Week 9: Multivibrators, MOSFET Amplifiers

Topics to cover …

- Multivibrators

- Single-stage MOSFET amplifiers
  - Common-source amplifier
  - Common-drain amplifier
  - Common-gate amplifier

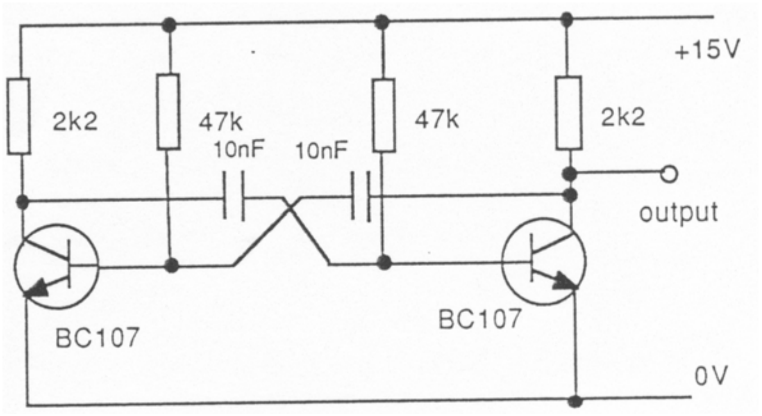
Reading Assignment:
Chap 14.1 - 14.5 of Jaeger and Blalock or
Chap 4.6 - 4.7 of Sedra & Smith

Multivibrators

- A multivibrator is used to implement simple **two-state systems** such as oscillators, timers and flip-flops.
- Three types:
  - **Astable** – neither state is stable.
    Applications: oscillator, etc.
  - **Monostable** - one of the states is stable, but the other is not;
    Applications: timer, etc.
  - **Bistable** – it remains in either state indefinitely.
    Applications: flip-flop, etc.

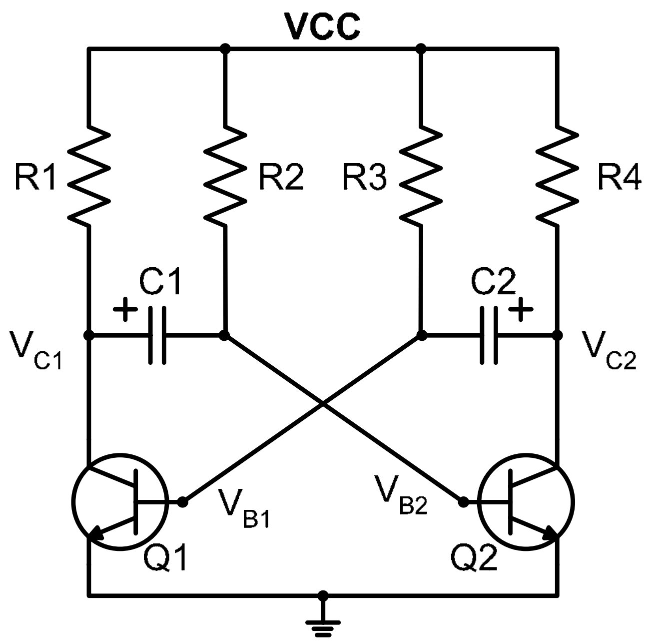
Reference: http://en.wikipedia.org/wiki/Multivibrator

Astable Multivibrator



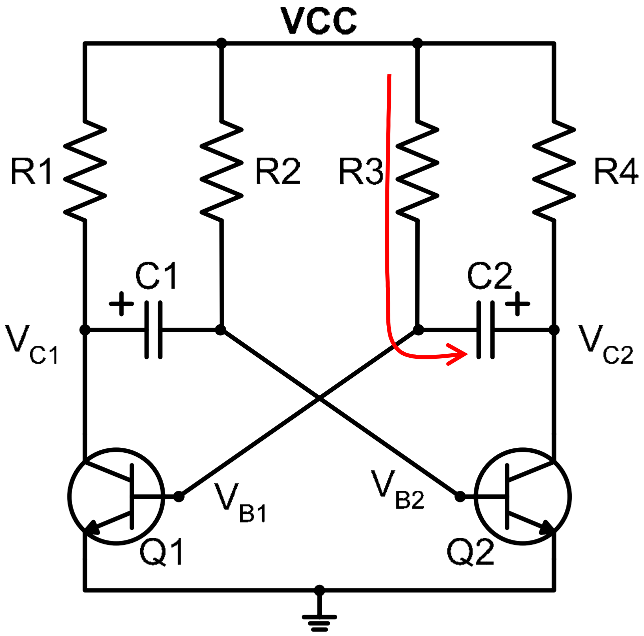
Circuit in Experiment A4

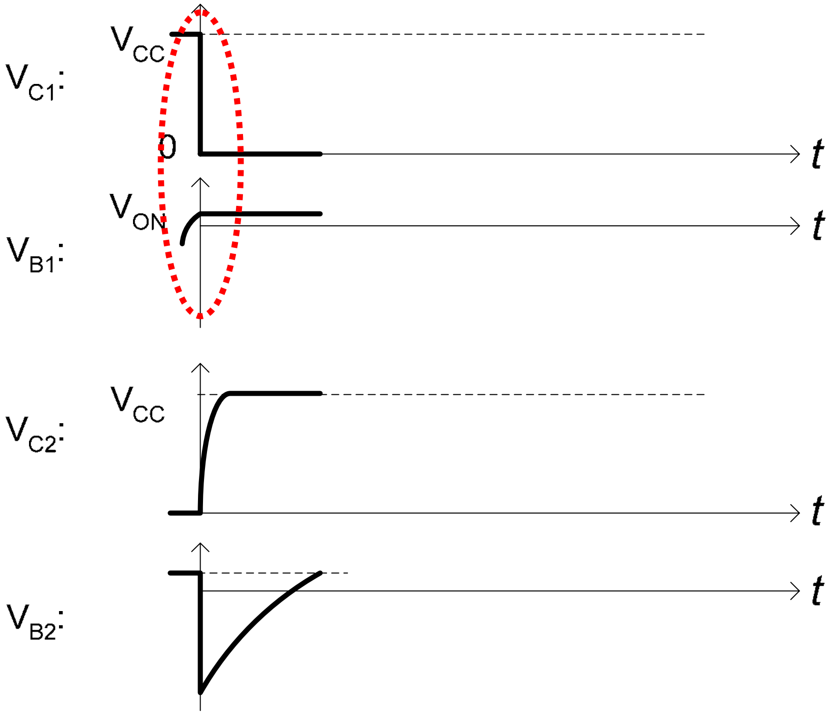
Redrawn



- Consists of two amplifying devices cross-coupled by resistors and capacitors.
- Typically, $R_2 = R_3$, $R_1 = R_4$, $C_1 = C_2$ and $R_2 >> R_1$.
- The circuit has two states
  - State 1: V_{C1} LOW, V_{C1} HIGH, Q_1 ON (saturation) and Q_2 OFF.
  - State 2: V_{C1} HIGH, V_{C2} LOW, Q_1 OFF and Q_2 ON (saturation).
- It continuously oscillates from one state to the other.

Basic Mode of Operational

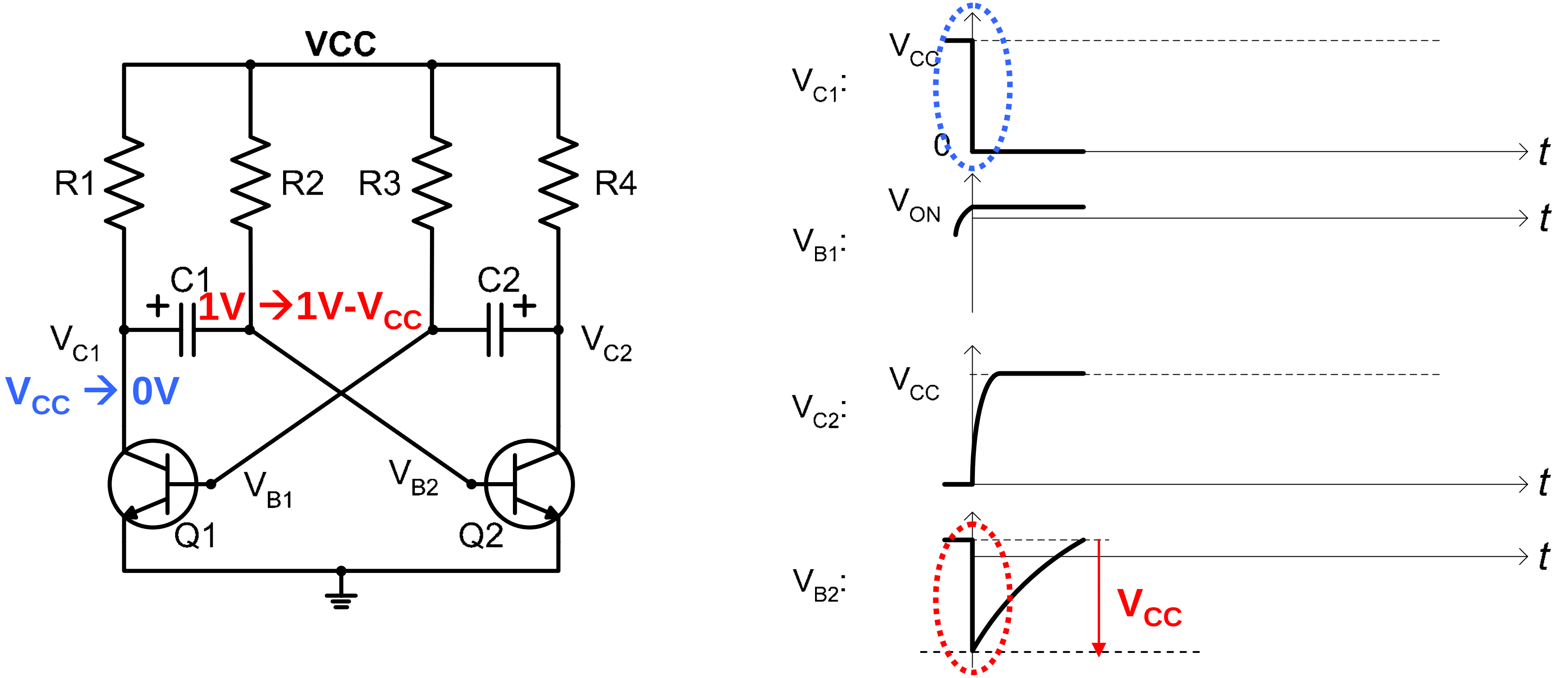




State 1:

- V_{B1} charges up through R_3 from below ground towards V_{CC}.
- When V_{B1} reaches V_{ON} (of $V_{BE,}$ ≈1V), Q_1 turns on and pulls V_{C1} from V_{CC} to V_{CESat} ≈ 0V.
- Due to forward-bias of the BE junction of Q_1, V_{B1} remains at 1V.

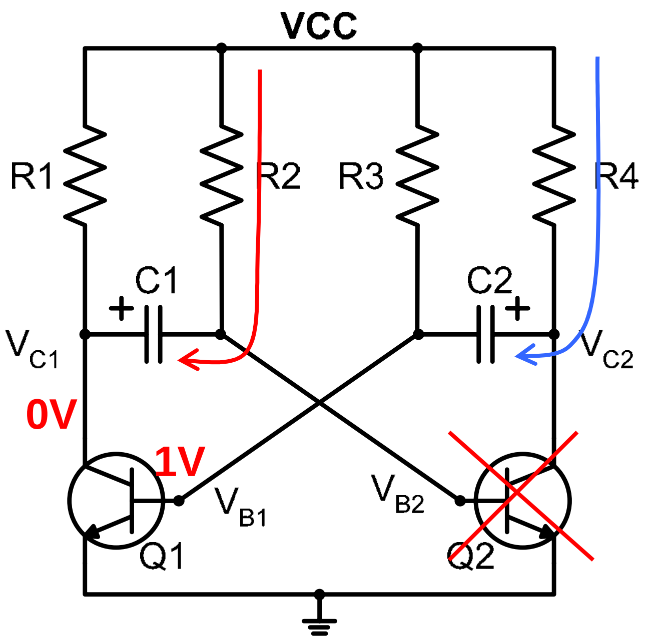
Basic Mode of Operational

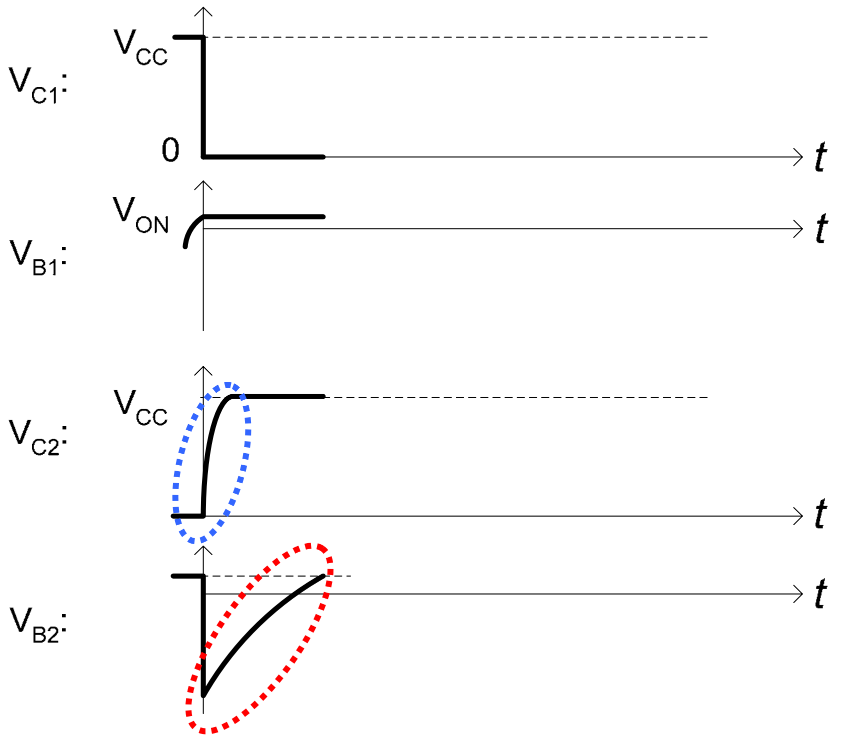


State 1 (cont'd):

- As C_1's voltage cannot change instantaneously, V_{B2} drops by V_{CC}.

