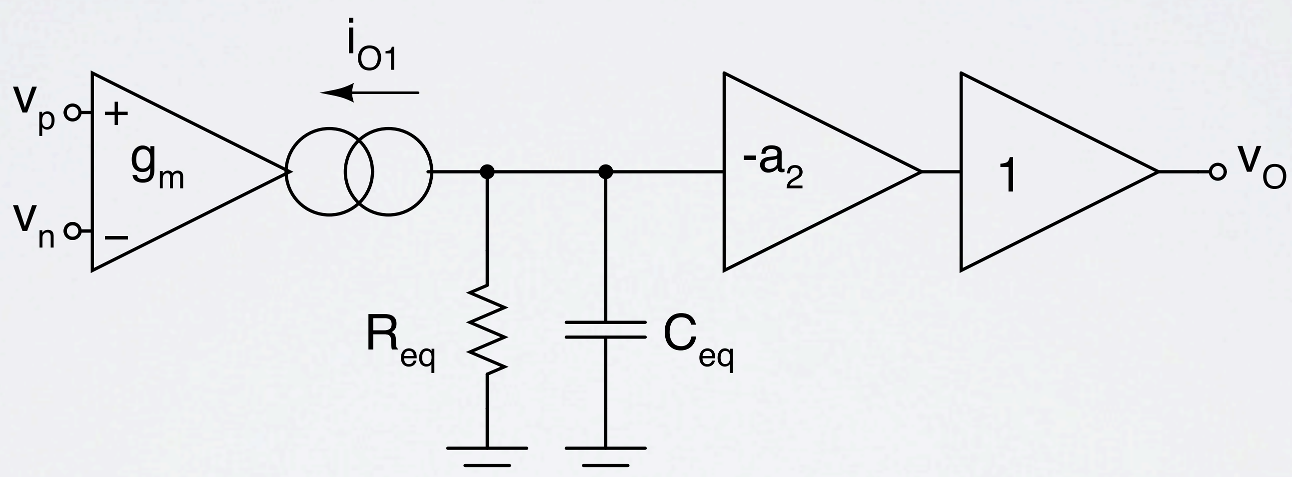
BANDWIDTH

INEL 5207 - Spring 2013

Frequency Limits

- Many opamps are internally compensated to have a single dominant pole at a relatively low frequency.



Noninverting Amplifier

- Open-loop gain can be wrien as:

$$a(s) = a_0 \frac{1}{1 + s/\omega_p}$$

a_0 = d.c. open-loop gain; $f_p = \frac{1}{2\pi R_{eq} C_{eq}}$ = pole freq.

- For the non-inverting amplifier

$$A = \frac{a}{1 + a\beta}$$

where $\beta = \frac{R_1}{R_1 + R_2}$.

- Using above $a(s)$ and $A_0 = \frac{a_0}{1 + \beta a_0}$,

$$A(s) = \frac{a(s)}{1 + a(s)\beta} = A_0 \frac{\omega_p(1 + \beta a_0)}{s + \omega_p(1 + \beta a_0)}$$

- Corner frequency is increased by $1 + \beta a_0$. Gain is decreased by the same factor.

- Gain-bandwidth product remains constant and equal to unity gain frequency, f_t.

$$GBP = f_t$$

$$\text{Since } A_f \simeq 1/\beta, \boxed{f_B = \beta f_t}$$

- This is only true for β constant and compensated opamp (dominant pole at low freq.)

Gain of n identical noninverting stages

- If $f_{cl} = \omega_p(1+\beta a_0)/2\pi$, then gain magnitude of one stage is

$$A = A_0 \frac{1}{\sqrt{1+(f/f_{cl})^2}}$$

- Gain of n identical stages is

$$A^n = A_0^n \left(1+(f/f_{cl})^2\right)^{-n/2}$$

- At corner frequency f_{3dB}, $A^n/A_0^n = 1/\sqrt{2}$ (i.e. -3dB). Thus,

$$f_{3dB} = f_{cl}\sqrt{2^{1/n}-1} = \frac{f_t}{A_0}\sqrt{2^{1/n}-1}$$

- To design an amplifier with bandwidth f_{bw} and gain K, we must select n such that $K = A_0^n$ and $f_{bw} \leq \frac{f_t}{A_0}\sqrt{\frac{1}{2^n}-1}$.

