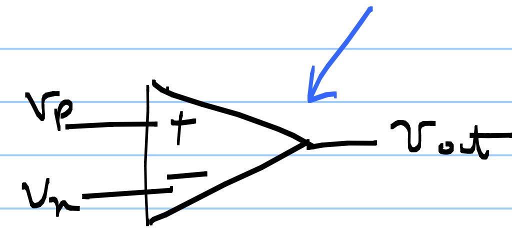
ECE 5411 – Lecture 21.

Note Title 4/18/2011

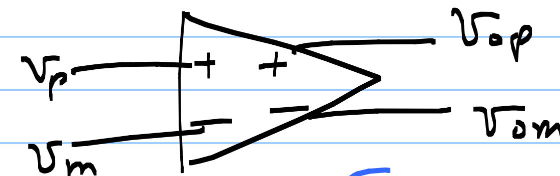
Operational Amplifiers (Opamps)



* opamp → High-gain Diff amplifier

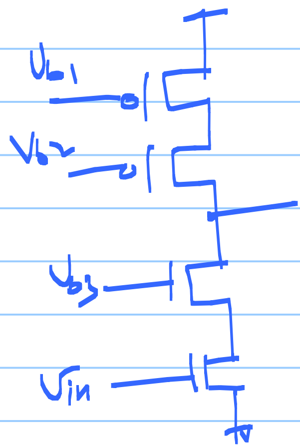
↓

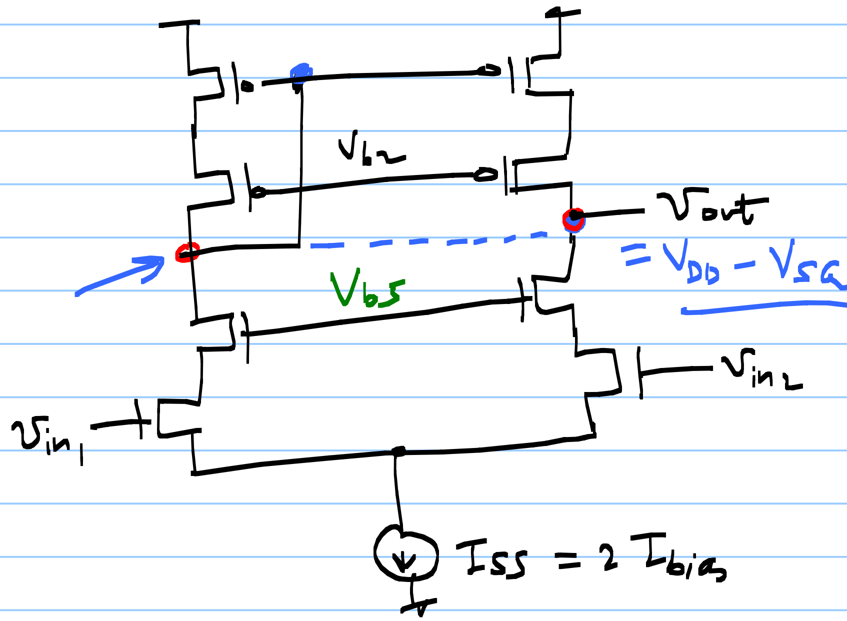
$10^1 \rightarrow 10^5$



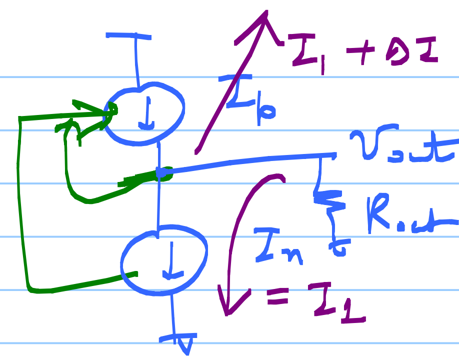
FD

* LM741
* IC – opamps





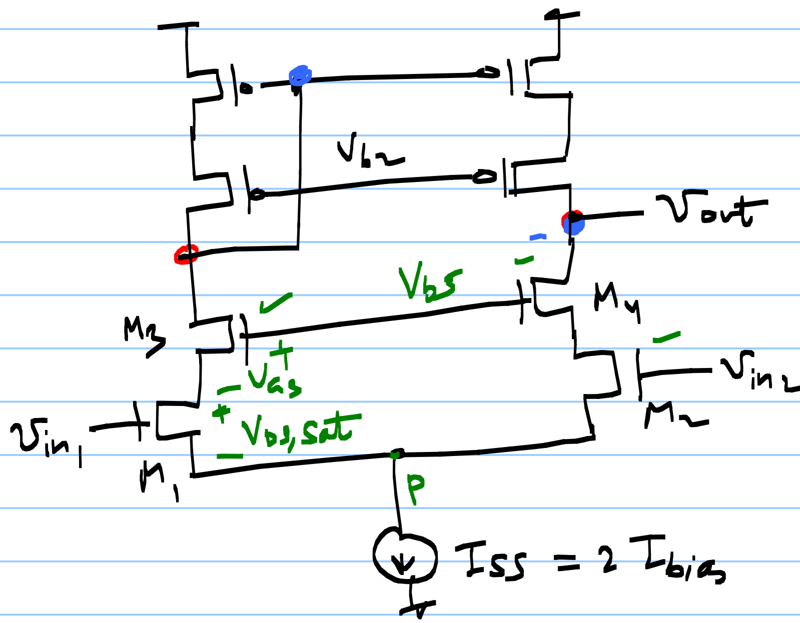
