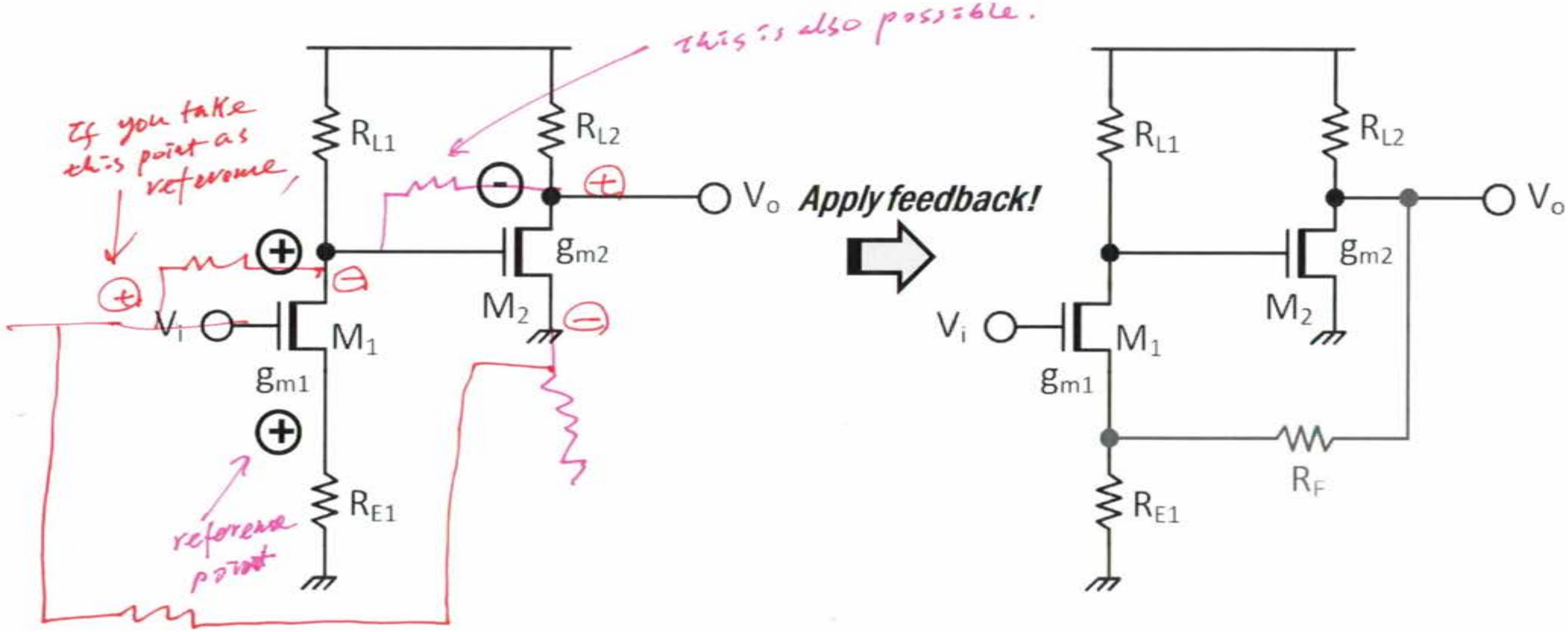
Feedback Design (1)

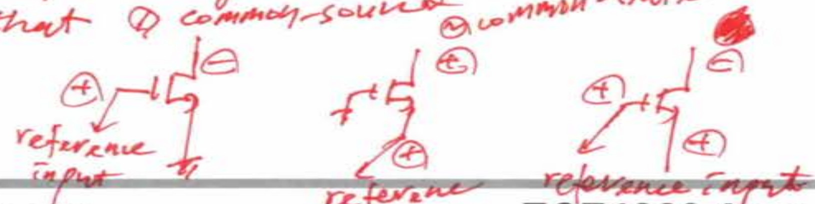
①

- ❑ First, it is important to identify signal phase relationship between nodes.
- ❑ Then, apply negative feedback (not positive feedback).



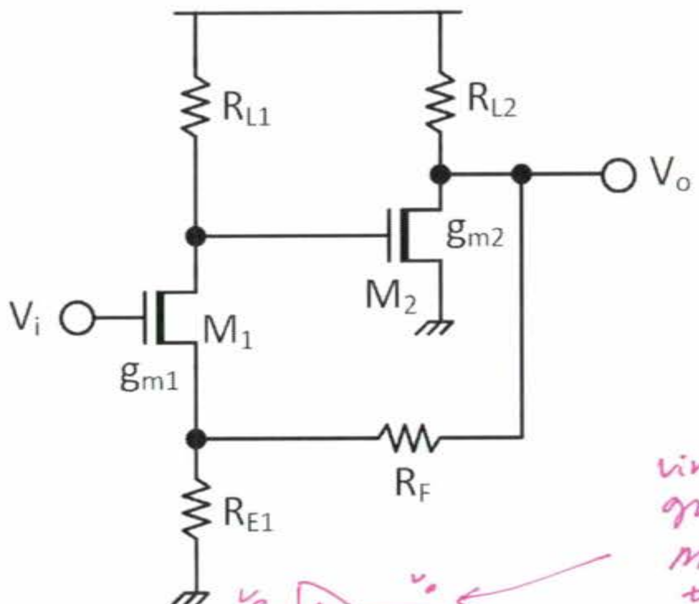
- ❑ In most cases, you have to make loop-gain (therefore, open-loop gain) very large (loop-gain >>1).
- ❑ This allows us to apply virtual-grounding concept for most cases of feedback designs.

(*) Keep reminding that ① common-source ② common-gate

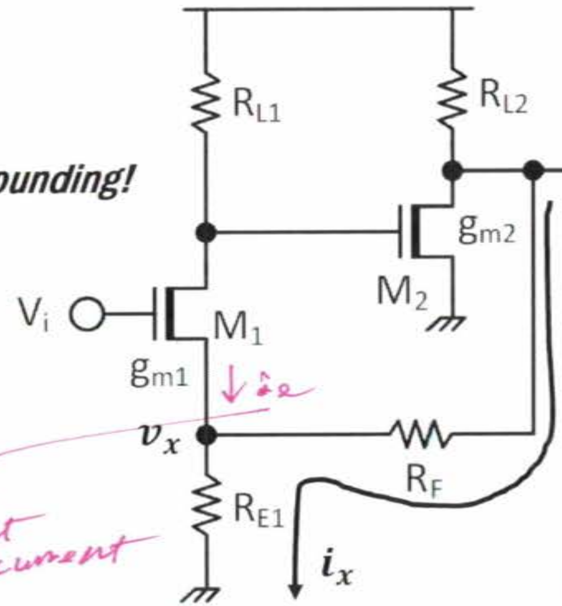


Feedback Design (2)

- Using virtual-grounding, identify main signal current path.
- Calculate overall closed-loop gain factor.