Inverting Amplifier

- Bw: $f_t \frac{R_1}{R_1+R_2}$; same than non-inv with gain $1 + R_2/R_1$
- $A = A_{ideal}\frac{1}{1+1/T}$; $A_{ideal} = -\frac{R_2}{R_1}$; $T = a\beta_{non-inv}$
- For the inverting amplifier, the gain-bandwidth product is equal to

$$GBP = f_t \frac{R_2}{R_1 + R_2}$$

so the bandwidth is always lower than that of a non-inverting amplifier with the same gain.

For inverting amp. $\boxed{f_B = \beta f_t}$ using β from non-inverting....

- Equivalently, we can say that $f_{bw} \times (1 + \frac{R_2}{R_1})$ is still constant and equal to f_t, but the the amplifier's gain magnitude of is only $\frac{R_2}{R_1}$.

Input Impedance

- Diff. input impedance r_d is typ. few $M\Omega$, common-mode r_c is in the $G\Omega$ for BJT. FETs are in the 100's $G\Omega$.

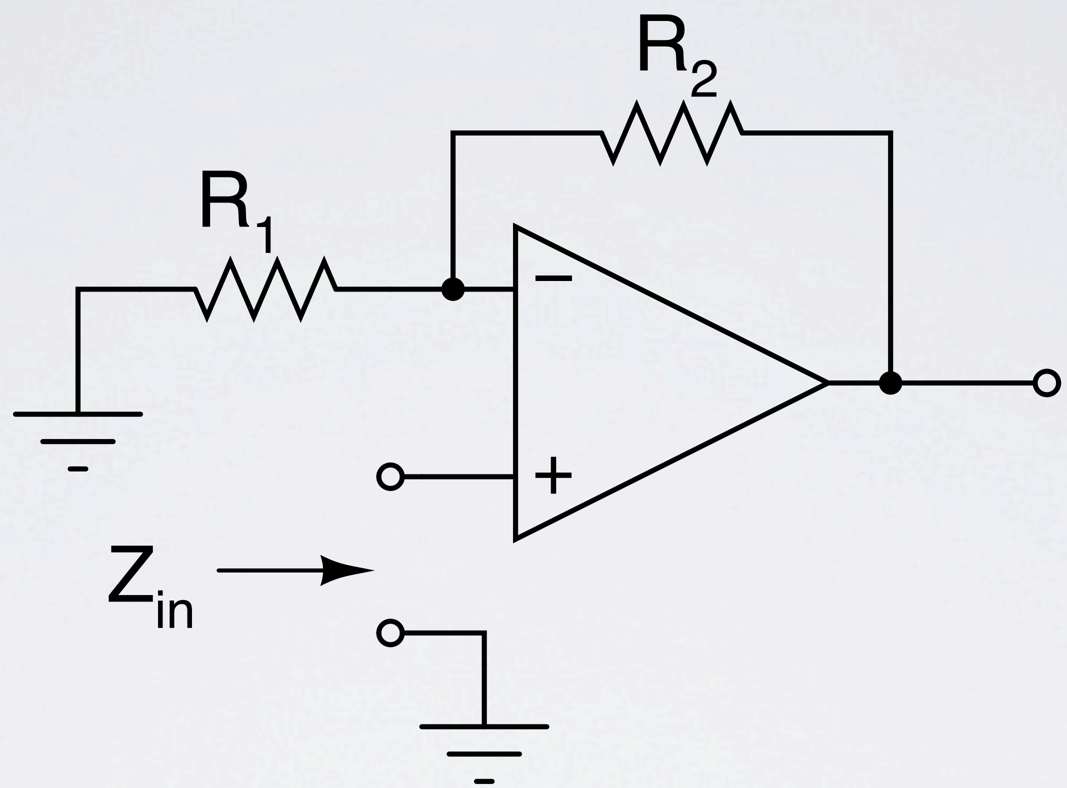
- Input capacitance for uA741 is about 1 pF . Appears in parallel with r_d and/or r_c.