Basic Mode of Operational

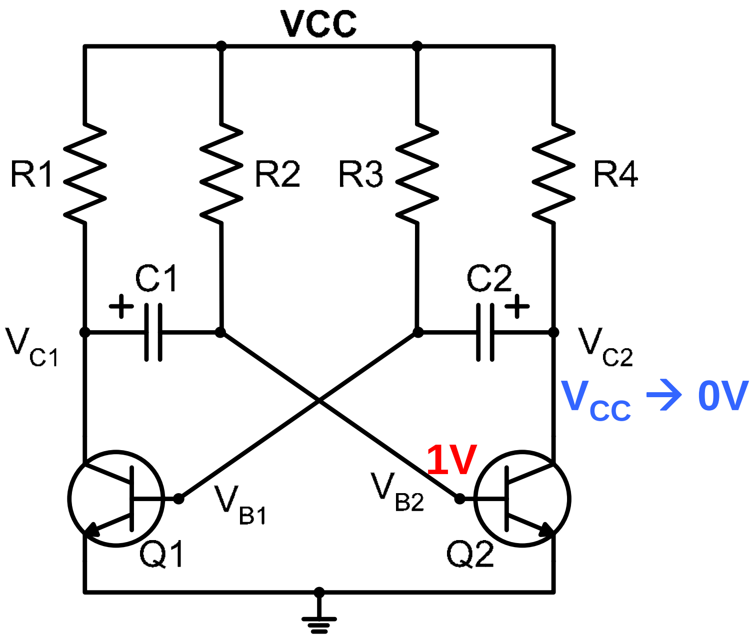


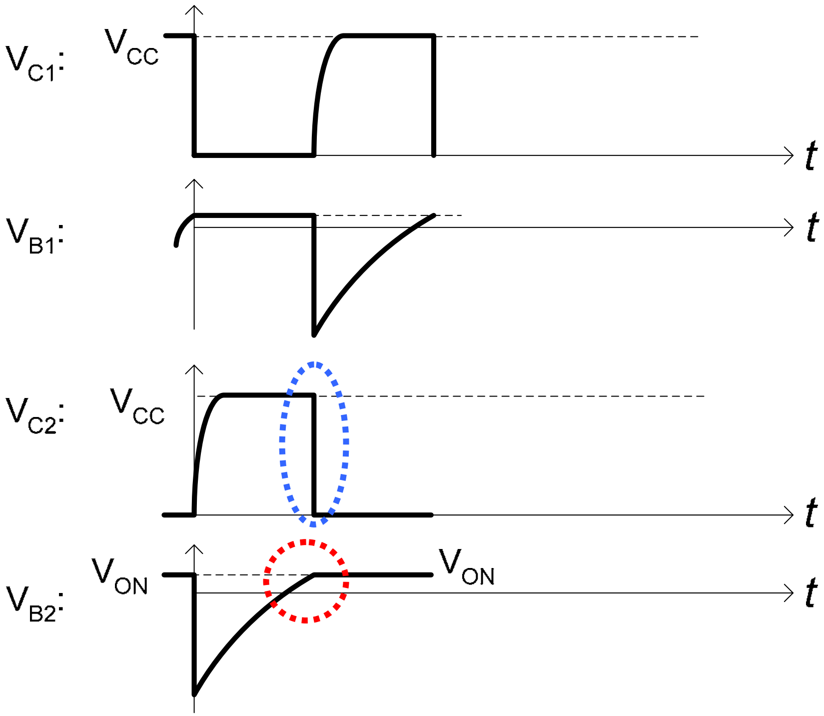


State 1 (cont’d):

- Q_2 turns off and V_{C2} charges up through R_4 to V_{CC} (speed set by the time constant R_4C_2).
- V_{B2} charges up through R_2 towards V_{CC} (speed set by R_2C_1, which is slower than the charging up speed of V_{C2}).

Basic Mode of Operational

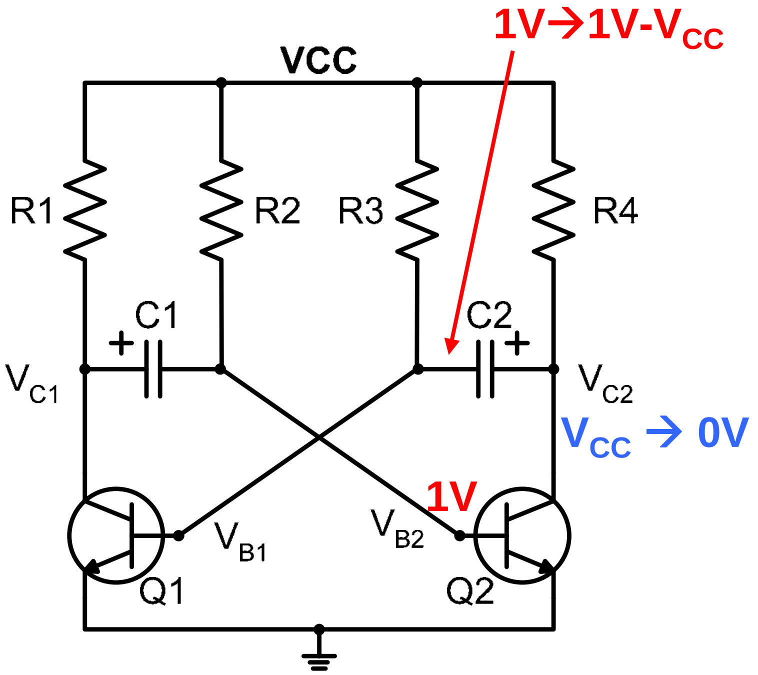


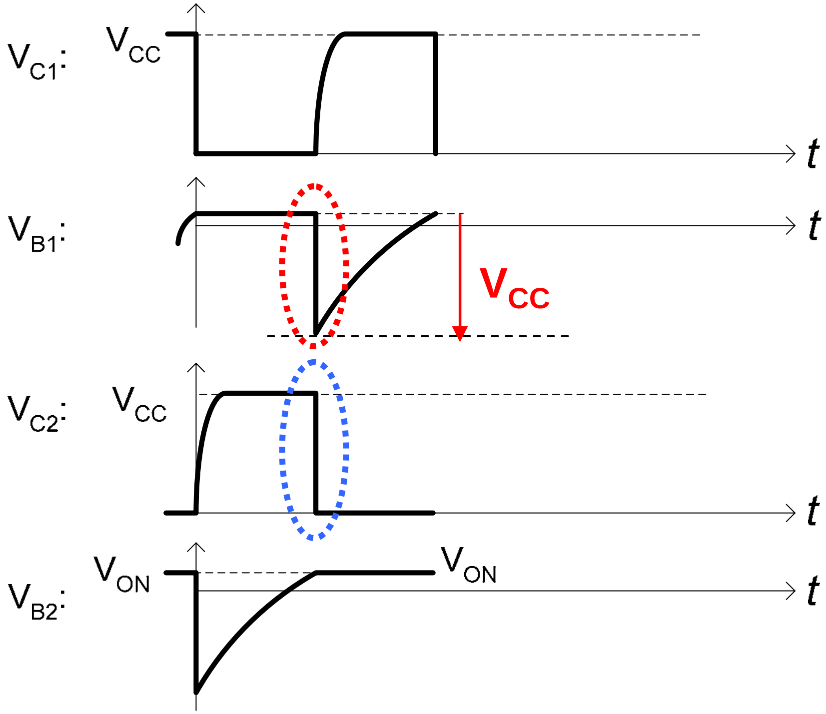


State 2:

- When V_{B2} reaches V_{ON}, Q_2 turns on and pulls V_{C2} from V_{CC} to 0V.
- V_{B2} remains at V_{ON}.

Basic Mode of Operational

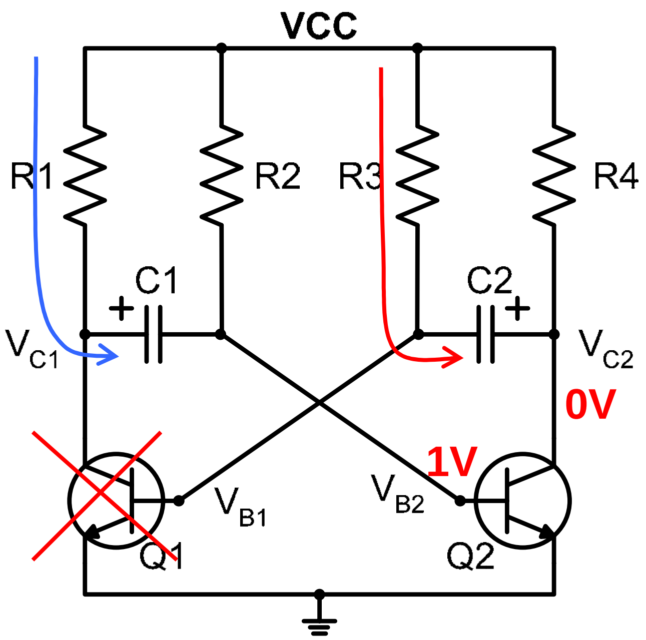


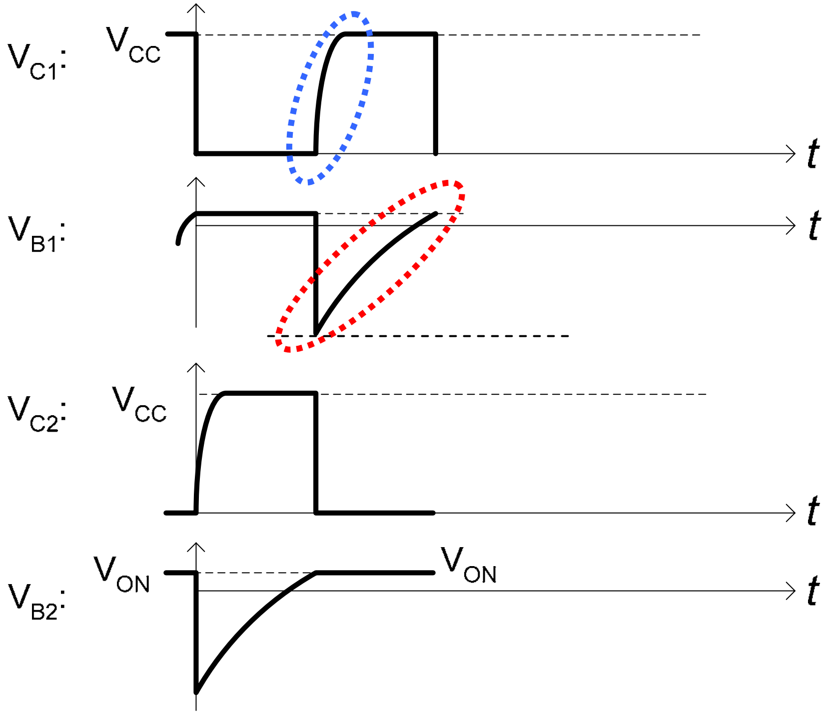


State 2 (cont'd):

- As C_2's voltage cannot change instantaneously, V_{B1} drops by V_{CC}.