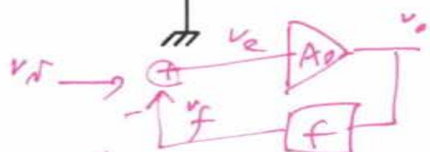


Virtual-grounding!



$$v_x = v_i$$
$$i_x = \frac{v_i}{R_{E1}}$$
$$v_o = v_i + i_x R_F$$
$$A_v = \frac{v_o}{v_i} = 1 + \frac{R_F}{R_{E1}}$$

virtual grounding means that the error current $i_e = 0$.



virtual grounding means $v_e = 0$.
$\Rightarrow v_i = v_f = f \cdot v_o$
$\Rightarrow A_v = \frac{v_o}{v_i} = \frac{1}{f}$

- Set the values of feedback elements (mostly, resistors) appropriately to meet a target closed-loop gain.

  ex) In this case, for 20-dB gain ⇒ $R_F/R_{E1}=9$

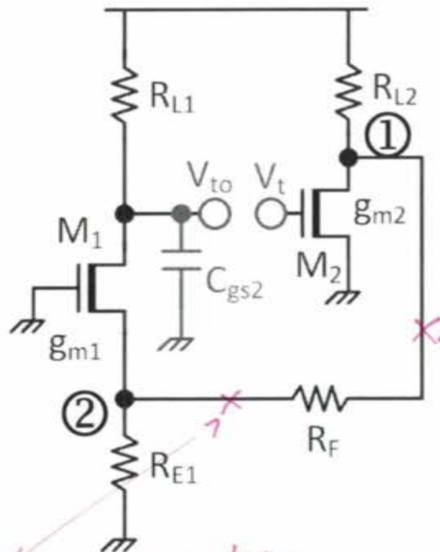
more exact expression → $A_v = \frac{1}{f}\frac{A_o f}{1+A_o f} = \frac{1}{f}\frac{T}{1+T}$, $T = A_o f$ = loop-gain

→ As long as $T \gg 1$, virtual grounding is a ~~valid~~ valid concept.

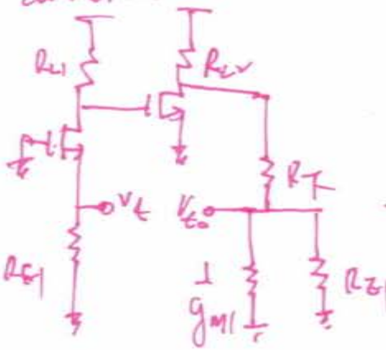
Feedback Design (3)

3

- To calculate loop-gain (=T), break the loop but include all loading effects. (*)



you can break the loop here.

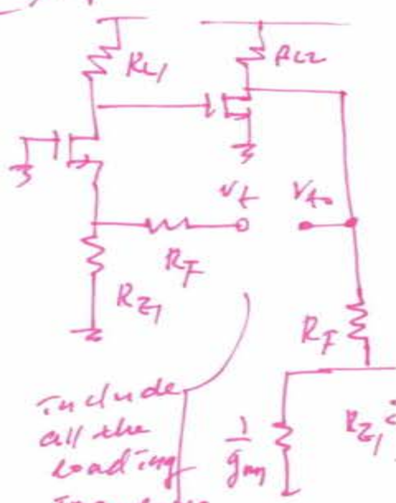


include all the loading impedances.

$$Loop\ Gain\ (=T) = \frac{v_{to}}{v_t} = \frac{v_1}{v_t} \times \frac{v_2}{v_1} \times \frac{v_{to}}{v_2}$$

$$\frac{v_1}{v_t} = g_{m2}\left\{R_{L2} \parallel \left(R_F + R_{E1} \parallel \frac{1}{g_{m1}}\right)\right\}$$
$$\approx g_{m2}\left\{R_{L2} \parallel \left(R_F + \frac{1}{g_{m1}}\right)\right\}$$
$$\approx g_{m2}(R_{L2} \parallel R_F)$$
$$\approx g_{m2}R_F$$

you can also break the loop at this point.



include all the loading impedance

$$\frac{v_2}{v_1} = \frac{R_{E1} \parallel \frac{1}{g_{m1}}}{R_F + R_{E1} \parallel \frac{1}{g_{m1}}} \approx \frac{\frac{1}{g_{m1}}}{R_F} = \frac{1}{g_{m1}R_F}$$

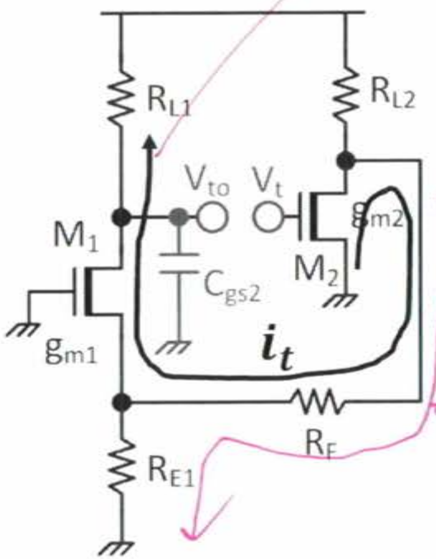
$$\frac{v_{to}}{v_2} = g_{m1}R_{L1}$$

$$\therefore T \approx g_{m2}R_F \times \frac{1}{g_{m1}R_F} \times g_{m1}R_{L1} = g_{m2}R_{L1}$$

(*) There could be many ways of breaking the loop. But for all cases, the loop gain will be same.

Feedback Design (3)

current path for loop gain calculation



current path for closed-loop gain calculation.