- For $f = 100kHz$, $X_c = 10M\Omega$ so it is comparable to r_d. At higher frecuencies, input impedance drops due to the input capacitance.

$$z_d = \frac{r_d}{1 + sC_d r_d}$$

- There is also a common-mode impedance.

Z_{in} for Input-series Feedback



- $z_{df} = z_d(1 + a\beta)$. Using $a = \frac{a_0}{1+j\frac{f}{fa}}$ yields

$$z_{df} = z_d(1 + a_0\beta)\frac{1 + j\frac{f}{f_a(1+\beta a_0)}}{1 + j\frac{f}{f_a}}$$

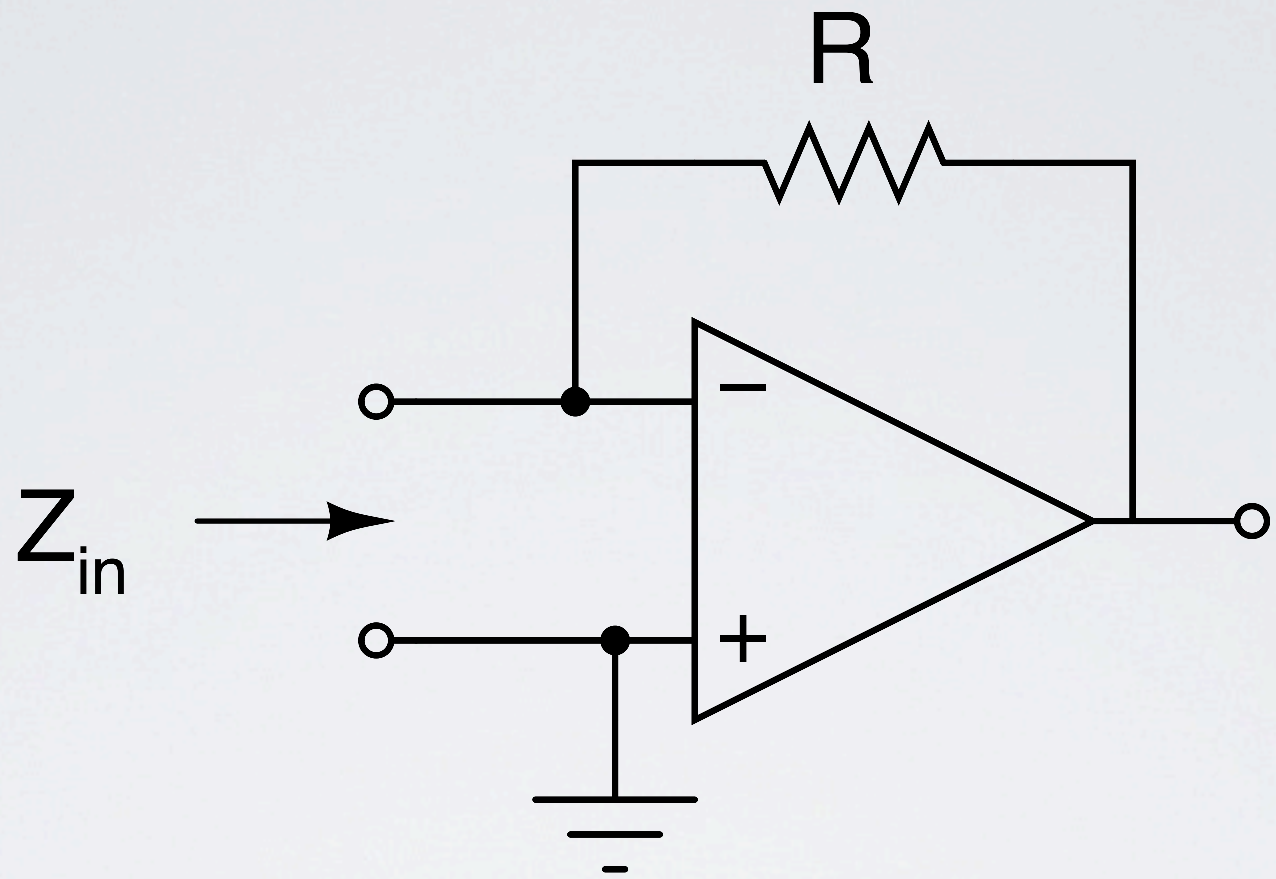
- Observe that f_a is the open-loop pole. Since $a_0 f_a = GBP = f_t$, we can write $f_a = \frac{f_t}{a_0}$. Generally $1 + \beta a_0 \approx \beta a_0$; thus

