Lecture 24 - Frequency Response of Amplifiers (II)

Open-Circuit Time-Constant Technique

December 6, 2005

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Reading assignment:

Howe and Sodini, Ch. 10, §§10.4.4-10.4.5. 10.6

Key questions

- Is there a fast way to assess the frequency response of an amplifier?
- Do all amplifiers suffer from the Miller effect?

1. Open-Circuit Time-Constant Technique

Simple technique to *estimate* bandwidth of an amplifier.

Method works well if amplifier transfer function has:

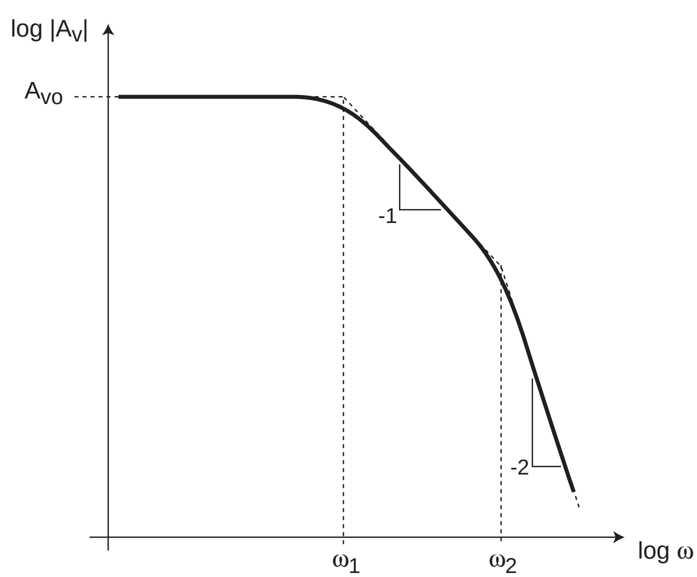
- a *dominant pole* that dominates the bandwidth
- no zeroes, or zeroes at frequencies much higher than that of dominant pole

Transfer function of form:

$$\frac{V_{out}}{V_s} = \frac{A_{vo}}{(1 + j\frac{\omega}{\omega_1})(1 + j\frac{\omega}{\omega_2})(1 + j\frac{\omega}{\omega_3})...}$$

with

$$\omega_1 \ll \omega_1,\ \omega_2,\ \omega_3,\ ...$$



$$\frac{V_{out}}{V_s} = \frac{A_{vo}}{(1 + j\frac{\omega}{\omega_1})(1 + j\frac{\omega}{\omega_2})(1 + j\frac{\omega}{\omega_3})...}$$

Multiply out the denominator:

$$\frac{V_{out}}{V_s} = \frac{A_{vo}}{1 + j\omega b_1 + (j\omega)^2 b_2 + (j\omega)^3 b_3...}$$

where:

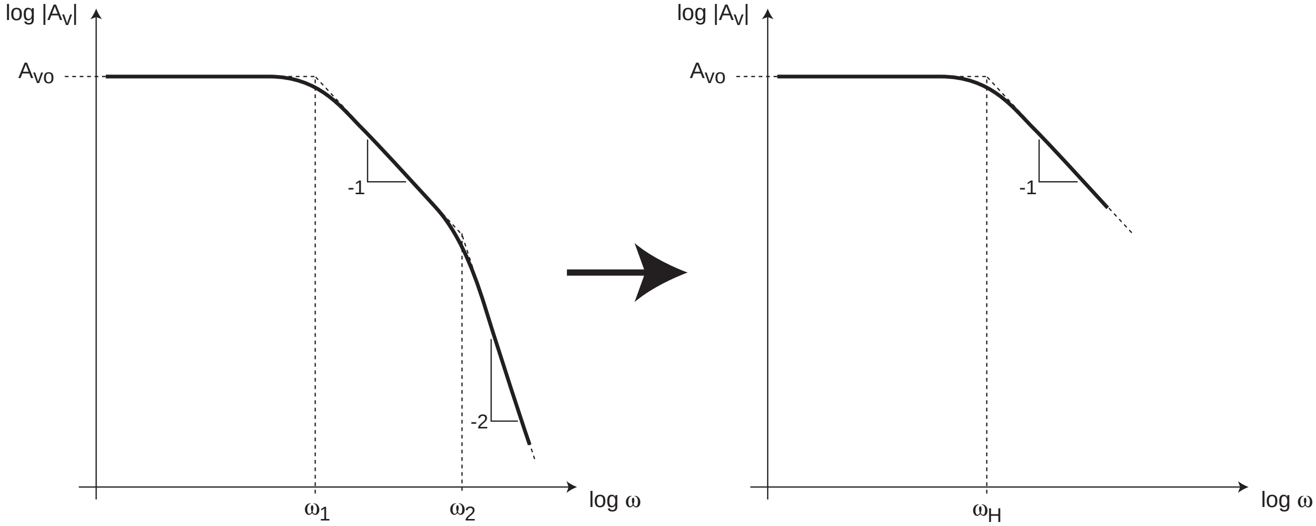
$$b_1 = \frac{1}{\omega_1} + \frac{1}{\omega_2} + \frac{1}{\omega_3} + ...$$