CM picture



$$V_{CM_o} = \frac{V_{out_1} + V_{out_2}}{2}$$

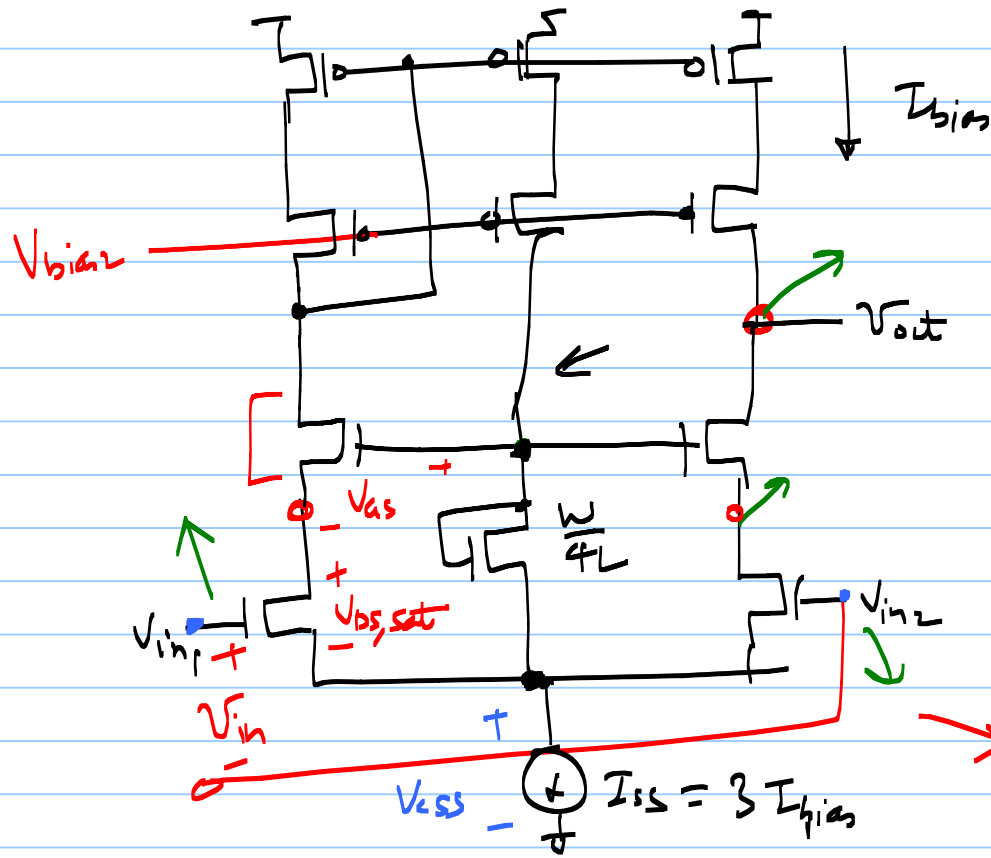
$\updownarrow$

$$V_{cm} = \frac{V_{DD}}{2}$$

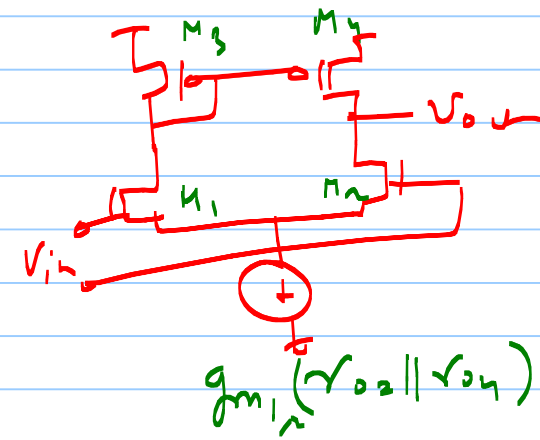


$$V_{b3} \geq V_P + V_{GS} + V_{DS,sat}$$

Telescopic



Cascode Diffamp "Telescopic"



$\rightarrow + g_{m1,2} (R_{ocasp} \| R_{ocasn})$

* $V_{cm,in} \geq V_{GS_{1,2}} + \underbrace{V_{CSS}}_{2V_{DS,sat}}$