Basic Mode of Operational

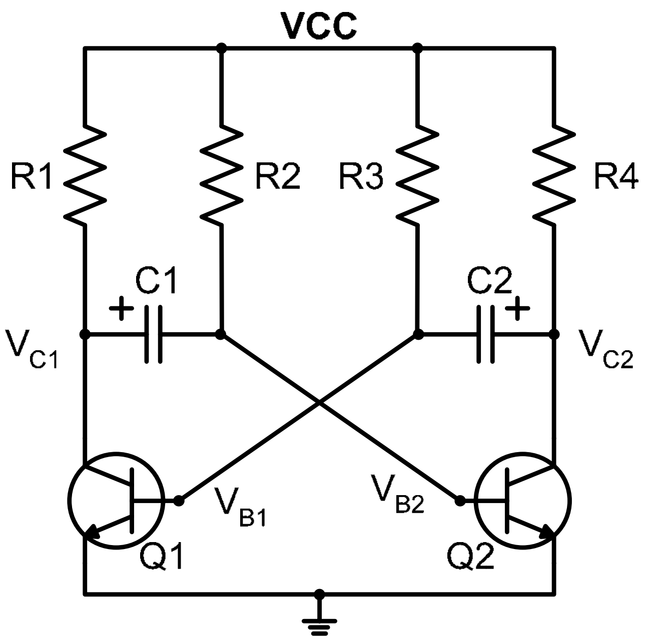


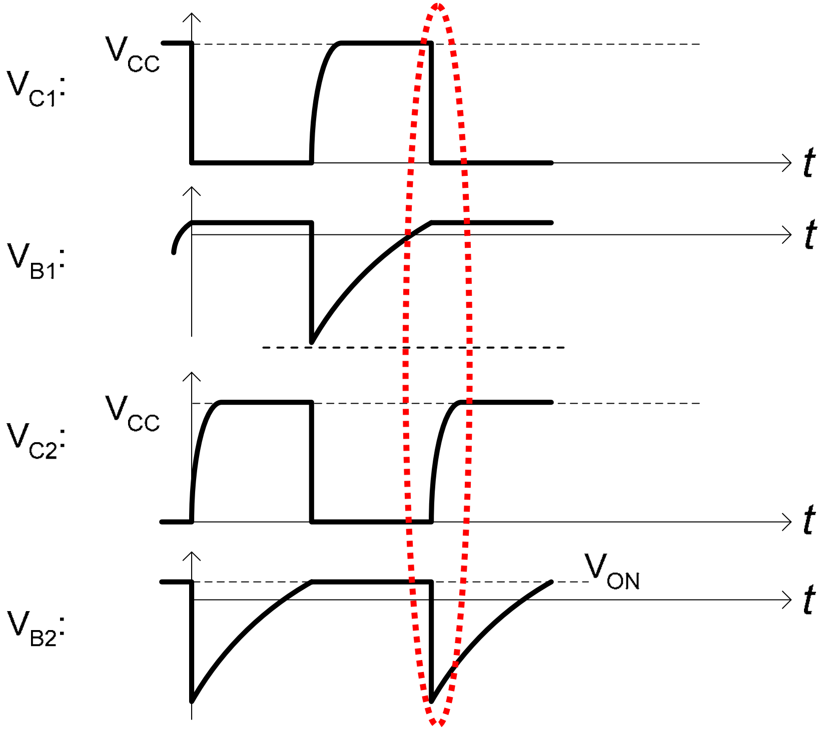


State 2 (cont'd):

- Q_1 turns off and V_{C1} charges up through R_1 to V_{CC}, at a rate set by R_1C_1.
- V_{B2} charges up through R_3 towards V_{CC}, at a rate set by R_3C_2, which is slower.

Basic Mode of Operational



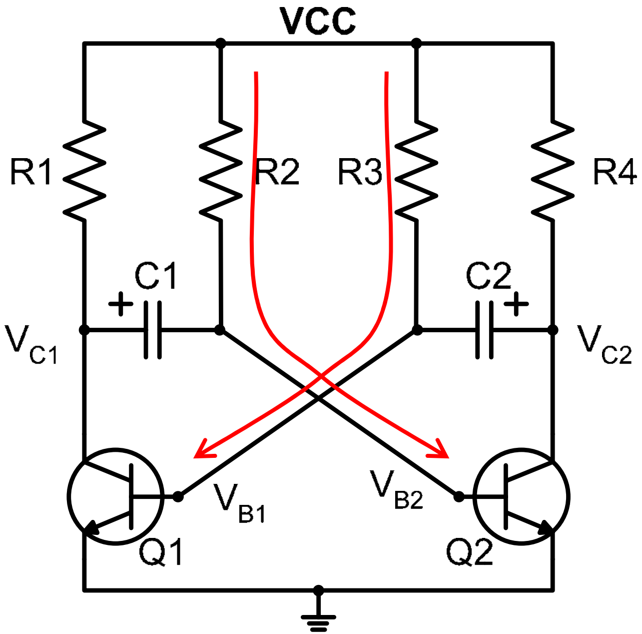


Back to state 1:

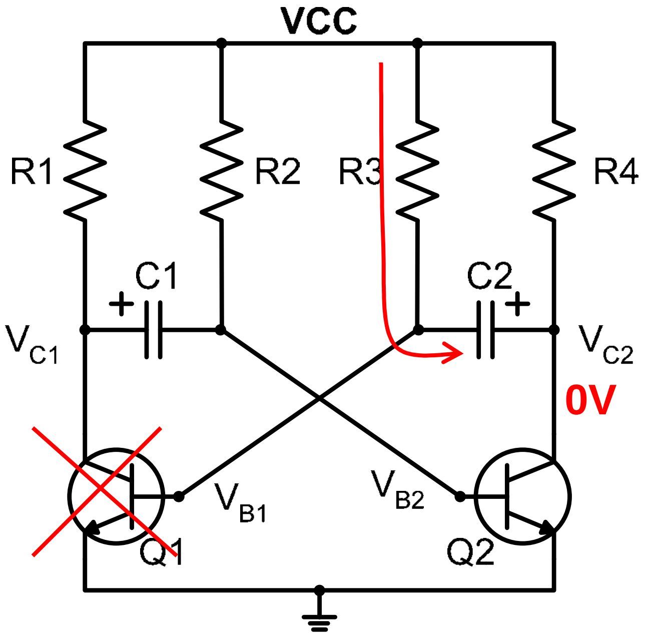
- When V_{B2} reaches Von, the circuit enters state 1 again, and the process repeats.

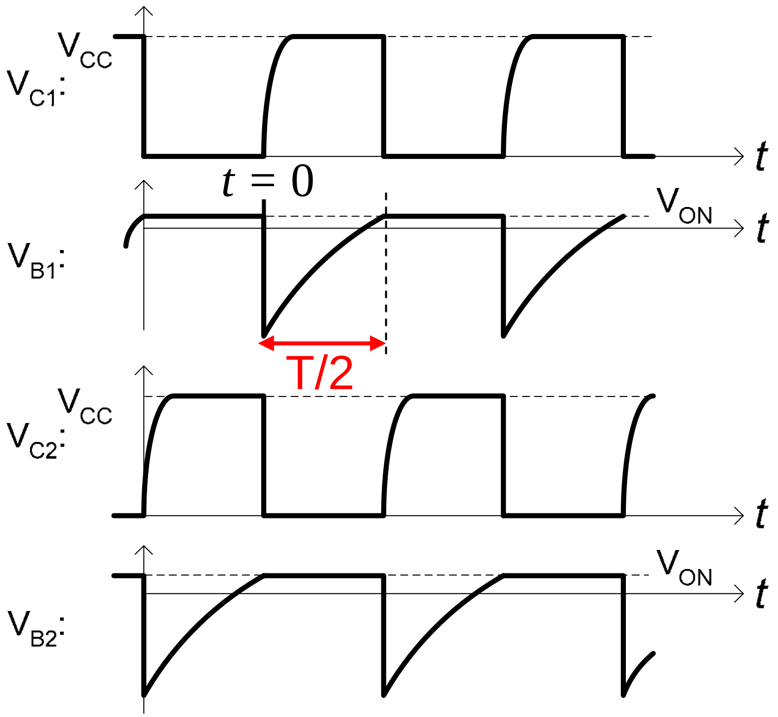
Initial Power-Up

- When the circuit is first powered up, neither transistor is ON.
- Parasitic capacitors between B and E of Q_1 and Q_2 are charged up towards V_{CC} through R_2 and R_3. Both V_{B1} and V_{B2} rise.
- Inevitable slight asymmetries will mean that one of the transistors is first to switch on. This will quickly put the circuit into one of the above states, and oscillation will ensue.



Multivibrator Frequency





$$v_{B1} = (V_{ON} - V_{CC}) + (2V_{CC} - V_{on})(1 - e^{-t/R_3C_2})$$

$$\approx -V_{CC} + 2V_{CC}(1 - e^{-t/R_3C_2}) \qquad \text{for } V_{ON} << V_{CC}$$

At t = T/2, $v_{B1}=V_{ON}$: $$V_{ON} = -V_{CC} + 2V_{CC}(1 - e^{-T/2R_3C_2})$$

Multivibrator Frequency

$$V_{ON} = -V_{CC} + 2V_{CC}(1 - e^{-T/2R_3C_2})$$

$$\therefore V_{CC} \approx 2V_{CC}(1 - e^{-T/2R_3C_2}) \qquad \text{for } V_{ON} << V_{CC}$$

$$\therefore 1 = 2(1 - e^{-T/2R_3C_2})$$

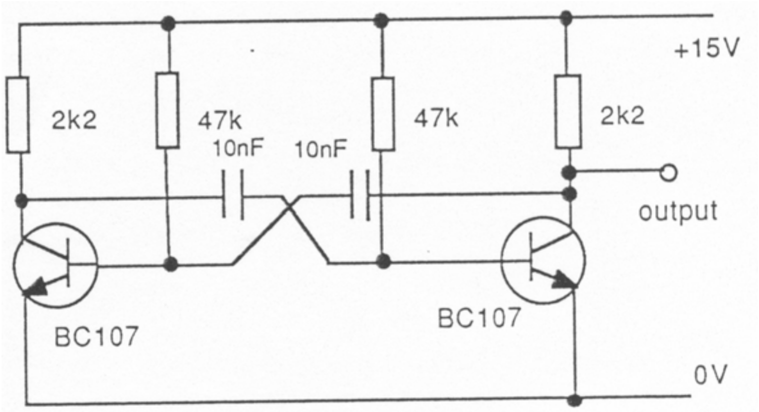
$$\therefore e^{-T/2R_3C_2} = 0.5$$

$$\therefore e^{-T/2R_3C_2} = 0.5$$

$$\therefore -\frac{T}{2R_3C_2} = -\ln 2$$

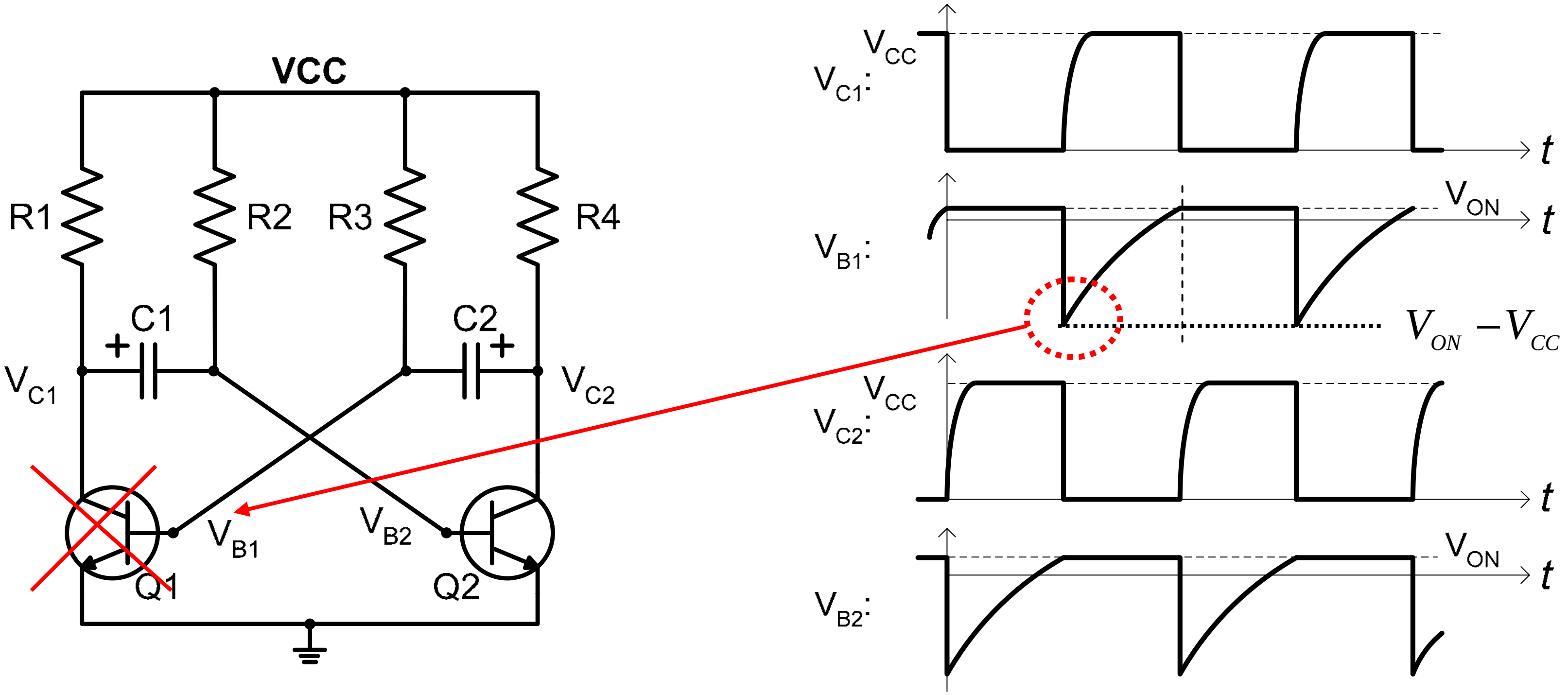
$$\boxed{\therefore T = 2(\ln 2)R_3C_2}$$