- **More intuitive approach to calculate loop-gain**

1) First, identify current path in the feedback loop.

$$\Rightarrow i_t = g_{m2} v_t$$

2) If feedback designed properly to maximize loop-gain, then all the loop current, i_t, will be delivered to the load of M_1 and develop output voltage $v_{to} = i_t R_{L1} = g_{m2} R_{L1} v_t$.

$$\therefore \textit{Loop Gain } (T) \approx g_{m2} R_{L1}$$

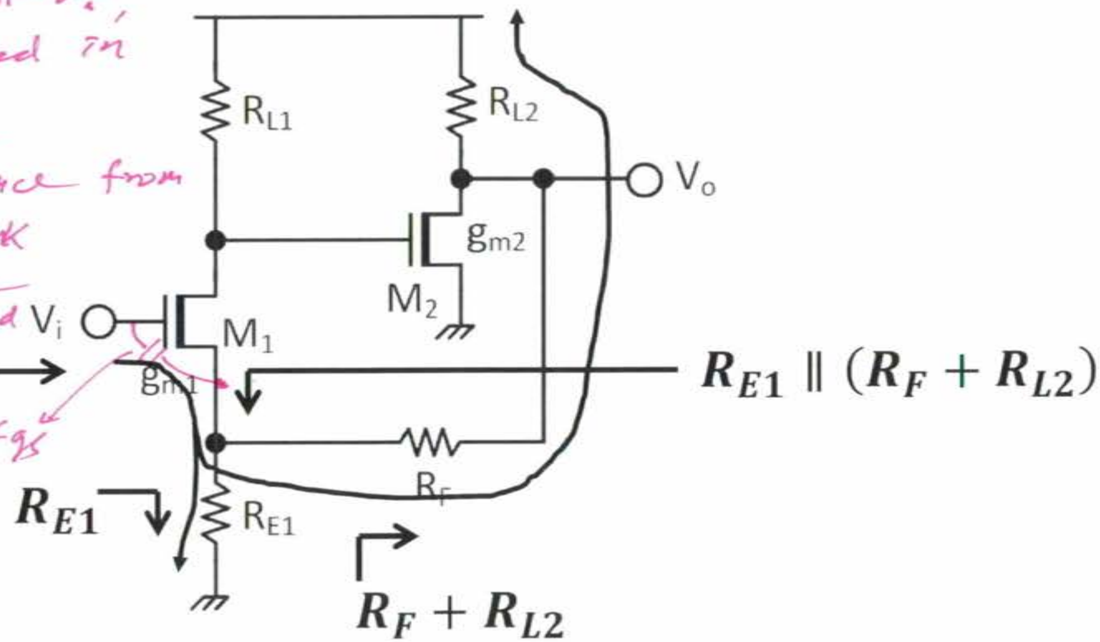
* A good way of building intuition on circuit designs is to catch current paths.

* Once you can identify main current paths, you can greatly simplify any calculation involved.

Feedback Design (4)

- Input impedance calculation: $Z_{inf} = Z_{in}(1+T)$, T = loop gain

NOTE: In view of input V_i, feedback is applied in series with $\frac{1}{sC_{gs}}$.
⇒ series impedance from ~~…~~ feedback
⇒ input impedance will be increased by (1+ loop gain). C_{gs}



$$Z_{in} = \frac{1}{sC_{gs1}} + (1+\beta)\{R_{E1} \parallel (R_F + R_{L2})\}, \beta = \frac{g_{m1}}{sC_{gs1}}$$

$$\approx \frac{1}{sC_{gs1}} + \beta R_{E1} = \frac{1+g_{m1}R_{E1}}{sC_{gs1}}$$

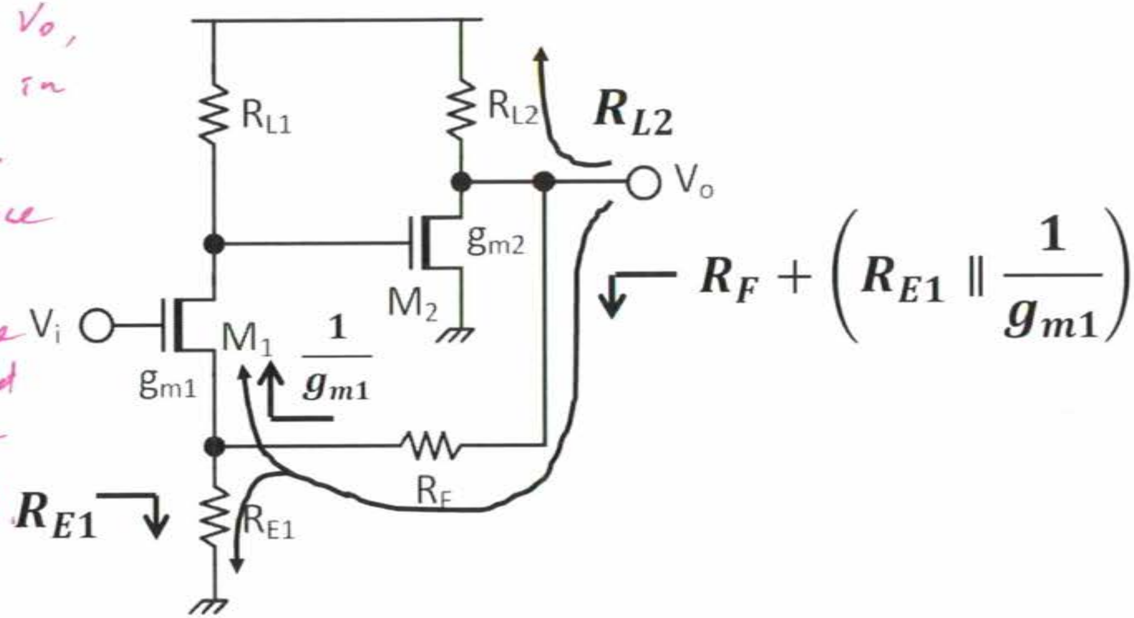
$$\therefore Z_{inf} = Z_{in}(1+T) = \frac{(1+g_{m1}R_{E1})(1+g_{m2}R_{L1})}{sC_{gs1}}$$

Note: input capacitance will be decreased further due to feedback.