$$f_a(1 + \beta a_0) \approx \beta a_0 f_a = \beta f_t$$

The above expression becomes

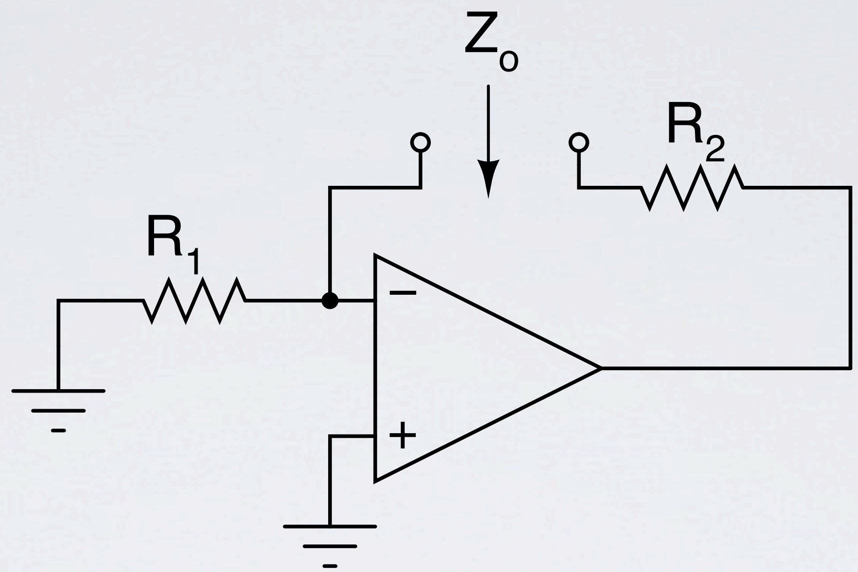
$$z_{df} = z_d(1 + a_0\beta)\frac{1 + j\frac{f}{\beta f_t}}{1 + j\frac{f}{f_a}}$$

Z_{in} for Input-shunt Feedback



$$Z_{if} = R_i \frac{1}{1 + a\beta} = R_i \frac{1 + j\frac{f}{f_a}}{1 + j\frac{f}{f_t}}$$

