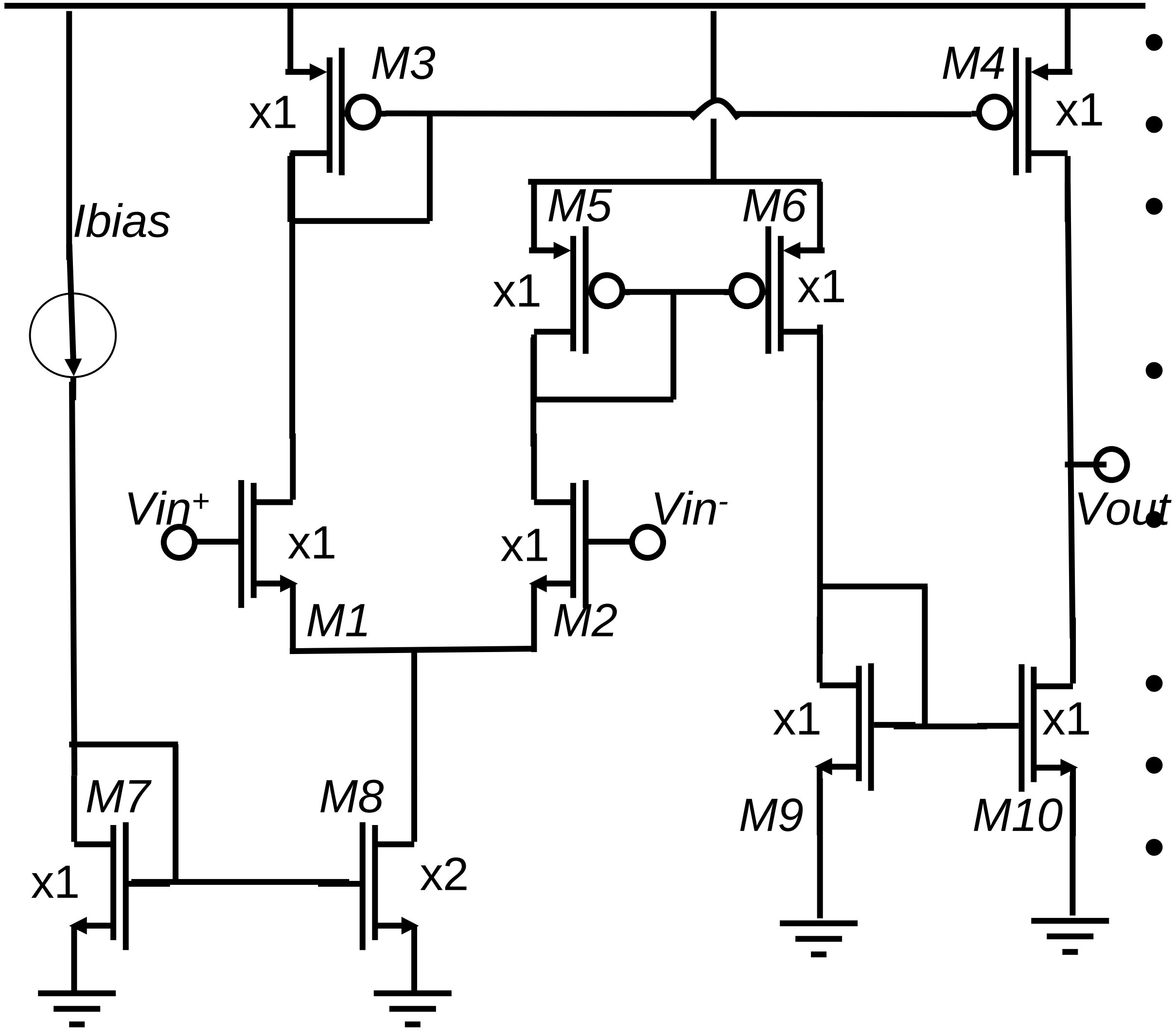
Lecture 15

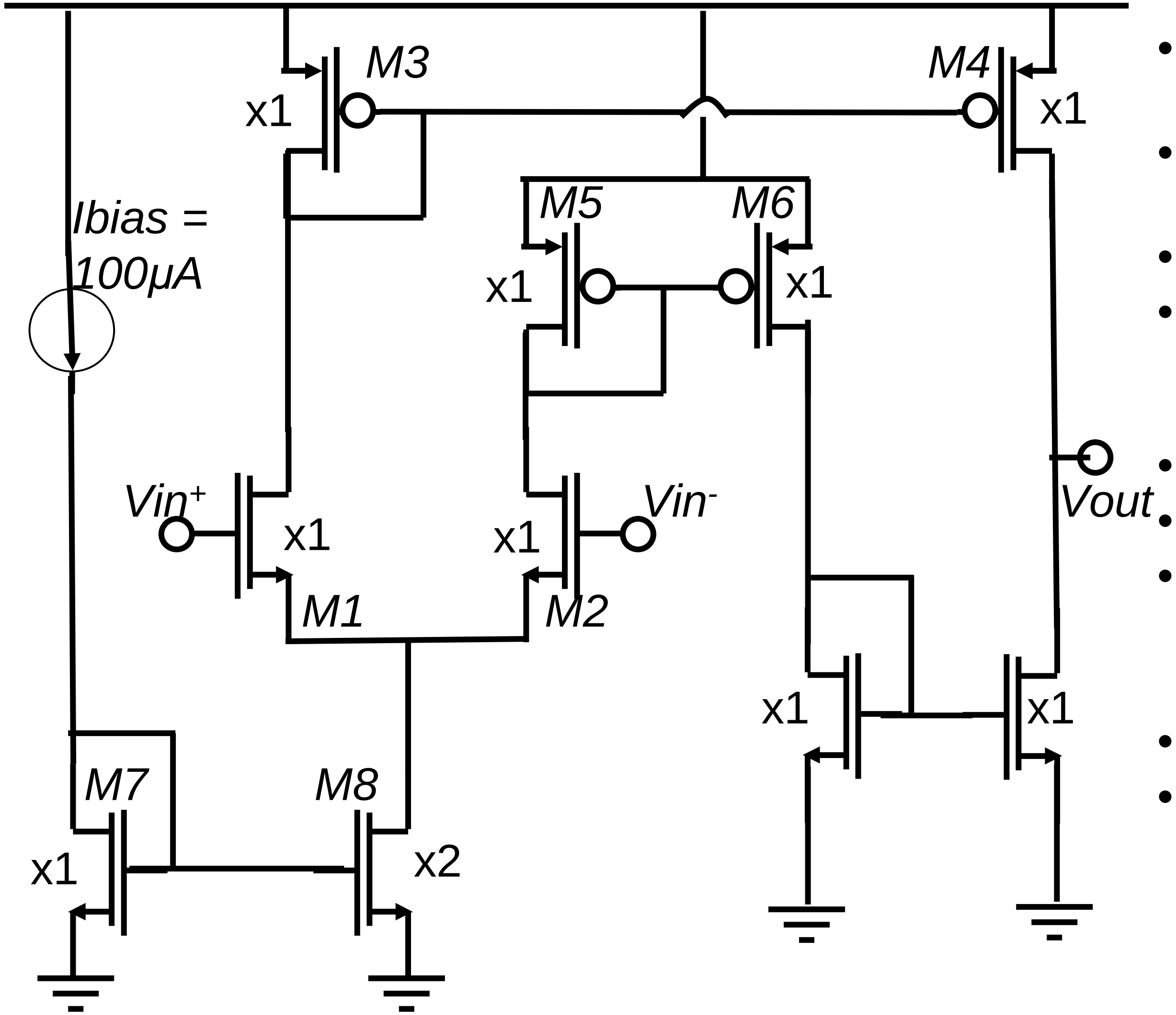
more op-amps

mirrored = similar gain



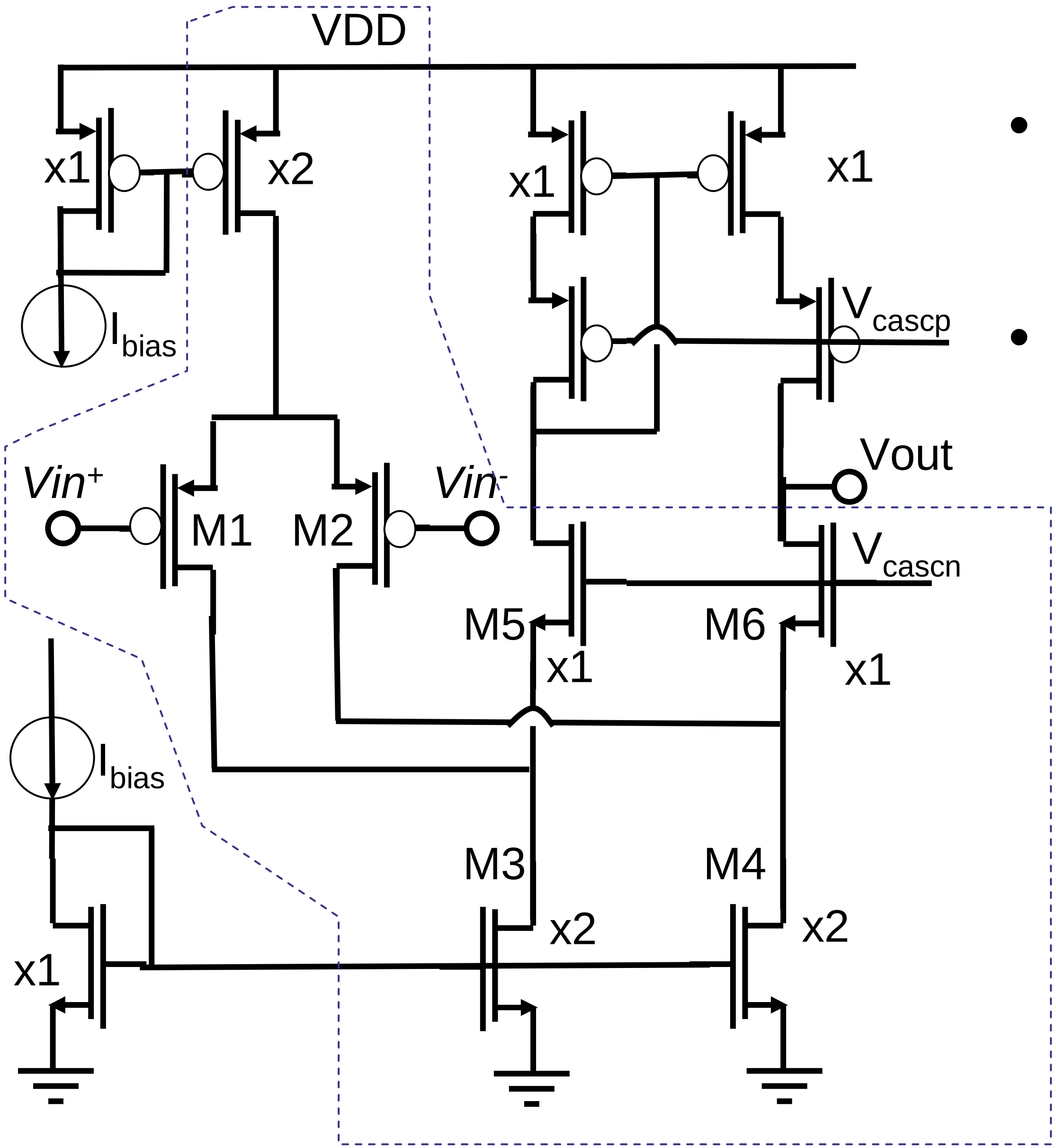
- If $Vin^{+} = -Vin^{-} = Vd/2$
- $Id1 = Ibias + gm_n Vd/2$
- $Id2 = Ibias - gm_n Vd/2$
- $Id4 = Id3 = Id1$
  $= Ibias + gm_n Vd/2$
- $Id10 = Id9 = Id6 = Id5 = Id2$
  $= Ibias - gm_n Vd/2$
- $Iout = Id4 - Id10$
  $= gm_n Vd$
- $Vout = Iout * Rout$
- $Rout = r_{on} || r_{op}$
- $Gain = gm_n (r_{on} || r_{op})$