or $$\boxed{f = \frac{1}{2(\ln 2)R_3C_2}}$$



For the above component values,
f =1.53kHz.

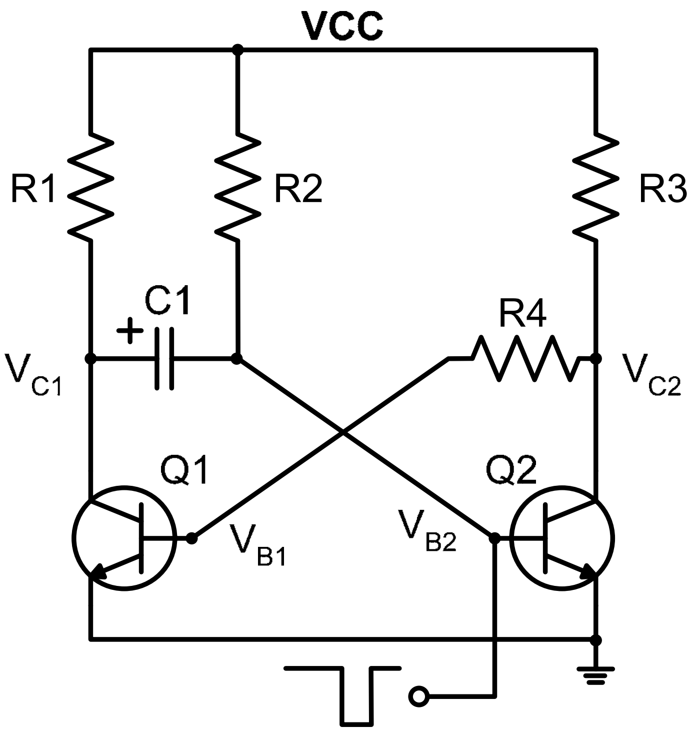
Supply Voltage Limit



- When V_{B1} is negative, BE junction of Q_1 is reverse-biased.
- Suppose the breakdown voltage of this junction is V_{break} (positive). then to avoid breakdown,

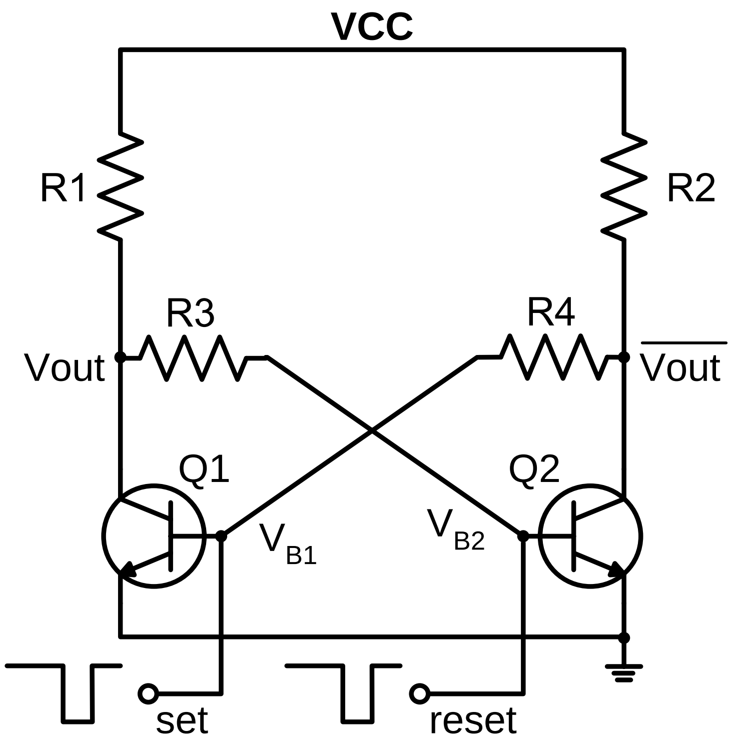
$$V_{ON} - V_{CC} > -V_{Break} \quad \Rightarrow \boxed{V_{CC} < V_{ON} + V_{Break}}$$

Mono-stable Multivibrator



- Capacitive path between V_{C2} and V_{B1} removed.
- Stable for one state (state 1 here)
  - Q_1 ON and Q_2 OFF
  - V_{C1} LOW, V_{C1} HIGH
- When V_{B2} is momentarily pulled to ground by an external signal
  - V_{C2} rises to V_{CC}
  - Q_1 turns on
  - V_{C1} pulled to 0V
- When the external signal goes high
  - V_{B2} charges up to V_{CC} through R_2
  - After a certain time T, V_{B2}=V_{ON}, Q_2 turns on
  - V_{C2} pulled to 0V, Q_1 turns off
  - Enters state 1 and remains there
- Can be used as a timer

Bi-stable Multivibrator



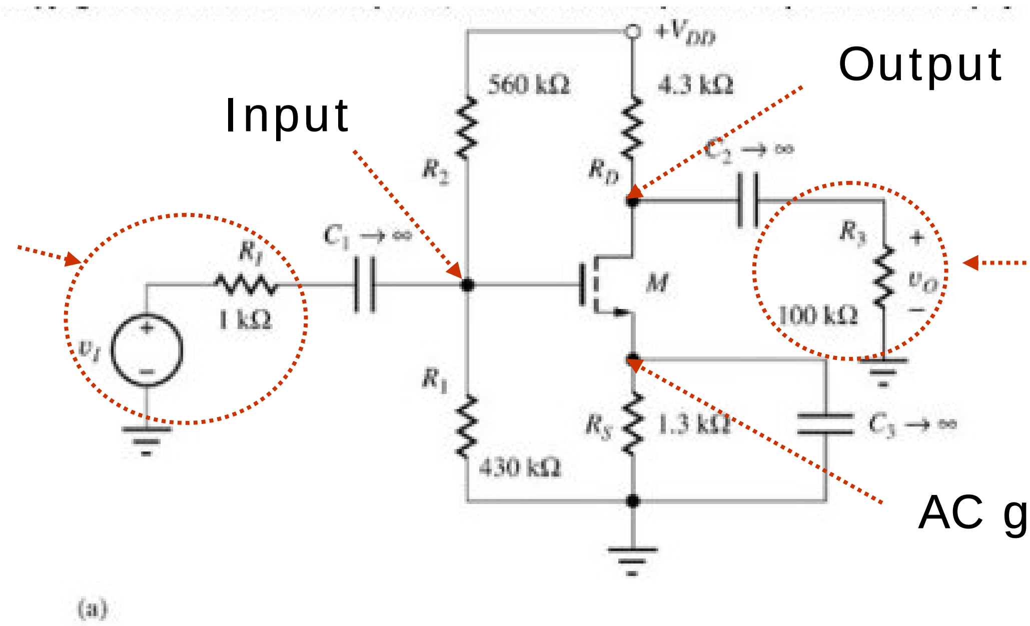
- Both capacitors removed
- Stable for either state 1 or 2
- Can be forced to either state by Set or Reset signals
- If Set is low,
  - Q_1 turns off
  - V_{C1} (V_{out}) and V_{B2} rises towards V_{CC}
  - Q_2 turns on
  - V_{C2} ($/V_{out}$) pulled to 0V
  - V_{B1} is latched to 0V
  - Circuit remains in state 2 until Reset is low
- If Reset is low
  - Similar operation
  - Circuit remains in state 1 until Set is low
- Behave as an RS flip-flop

Topics to cover …

- Multivibrators

- Single-stage MOSFET amplifiers
  - Common-source amplifier
  - Common-drain amplifier
  - Common-gate amplifier

Common-Source Amplifier



Source

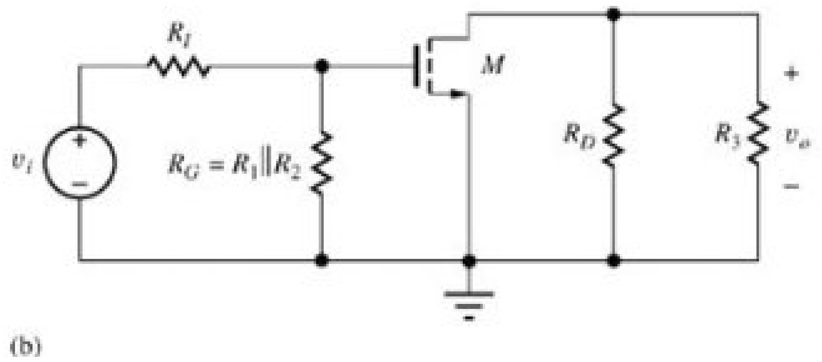
Input

Output

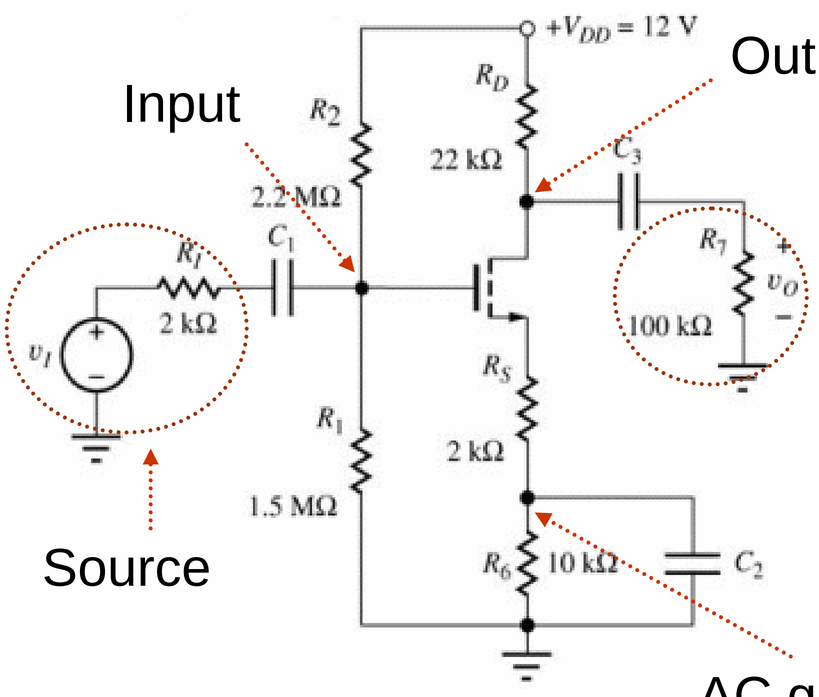
Load

AC ground

AC Equivalent:



CS Amplifier With Source Resistor



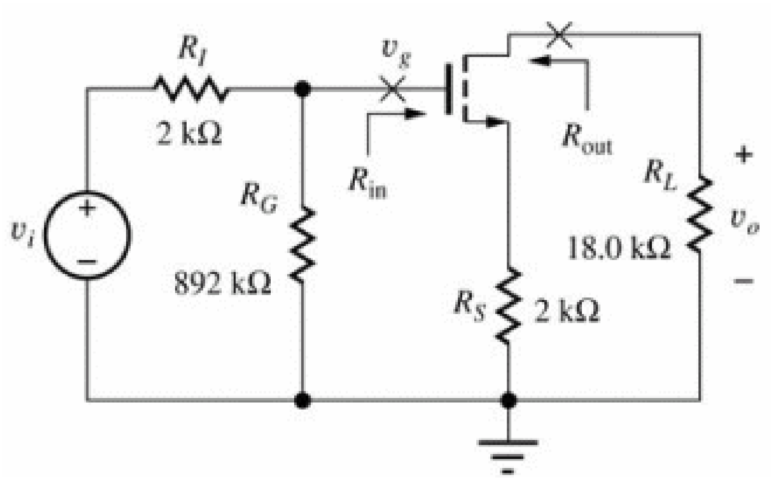
Input

Output

Load

Source

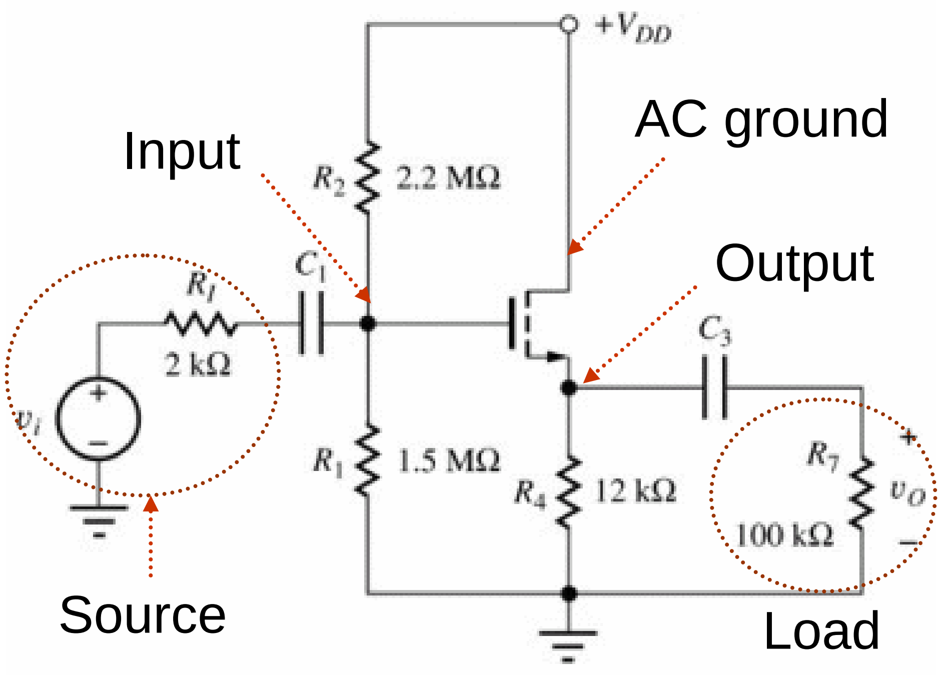
AC ground



AC Equivalent

Also named **Source Degenerated Common Source Amplifier**

Common-Drain Amplifier/Source Follower



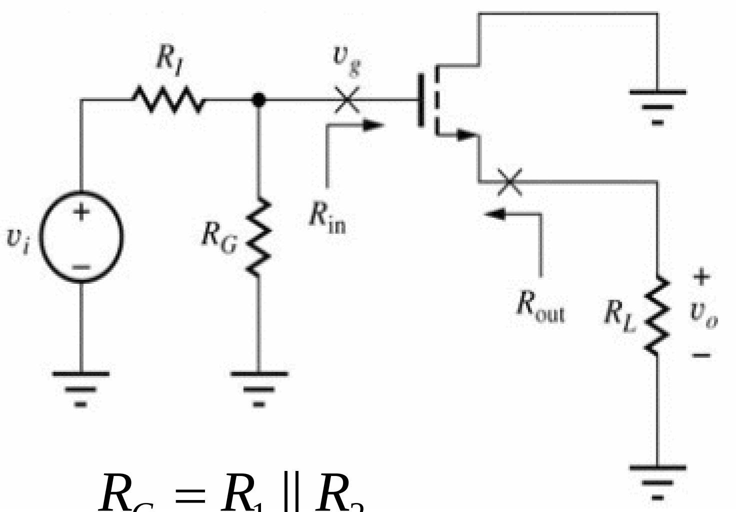
Input

AC ground

Output

Source

Load

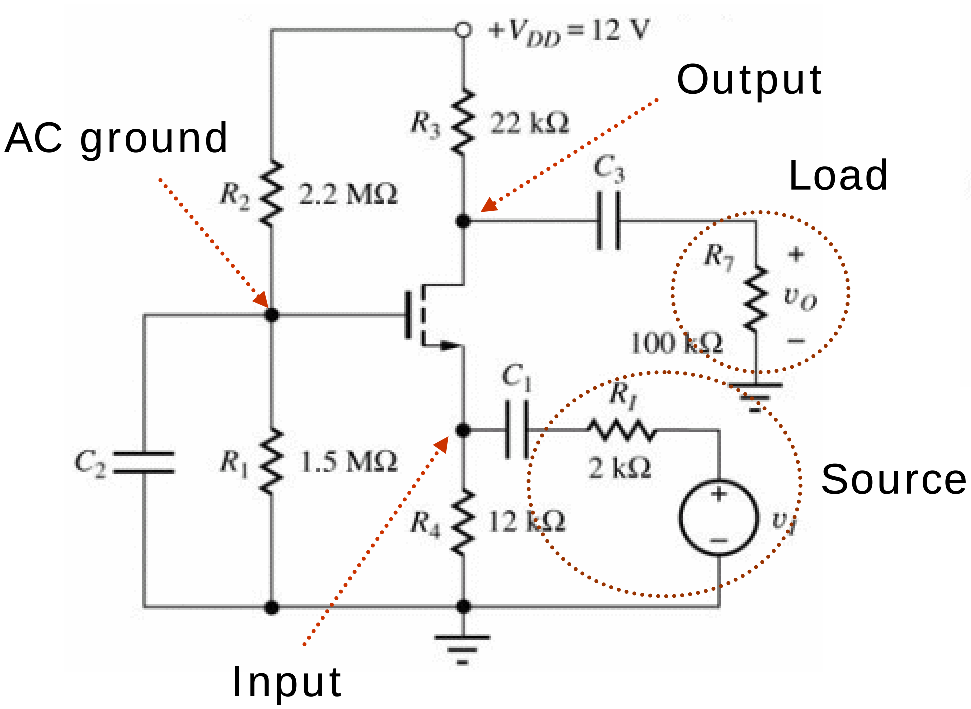


$$R_G = R_1 \parallel R_2$$

$$R_L = R_4 \parallel R_7$$

AC equivalent

Common Gate Amplifier



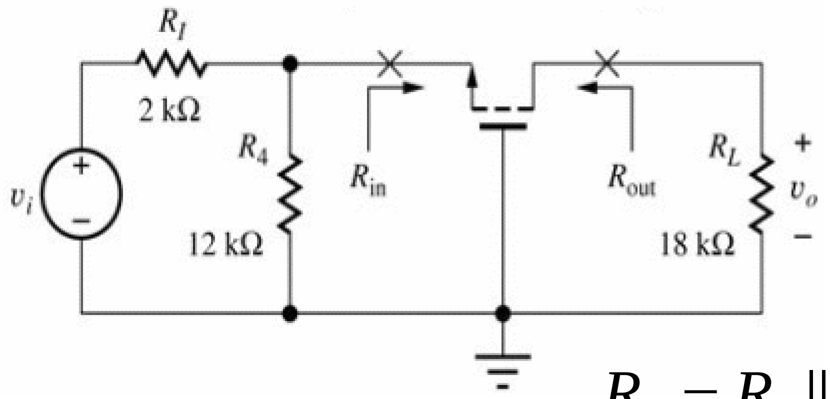
AC ground

Output

Load

Source

Input



$$R_L = R_3 \parallel R_7$$

AC equivalent

Topics to cover …

- Multivibrators

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  - Common-source amplifier
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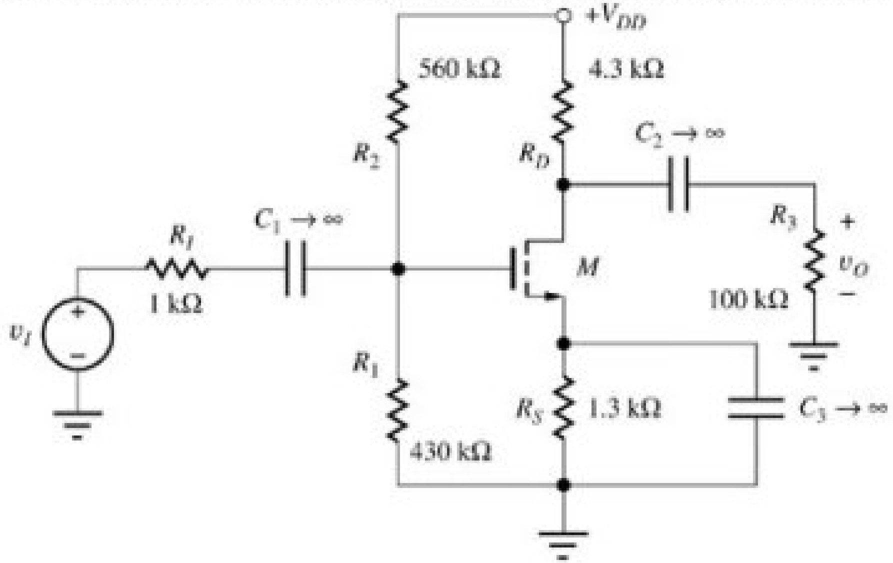
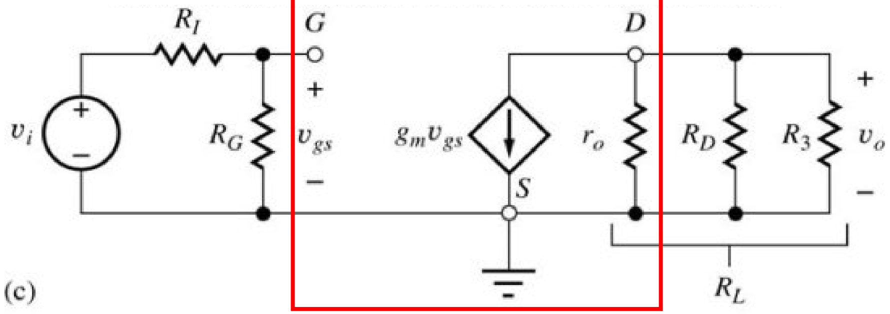
Common-Source Amplifier

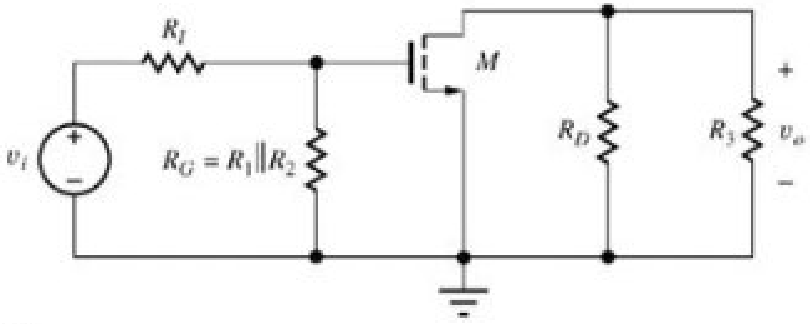


(a)

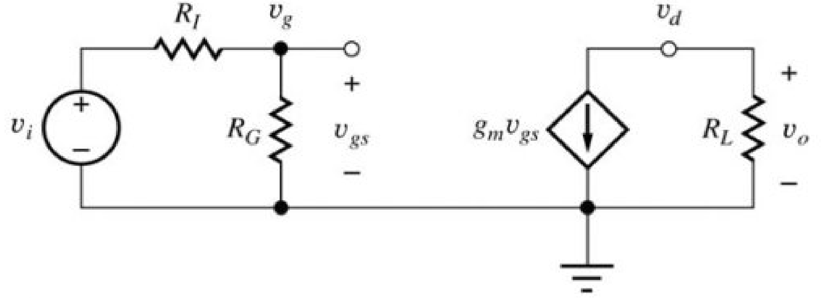
nMOS small-signal model



(c)



(b)