* $V_{cm,max} = ?$

$$V_{D_{1,2}} \leq V_{DD} - V_{SG} - V_{DS,sat}$$

$+ V_{THN}$ $\qquad$ $+ V_{THN}$

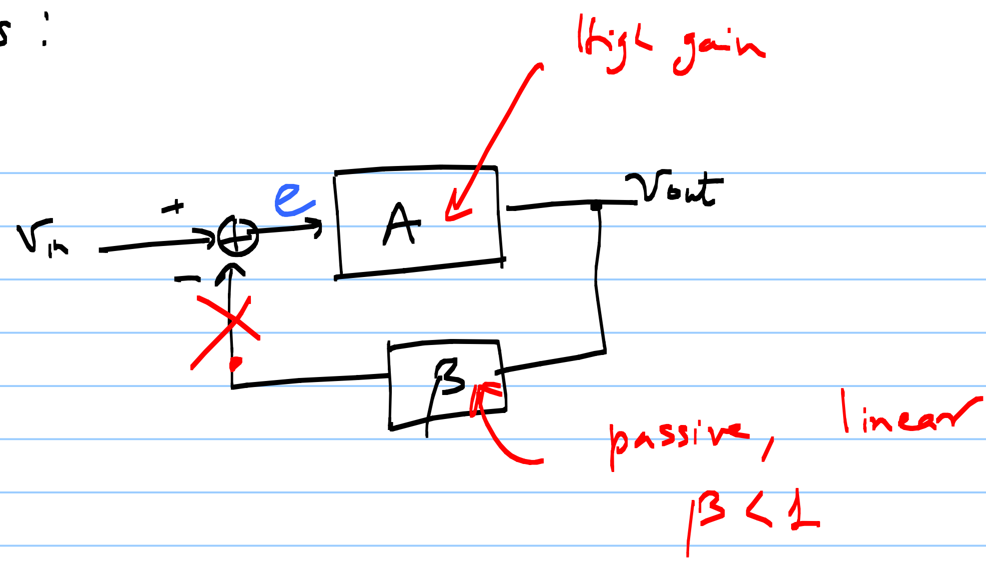
$$V_{cm,in} \leq V_{DD} - V_{SG} - V_{DS,sat} + V_{THN}$$

$$V_{cm,in} \in \left[V_{GS_{1,2}} + V_{CSS} , \; V_{DD} - V_{SG} - V_{SD,sat} + V_{THN} \right].$$

$$V_{in,cm} - V_{THN} + V_{DS,sat} \leq V_{out} \ll V_{DD} - 2V_{SD,sat}$$

Performance Parameters :

