EE 435
Lecture 10

Laboratory Support
Positive Feedback Amplifiers
Transconductance vs Voltage Gain
OTA Applications

An Experiment

Is something like this useful?

Executive Summary: Thanks to Mathew

Lecture 7

Small signal properties of the quarter circuit are identical to the counterpart

Cascode configuration for the quarter circuit can increase gain without degrading gb compared against a single transistor

- Achieved by an increased output impedance
- Referred to as the “telescopic cascode” op amp

Obtaining two port characteristics can be achieved by various methods, such as the open short, or as demonstrated a load termination approach.

- Solutions can be monstrous depending on the method used. Simplifications may be necessary for practical insight into the design.

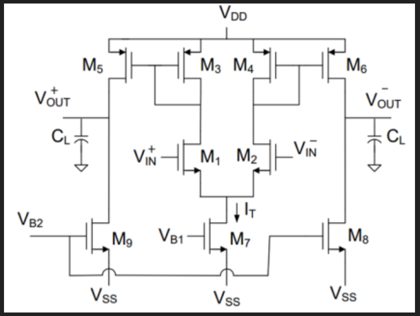
Executive Summary: Thanks to Steven

Lecture 8

Topic - Folded-Cascode Amplifiers and Current Mirror Op Amps

Folded-Cascode Op Amp Summary:

- \+ Improved output swing
- \+ Can feed output to input to create buffer
- \- Large Size Overhead
- \- Deterioration of Ao
- \- Deterioration of GB Power Efficiency

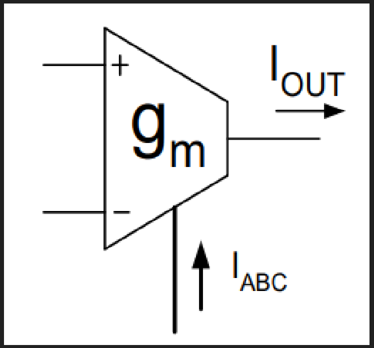


Current Mirror Op Amp Summary:

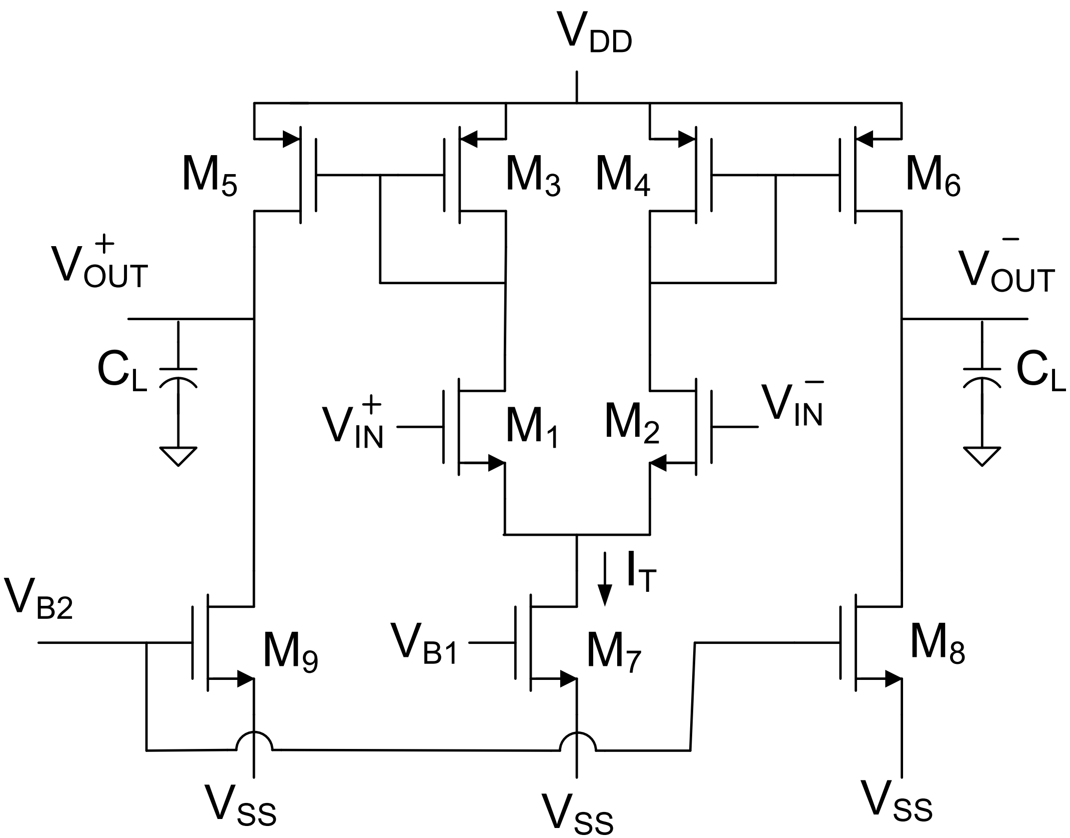
- \+ Very Simple!
- \+ Offer Easy gm enhancement
- \+ Applications as an OTA