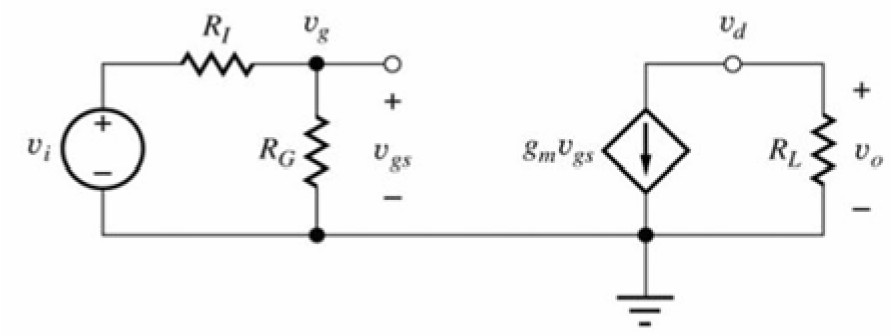


(d)

$$R_L = r_o \| R_D \| R_3$$

AC Equivalents

Voltage Gain



Terminal voltage gain from gate and drain is:

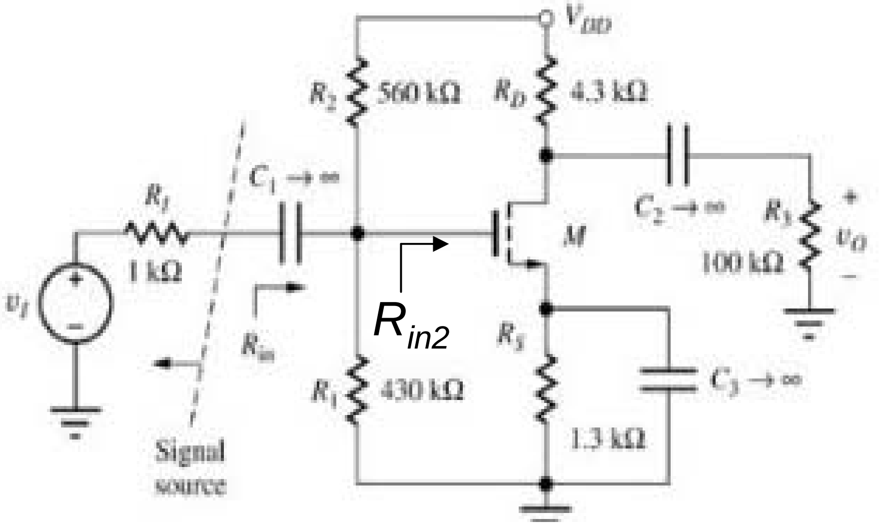
$$A_{vt} = \frac{v_d}{v_g} = \frac{v_o}{v_{gs}} = -g_m R_L$$

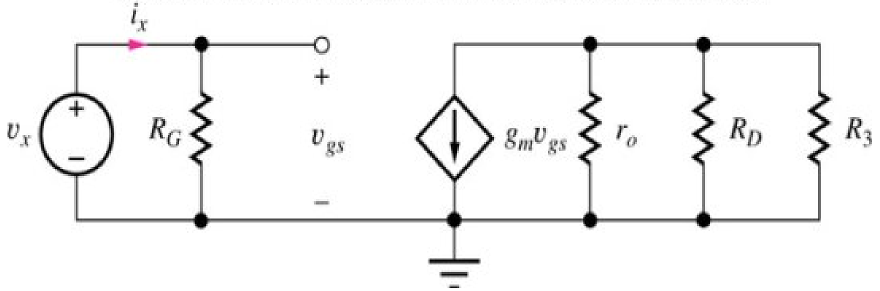
Overall voltage gain from source v_i to v_o:

$$A_v = \frac{v_o}{v_i} = \left(\frac{v_o}{v_{gs}}\right)\left(\frac{v_{gs}}{v_i}\right) = A_{vt}\left(\frac{v_{gs}}{v_i}\right)$$

$$\therefore A_v = -g_m R_L \left[\frac{R_G}{R_I + R_G}\right]$$

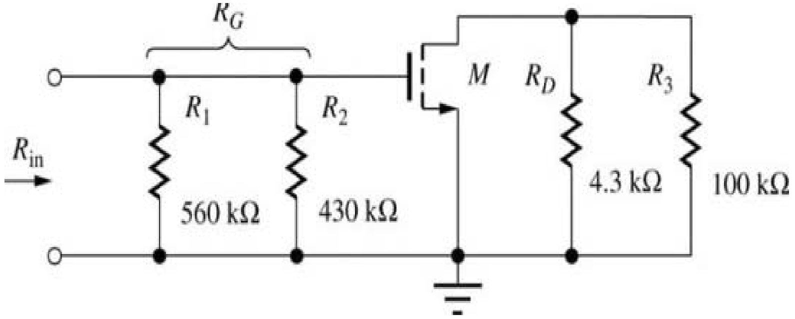
Input Resistances





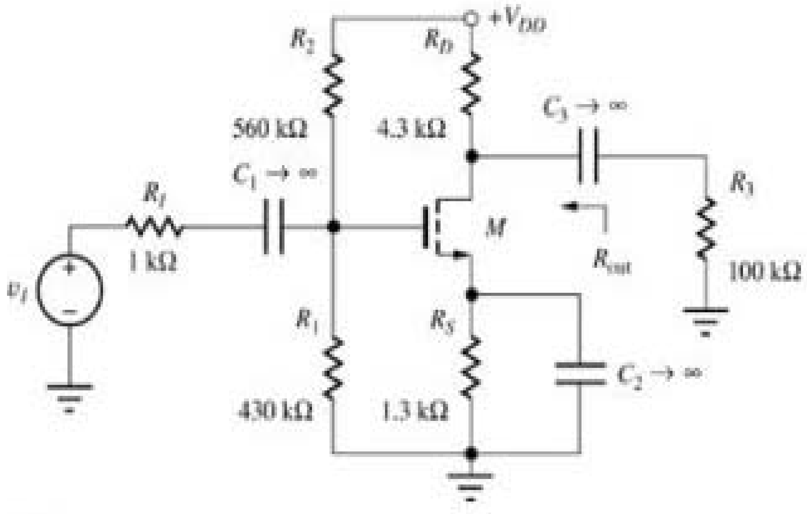
$$v_x = i_x R_G$$

$$R_{in} = R_G$$

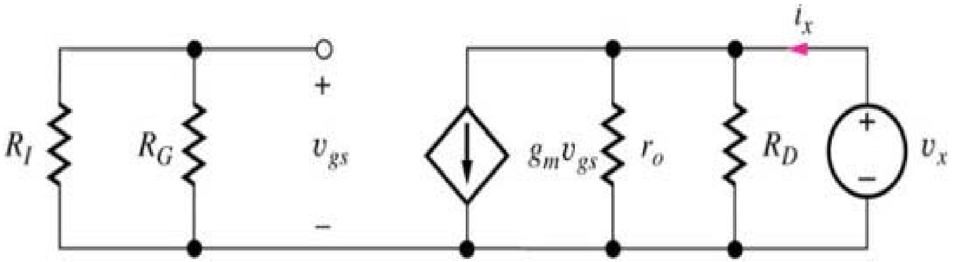


- Input resistance (R_{in2}) looking into the gate terminal is infinite.
- Input resistance (R_{in}) looking into the coupling capacitor

Output Resistance



(b)

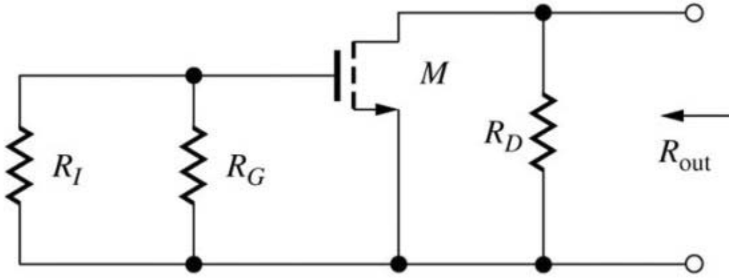


$v_{gs}=0$.

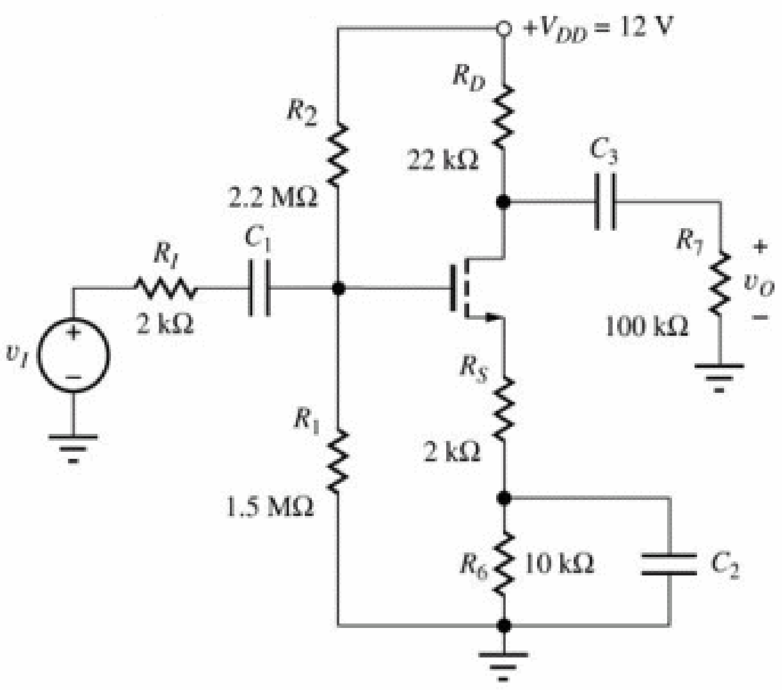
Output resistance looking into the output coupling capacitor:

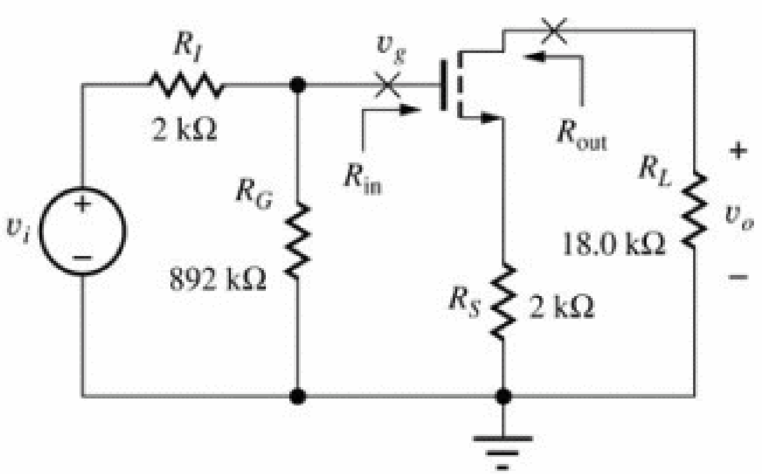
$$R_{out} = \frac{v_x}{i_x} = R_D \| r_o \cong R_D$$

As $r_o >> R_D$.