Feedback Design (5)

- Output impedance calculation: $Z_{outf} = \frac{Z_{out}}{1+T}$, T = loop gain

NOTE: In view of output V_o, feedback is applied in parallel with R_{L2}.
⇒ parallel impedance from feedback
⇒ output impedance will be decreased by a factor of (1 + loop gain)



$$Z_{out} = R_{L2} \parallel \left\{R_F + \left(R_{E1} \parallel \frac{1}{g_{m1}}\right)\right\}, \quad R_{L2} \gg \left(R_F + \left(R_{E1} \parallel \frac{1}{g_{m1}}\right)\right)$$

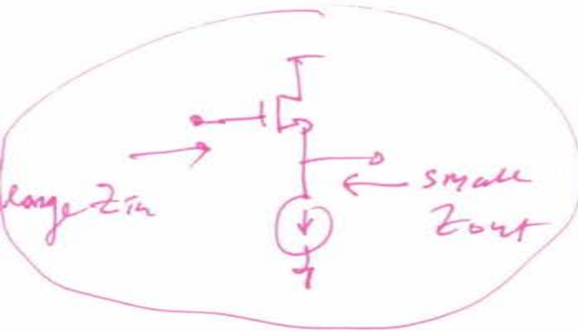
$$\approx R_F + \left(R_{E1} \parallel \frac{1}{g_{m1}}\right) \approx R_F + \frac{1}{g_{m1}} \approx R_F$$

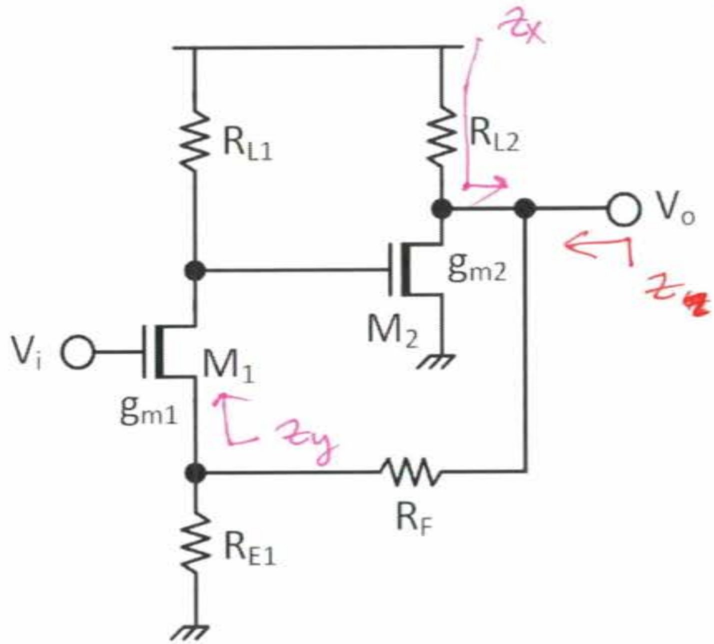
$$\therefore Z_{outf} = \frac{Z_{out}}{1+T} = \frac{R_F}{1+g_{m2}R_{L1}}$$

Feedback Design (5)

②

- Topology evolution for more ideal feedback (better loop-gain)





※ ideal feedback
⇒ loop gain = ∞

To make larger loopgain
⇒ ① Zx ~~...~~
need to be larger,

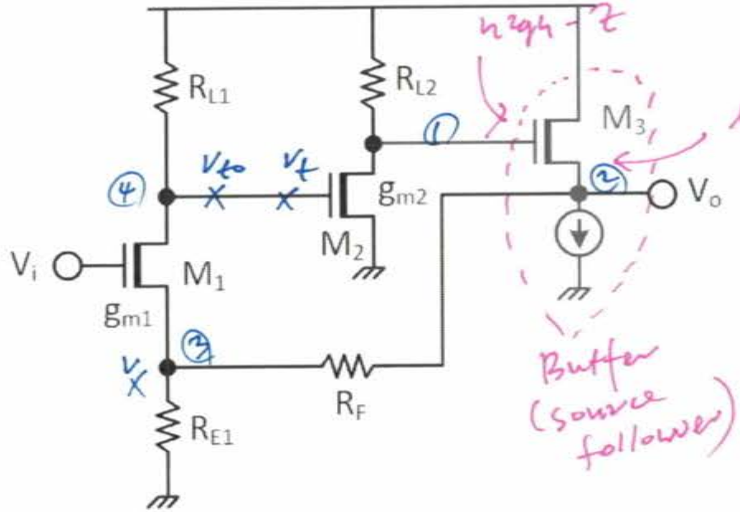
② Zy
need to be large

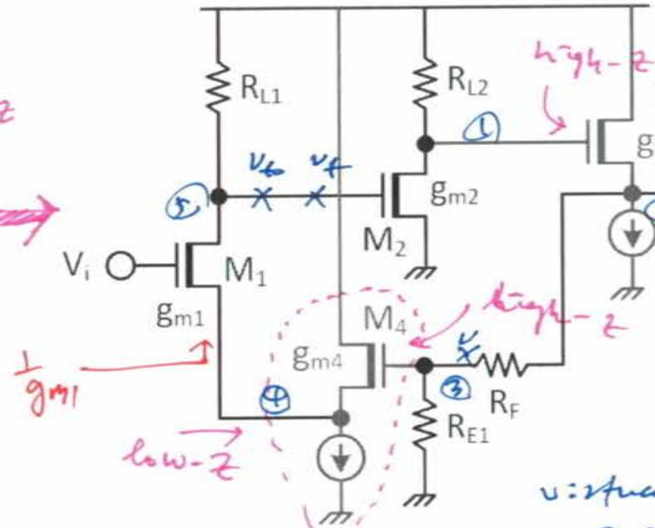
To make more idealistic voltage-mode driving to next stage,
⇒ Zz is the better, smaller

How to make these changes?
⇒ use "Buffering"

Feedback Design (6)

- Topology evolution for more ideal feedback (better loop-gain)





$$\frac{v_④}{v_③} = \frac{g_{m4}\cdot\frac{1}{g_{m1}}}{1+g_{m4}\cdot\frac{1}{g_{m1}}} = \frac{1}{2} \text{ if } g_{m4}=g_{m1}$$

virtual grounding → $v_X = v_i$

$$A_v = 1 + \frac{R_F}{R_{E1}}$$

$$\text{loop gain } (T) = \frac{v_{to}}{v_t} = \frac{v_①}{v_t}\cdot\frac{v_②}{v_①}\cdot\frac{v_③}{v_②}\cdot\frac{v_④}{v_③}$$

$$= (g_{m2}R_{L2})(1)\left(\frac{\frac{1}{g_{m1}} \,//\, R_{E1}}{R_F + \frac{1}{g_{m1}}//R_{E1}}\right)(g_{m1}R_{L1})$$

$$\simeq g_{m2}R_{L2}\,\frac{\frac{1}{g_{m1}}}{R_F}\,g_{m1}R_{L1}$$

$$= g_{m2}R_{L2}\cdot\left(\frac{R_{L1}}{R_F}\right)$$

see page-③ without M_3-buffering $T = g_{m2}R_{L1}$

virtual grounding → $v_X = v_i$ → $A_v = 1 + \frac{R_F}{R_{E1}}$

$$T = \frac{v_①}{v_t}\cdot\frac{v_②}{v_①}\cdot\frac{v_③}{v_②}\cdot\frac{v_④}{v_③}\cdot\frac{v_⑤}{v_④}$$

$$= (g_{m2}R_{L2})(1)\left(\frac{R_{E1}}{R_F+R_{E1}}\right)\left(\frac{1}{2}\right)(g_{m1}R_{L1})$$