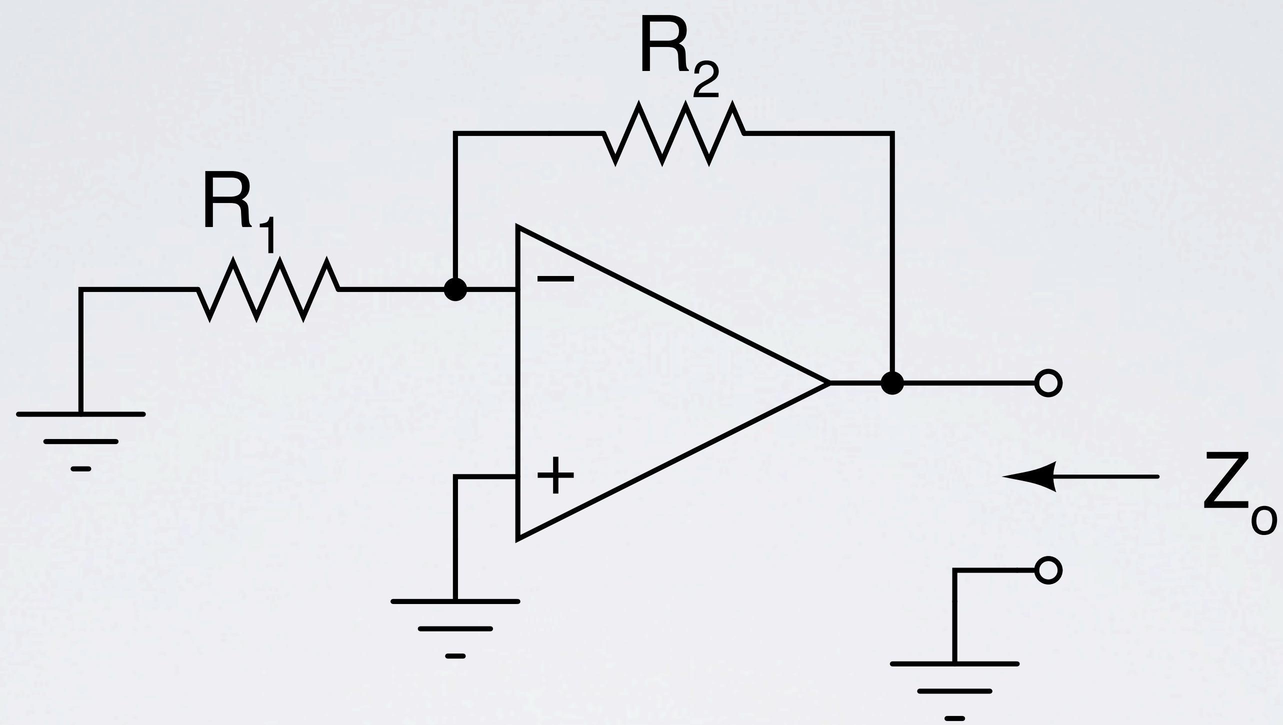
Z_o for Output-series feedback



- $Z_{of} = R(1 + a\beta)$. Using $\beta = 1$and our previous result

$$R_{of} = R(1 + a_0\beta)\frac{1 + j\frac{f}{f_t}}{1 + j\frac{f}{f_a}}$$

Z_o for Output-shunt feedback



$$Z_o = \frac{r_o}{1+\beta a} = r_o(1+a_0\beta)\frac{1+j\frac{f}{\beta f_t}}{1+j\frac{f}{f_a}}$$

Transient Response

- A follower have a gain given by $A = \frac{1}{1+j\frac{f}{f_t}}$.