If there is a dominant pole, the low frequency behavior well described by:

$$\frac{V_{out}}{V_s} \simeq \frac{A_{vo}}{1 + j\omega b_1} = \frac{A_{vo}}{1 + j\frac{\omega}{\omega_H}}$$

Bandwidth then:

$$\omega_H \simeq \frac{1}{b_1}$$



It can be shown (see Gray & Meyer, 3rd ed., p. 502) that coefficient b_1 can be found exactly through:

$$b_1 = \sum_{i=1}^{n} \tau_i = \sum_{i=1}^{n} R_{Ti} C_i$$

where:

τ_i is *open-circuit time constant* for capacitor C_i

R_{Ti} is Thevenin resistance across C_i
(with all other capacitors open-circuited)

Bandwidth then:

$$\omega_H \simeq \frac{1}{b_1} = \frac{1}{\Sigma_{i=1}^{n} \tau_i} = \frac{1}{\Sigma_{i=1}^{n} R_{Ti} C_i}$$

Summary of open-circuit time constant technique:

1. shut-off all independent sources
2. compute Thevenin resistance R_{Ti} seen by each C_i with all other C's open
3. compute open-circuit time constant for C_i as

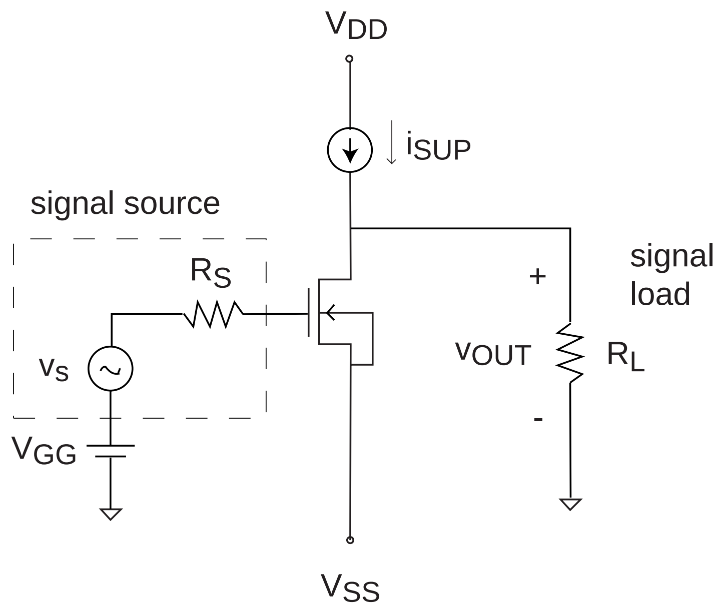
$$\tau_i = R_{Ti} C_i$$

4. conservative estimate of bandwidth:

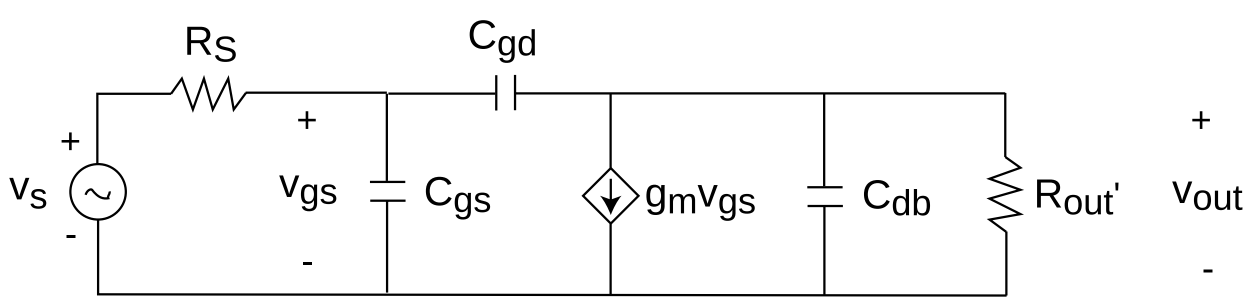
$$\omega_H \simeq \frac{1}{\Sigma \tau_i}$$

Works also with other transfer functions: $\frac{I_{out}}{V_s}$, $\frac{V_{out}}{I_s}$, $\frac{I_{out}}{I_s}$.

2. Application of OCT to evaluate bandwidth of common source amplifier

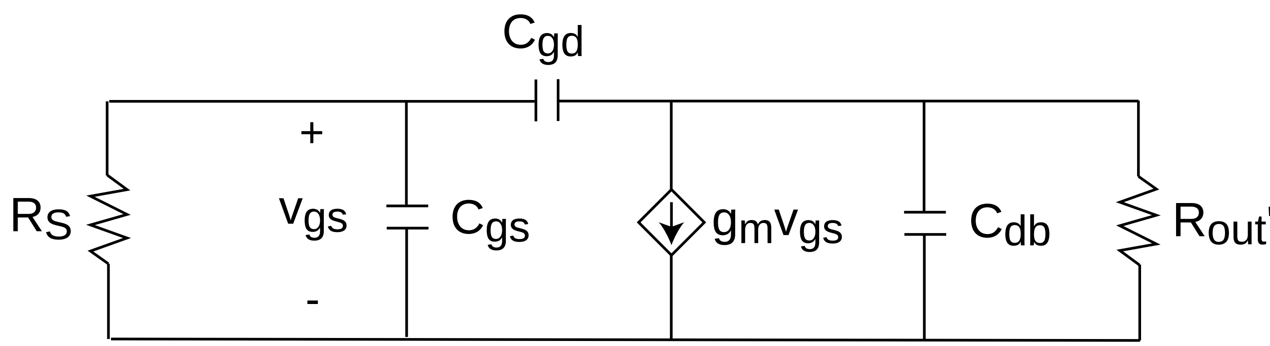


Small-signal equivalent circuit model (assuming current source has no parasitic capacitance):

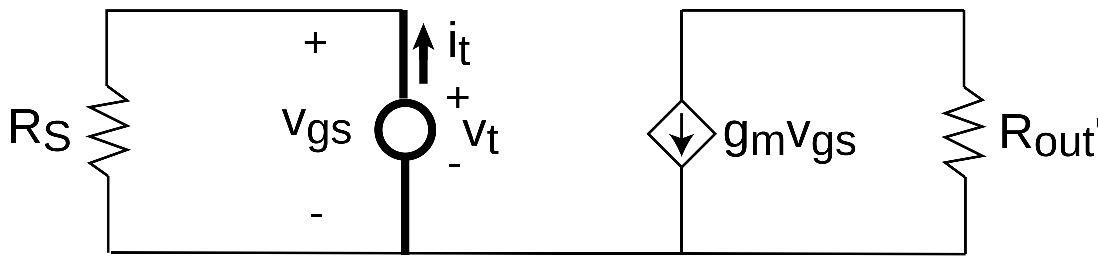


Three capacitors $\Rightarrow$ three time constants

☐ First, short v_s:



☐ Time constant associated with C_{gs}



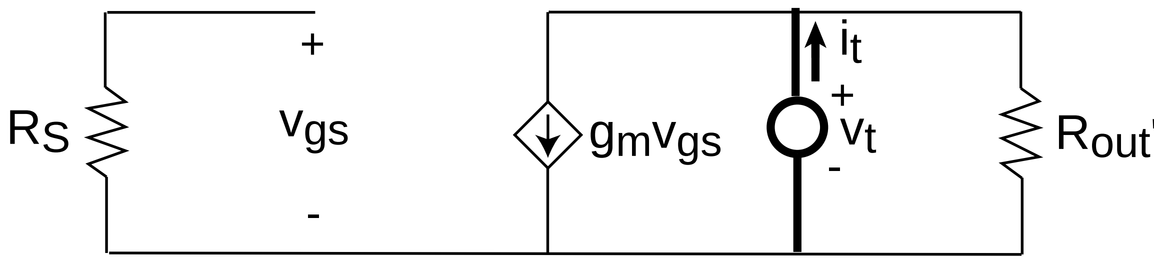
Clearly:

$$R_{Tgs} = R_S$$

and time constant associated with C_{gs} is:

$$\tau_{gs} = R_S C_{gs}$$

□ Time constant associated with C_{db}:



Note:

$$v_{gs} = 0$$

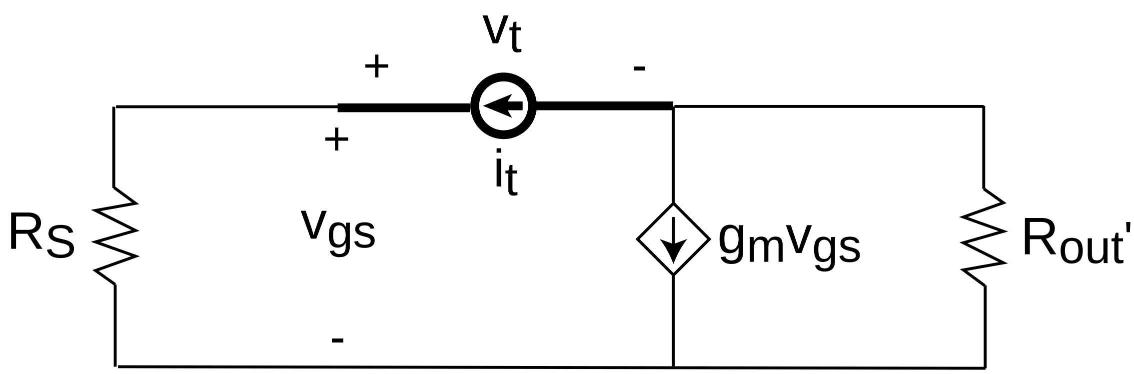
Then:

$$R_{Tdb} = R'_{out}$$

and time constant associated with C_{gs} is:

$$\tau_{gs} = R'_{out} C_{db}$$

Time constant associated with C_{gd}:



Note:

$$v_{gs} = i_t R_S$$

Also:

$$v_t = v_{gs} + (g_m v_{gs} + i_t)R'_{out}$$

Putting it all together, we have:

$$v_t = i_t[R_S + R_{out'}(1 + g_m R_S)]$$

Then:

$$R_{Tgd} = R_S + R_{out'}(1 + g_m R_S) = R_{out'} + R_S(1 + g_m R_{out'})$$

and time constant associated with C_{gd}:

$$\tau_{gd} = [R_{out'} + R_S(1 + g_m R_{out'})]C_{gd}$$

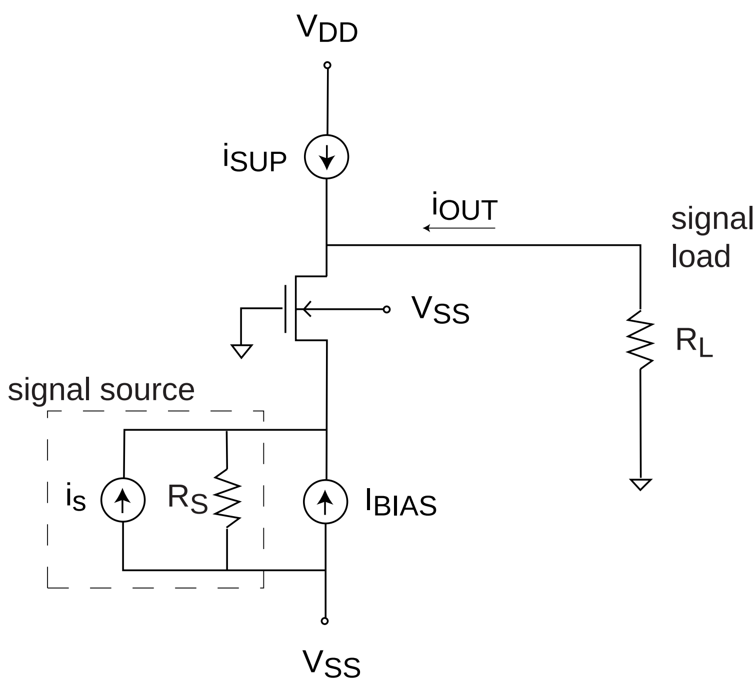
The bandwidth is then:

$$\omega_H \simeq \frac{1}{\Sigma\tau_i} = \frac{1}{R_S C_{gs} + [R'_{out} + R_S(1 + g_m R'_{out})]C_{gd} + R'_{out} C_{db}}$$

Identical result as in last lecture.

Open circuit time constant technique evaluates bandwidth neglecting $-\omega^2$ term in the denominator of A_v
$\Rightarrow$ conservative estimate of ω_H.

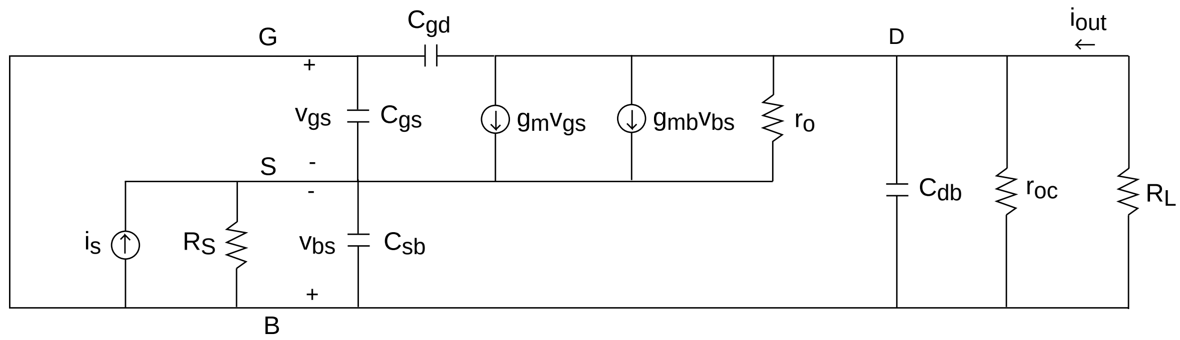
3. Frequency response of common-gate amplifier

