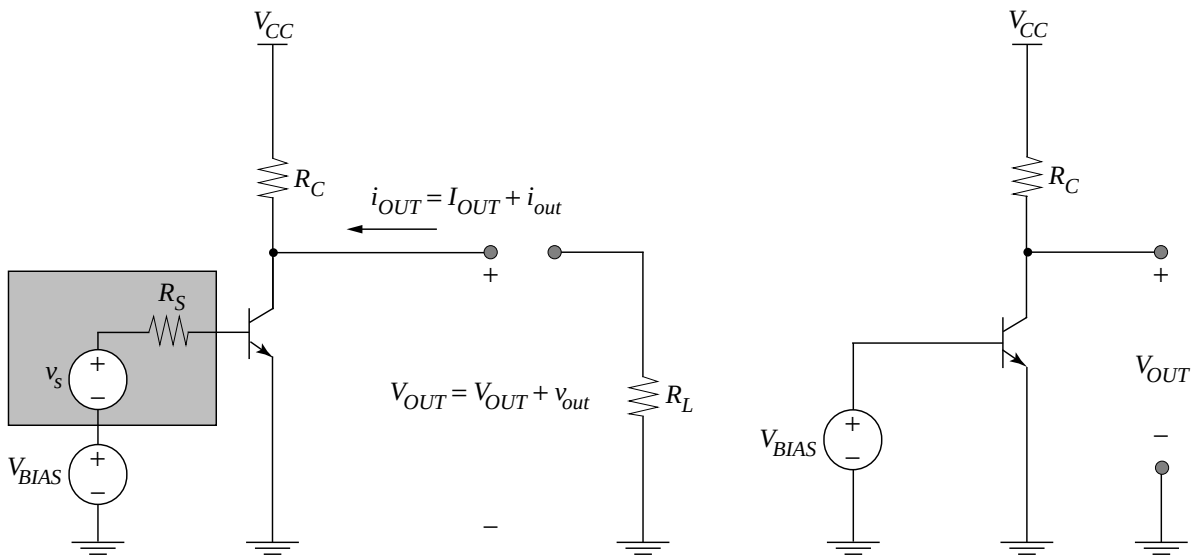
- Short-circuit the input resistance ($R_S = 0\ \Omega$) and short-circuit the output port ($R_L = 0\ \Omega$) to find the transconductance $G_m$:




$$G_m = \left.\frac{i_{out}}{v_{in}}\right|_{R_S = 0,\ R_L = 0}$$

# Common-Emitter (CE) Amplifier

- 1. Bias amplifier in high-gain region
- 2. Determine two-port model parameters



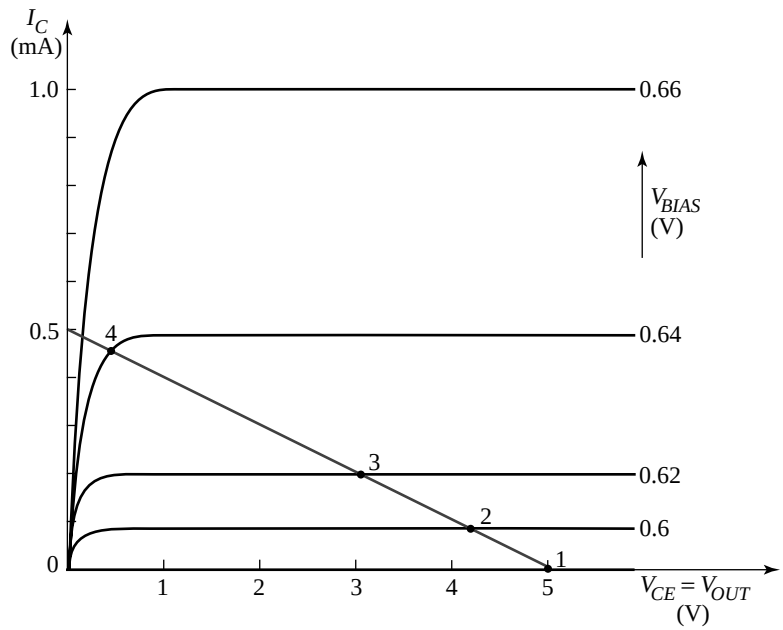

- Note that the source resistor $R_S$ and the load resistor $R_L$ are *disconnected* for determining the bias point

