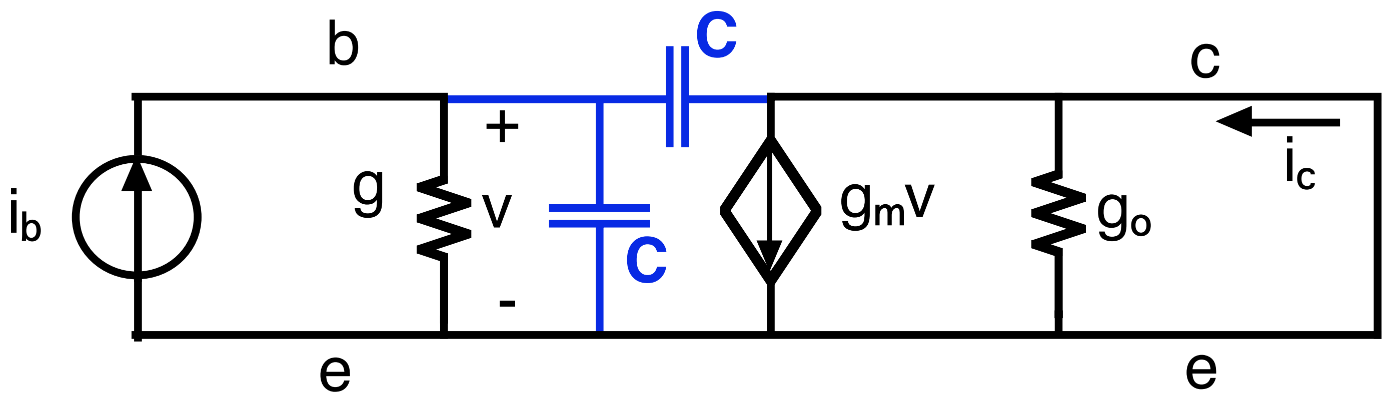
6.012 - Electronic Devices and Circuits

Lecture 24 - Intrinsic Limits of Transistor Speed - Outline

- **Announcements**
  - **Handouts - Lecture Outline and Summary**
  - **Problem Set No. 10 - Don't forget, there is one, and it is due Friday!**
  - **Final - Monday, Dec. 15, 9:00 am -noon, duPont Gymnasium**
- **Review - Dealing with shunting feedback capacitances: C and C_{gd}**
  - **The Miller effect: any C bridging a gain stage looks bigger at the input**
  - **The Marvelous cascode: CE/S-CB/G (E/SF-CB/G work, too - see A741)**
    large bandwidth, large output resistance
    used in gain stages and in current sources
- **Intrinsic high frequency limits for transistors**
  - **General approach**
- **Limits for BJTs:**
  - **Metrics**
  - **Design lessons**
- **Limits for MOSFETs:**
  - **Metric**
  - **Design lessons**

Intrinsic $_{HI}$'s for the BJTs - short-circuit current gain



The common-emitter short-circuit current gain is:

$$_{sc}(j\ \ ) \equiv \frac{i_c(j\ \ )}{i_b(j\ \ )} = \frac{[g_m \quad j\ \ C\ \ ]}{\{g\ \ + j\ \ [C\ \ + C\ \ ]\}}$$

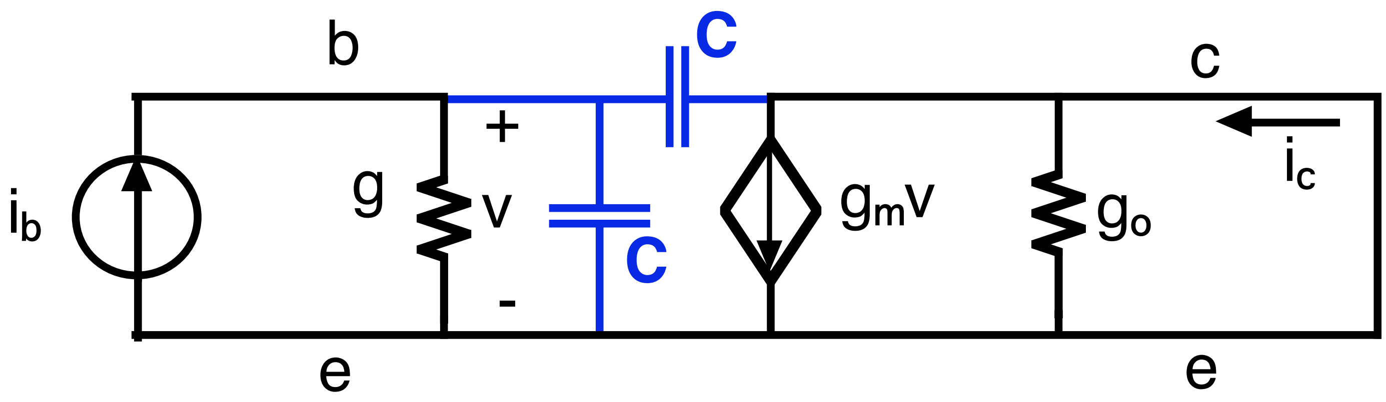
there is one pole, call it $_p$, and one zero, $_z$:

$$_p = \frac{g}{[C\ \ + C\ \ ]}, \qquad _z = \frac{g_m}{C}$$

Of these two, $_p$ is much smaller and this is the 3dB point of the common-emitter short-circuit current gain. We give it the name .

$$\equiv \frac{g}{[C\ \ + C\ \ ]}$$

Intrinsic $_{HI}$'s for the BJTs - short-circuit current gain, cont.



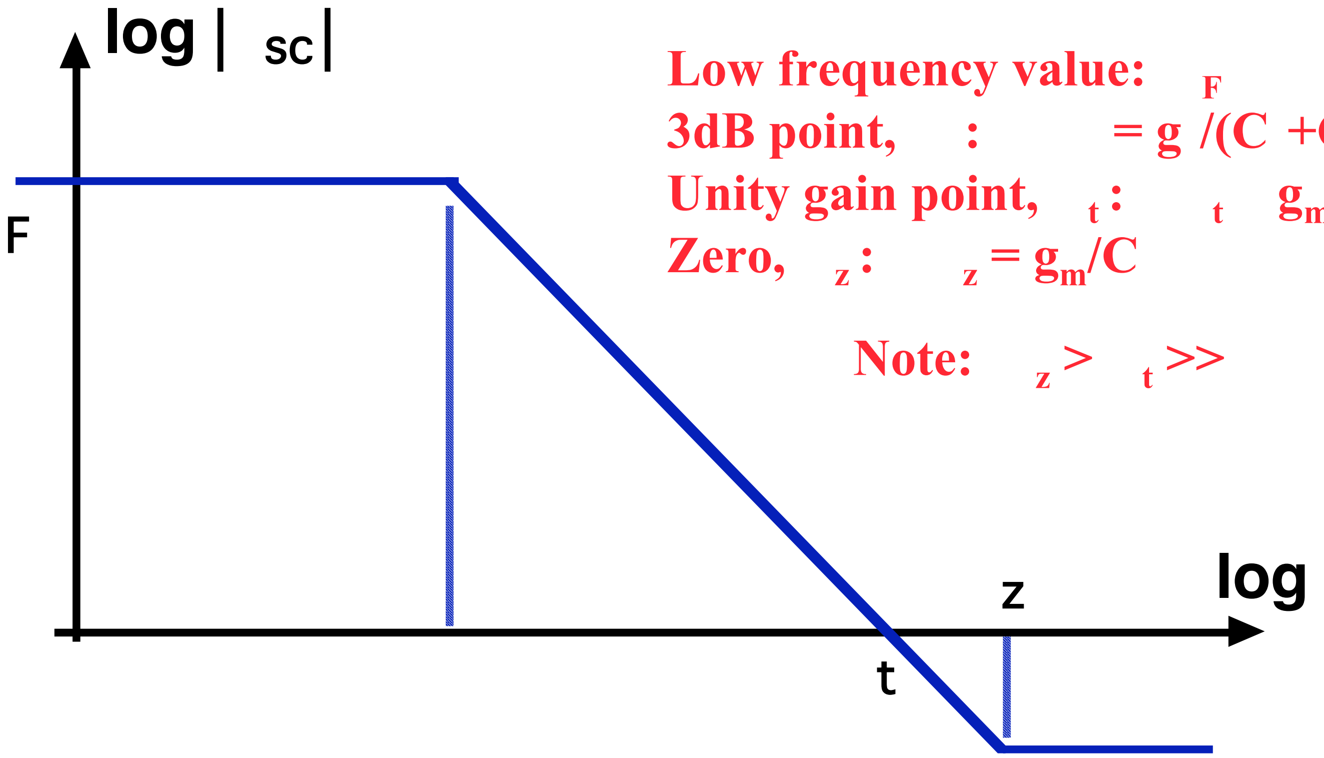
The magnitude of $_{sc}$ is greater than one at frequencies higher than . The frequency at which it is one is called $_t$.