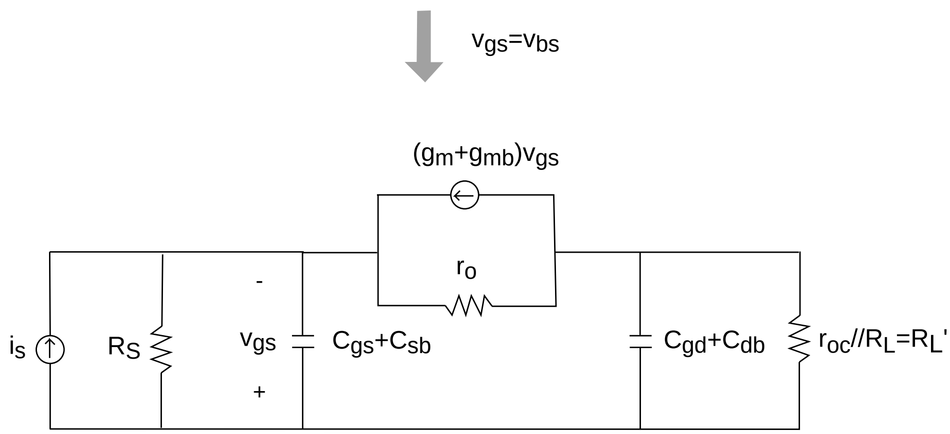


Features:

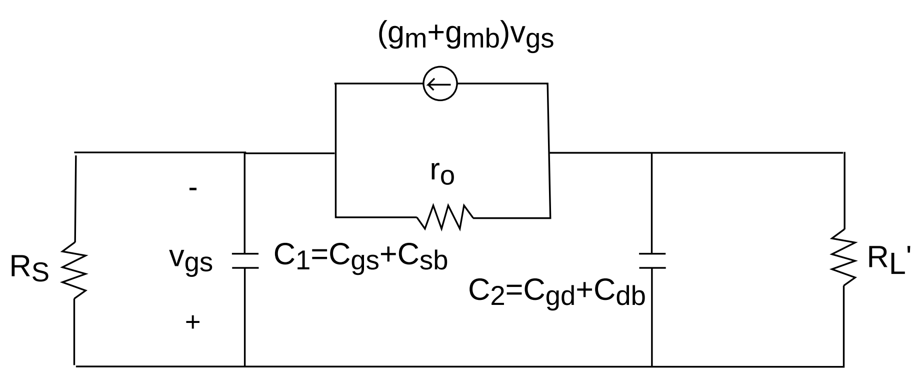
- current gain $\simeq$ 1
- low input resistance
- high output resistance
- $\Rightarrow$ good current buffer

Small-signal equivalent circuit model:

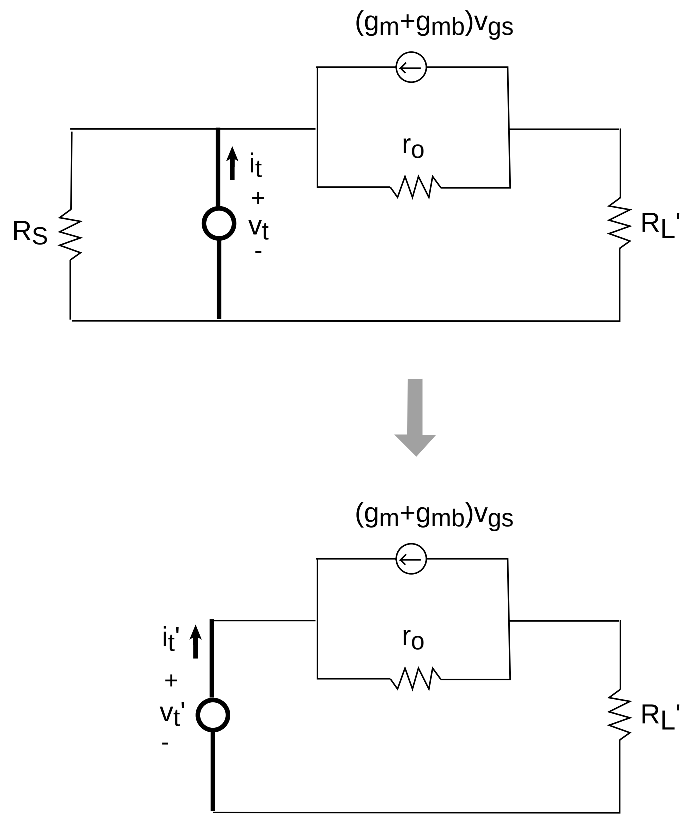




☐ Frequency analysis: first, open i_s:



□ Time constant associated with C_1:



Don't need to solve:

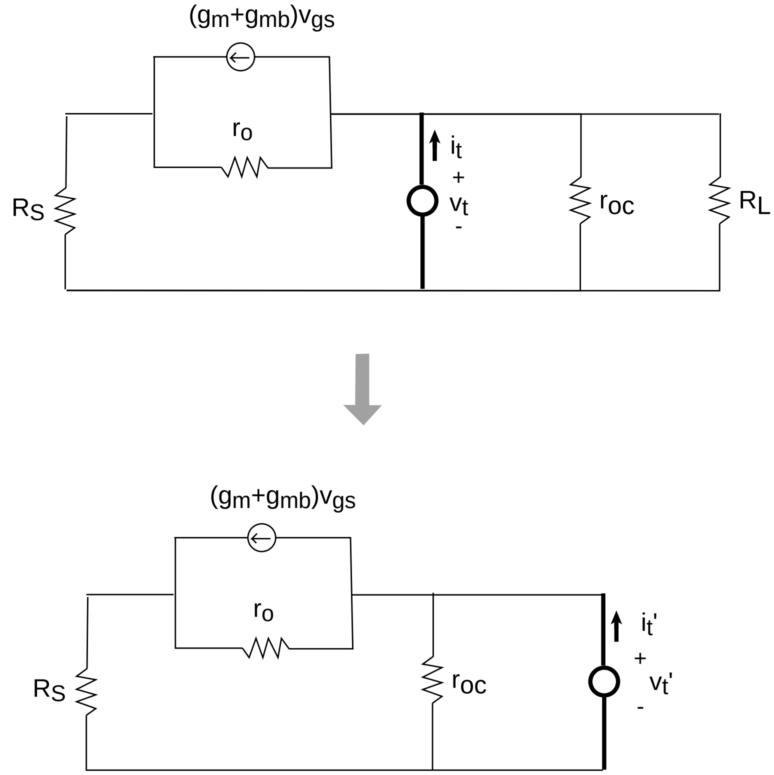
- test probe is in parallel with R_S,
- test probe looks into input of amplifier $\Rightarrow$ sees R_{in}!

$$R_{T1} = R_S // R_{in}$$

And:

$$\tau_1 = (C_{gs} + C_{sb})(R_S // R_{in})$$

□ Time constant associated with C_2:



Again, don't need to solve:

- test probe is in parallel with R_L,
- test probe looks into output of amplifier ⇒ sees R_{out}!

$$R_{T2} = R_L // R_{out}$$

And:

$$\tau_2 = (C_{gd} + C_{db})(R_L // R_{out})$$

□ Bandwidth:

$$\omega_H \simeq \frac{1}{(C_{gs}+C_{sb})(R_S//R_{in})+(C_{gd}+C_{db})(R_L//R_{out})}$$

No capacitor in Miller position → no Miller-like term.

Simplify:

- In a current amplifier, $R_S \gg R_{in}$:

$$R_{T1} = R_S//R_{in} \simeq R_{in} \simeq \frac{1}{g_m+g_{mb}} \simeq \frac{1}{g_m}$$

- At output:

$$R_{T2} = R_L//R_{out} = R_L//r_{oc}//\{r_o[1+R_S(g_m+g_{mb}+\frac{1}{r_o})]$$

or

$$R_{T2} \simeq R_L//r_{oc}//[r_o(1+g_mR_S)] \simeq R_L$$

Then:

$$\omega_H \simeq \frac{1}{(C_{gs}+C_{sb})\frac{1}{g_m}+(C_{gd}+C_{db})R_L}$$

If R_L is not too high, bandwidth can be rather high (and approach ω_T).

Key conclusions

- Open-circuit time-constant technique: simple and powerful method to estimate bandwidth of amplifiers.
- Common-gate amplifier:
  - no capacitor in Miller position ⇒ no Miller effect
  - if R_L is not too high, CG amp has high bandwidth
- R_S, R_L affect bandwidth of amplifier