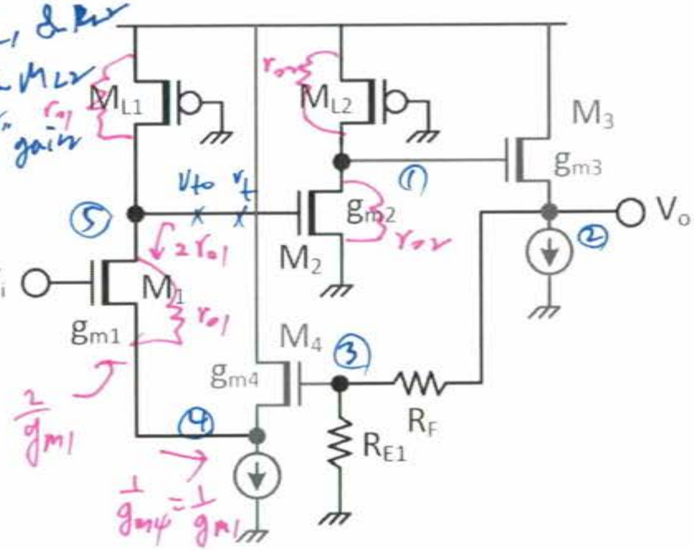
$$= g_{m2}R_{L2}\left(\frac{1}{2}g_{m1}R_{L1}\,\frac{R_{E1}}{R_F+R_{E1}}\right)$$

$$\simeq g_{m2}R_{L2}\left(\frac{R_{L1}}{R_F}\right)\underbrace{\left(\frac{1}{2}g_{m1}R_{E1}\right)}_{\text{extra-gain boosting by } M_4}$$

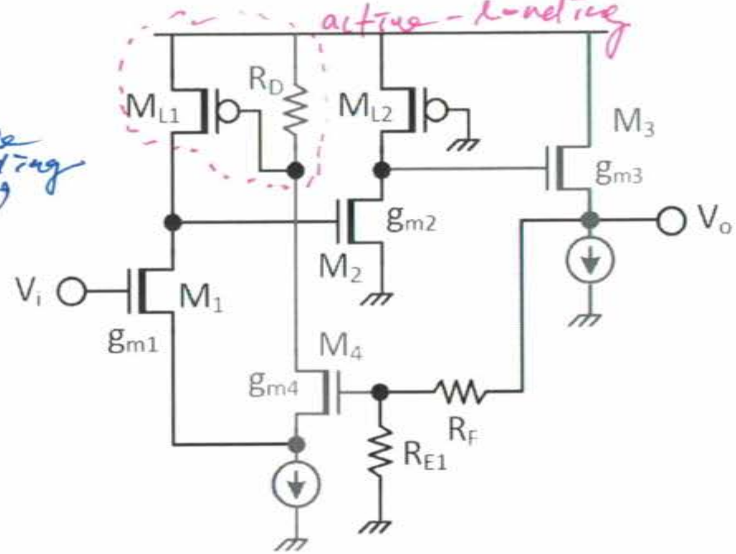
Feedback Design (7)

- **Topology evolution for more ideal feedback (better loop-gain)**

① Replace R_{L1} & R_{L2} with M_{L1} & M_{L2} respectively to increase gain



active-loading →



assume that $r_{oL1} = r_{o1}$, $r_{oL2} = r_{o2}$, $g_{m1} = g_{m4}$

$$T = \frac{v_1}{v_t}\,\frac{v_2}{v_1}\,\frac{v_3}{v_2}\,\frac{v_4}{v_3}\,\frac{v_5}{v_4}$$

$$= \left(\frac{1}{2} g_{m2} r_{o2}\right)(1)\left(\frac{R_{E1}}{R_F + R_{E1}}\right)\left(\frac{g_{m4}\cdot\frac{2}{g_{m1}}}{1 + g_{m4}\frac{2}{g_{m1}}}\right)\left(g_{m1}\cdot 2r_{o1} \,\|\, r_{o1}\right)$$

$$= \left(\frac{1}{2} g_{m2} r_{o2}\right)\left(\frac{R_{E1}}{R_F + R_{E1}}\right)\left(\frac{2}{3}\right)\left(\frac{2}{3} g_{m1} r_{o1}\right)$$

$$T = \left(\frac{1}{2} g_{m2} r_{o2}\right)\left(\frac{R_{E1}}{R_F + R_{E1}}\right)\left(\frac{2}{3}\right)\left(\frac{2}{3} g_{m1} r_{o1}\right)$$
$$\times \underline{\left(1 + g_{mL1} R_D\right)}$$

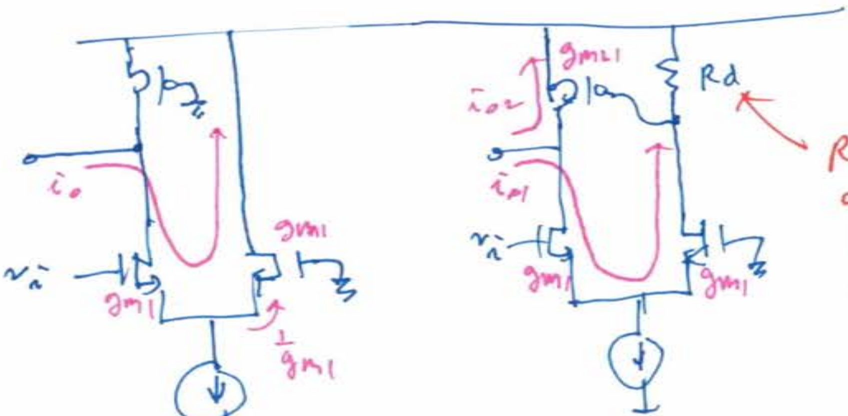
extra gain boosting by the active-loading

Feedback Design (7)