① Gain :



$$\frac{V_{out}}{V_{in}} = \frac{A}{1+A\beta}$$

$e(t) \longrightarrow 0$

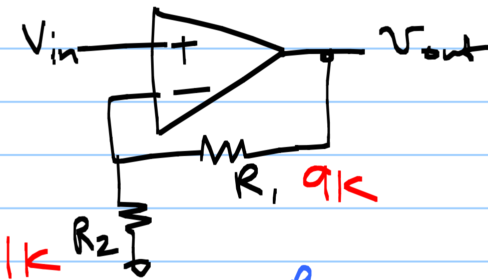
$A\beta >> 1$

$A\beta \rightarrow$ open "loop gain"

$\frac{A}{1+A\beta} \rightarrow$ closed loop gain

$$\frac{v_{out}}{v_{in}} = \frac{A}{1+A\beta} \simeq \frac{A}{A\beta} \simeq 1/\beta$$

$A_{CL} = 10$



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

$$= \frac{1}{\beta}\left[1 - \frac{1}{A\beta}\right]$$

← relative error

$$\beta = \frac{R_2}{R_1 + R_2} < 1$$

$$\frac{1}{1+x} \simeq 1 - x + x^2 - x^3 + \cdots$$

$$= 1 - x$$

$|x| << 1$

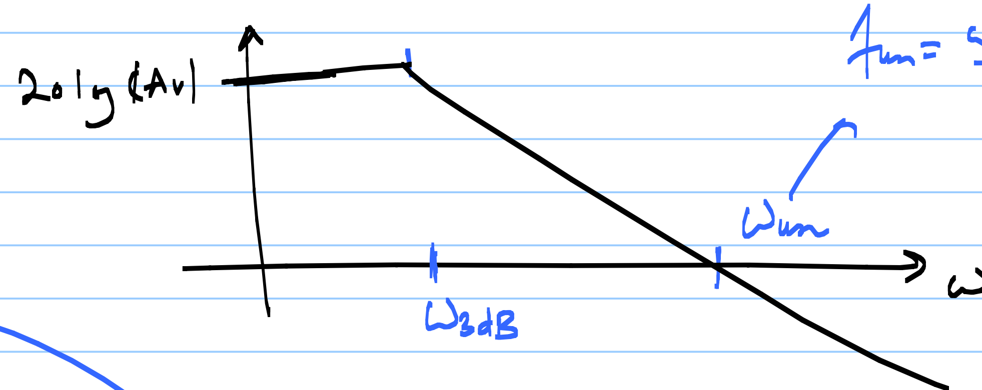
$$A_{CL} = \frac{1}{\beta} = 10$$

< 1% relative error in gain

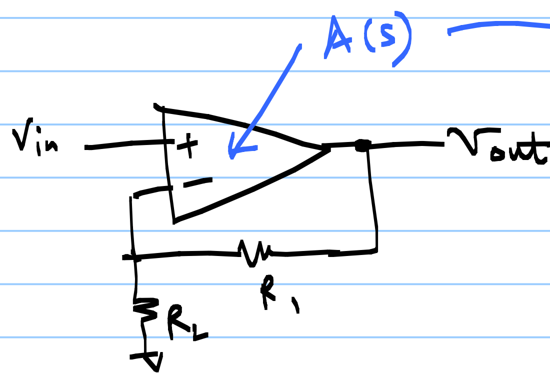
$$\frac{1}{A\beta} < \frac{1}{100}$$

$$\frac{1}{A} < \frac{1}{1000} \Rightarrow A > 1000 \rightarrow 60\ dB$$

② Small-Signal Bandwidth:



$$f_{un} = \frac{\omega_{un}}{2\pi}$$



$$A(s) = \frac{A_0}{(1 + s/\omega_0)}$$

$$\frac{V_{out}}{V_{in}}(s) = \frac{A(s)}{1 + A(s)\beta}$$

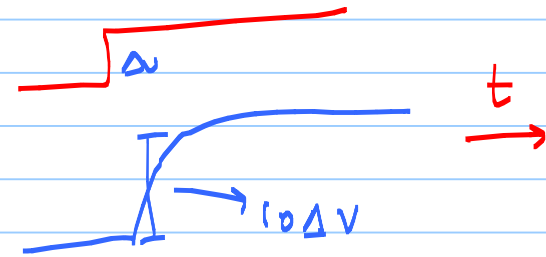
$$= \frac{\frac{A_0}{(1+s/\omega_0)}}{1 + \beta\frac{A_0}{(1+s/\omega_0)}} = \frac{A_0}{1 + s/\omega_0 + \beta A_0}$$