mirrored = higher output range



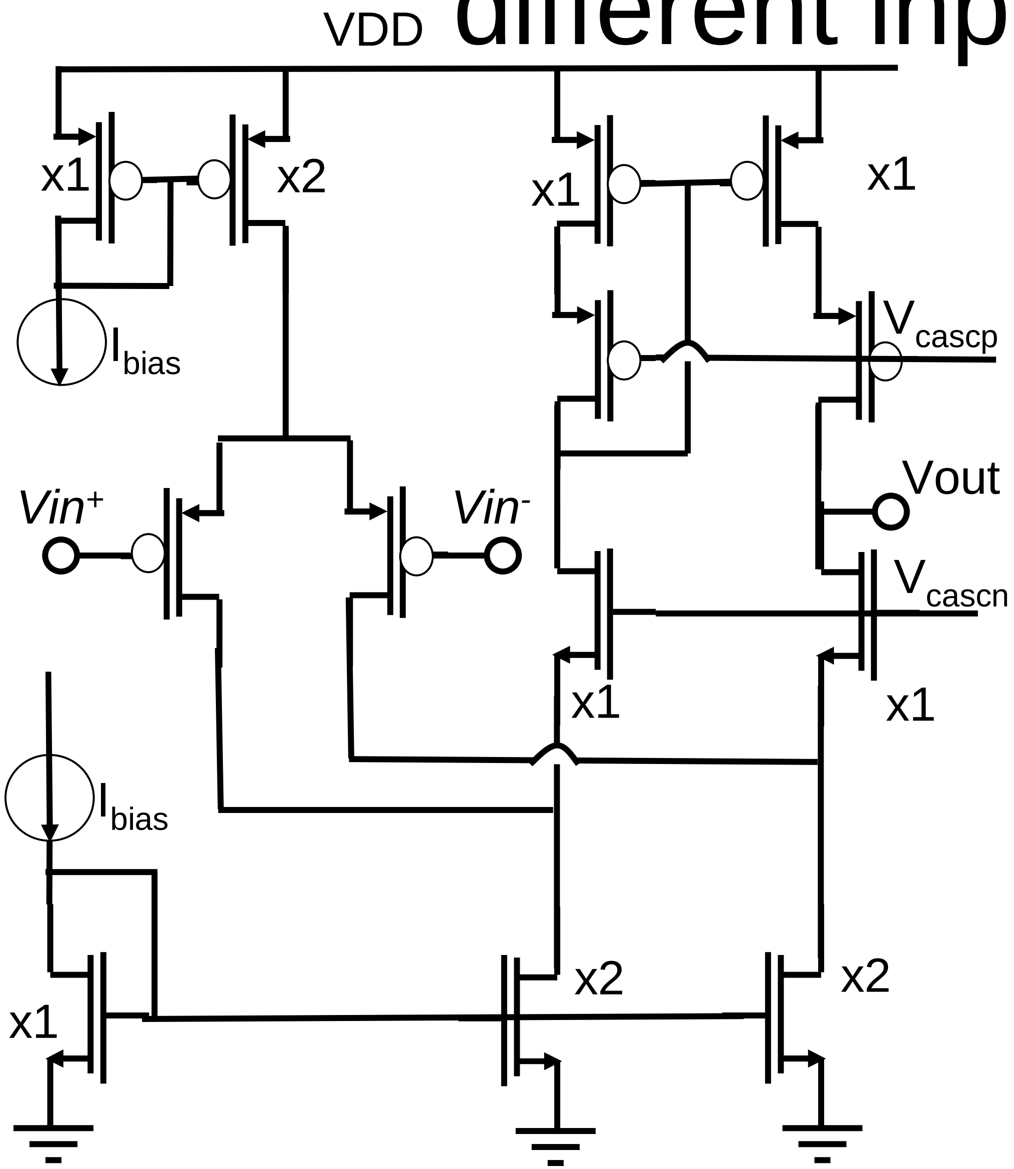
- Compared to basic op-amp, adding mirrors on output
- same gain
  - $\sim gm(r_{on}||r_{op})$
- same rout (not so good)
  - $\sim r_{on}||r_{op}$
- Same max output current
- ~same added mirror pole
  - At gm/2Cgs
  - Not too bad
- ~same CMRR
- same input range
- better output range
  - $Vout < V_{DD}-V_{ODP}$
  - $Vout > V_{ODN}$
- More dc current consumed
- Can increase gain w/cascodes at output (costs some output range)

