Lecture 20 - Linear Amp. Analysis and Design I - Outline

- **Announcements**
  Handouts - Lecture Outline and Summary
  Announcements - Design Problem due in under two weeks

- **Review** - Differential Amplifier Basics
  Difference- and common-mode signals:
  $v_{ID} = v_{IN1} - v_{IN2}$ and $v_{IC} = (v_{IN1} + v_{IN2})/2$ [$v_{IN1} = v_{IC} + v_{ID}/2$, $v_{IN2} = v_{IC} - v_{ID}/2$]
  Half-circuits: half of original with wires shorted or broken (familiar, easy analyses)

- **Performance metrics** - specific to diff. amps.
  Difference- and common-mode gains
  Common-mode rejection ratio
  Input and output resistances
  Common-mode input voltage swing; output voltage swing and DC value

- **Non-linear loads**
  The limitation of resistive loads: Gain limited by voltage supply
  Non-linear loads: High incremental resistance w. small voltage drop

- **Active loads**
  Current mirror load
  Lee load

Differential Amplifiers - what's the big deal?

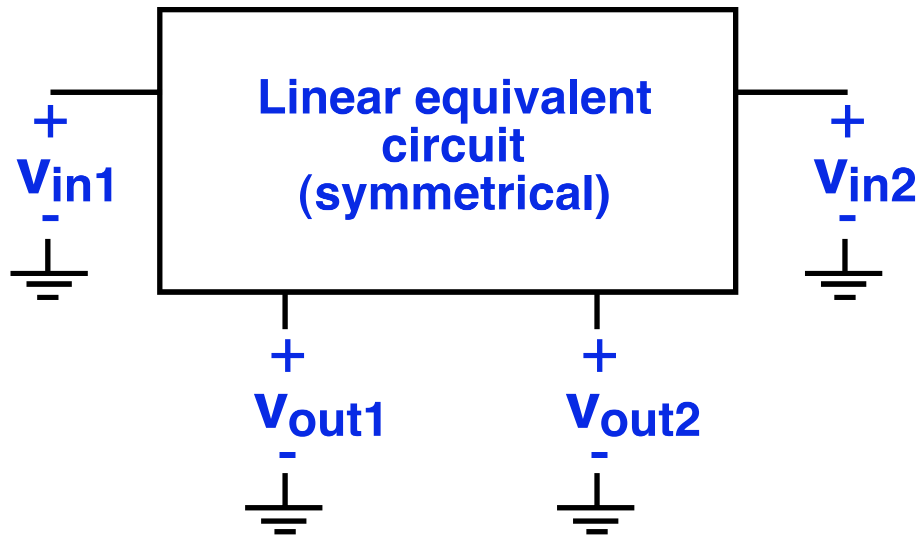
Intrinsic advantages and features:

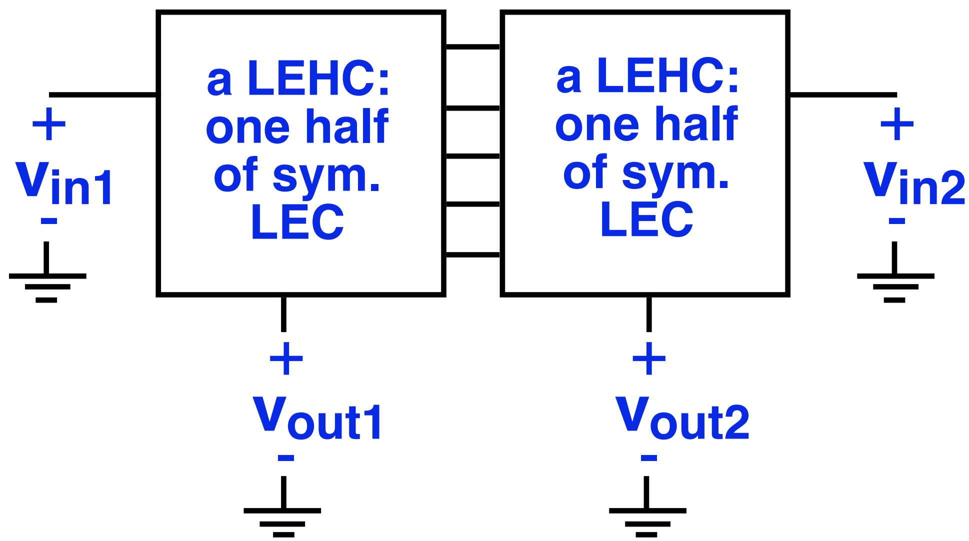
- large difference mode gain
- small common mode gain
- easy to cascade stages without coupling capacitors
- no emitter/source capacitor required in CE/CS stages

Performance metrics:

- difference mode voltage gain, A_{vd}
- common mode voltage gain, A_{vc}
- common mode rejection ratio, CMRR
- input resistance, R_{in}
- output resistance, R_{out}
- common mode input voltage range
- output voltage swing
- DC offset on output