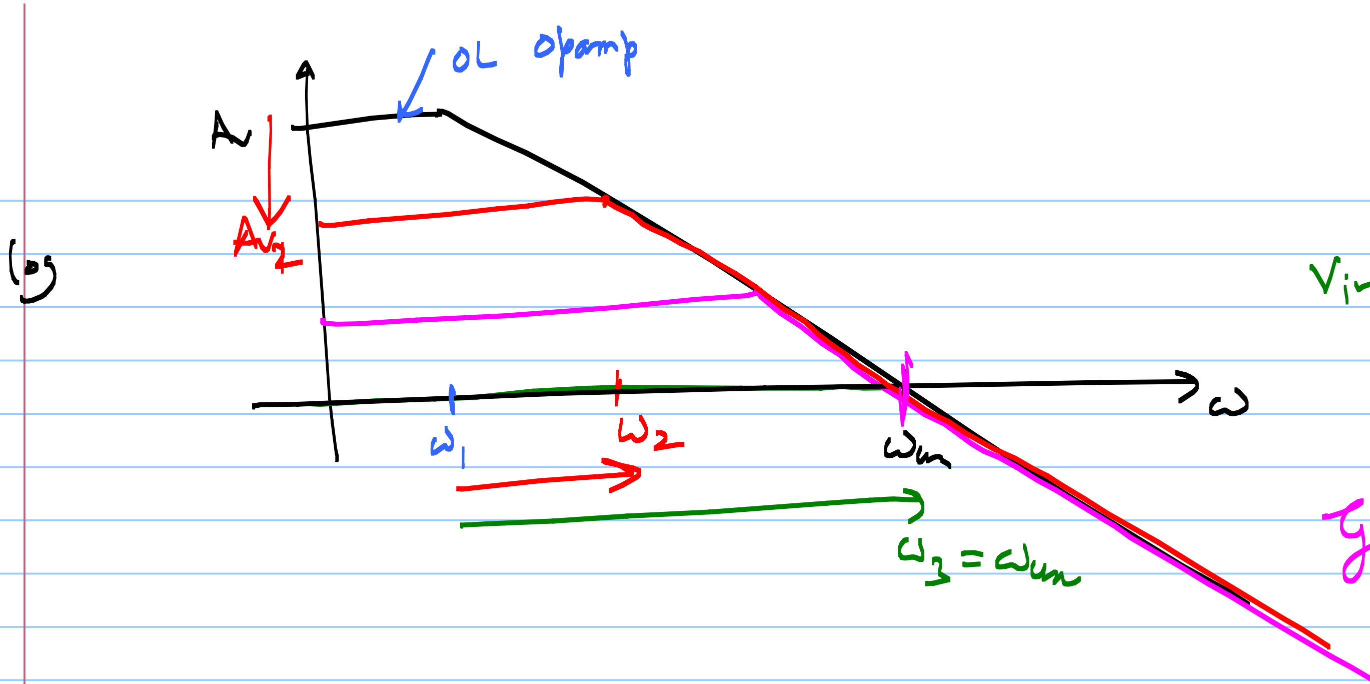
$$= \frac{A_0}{(\beta A_0 + 1) + s/\omega_0} = \frac{\frac{A_0}{1+\beta A_0}}{1 + \frac{s}{\omega_0(1+\beta A_0)}} = \frac{A_{CL}}{1 + s/\omega_{3dB}}$$