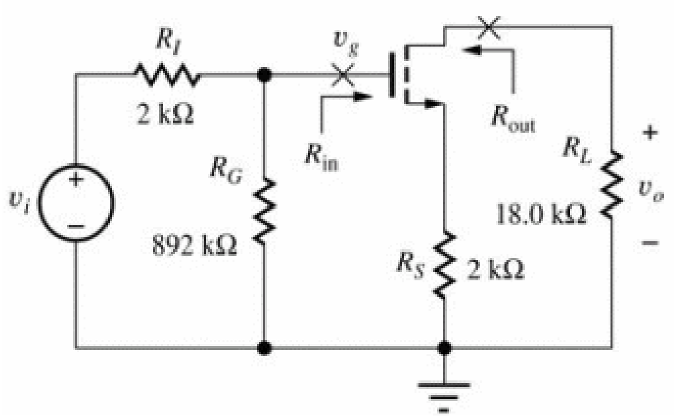
C-S Amplifier With Source Resistor

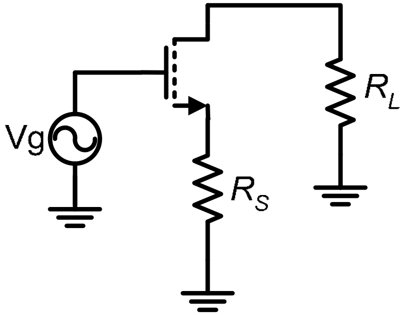


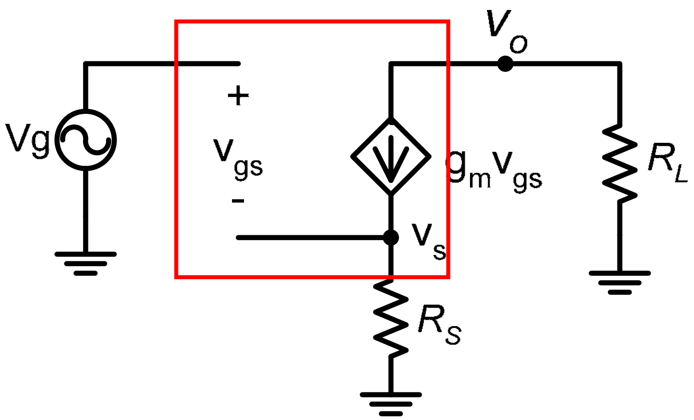


AC Equivalents

Terminal Voltage Gain







Terminal voltage gain:

$$i_d = g_m v_{gs}$$

$$v_{gs} = v_g - i_d R_S$$

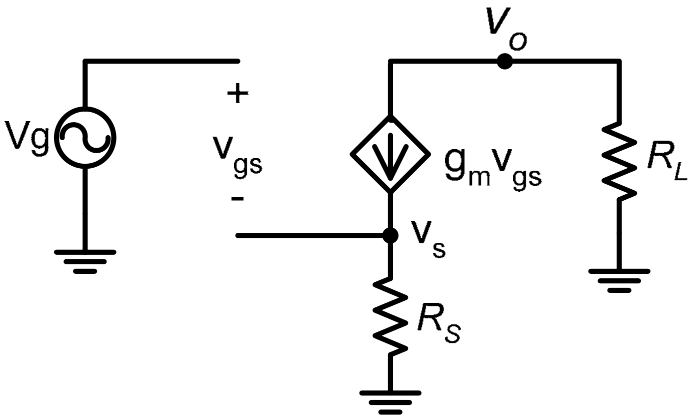
$$i_d = g_m (v_g - i_d R_S) \Rightarrow i_d = \frac{g_m v_g}{1 + g_m R_S}$$

$$v_o = -i_d R_L \Rightarrow A_{vt}^{CS} \equiv \frac{v_o}{v_g} = -\frac{g_m R_L}{1 + g_m R_S}$$

Voltage gain is less sensitive to g_m after adding R_S.

Note: body effect and r_o have been ignored.

Input Signal Range



$$\because i_d = \frac{g_m v_g}{1 + g_m R_S}$$

$$v_{gs} = v_g - i_d R_S = v_g - \frac{g_m R_S v_g}{1 + g_m R_S}$$

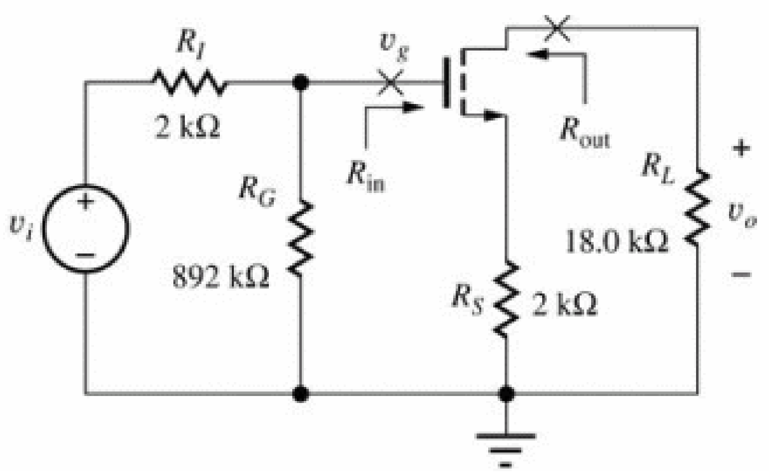
$$\therefore v_{gs} = \frac{v_g}{1 + g_m R_S}$$

Input signal range: magnitude of v_{gs} must be less than $0.2(V_{GS} - V_{TN})$

$$|v_{gs}| = \frac{|v_g|}{1 + g_m R_S} \le 0.2(V_{GS} - V_{TN}) \qquad |v_g| \le 0.2(V_{GS} - V_{TN})(1 + g_m R_S)$$

Presence of R_S increases input range.

R_{in} and Overall voltage gain



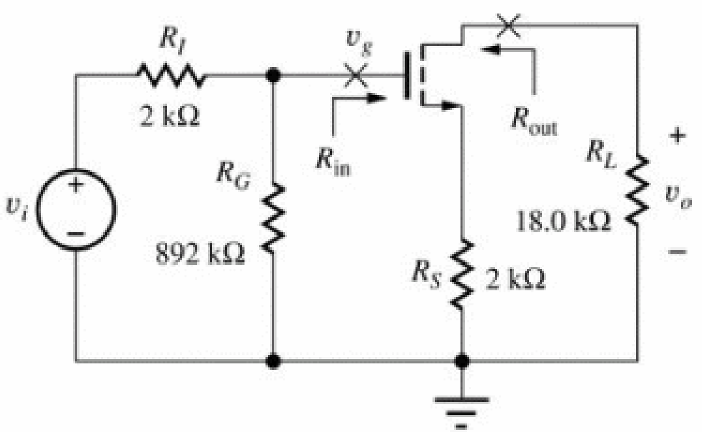
Input resistance looking into the gate terminal:

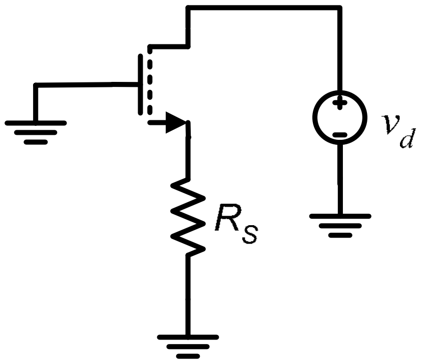
$$R_{in}^{CS} = \infty$$

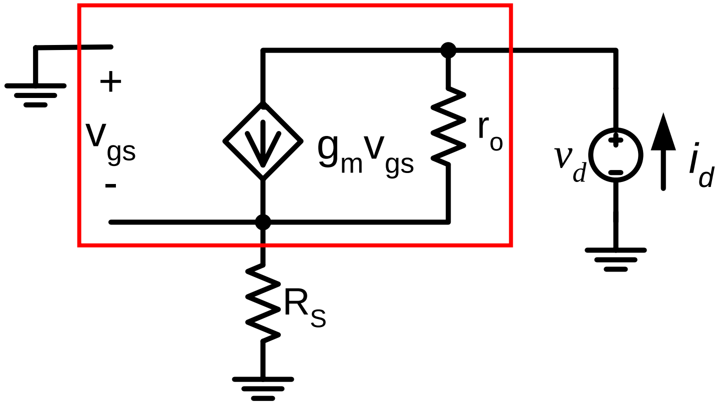
Overall voltage gain:

$$A_v^{CS} = A_{vt}^{CS}\left[\frac{R_G}{R_I + R_G}\right]$$

Output Resistance







Include r_o in the model

Output resistance:

$$v_s = i_d R_S$$

$$v_d = v_s + r_o[i_d - g_m(-v_s)]$$

$$v_d = i_d R_S + r_o(i_d + g_m i_d R_S)$$

$$\frac{v_d}{i_d} = R_S + r_o + r_o g_m R_S \cong r_o(1 + g_m R_S) \qquad \text{for } R_S << r_o$$

$$\therefore R_{out}^{CS} = r_o\left(1 + g_m R_S\right)$$

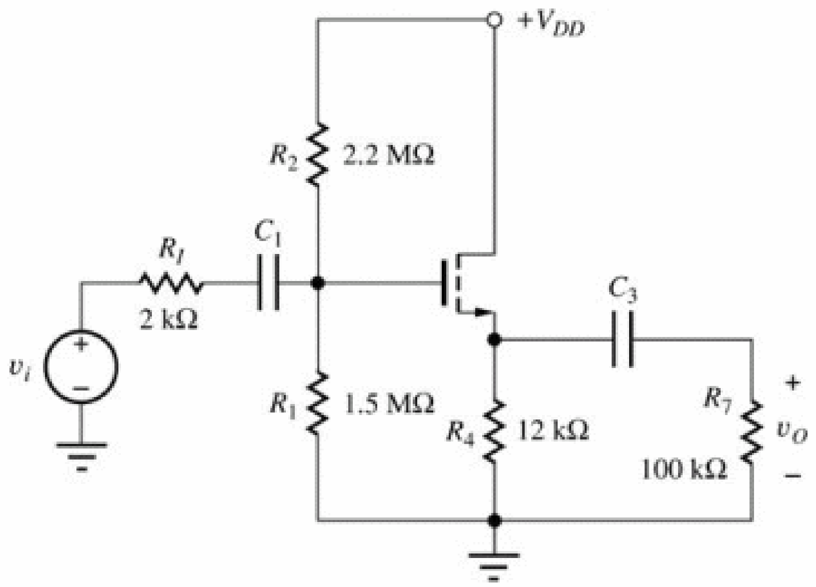
Summary of Common Source Amplifier

- Large and Inverting voltage gain
- Infinite input resistance looking into the Gate terminal
- Large output resistance
- Input signal voltage range depends on source resistance
- Suitable for internal voltage gain stage
  - Need a voltage buffer to drive low load resistance.

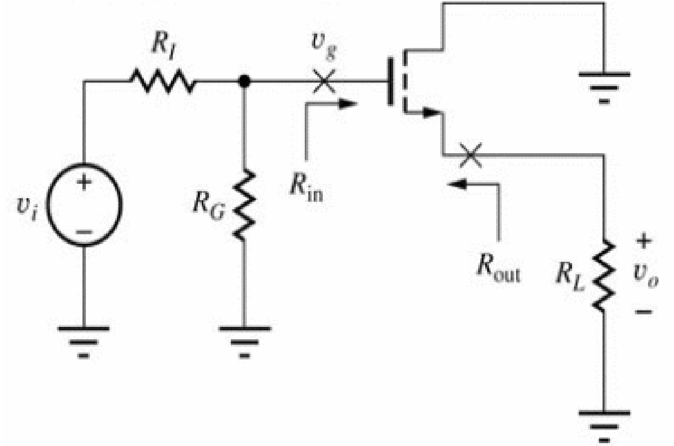
Topics to cover …

- MOSFET circuits DC analysis
- Building small signal model for MOSFET
- Single-stage MOSFET amplifiers
  - Common-source amplifier
  - Common-drain amplifier
  - Common-gate amplifier

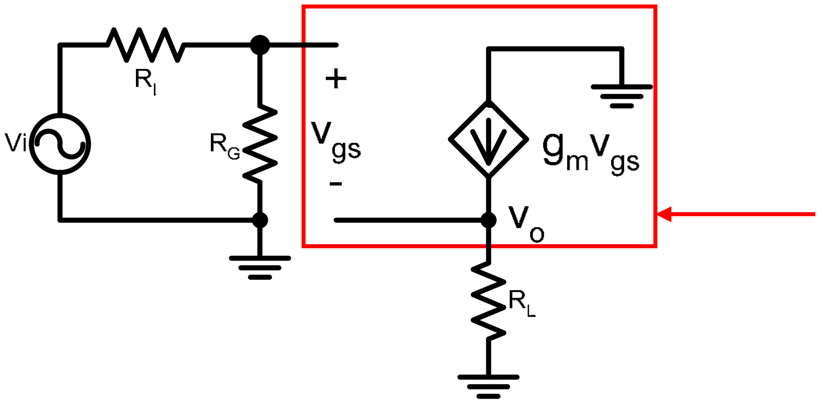
CD Amplifier / Source Follower



AC equivalent:

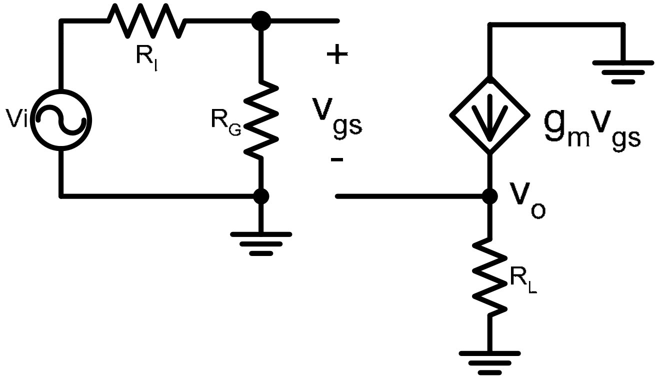


$$R_G = R_1 \parallel R_2 \qquad R_L = R_4 \parallel R_7$$



nMOS small-signal model

Small Signal Analysis



$$v_o = g_m(v_g - v_o)R_L$$

Terminal voltage gain:

$$\therefore A_{vt}^{CD} = \frac{v_o}{v_g} = +\frac{g_m R_L}{1+g_m R_L}$$

For most cases, $g_m R_L >> 1$, terminal voltage gain is close to 1. Hence the name source follower.