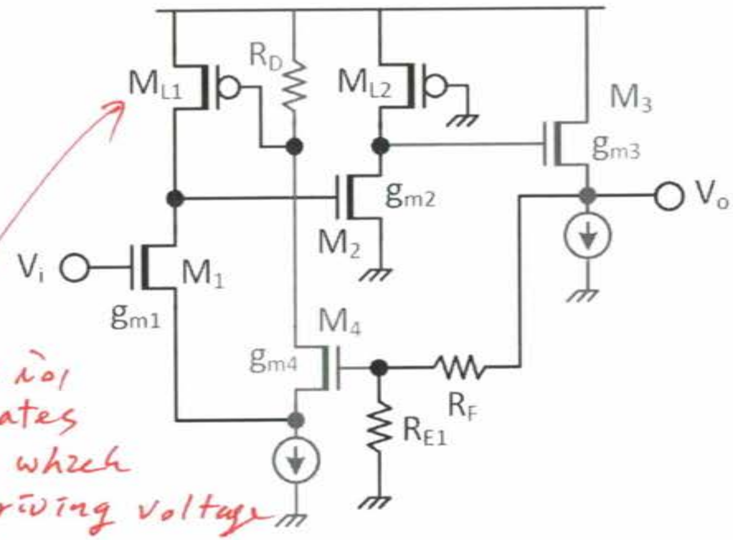
6

- ☐ **Topology evolution for more ideal feedback (better loop-gain)**

Details on extra gain boosting by active-loading



Rd senses i_{o1} and creates $R_d \cdot i_{o1}$ which is a driving voltage for the pMOS.



$i_o = \frac{1}{2} g_{m1} v_i$

$i_o = i_{o1} + i_{o2}$

$i_{o1} = \frac{1}{2} g_{m1} v_i$

$i_{o2} = i_{o1} R_d \cdot g_{mL1}$

$= \frac{1}{2} g_{m1} v_i (1 + g_{mL1} R_d)$

compare

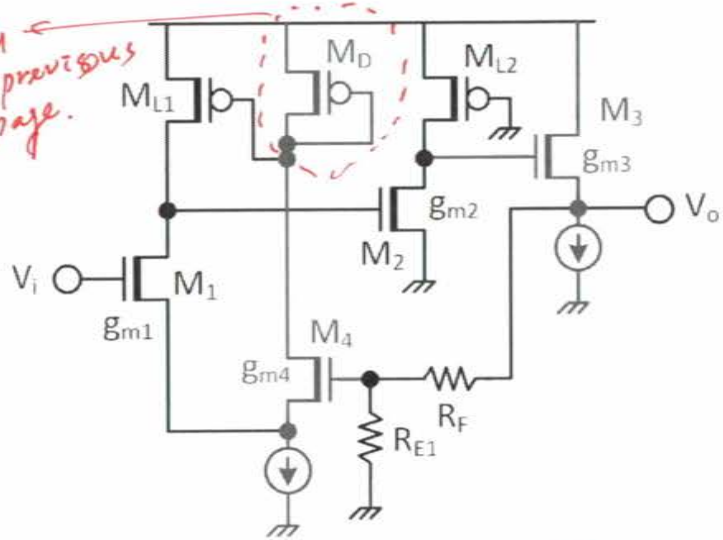
$\rightarrow i_o = \frac{1}{2} g_{m1} v_i \underline{(1 + g_{mL1} R_d)}$

extra gain boosting by the active-loading

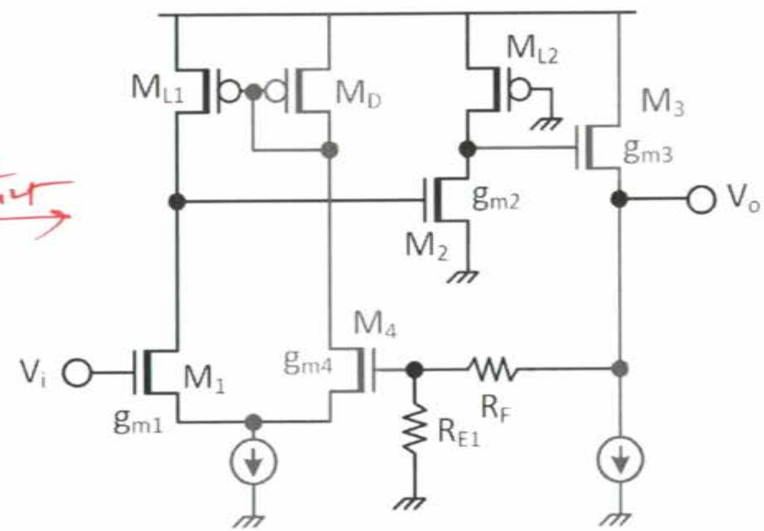
Feedback Design (8)

- Topology evolution for more ideal feedback (better loop-gain)

R_d ← in previous page.



same circuit

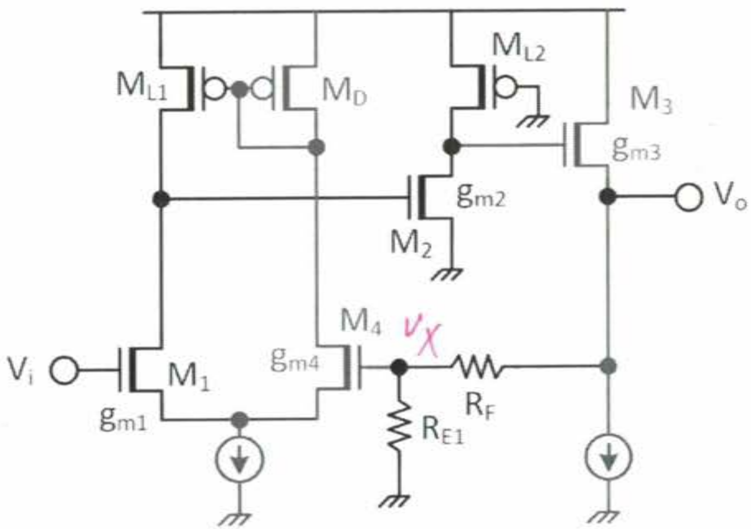


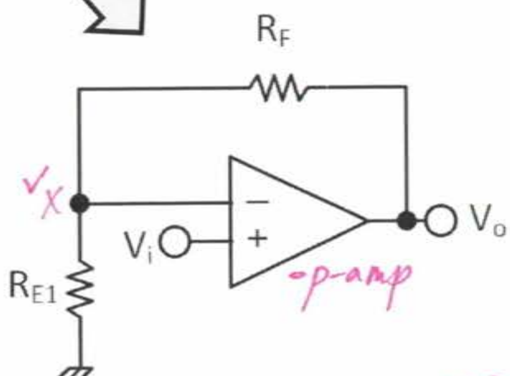
R_d is replaced by $\frac{1}{g_{mD}}$ of M_D

$$T = \left(\frac{1}{2} g_{m2} r_{o2}\right)\left(\frac{R_{E1}}{R_F + R_{E1}}\right)\left(\frac{2}{3}\right)\left(\frac{2}{3} g_{m1} r_{o1}\right)\left(1 + \frac{g_{mL1}}{g_{mD}}\right)$$

By controlling the sizes of M_{L1} & M_D, the ratio of $\frac{g_{mL1}}{g_{mD}}$ can be controlled.