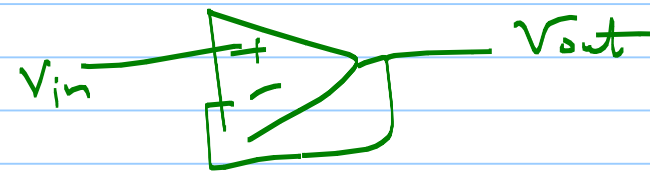
$$A_{CL} \rightarrow \frac{A_0}{1+\beta A_0}$$

$$\omega_{3dB} \rightarrow \omega_0(1+\beta A_0)$$

$$\frac{1}{\beta} = 10$$







Gain − BW trade off

* Assuming Dominant pole response

$$\frac{V_{out}}{V_{in}} = \frac{A_{CL}}{1 + s\tau} = \frac{A_{CL}}{1 + s/\omega_{3dB}}$$

$$\tau = \frac{1}{\omega_o(1 + A_o\beta)}$$

$$\omega_{3dB} = \omega_o(1 + A_o\beta)$$

$$\simeq \omega_o A_o \beta$$

$$= \omega_{un} \cdot \beta$$

$$= \omega_{un} \cdot \frac{1}{A_{CL}}$$

$$\Rightarrow \boxed{\omega_{3dB} \times A_{CL} = \omega_{un}}$$

GB Trade off

V_{in}

$= a\,u(t) \overset{\mathcal{L}}{\longleftrightarrow} \frac{a}{s}$

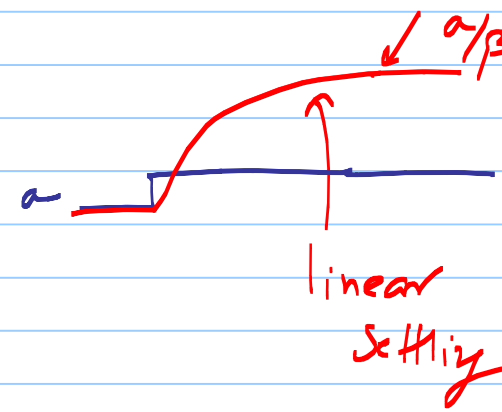
$A_{CL}(s) = \frac{A_{CL}}{(1 + s\tau)}$ → $\tau = \frac{1}{\omega_o(1+A_o\beta)}$

$V_{out}(s) = A_{CL}(s) \cdot \frac{a}{s}$

$= \frac{a\,A_{CL}}{s(1+s\tau)}$

$V_{out}(t) = \mathcal{L}^{-1}(\checkmark) = a \cdot \frac{1}{\beta}\,(1 - e^{-t/\tau})\,u(t)$