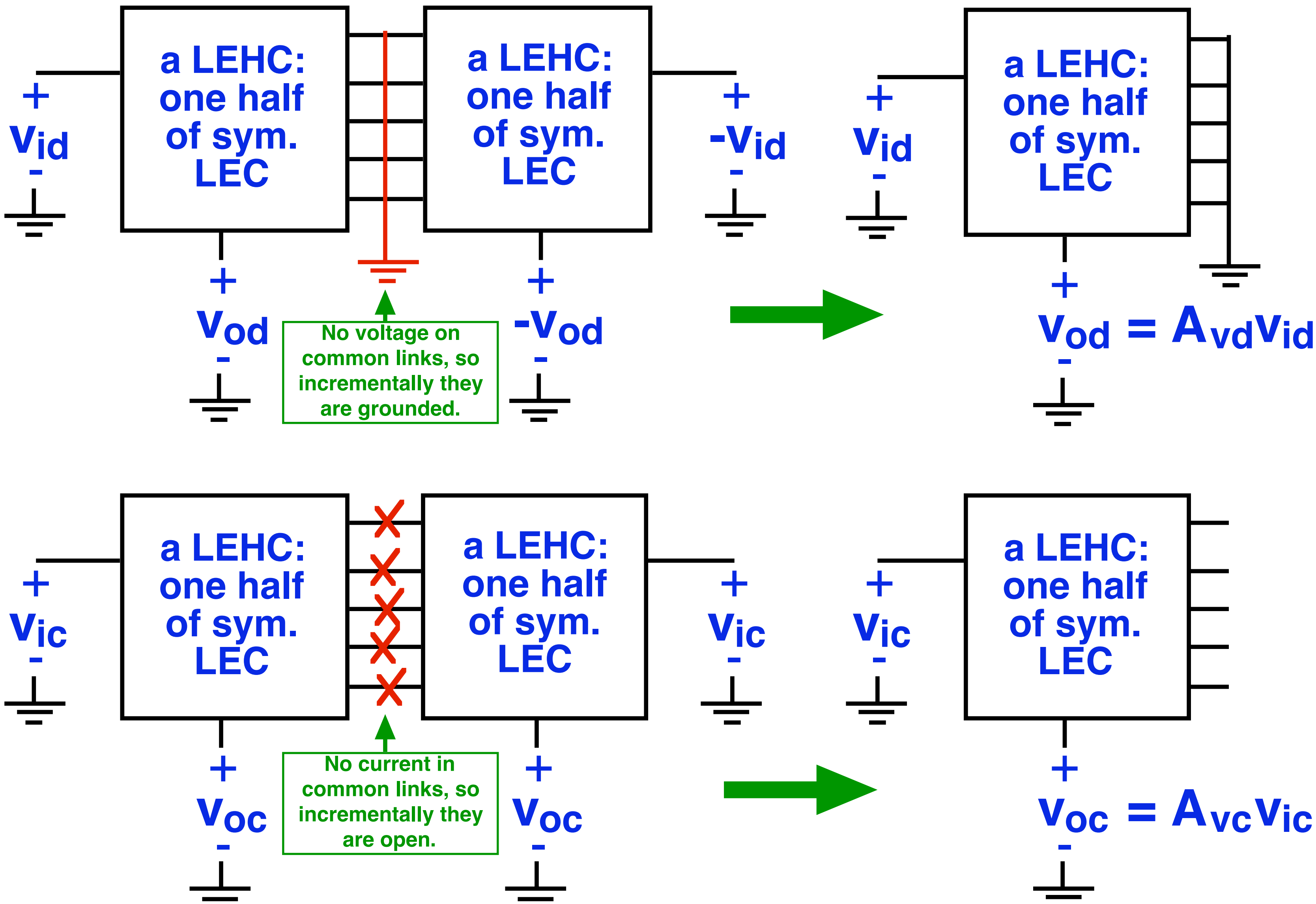
Differential Amplifier Analysis -
incremental analysis exploiting symmetry and superposition





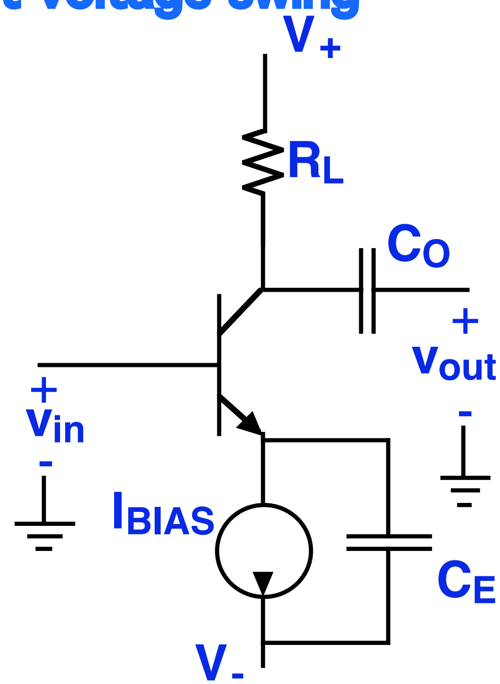
Differential Amplifier Analysis -

incremental analysis exploiting symmetry and superposition



Resistor Loads: the limit on maximum gain

- linear resistor loads require a compromise between voltage gain and output voltage swing



Maximum Voltage gain

$$\text{Bipolar}: \quad \left|A_{v,\max}\right| = g_m R_L = \frac{q I_C R_L}{kT} \leq \frac{\left[I_C R_L\right]_{\max}}{V_{thermal}}$$

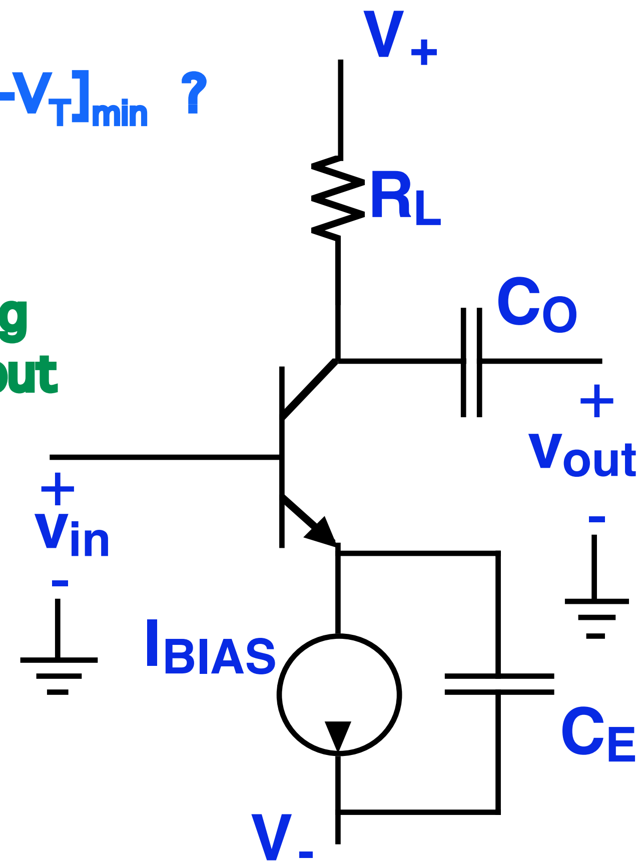
$$\text{MOSFET}^*: \quad \left|A_{v,\max}\right| = g_m R_L = \frac{2 I_D R_L}{\left[V_{GS} - V_T\right]} \leq \frac{2\left[I_D R_L\right]_{\max}}{\left[V_{GS} - V_T\right]_{\min}}$$

What are $[I_C R_L]_{max}$, $[I_D R_L]_{max}$, and $[V_{GS}-V_T]_{min}$?