OTA Summary:

- Converts voltage to current
- Good at high frequency components
- High adjustment ranges
- Gain can be programmed by DC current
- Often used open loop



Basic Current Mirror Op Amp



CMFB not shown

$$A_{Vd} = \frac{-g_{mEQ}}{sC_L + g_{0EQ}} = \frac{-\frac{g_{m1}}{2}M}{sC_L + g_{0EQ}}$$

$$g_{mEQ} = M\frac{g_{m1}}{2}$$

$$g_{OEQ} = g_{O6} + g_{O8}$$

$$GB = M\frac{g_{m1}}{2C_L}$$

$$A_{VO} = \frac{M \bullet \frac{g_{m1}}{2}}{g_{O6} + g_{O8}}$$

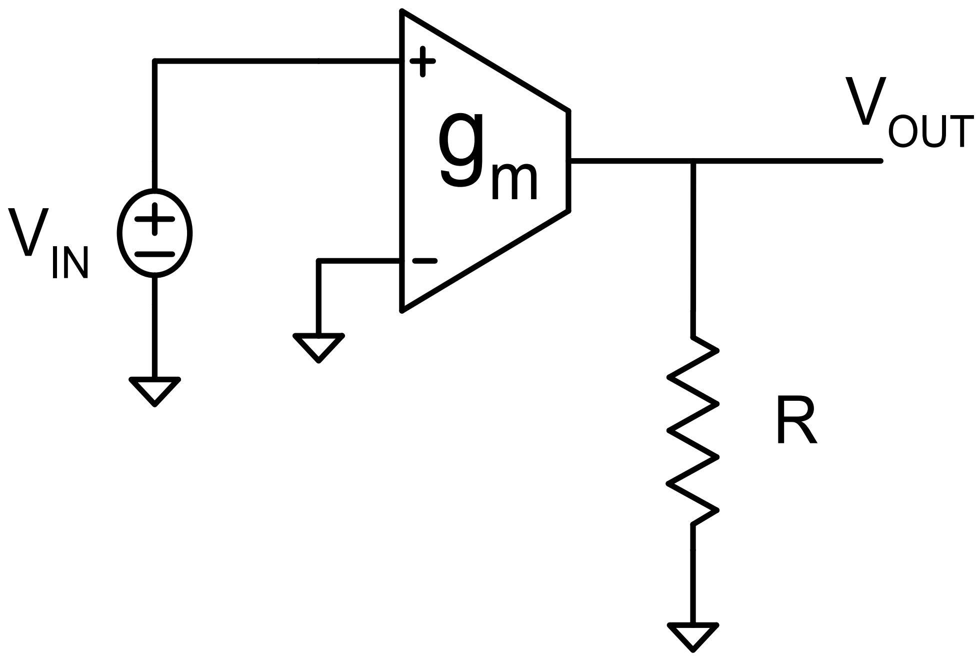
$$SR = \frac{M \bullet I_T}{2C_L}$$

Basic Current Mirror Op Amp

- Current-Mirror Op Amp offers strategy for g_m enhancement
- Very Simple Structure
- Has applications as an OTA
- Based upon small signal analysis, performance appears to be very good !
- But – how good are the properties of the CMOA?

Is this a real clever solution?

OTA Applications



$$V_{OUT} = g_m R \bullet V_{IN}$$

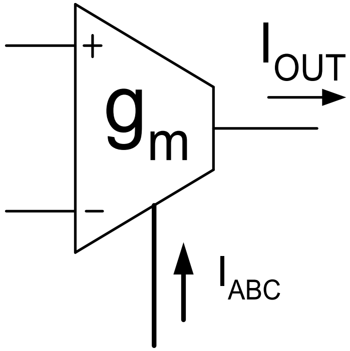
g_m is controllable with I_{ABC}

Voltage Controlled Amplifier

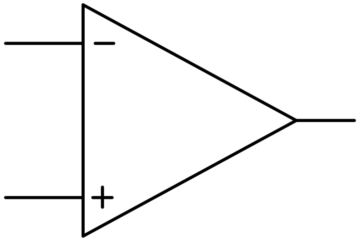
Note: Technically current-controlled, control variable not shown here and on following slides