# Biasing the CE Amplifier

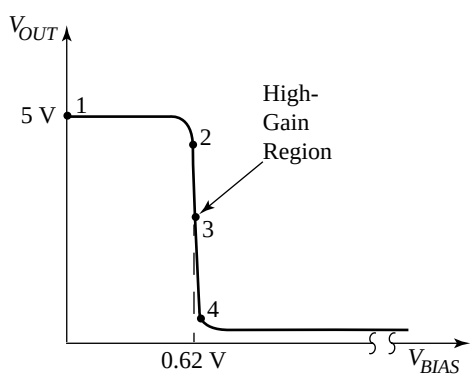
- Graphical approach: plot $I_C$ as a function of the DC base-emitter voltage $V_{BIAS}$ (note: normally plot vs. base current, so we must return to Ebers-Moll):

$$I_C = I_S e^{V_{BE}/V_{th}} = I_S e^{V_{BIAS}/V_{th}} \qquad \text{(forward active)}$$

Load line for $R_C$ = 10 kΩ; range of variation for $V_{BIAS}$ is only 600 mV - 660 mV




(a)




(b)

# Transfer Curve

- The load line was plotted, assuming that $V_{CC}$ = 5 V and that the collector resistor $R_C$ = 10 kΩ, with the equation:

$$I_C = \left(\frac{1}{R_C}\right)(V_{CC} - V_{OUT})$$

  The transfer curve is defined by intersections between the load line $I_C$ ($V_{OUT}$) and the family of collector current characteristics $I_C(V_{BIAS}, V_{OUT})$

- Where to operate? Maximize potential "swing" in $v_{OUT}$ by placing $V_{OUT}$ halfway between cutoff and saturation ... (5 V + 0.2 V)/2 = 2.5 V (approx.)

  Solve for the input bias voltage: $I_S = 10^{-15}$ A

$$I_C = \frac{V_{CC} - V_{OUT}}{R_C} \approx \frac{V_{CC}}{2R_C} = 0.25 \text{ mA}$$

$$V_{BIAS} = V_{th}\ln\left(\frac{I_C}{I_S}\right) = (26 \text{ mV})\ln\left(\frac{250\ \mu\text{A}}{10^{-15}\ \text{A}}\right) = 682 \text{ mV}$$

  The operating point is defined by:

$$\boldsymbol{Q}(V_{BE} = 0.682 \text{ V}, V_{CE} = 2.5 \text{ V}, I_C = 250\ \mu\text{A})$$

# Small-Signal Model of CE Amplifier

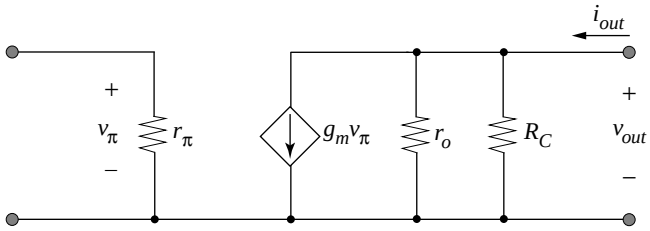
- The small-signal model is evaluated at ***Q***; we assume that the current gain is $\beta_o = 100$ and the Early voltage is $V_{An} = 25$ V:

$$g_m = I_C / V_{th} = 10 \text{ mS (at room temperature)}$$

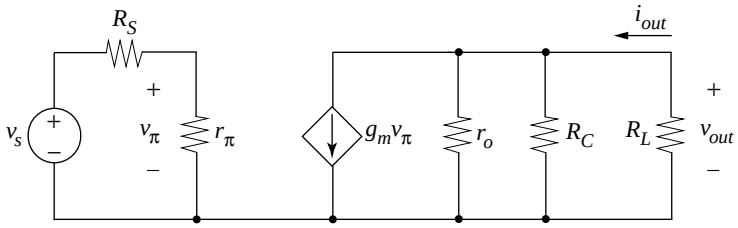
$$r_\pi = \beta_o / g_m = 10 \text{ k}\Omega$$

$$r_o = V_{An} / I_C = 100 \text{ k}\Omega$$

- Substitute small-signal model for BJT; $V_{CC}$ and $V_{BIAS}$ are short-circuited for small-signals




(a)




(b)