Input resistance looking into Gate:

$$R_{in}^{CD} = \infty$$

Overall voltage gain:

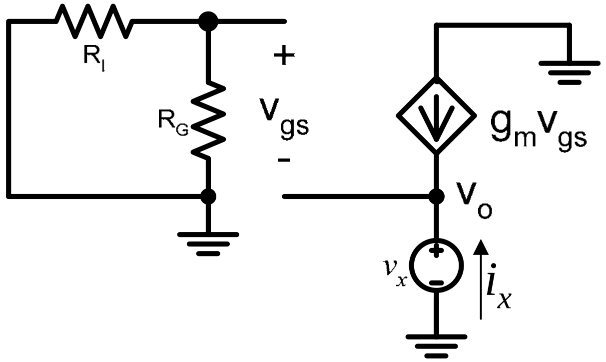
$$A_v^{CD} = A_{vt}^{CD}\left[\frac{R_G}{R_I + R_G}\right]$$

Input signal range:

$$\left|v_{gs}\right| = \frac{\left|v_g\right|}{1+g_m R_L} \le 0.2(V_{GS} - V_{TN})$$

$$\left|v_g\right| \le 0.2(V_{GS} - V_{TN})(1+g_m R_L)$$

Output Resistance



(ignore the r_o)

Output resistance: $i_x = -g_m v_{gs} = -g_m(-v_x) = g_m v_x$

$$R_{out} = \frac{v_x}{i_x} = \frac{1}{g_m}$$

Note: in the analysis for CD amplifier the body effect has be ignored. More accurate analysis should include the body effect.

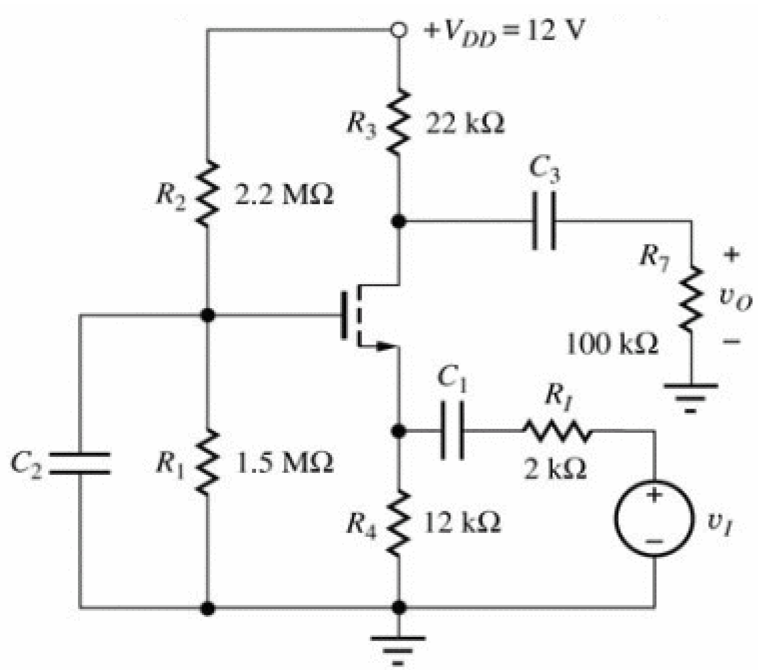
Summary of Source Follower

- Unity voltage gain
- Infinite input resistance (excluding the bias resistors)
- Low output resistance (=1/Gm)
- Large input signal voltage range
- Suitable for voltage buffer

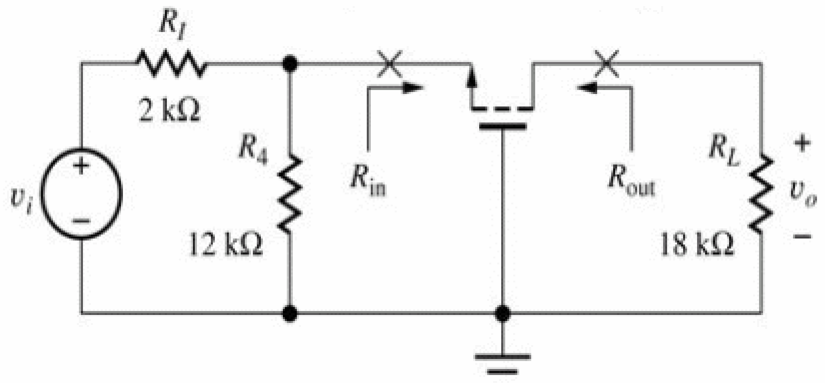
Topics to cover …

- MOSFET circuits DC analysis
- Building small signal model for MOSFET
- Single-stage MOSFET amplifiers
  - Common-source amplifier
  - Common-drain amplifier
  - Common-gate amplifier

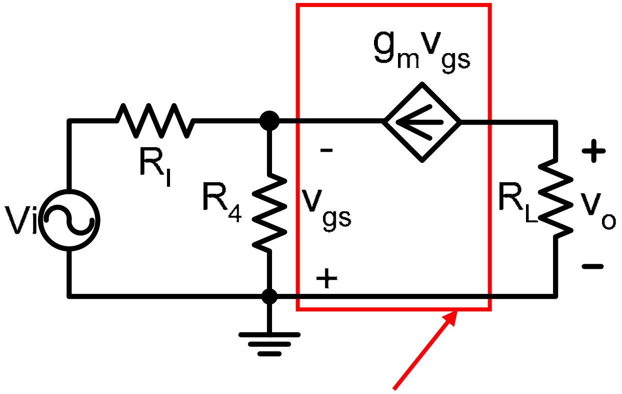
Common Gate Amplifier



$$R_L = R_3 \parallel R_7$$

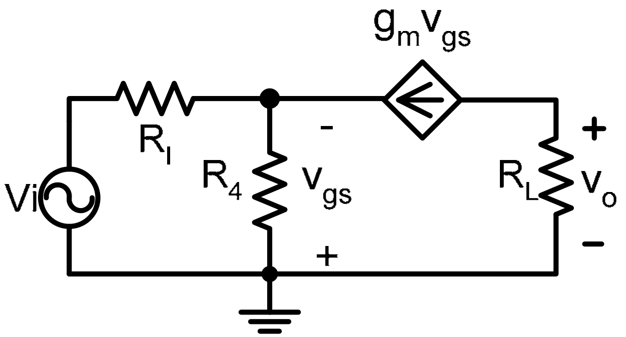


AC equivalent



nMOS small-signal model

Small Signal Analysis



Terminal voltage gain:

$$v_o = -g_m v_{gs} R_L$$
$$= -g_m R_L(-v_s)$$

$$A_{vt}^{CG} = +g_m R_L$$

The gain is non-inverting

Input resistance looking into Source:

$R_{in}^{CG} = \frac{1}{g_m}$ (same as the R_{out} of CD)

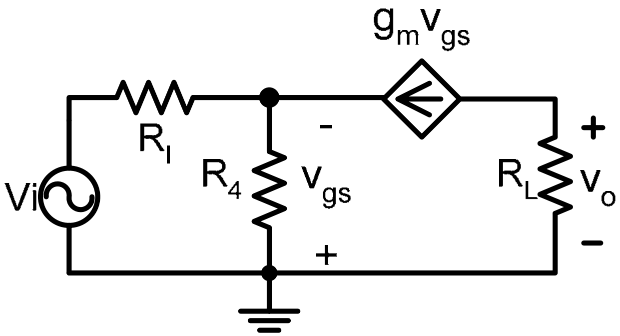
Overall voltage gain:

$$A_v^{CG} = \frac{v_o}{v_i} = \left(\frac{v_o}{v_g}\right)\left(\frac{v_g}{v_i}\right) = A_{vt}^{CG}\left[\frac{R_4 \| R_{in}^{CG}}{R_I + \left(R_4 \| R_{in}^{CG}\right)}\right]$$

$$= \frac{g_m R_L}{1 + g_m (R_I \| R_4)}\left(\frac{R_4}{R_I + R_4}\right)$$

For $R_I >> R_4$, $A_v^{CG} \cong \frac{g_m R_L}{1 + g_m R_I}$

Input Signal Range



Input signal range:

$$-v_{gs} = \frac{R_4 \| (1/g_m)}{R_I + R_4 \| (1/g_m)} v_i$$

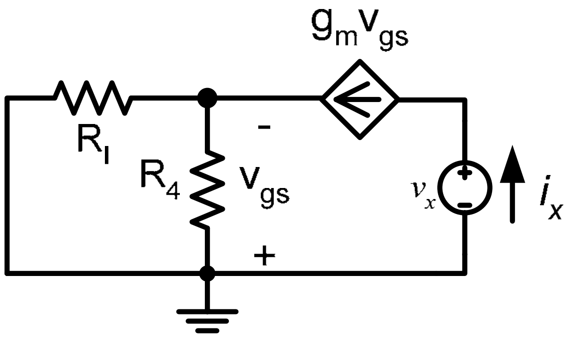
$$\cong \frac{1/g_m}{R_I + 1/g_m} v_i \qquad \text{for } 1/g_m >> R_4$$

$$= \frac{1}{1+g_m R_I} v_i$$

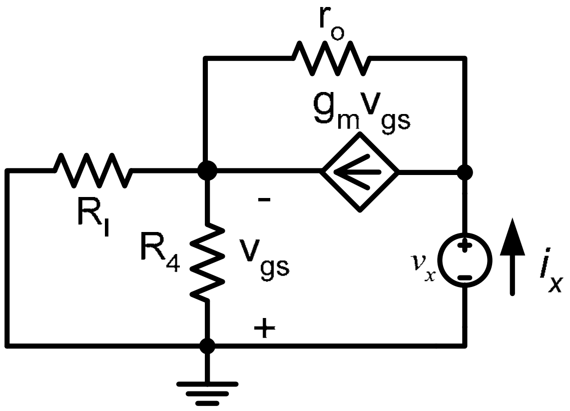
$$|v_i| \leq 0.2(V_{GS} - V_{TN})(1+g_m R_I)$$

Relative size of g_m and R_I determine signal-handling limits.

Output Resistance



$$R_{th} = R_I \parallel R_4$$



Output resistance:

$$i_x = g_m v_{gs} = g_m(-R_{th} i_x)$$

$$i_x = 0 \text{ and thus } R_{out} = \infty$$

Including the r_o in the transistor,

$$i_x = g_m(-v_s) + (v_x - v_s)/r_o$$

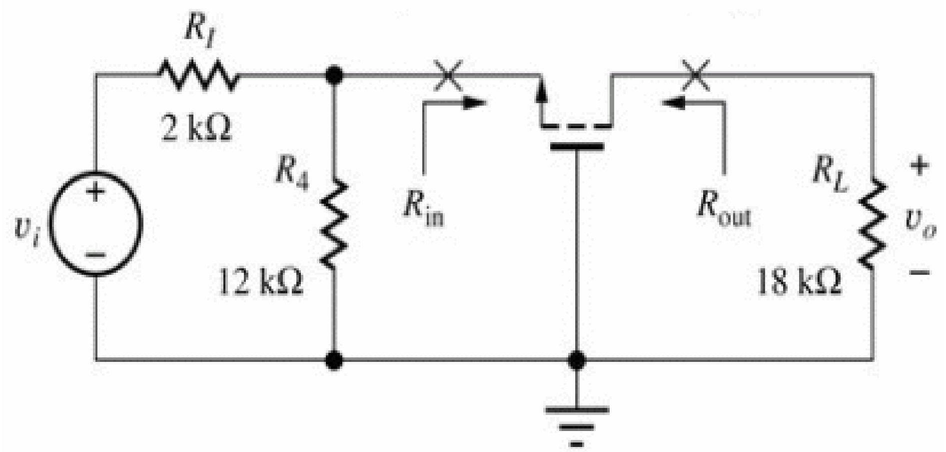
$$= -v_s(g_m + 1/r_o) + v_x/r_o$$

$$v_s = R_{th} i_x$$

$$R_{out} \equiv \frac{v_x}{i_x} = r_o\left(1 + R_{th}(g_m + 1/r_o)\right)$$

$$\cong r_o\left(1 + g_m R_{th}\right)$$

Current Gains



Terminal current gain:

Since $I_D = I_S$, the terminal current is unity.

Overall current gain:

$$A_I = \frac{R_4}{R_4 + 1/g_m} \cong 1$$

Summary of Common Gate Amplifier

- Unity Current Gain
- Large Non-inverting voltage gain
- Low input resistance (=1/Gm)
- Large output resistance
- Input voltage range depends on $g_m R_l$
- Suitable for current buffer