* For a MOSFET $g_m = (2KI_D)^{1/2} = K(V_{GS}-V_T) = 2I_D/(V_{GS}-V_T)$

Resistor Loads: cont.

- What are $[I_C R_L]_{max}$, $[I_D R_L]_{max}$, and $[V_{GS}-V_T]_{min}$?

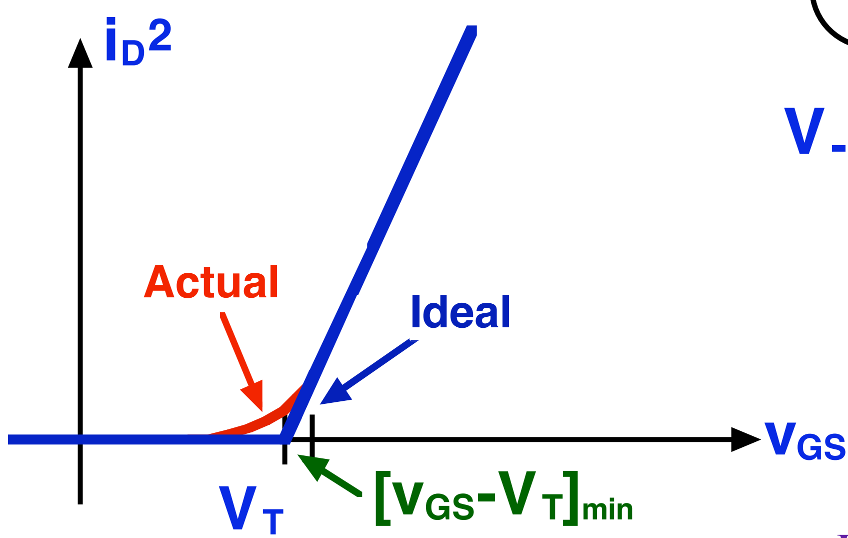


$[I_C R_L]_{max}$, $[I_D R_L]_{max}$:

Determined by the desired voltage swing at output and/or the common-mode input voltage range

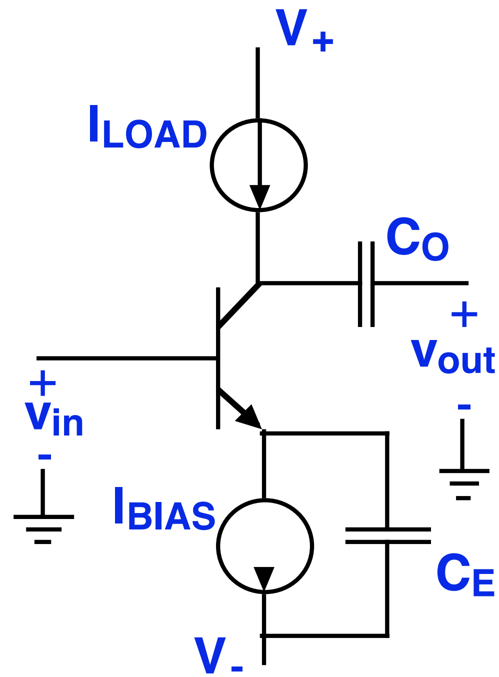
$[V_{GS}-V_T]_{min}$:

Determined by the process spread in V_T, and by how close to threshold the gate can safely be biased before the depletion approximation model fails.



Current Source Loads: the limit on maximum gain

- current source loads eliminate the compromise between voltage gain and output voltage swing



Maximum Voltage gain

$$\text{Bipolar}: \quad |A_{v,\max}| = \frac{g_m}{g_{oL} + g_{oQ}} = \frac{qI_C/kT}{I_C/V_{AL} + I_C/V_{AQ}} = \frac{V_{A,eff}}{V_{thermal}}$$

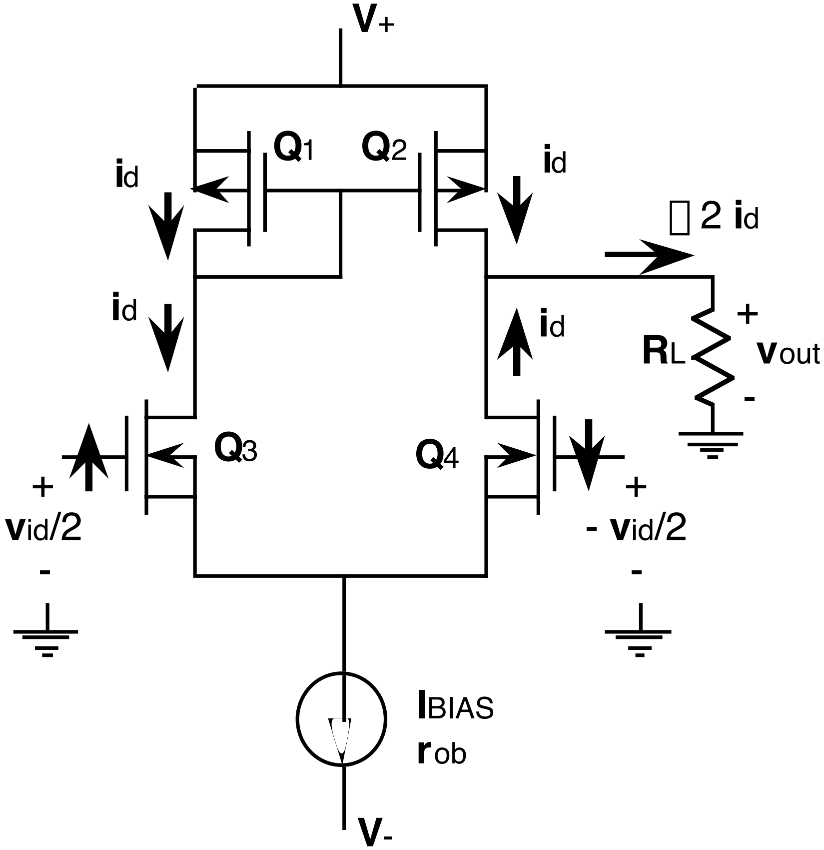
$$\text{MOSFET*}: \quad |A_{v,\max}| = \frac{g_m}{g_{oL} + g_{oQ}} = \frac{2I_D/[V_{GS} - V_T]}{I_D/V_{AL} + I_D/V_{AQ}} \approx \frac{2V_{A,eff}}{[V_{GS} - V_T]_{\min}}$$