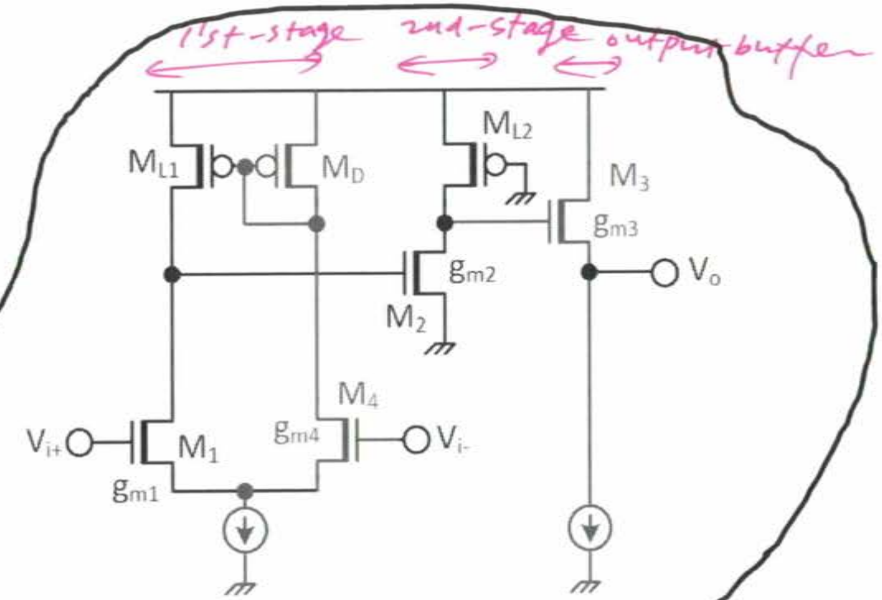
Feedback Design (9)



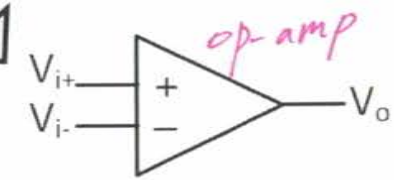


Non-inverting amplifier

$$A_v = \frac{v_o}{v_i} = \left(1 + \frac{R_F}{R_{E1}}\right)$$



This is basically
⇒ 2-stage op-amp with output buffer.

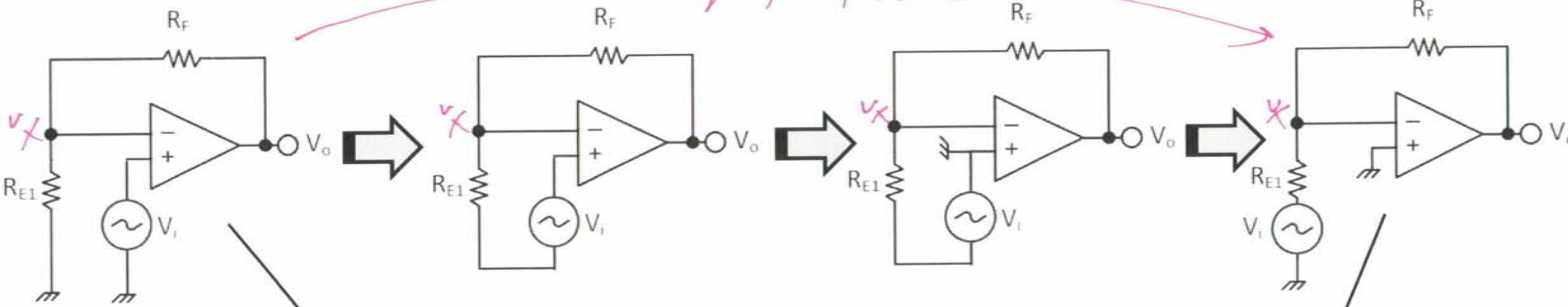


⇒ The output buffer provides a low output impedance to maximize driving efficiency for a resistive load

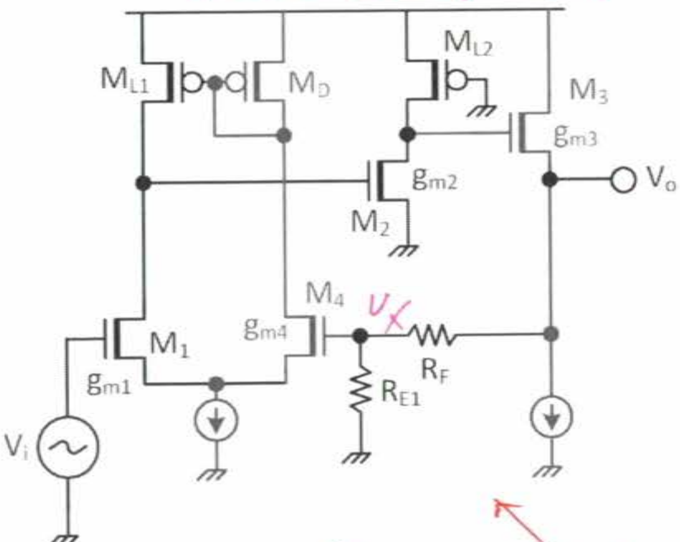
⇒ In case that load is pure capacitive, the output buffer may not be necessary.

Feedback Design (10)

change of reference

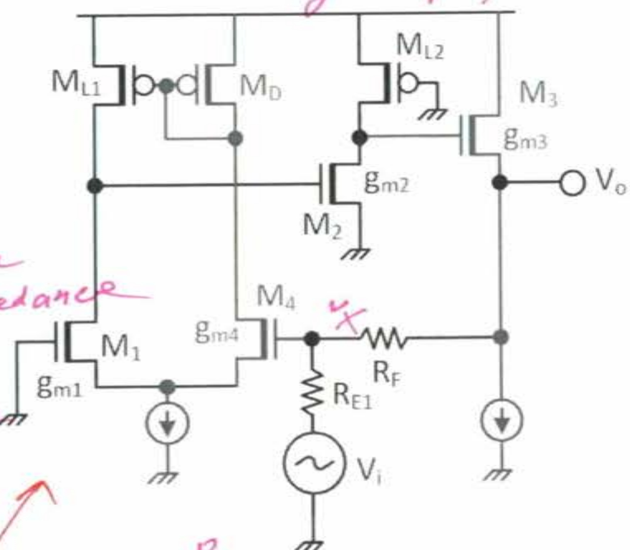


Non-inverting amplifier



same topology
⇒ same loop gain
⇒ same output impedance
⇒ only difference is input impedance