Folded cascode



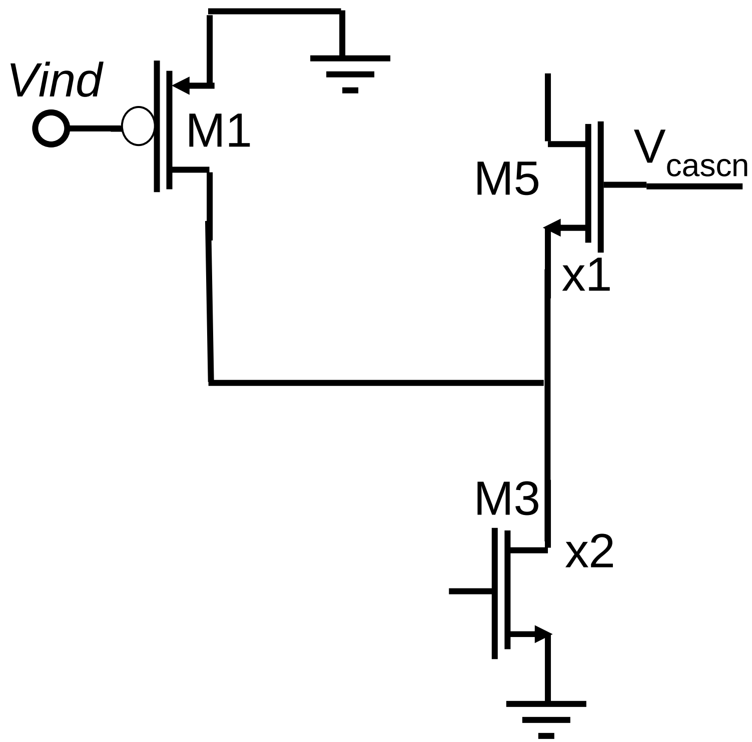
- "bottom part" (inside dashed line) of interest:
  - top part same as telescopic
- DC analysis
  - $I_{D1} = I_{bias} - gmV_{din}/2$
  - $I_{D2} = I_{bias} + gmV_{din}/2$
  - $I_{D3} = I_{D4} = 2I_{bias}$
  - KCL: $I_{D5} = I_{D3} - I_{D1}$
  - KCL: $I_{D6} = I_{D4} - I_{D2}$
  - $I_{D5} = I_{bias} + gmV_{din}/2$
  - $I_{D6} = I_{bias} - gmV_{din}/2$