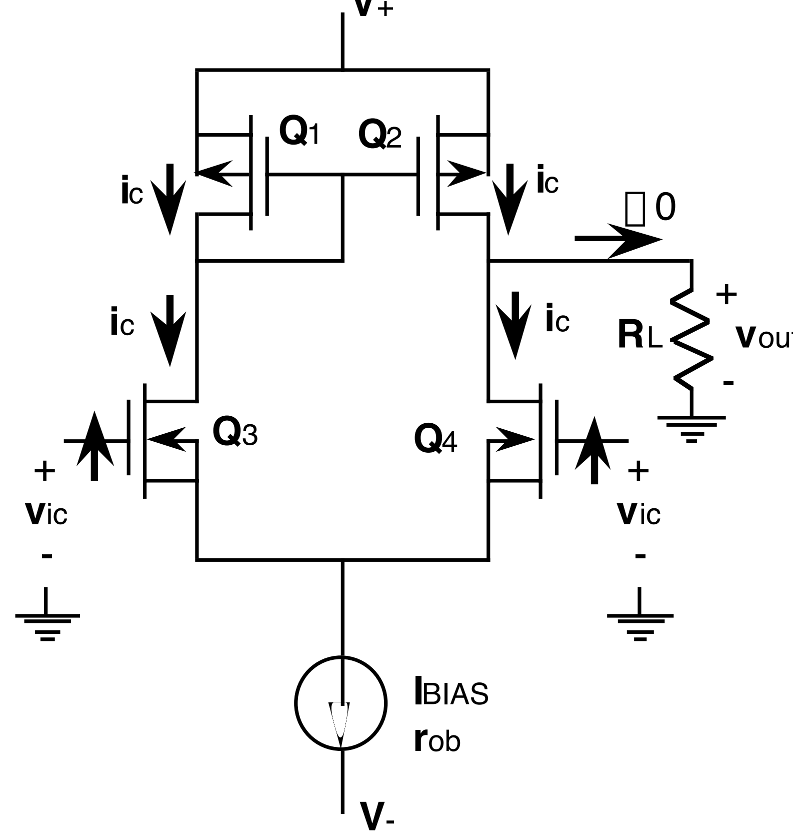
$$\text{with} \quad V_{A,eff} \equiv \frac{V_{AL}V_{AQ}}{[V_{AL} + V_{AQ}]}$$

Typically $V_{A,eff} >> [I\,R_L]_{max}$

Active Loads: The current mirror load

- large R in difference-mode and small R in common mode
- efficient conversion from double-ended to single-ended output