$$|\ _{sc}(j\ )| = \sqrt{\frac{[g_m^2 + \ ^2C^2]}{\{g^2 + \ ^2[C\ + C\ ]^2\}}}$$

Setting this equal to one and solving for we find that $_t$ is:

$$_t = \sqrt{\frac{[g^2 + g_m^2]}{\{[C\ + C\ ]^2 \quad C^2\}}} \qquad \frac{g_m}{[C\ + C\ ]}$$

BJT short-circuit current gain, $\ _{sc}(j\ )$, and $\ _T$



Low frequency value: $\ _F$

3dB point, : $= g\ /(C\ +C\ )$

Unity gain point, $\ _t$**:** $\ _t\quad g_m/(C\ +C\ )$

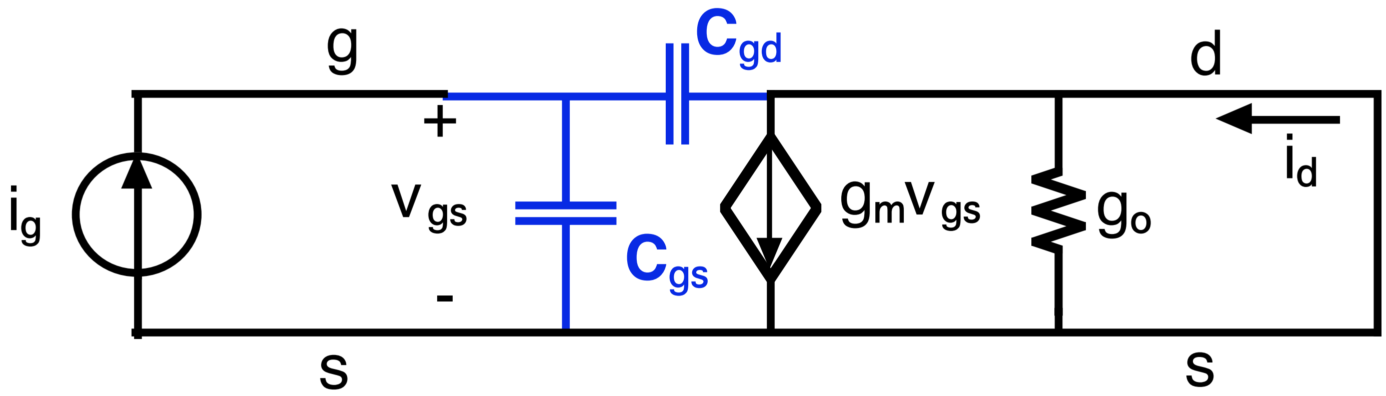
Zero, $\ _z$**:** $\ _z = g_m/C$

Note: $\ _z > \ _t >> \quad (= \ _t/\ _F)$

$$\ _t \quad \frac{g_m}{[C\ \ +C\ \ ]} = \frac{g_m}{\{g_m\ \ _{trB}+C_{eb,dp}+C_{cb,dp}\}} = \frac{qI_C/kT}{\{[qI_C/kT]\ \ _{trB}+C_{eb,dp}+C_{cb,dp}\}}$$

In the limit of large I_C: $\ _t(\text{BJT}) \quad \frac{1}{\ _{trB}} = \frac{2D_{eB}}{w_B^2} = \frac{2\ \ _e V_{thermal}}{w_B^2}$

Intrinsic $_{HI}$'s for the MOSFETs - short-circuit current gain



The common-source short-circuit current gain is:

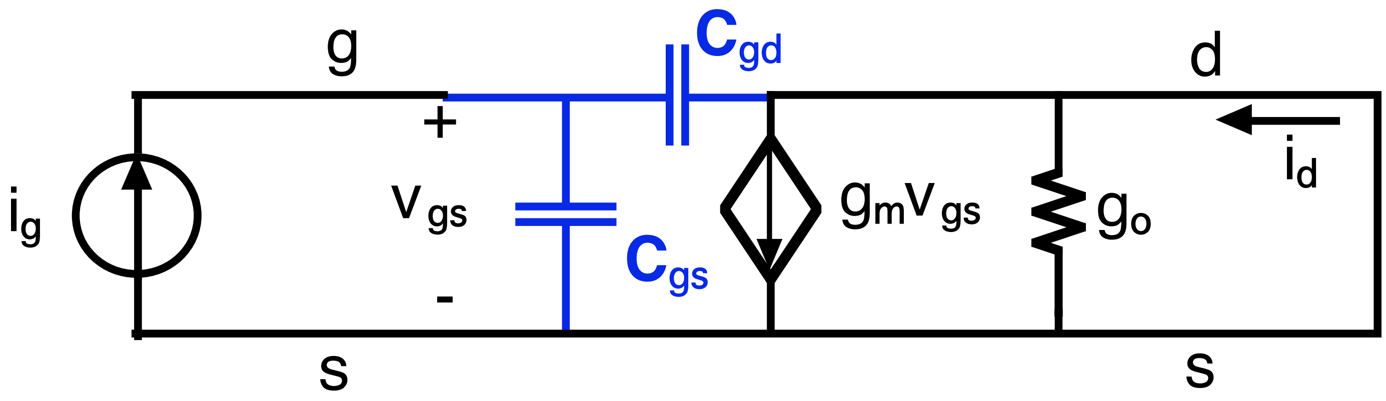
$$_{sc}(j\quad) \equiv \frac{i_d(j\quad)}{i_g(j\quad)} = \frac{\left[g_m \quad j\ C_{gd}\right]}{j\ \left[C_{gs} + C_{gd}\right]}$$

there is one pole at = 0, and one zero, call it $_z$:

$$_z = \frac{g_m}{C_{gd}}$$

The magnitude of $_{sc}$ is infinity at DC, and it decreases linearly with increasing frequency.

Intrinsic $_{HI}$'s for the MOSFETs - short-circuit current gain, cont.



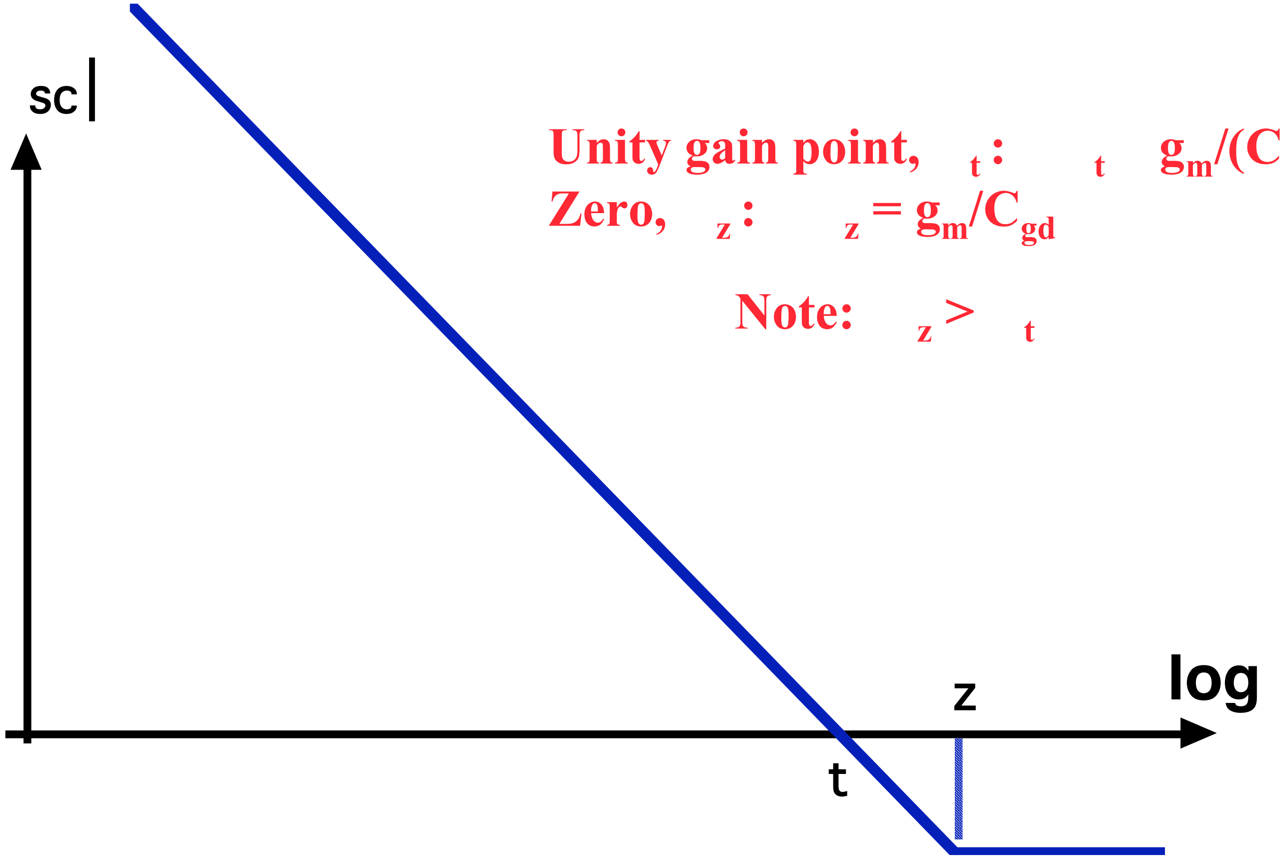
The magnitude of $_{sc}$ is one at a frequency which is called $_t$:

$$\left| \ _{sc}(j\ )\right| = \sqrt{\frac{\left[g_m^2 + \ ^2 C_{gd}^2\right]}{\left\{\ ^2\left[C_{gs}+C_{gd}\right]^2\right\}}}$$

Setting this equal to one and solving for we find:

$$_t = \sqrt{\frac{g_m^2}{\left\{\left[C_{gs}+C_{gd}\right]^2 \quad C_{gd}^2\right\}}} \qquad \frac{g_m}{\left[C_{gs}+C_{gd}\right]}$$

MOSFET short-circuit current gain, $_{sc}(j\ )$, and $_T$



Unity gain point, $_t$: $\;_t \quad g_m/(C_{gs}+C_{gd})$

Zero, $_z$: $\;_z = g_m/C_{gd}$

Note: $_z >\ _t$

$$_t(\text{MOSFET}) \quad \frac{g_m}{[C_{gs}+C_{gd}]} \quad \frac{g_m}{C_{gs}} = \frac{\frac{W}{L}\ {}_e C^*_{ox}[V_{GS} \quad V_T]}{\frac{2}{3}WLC^*_{ox}} = \frac{3}{2}\,\frac{{}_e[V_{GS} \quad V_T]}{L^2}$$

Looking more at $_T$ for BJTs and MOSFETs:

For a MOSFET we have

$$_t(\text{MOSFET}) \quad \frac{3}{2}\frac{_e[V_{GS} \quad V_T]}{L^2}$$

The average E-field in the channel, E_y, is

$$E_y \quad \frac{[V_{GS} \quad V_T]}{L}$$

So we can also write $_T$ as

$$_t(\text{MOSFET}) \quad \frac{3}{2}\ _e\frac{[V_{GS} \quad V_T]}{L}\frac{1}{L} \quad \frac{\bar{s}_y}{L} \quad \frac{1}{_{trChannel}}$$

This is identical to the form we have for $_T$ in a BJT

$$_t(\text{BJT}) \quad \frac{1}{_{trB}} = \frac{2D_{eB}}{w_B^2} = \frac{2\ _eV_{thermal}}{w_B^2}$$

What happens when we have velocity saturation?

$$_t(\text{MOSFET}) \quad \frac{s_{sat}}{L}, \qquad _t(\text{BJT}) \quad \frac{s_{sat}}{w_B}$$

$_T$ still decreases with L and w_B, but not as quickly!

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Lecture 24 - Intrinsic Limits of Transistor Speed - Summary

- **Intrinsic high frequency limits for transistors**

  General approach: short-circuit current gains

- **Limits for BJTs:**

  Metrics - CE short-circuit current gain 3B pt: $= g\ /(C\ + C\ )$

  CE short-circuit current gain unit gain pt: $_T = g_m/(C\ + C\ )$

  $_T$ approaches 1/ $_b$ as I_c increases and $_b = w_B{}^2/2D_{min,B}$

  so $_T \approx 2D_{min,B}/w_B{}^2 = 2\ _e V_{th}/w_B{}^2$

  CB short-circuit current gain unit gain pt: $= g_m/C$

  Design lessons - bias at high collector current

  minimize w_B (win as $w_B{}^2$)

  use npn over pnp ($_e >>\ _h$)

- **Limits for MOSFETs:**

  Metric - CS short-circuit current gain unit pt: $_T = g_m/[(C_{gs}+C_{gd})^2 - C_{gd}{}^2]^{1/2}$

  $_T$ is approximately $g_m/C_{gs} = 3\ _e(V_{GS}-V_T)/2L^2$

  $g_m = (W/L)\ _e C_{ox}{}^*(V_{GS}-V_T)$ and $C_{gs} = (2/3)WLC_{ox}{}^*$

  so $_T \approx 3\ _e(V_{GS}-V_T)/2L^2$

  Design lessons - bias at large I_D

  minimize L (win as L^2)

  use n-channel over p-channel ($_e >>\ _h$)