Folded cascode = high gain, different input range

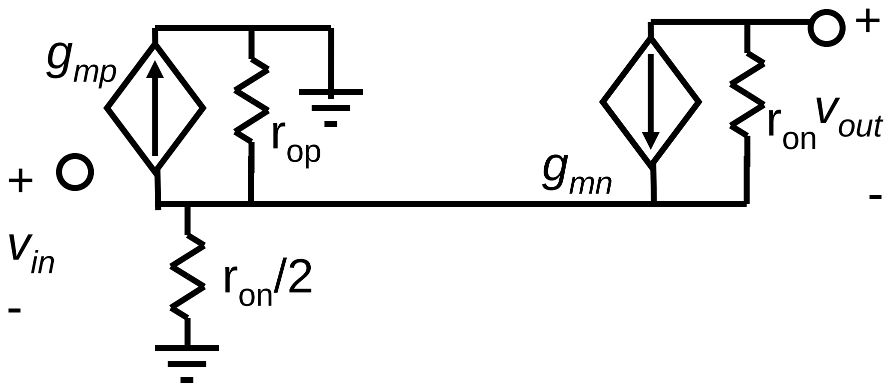


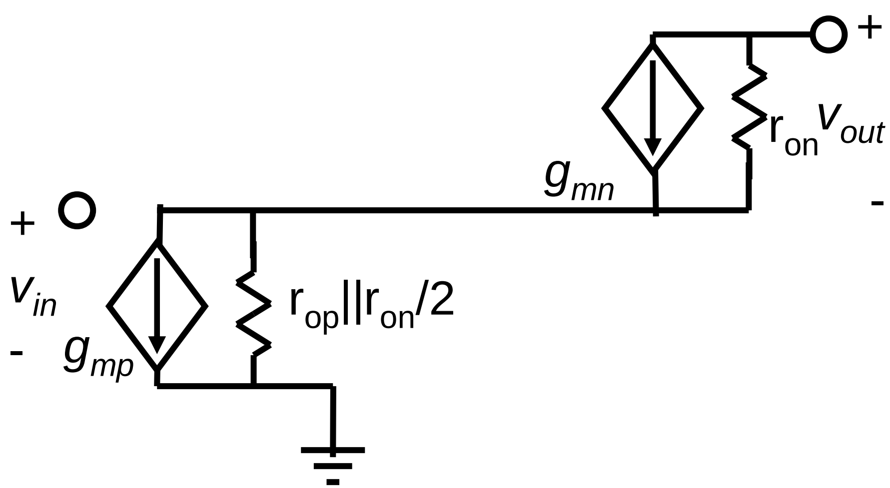
- Compared to telescopic op-amp, folded cascodes
- similar gain (good)
  - $\sim(gmr_o)^2$ vs gmr_o
  - Really slightly lower:
  - $g_{mp(}((r_{op}||r_{ob})\ g_{mn}r_{on})||(g_{mp}r_{op}{}^2))$
    - $r_{ob}\sim r_{on}/2$
- similar rout (not so good)
  - $((r_{op}||r_{ob})\ g_{mn}r_{on})||(g_{mp}r_{op}{}^2)\ \sim gmr_o{}^2$
- Same max output current
- ~same BW besides output pole
- ~same CMRR
- Better input range
  - Vin > V_{ODn}-V_{THp}<0 !!!!
  - Vin < V_{DD}-2V_{OD}-V_{THp}
  - Can go below ground!
- Better output range (V_{cascn} can be low)
  - Vout < V_{cascp}+$|V_{THP}|$
  - Vout > V_{cascn}-$|V_{THN}|$