Difference-mode inputs

$v_{out} = [2g_{m3}/(g_{o2}+g_{o4}+G_L]v_{id}/2$

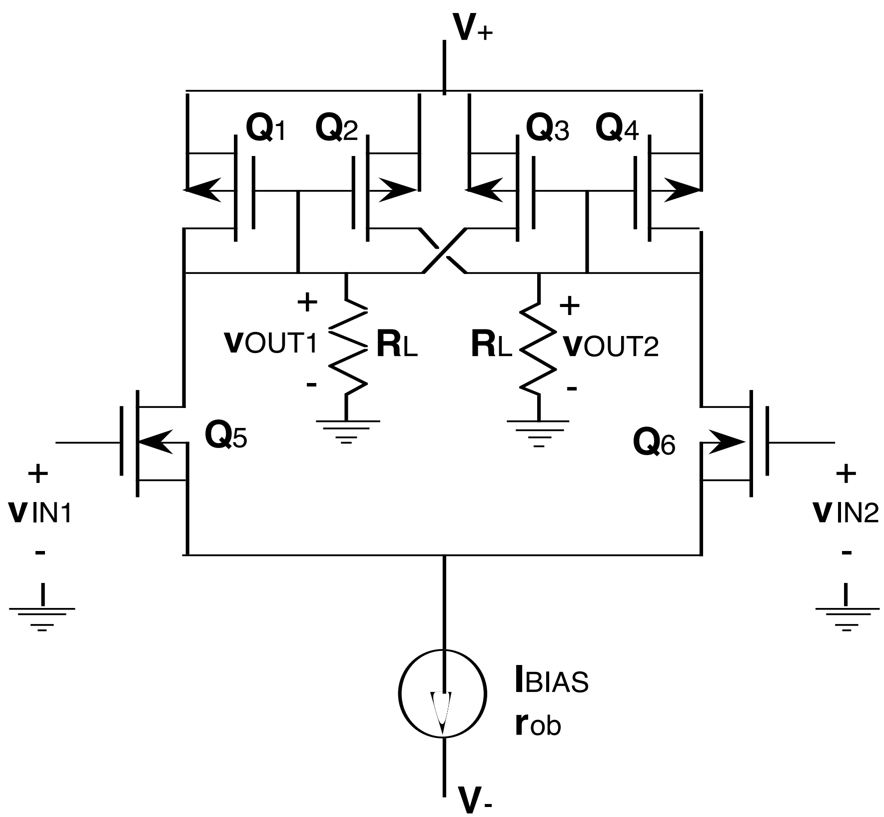
Common-mode inputs

$v_{out} = [g_{ob}/2(g_{m2}+g_{o4}+G_L)]v_{ic} \approx g_{ob}/2g_{m2}v_{ic}$

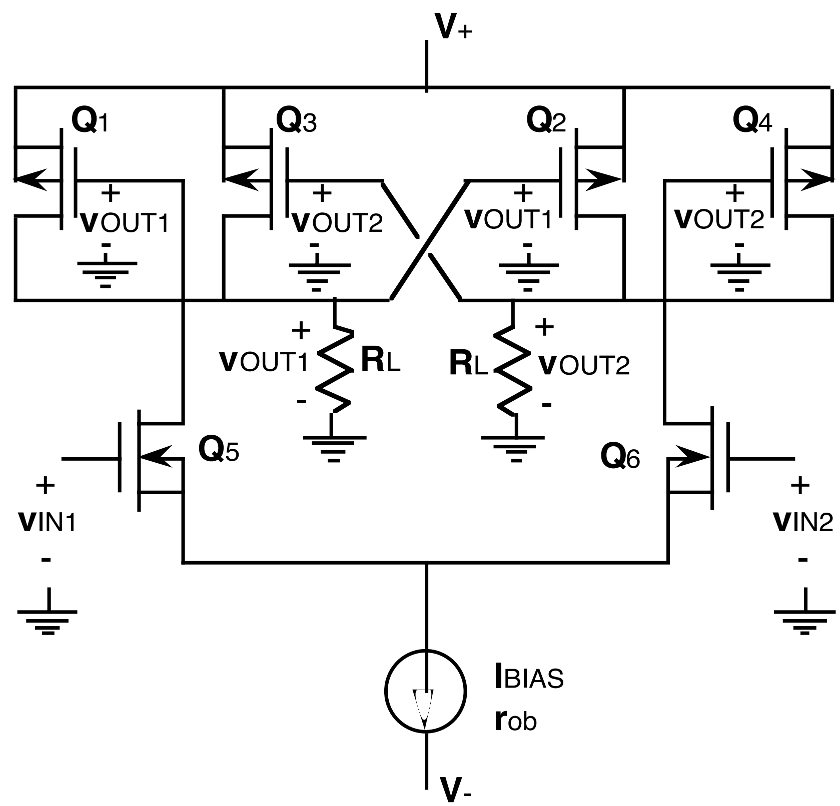
With both inputs: $v_{out} \approx [2g_{m3}/(g_{o2}+g_{o4}+G_L]v_{id}/2 + g_{ob}/2g_{m2}v_{ic}$

Active Loads - The Lee load

a load for a fully-differential stage that looks like a large resistance in difference-mode and small resistance in common-mode