↑ final value



for 1% settling

$t_{1\%} = 4.6\,\tau = 5\,ns$ with $\frac{1}{\beta} = 10$

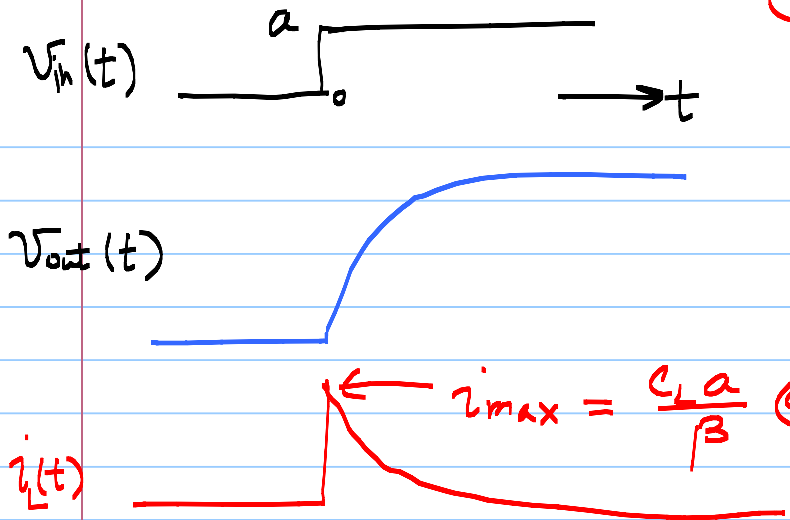
↳ $1/\omega_{3dB} = 1.09\,ns$

$$\omega_{um} = \omega_{3dB} \times A_{cL}$$

$$= 10 \times \frac{1}{1.09\,ns}$$

$$= 9.2 \times 10^{9}\ rad/s \xrightarrow{1/2\pi} f_{um} = 1.47\ GHz$$

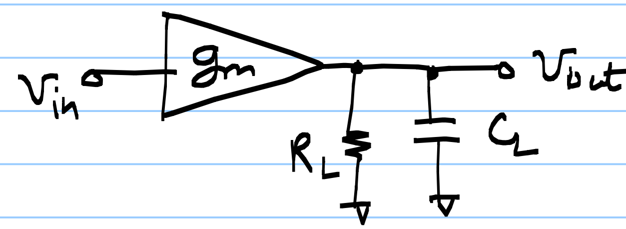
③ Large Signal Bandwidth



$a\,u(t)$

$\frac{a}{\beta}\left(1-e^{-t/\tau}\right)u(t)$

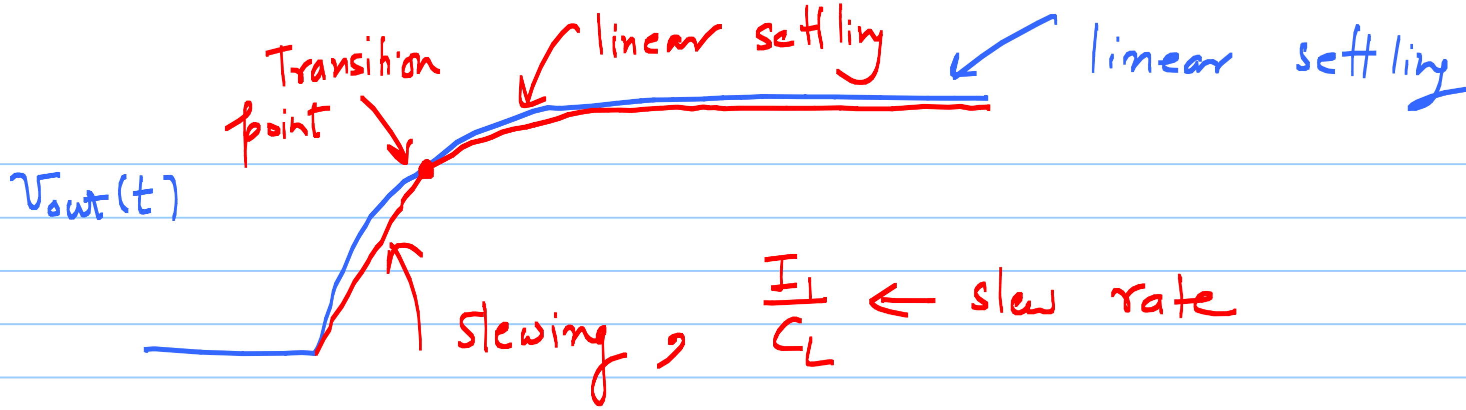
$i_{max} = \frac{C_L a}{\beta}$ @ $t=0$



If the max current needed to drive the load $i_{max} > I_1$, the max current sourced/sunk by the amplifier ⇒ slewing occurs.

$$i_L(t) = C_L \frac{d v_{out}}{dt}$$

$$= C_L \frac{a}{\beta} e^{-t/\tau} \cdot u(t)$$



Slewing, $\frac{I_L}{C_L}$ ← slew rate

* Slewing is a non-linear behavior
↳ leads to distortion in output signal.

↳ mandates experience and careful simulations.

④ Output Swing –

trades-off with device size, overdrive, bias currents & speed.

↳ fully-differential circuits

⑤ Linearity:

① use fully-diff implementation to suppress even-order harmonics

② Allow efficient open-loop gain so that the closed-loop system achieves reasonable linearity.

⑥ Noise & offset:

The input noise and offset of opamps determine the minimum signal level, which can be with reasonable quality.

↳ noise analysis

⑦ Power Supply rejection:

Supply noise leaks into the signal path

↳ use fully-differential opamps.