Folded cascode: half circuit

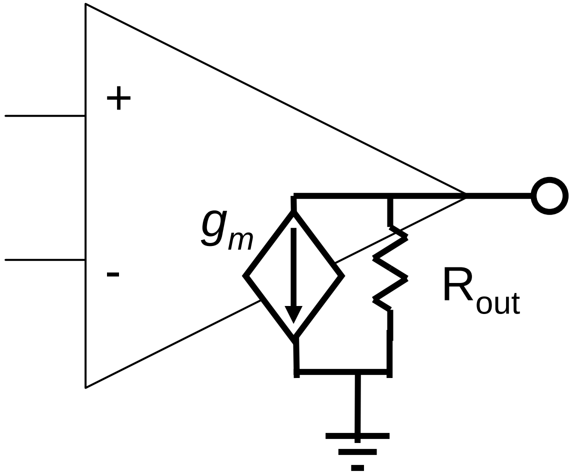


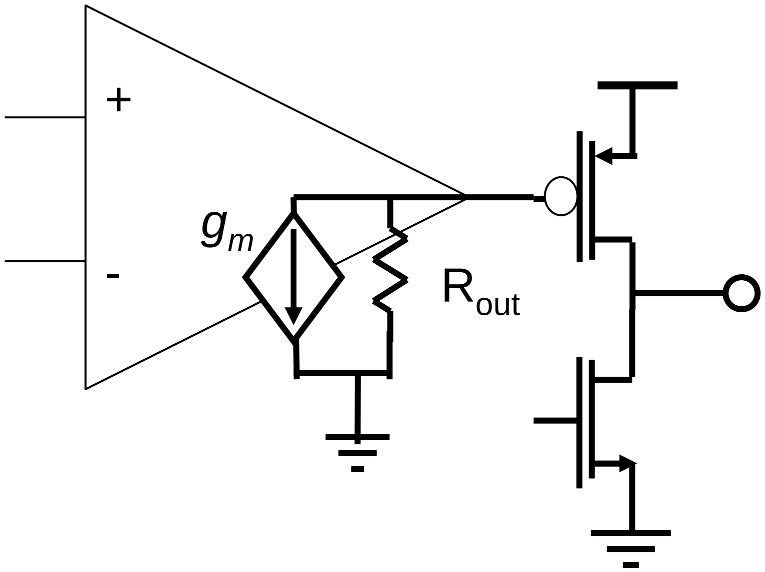
- SS analysis
- Ss half circuit:
  - Same as cascode, except
  - Input pfet, cascode nfet
  - Mirror (m3) rout in parallel with CS output
- So Rout = $g_{mn}\cdot r_{on}\cdot(r_{op}||r_{on}/2)$





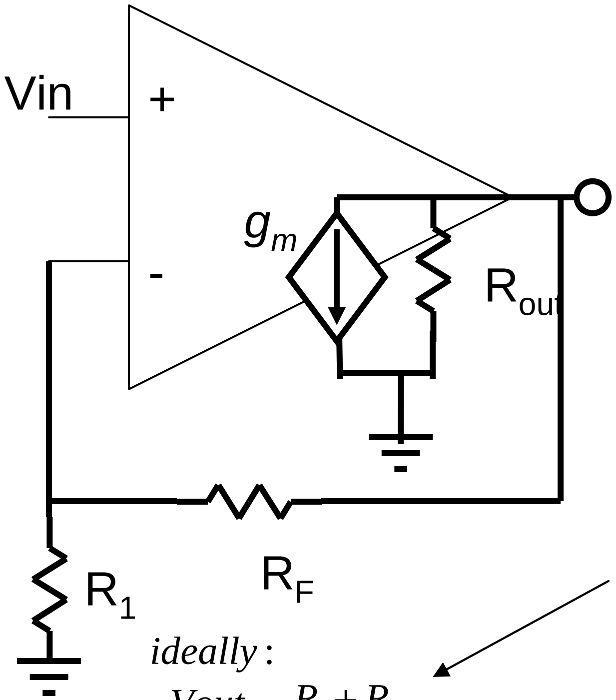
1 vs 2-stage OP-Amps





- 1-stage Op-Amps (OTAs)
  - Simple
  - Telescopic
  - Mirrored
  - Folded cascode
- All OTAs Have $A=gmR_{out}$
  - Where gm is that of a single transistor (2Id/Vod)
  - Get more gain with bigger R_{out} (cascodes, etc)
  - Dominant pole on output:
  - $\omega_p = 1/((R_{out}||R_L)(C_L+2C_{db}))$
- 2-stage: take OTA, add 2nd stage: usually CS
- Get $A=A_{OTA}*gmR_{out}$
- So separate gain from Rout
- Can separately design input/output
- Get output pole, plus intermediate pole at OTA output:
  - $\omega_p = 1/((R_{outOTA})(C_{GS}+2C_{db}))$