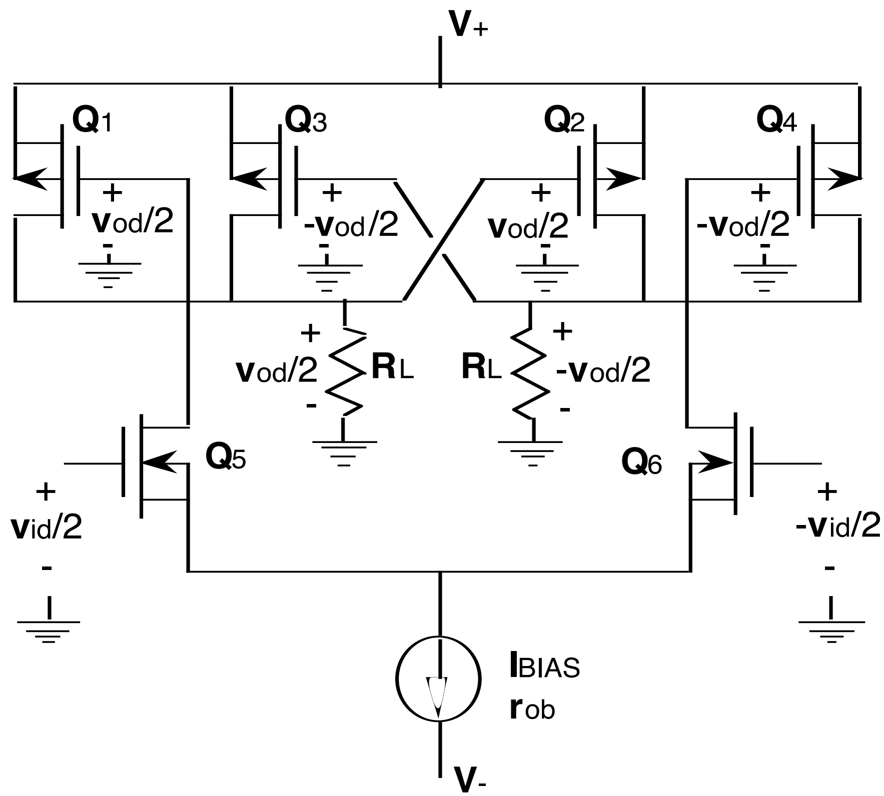


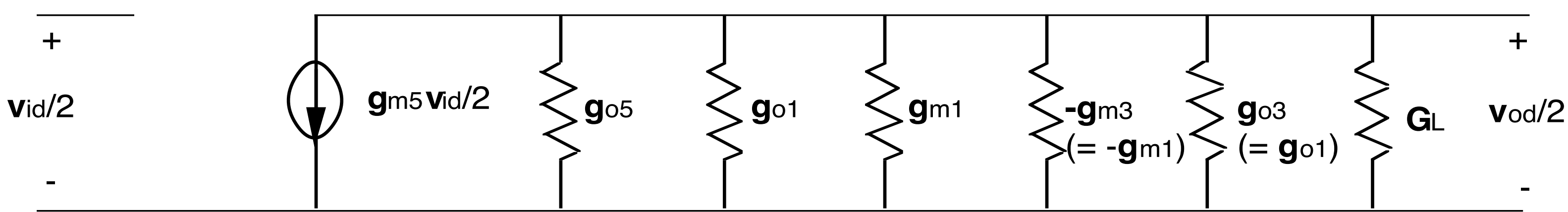
Normal format



Drawn to highlight cross-coupling

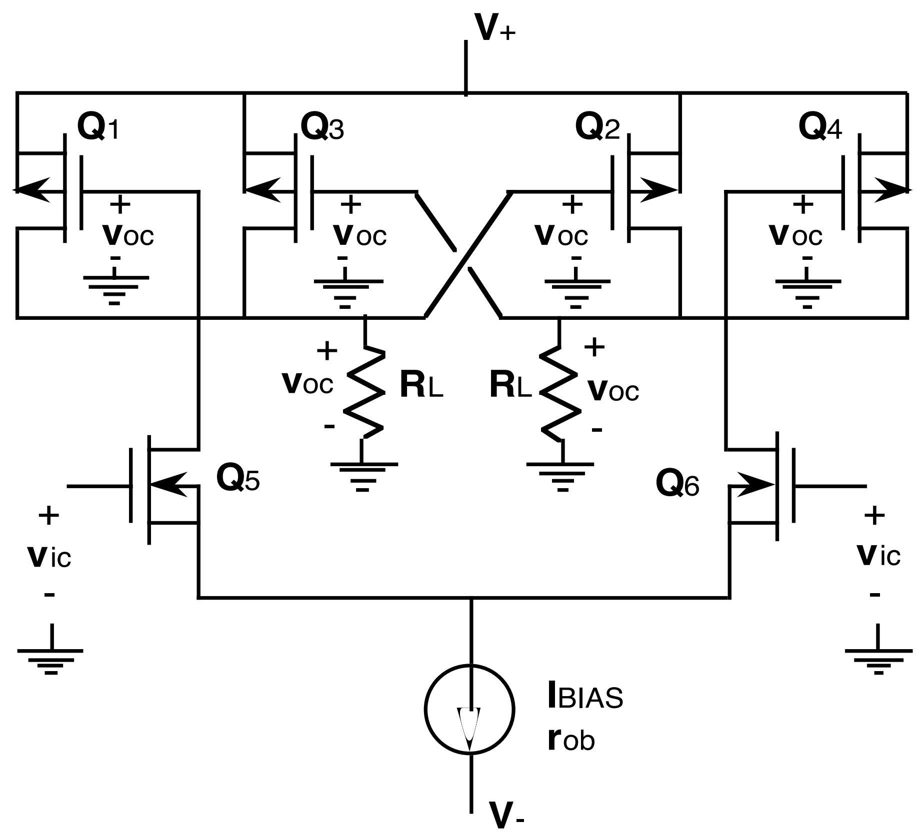
The Lee load: analysis for difference-mode inputs

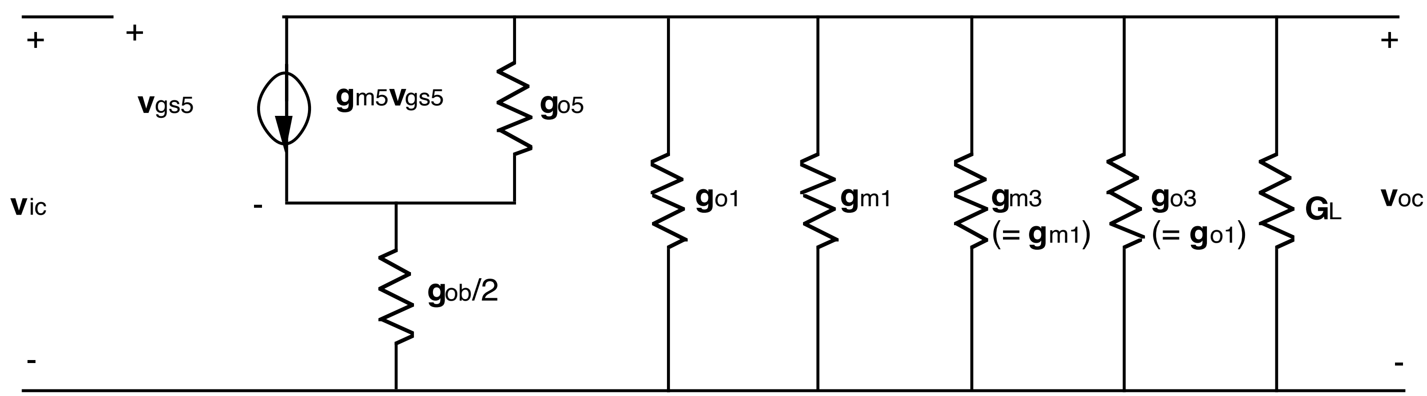




Difference mode: $A_{vd} = v_{od}/v_{id} = g_{m5}/(g_{o5} + 2g_{o1} + G_L)$

The Lee load: analysis for common-mode inputs





Common mode: $A_{vc} = v_{oc}/v_{ic} = g_{ob}/2(2g_{o1} + 2g_{m1} + G_L) \approx g_{ob}/4g_{m1}$

Achieving the maximum gain: Comparing linear resistors, current sources, and active loads

MAXIMUM GAIN	Bipolar	MOSFET
Linear resistor loads	$\approx \dfrac{[I_C R_L]_{\max}}{V_{thermal}}$	$\approx \dfrac{[I_D R_L]_{\max}}{[V_{GS} - V_T]_{\min}}$
Current source loads	$\approx \dfrac{2V_{A,eff}}{V_{thermal}}$	$\approx \dfrac{2V_{A,eff}}{[V_{GS} - V_T]_{\min}}$
Active loads: Difference mode	$\dfrac{V_{A,eff}}{V_{thermal}}$	$\dfrac{V_{A,eff}}{[V_{GS} - V_T]_{\min}}$
Active loads: Common mode	$\dfrac{V_{thermal}}{V_{A,bias}}$	$\dfrac{[V_{GS} - V_T]_{\min}}{V_{A,bias}}$