Inverting amplifier



$A_V = 1 + \frac{R_F}{R_{E1}}$

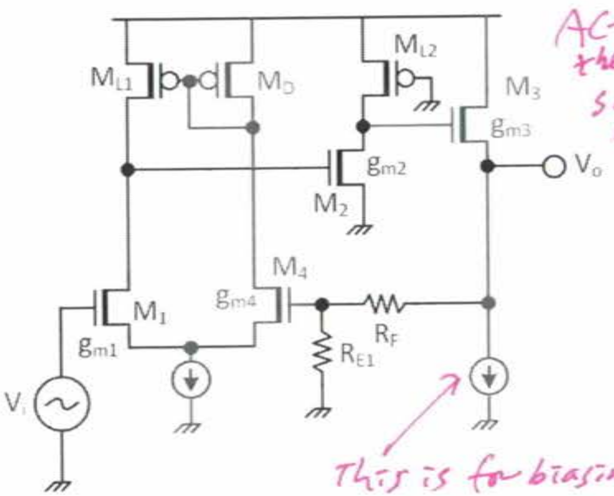
~~low~~ high input impedance (better for being driven by voltage mode)

$A_V = -\frac{R_F}{R_{E1}}$

low input impedance (better for being driven by current mode)

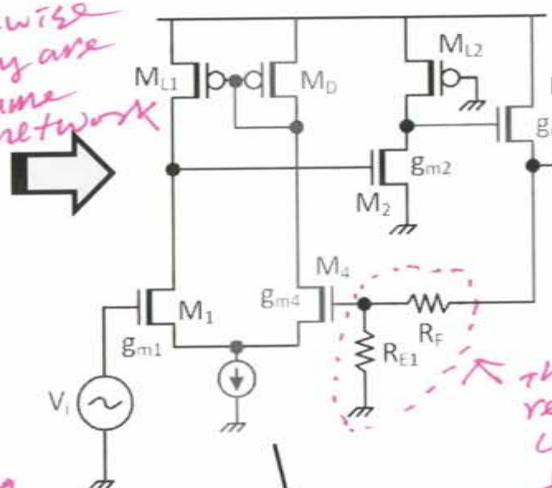
Feedback Design (11)

(14)

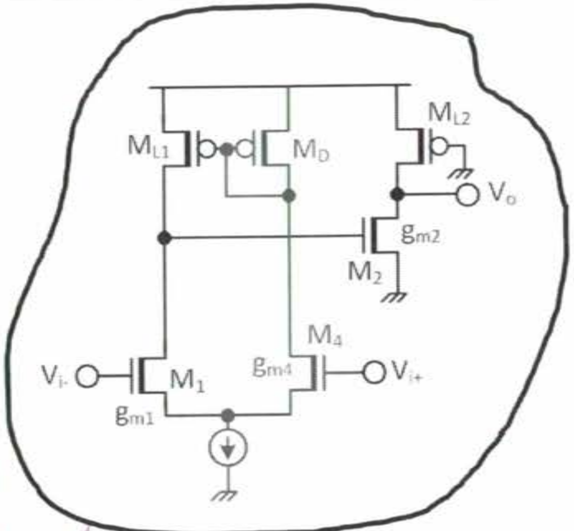


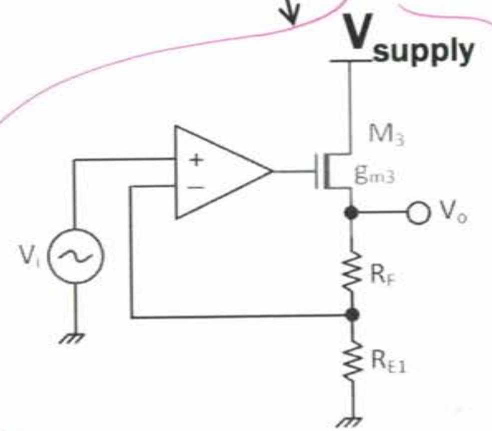
This is for biasing M_3

AC-wise they are same network

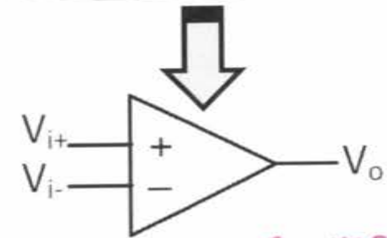


these resistors can be used for biasing M_3.





This is a standard topology of a linear regulator which will be found of very popular use in many RF/analog ICs.



2-stage op-amp

if you drive a capacitive load, you don't need a low output impedance (why?)

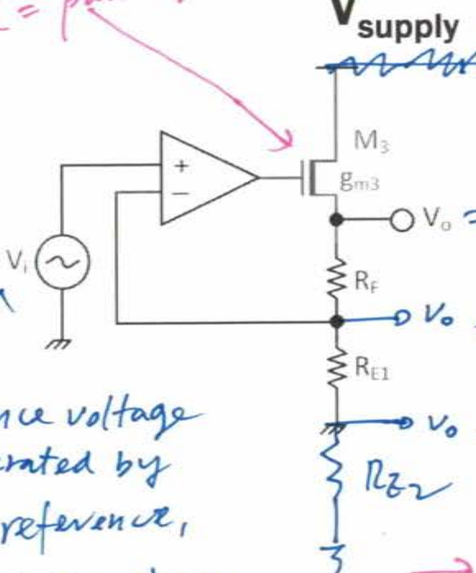
Feedback Design (11)

15

A background for linear regulator

In a mixed-mode systems, supply voltage can be quite noisy due to lots of noise coupling from digital and RF paths.

this transistor provides current. (= passing transistor).



$V_o = V_i\left(1+\frac{R_F}{R_{E1}+R_{E2}}\right)$

$V_o = V_i$

$V_o = V_i\left(1-\frac{R_{E1}}{R_{E1}+R_{E2}}\right)$

These voltages can be used as supply voltages to other circuits.

⇒ These are clean (regulated) voltage.

This reference voltage can be generated by a bandgap reference, which is very clean reference voltage/current generator.

→ This is a general way of creating a clean supply voltage in integrated circuits.

→ The transistor M_3 provides a necessary current to other circuits.

NOTE: This regulator topology is basically the same as the inverting and non-inverting feedback amplifiers.
(we will study this regulator in detail later).