1 vs 2-stage OP-Amps: feedback effects



ideally:

$$\frac{Vout}{Vin}=\frac{Z_1+Z_f}{Z_1}$$

really

$$\frac{Vout}{Vin}=\frac{A(Z_1+Z_f)}{AZ_1+Z_1+Z_f+R_{out}}$$

$$=\frac{gmR_{out}(Z_1+Z_f)}{gmR_{out}Z_1+Z_1+Z_f+R_{out}}$$

ideally:

$$\frac{Vout}{Vin}=\frac{R_1+R_f}{R_1}$$

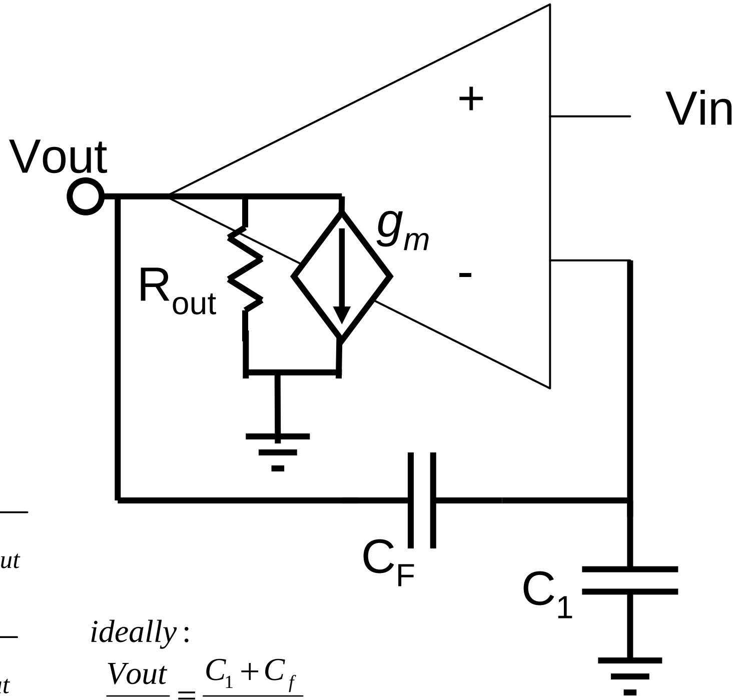
really

$$\frac{Vout}{Vin}=\frac{gmR_{out}(R_1+R_f)}{gmR_{out}R_1+R_1+R_f+R_{out}}$$

$$\xrightarrow[Rout-->\infty]{}\frac{R_1+R_f}{R_1+\frac{1}{gm}}$$

As send Rout →∞

Resistibe FB: Get gain error!



ideally:

$$\frac{Vout}{Vin}=\frac{C_1+C_f}{C_f}$$

really

$$\frac{Vout}{Vin}=\frac{gmR_{out}\left(\frac{1}{j\omega C_1}+\frac{1}{j\omega C_f}\right)}{gmR_{out}\frac{1}{j\omega C_1}+\frac{1}{j\omega C_1}+\frac{1}{j\omega C_f}+R_{out}}$$

$$=\frac{gmR_{out}(j\omega C_1+j\omega C_f)}{gmR_{out}j\omega C_f+j\omega C_1+j\omega C_f+j\omega C_f\,j\omega C_1 l}$$

$$\xrightarrow[Rout-->\infty]{}\frac{C_1+C_f}{C_f}\,\frac{1}{1+j\omega\, C_1/gm}$$

Capacitive FB: Get pole, but gain right