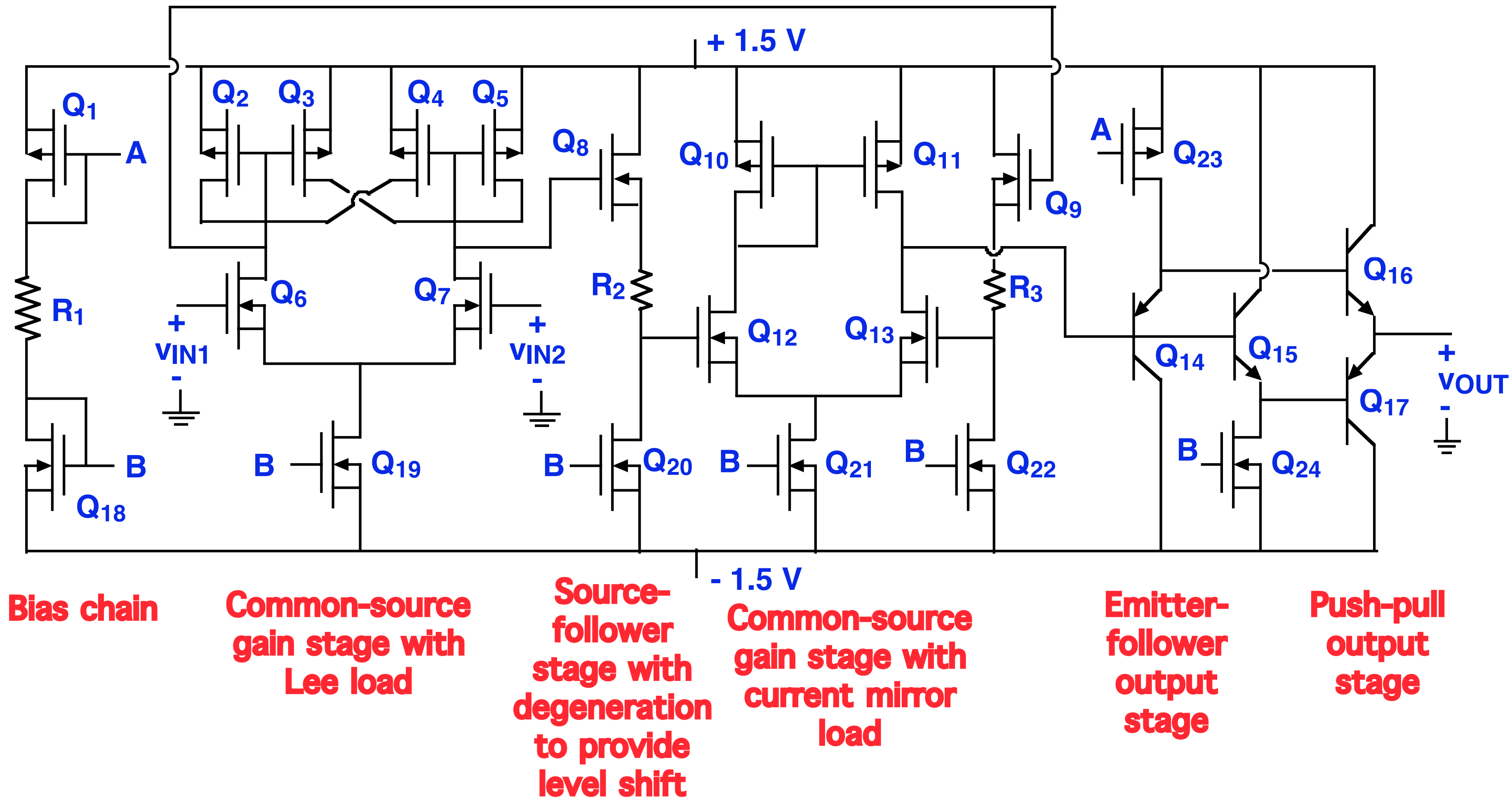
Observations:

- Non-linear (current source) loads typically yield higher gain than linear resistors, i.e. $V_{A,eff} >> [I_D R_L]_{max}$
- Bias level is not important to BJT stage gain
- A MOSFET should be biased at low level for high gain
- For active loads what increases A_{vd}, decreases A_{vc}