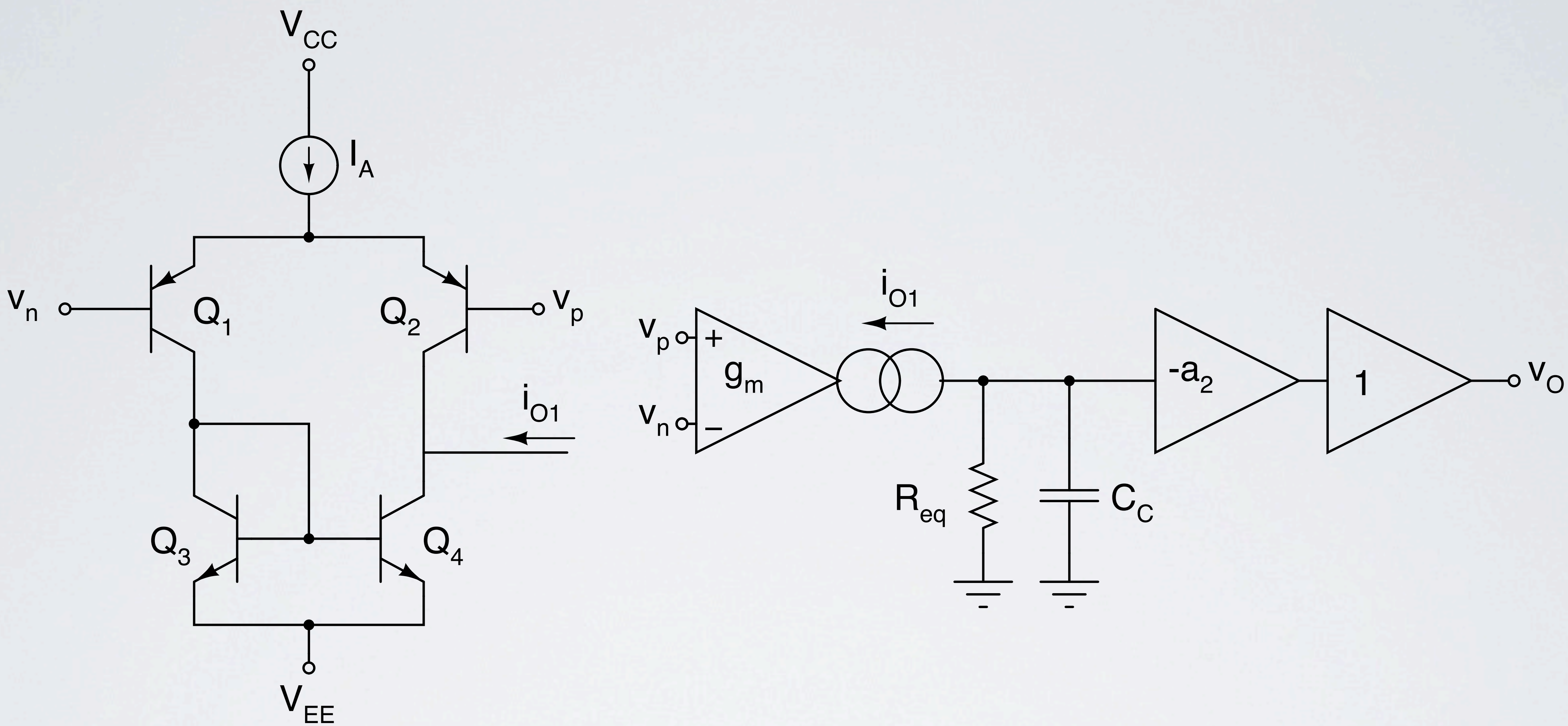
- Step response is $v_o = V_m(1 - e^{-t/\tau})$, where $\tau = \frac{1}{2\pi f_t}$.

- Rise time t_r is time from 10% to 90% of V_m.

$$t_r = \frac{0.35}{f_t}$$

- Ringing due to higher frecuency poles.

Slew Rate



- i_{O1} is limited to $\pm I_A$. Output can not change faster than

$$SR = \frac{I_A}{C_C}$$

- Fastest part of step response occurs at $t = 0$, and is

$$\frac{dv_O}{dt}\Big|_{t=0} = \frac{V_{om}}{\tau} = 2\pi f_t V_{om}$$

- If $V_{om} > \frac{SR}{2\pi f_t}$ then the output is slew-rate limited and changes linearly, not exponentially. Also $v_n \neq v_p$.

- If gain is larger than 1, replace f_t with βf_t on the above expressions.

- Analysis shows that $f_t \approx \frac{g_{m1}}{2\pi C_C}$ so $C_C = \frac{g_{m1}}{2\pi f_t}$ and

$$SR = \frac{I_A}{C_C} = \frac{2\pi f_t I_A}{g_{m1}}$$

- SR can be increased by increasing I_A

- SR can be increased by decreasing g_{m1}using a FET input stage or adding resistors to the differential stage's emier (emier degeneration).

- Using opamps with higher f_t.

- Full-power bandwidth (FPB): maximum frequency at which the opamp will yield an undistorted sinusoidal output with the largest possible amplitude. Assuming saturation at $\pm V_{sat}$,

$$FPB = \frac{SR}{2\pi V_{sat}}$$

- Seling time: time it takes for the response to a large input step to remain within a specific error band. Example: AD843 will has $t_s = 135ns$ to 0.01% of a 10V step.