6.012 - Electronic Devices and Circuits

Fall 2003 Design Problem Circuit

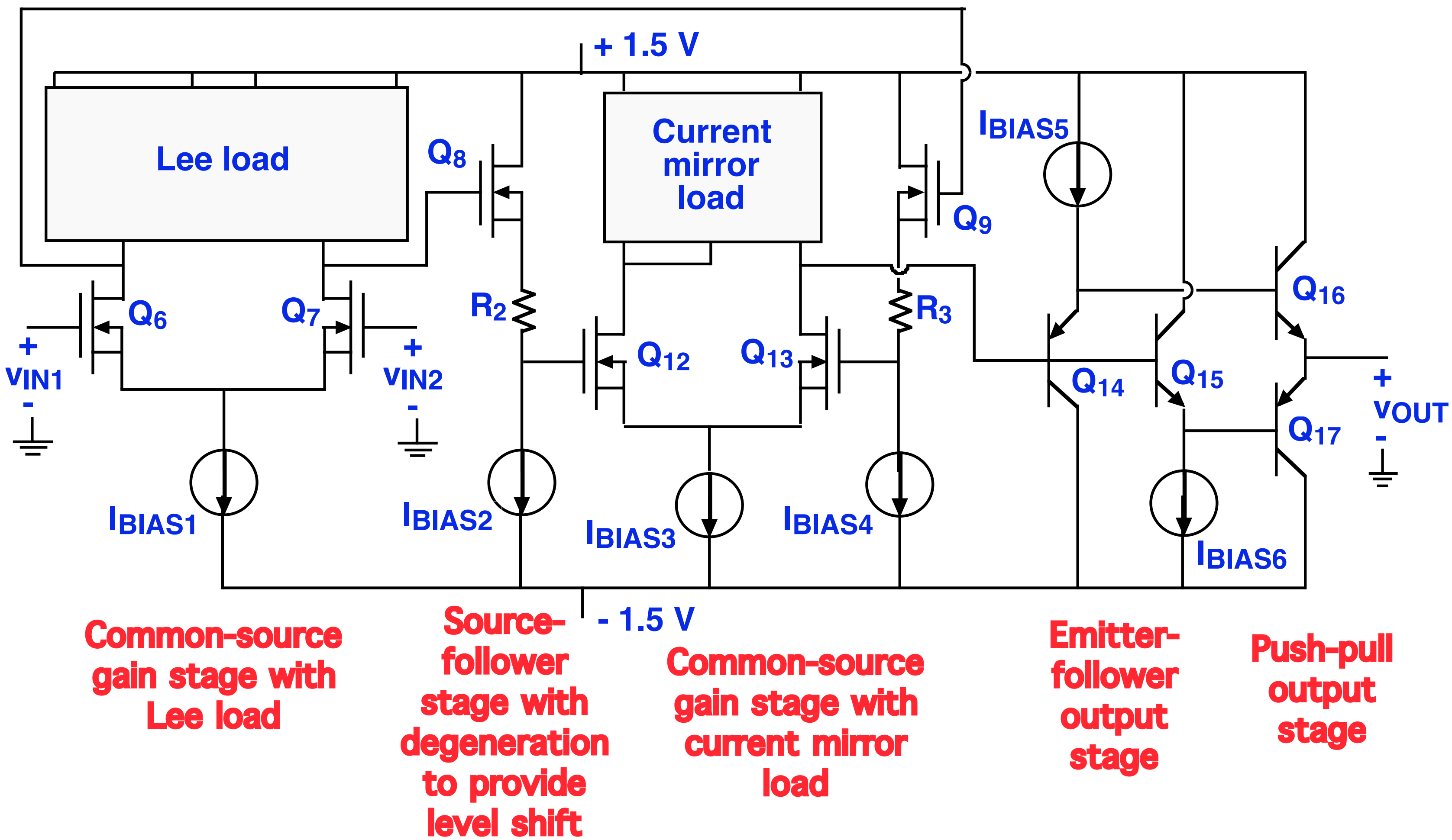
Full schematic



6.012 - Electronic Devices and Circuits

Fall 2003 Design Problem Circuit

Conceptual schematic: full circuit

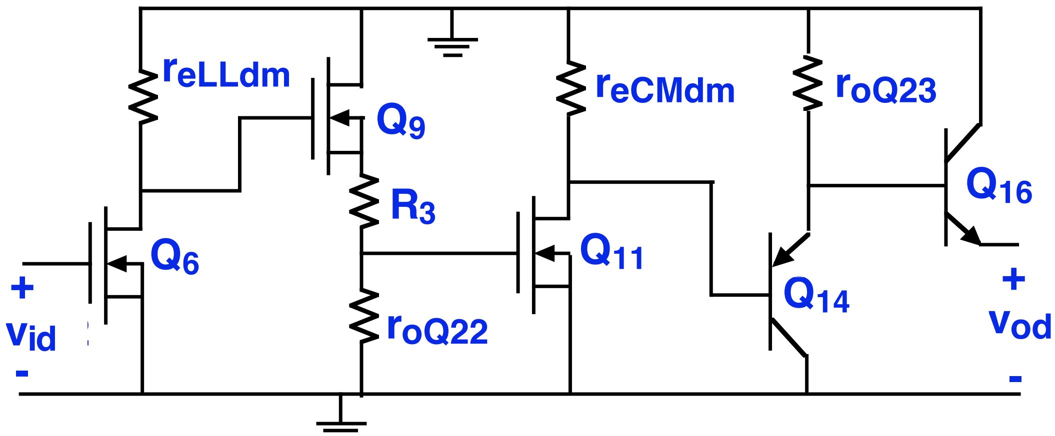


Fall 2003 Design Problem Circuit

Conceptual schematic

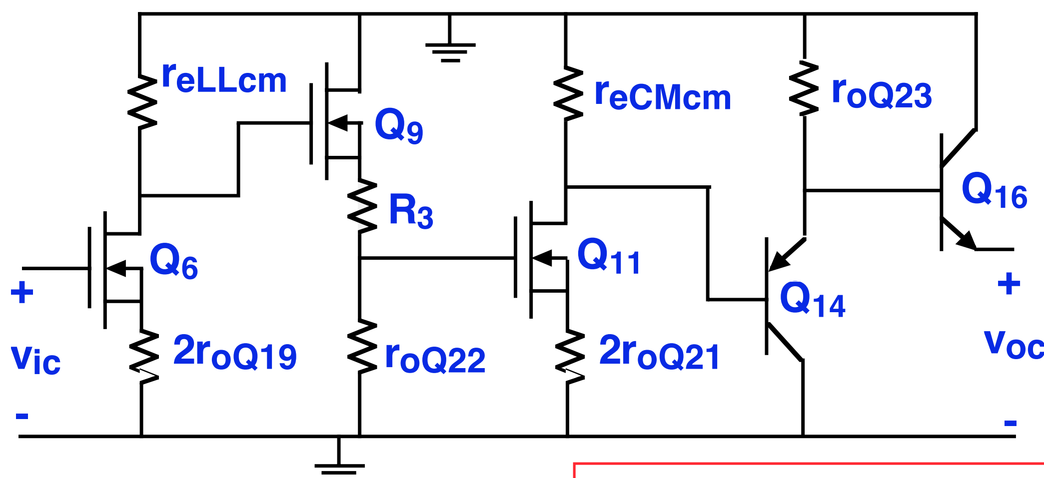
$v_{in1} = v_{ic} + v_{id}/2$
$v_{in2} = v_{ic} - v_{id}/2$
$v_{out} = v_{oc} + v_{od}$

Difference-mode inputs



$v_{od} = A_{vd}\, v_{id}$

Common-mode inputs



$v_{oc} = A_{vc}\, v_{ic}$

$v_{out} = A_{vc}\, v_{ic} + A_{vd}\, v_{id}$

Lecture 20 - Linear Amp. Analysis and Design I - Summary

- **Performance metrics - specific to diff. amps.**
  - Difference- and common-mode gains: $A_{vd} = v_{od}/v_{id}$, $A_{vc} = v_{oc}/v_{ic}$
  - Common-mode rejection ratio: $CMRR = A_{vd}/A_{vc}$
  - Input and output resistances
  - Common-mode input voltage swing
- **Non-linear loads**
  - Transistors biased in their constant current regions
    - BJTs in their FAR
    - MOSFETs in saturation
  - Optimum bias point for high gain: MOSFET at low I_D, BJT at any I_C
- **Active loads**
  - Current mirror load
    - Achieves double- to single-ended conversion without loss of gain
    - Has high resistance for difference-mode signals
    - Has low resistance for common-mode signals
  - Lee Load
    - Maintains differential signals
    - Has high resistance for difference-mode signals
    - Has low resistance for common-mode signal