OTA Circuits

OTA often used open loop



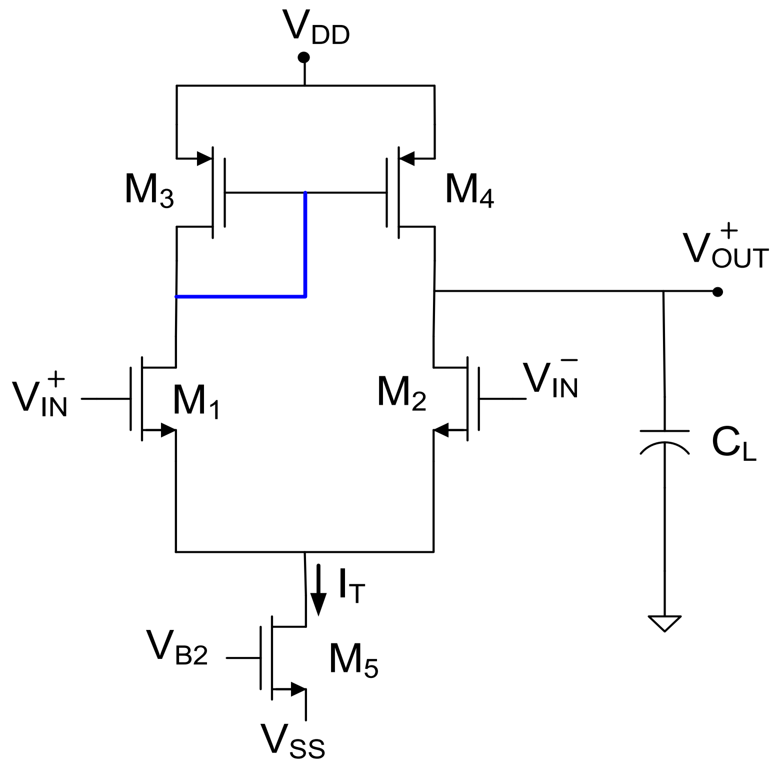
Recall: Op Amp almost never used open loop



Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

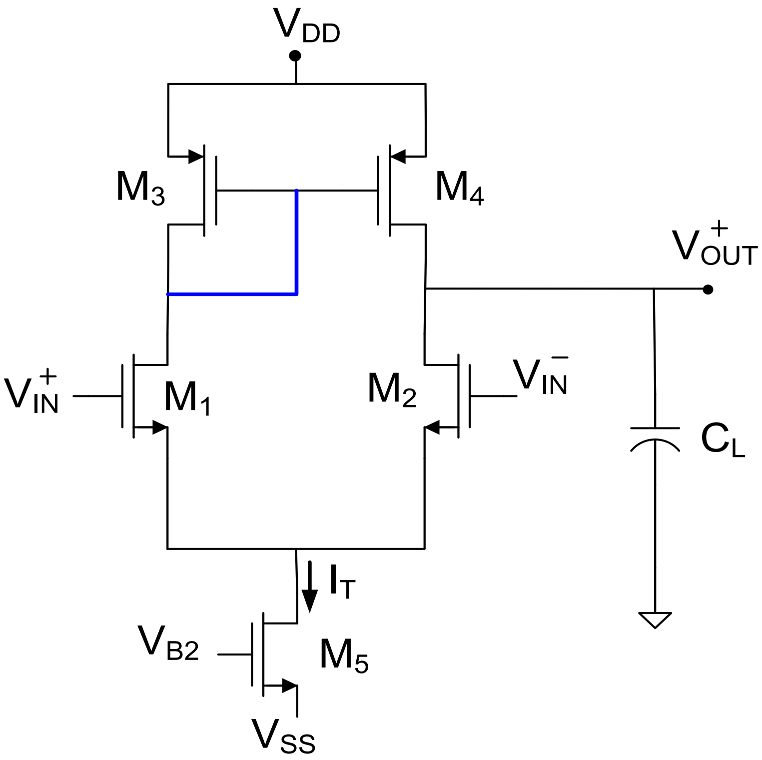
Challenge to students: Resolve what may appear to be conflicting statements. Will discuss this issue during the next lecture.

Laboratory Support:



Recall from Lecture 6

Design space for single-stage op amp



Performance Parameters in Practical Parameter Domain $\{ V_{EB1}\ V_{EB3}\ V_{EB5}\ P\}$:

$$A_0 = \left[\frac{1}{\lambda_1 + \lambda_3}\right]\left(\frac{2}{V_{EB1}}\right)$$

$$GB = \left(\frac{P}{V_{DD} C_L}\right)\left[\frac{1}{V_{EB1}}\right]$$

$$SR = \frac{P}{(V_{DD} - V_{SS})C_L}$$

$$V_{OUT} < V_{DD} - |V_{EB3}|$$

$$V_{OUT} > V_{ic} - V_{T2}$$

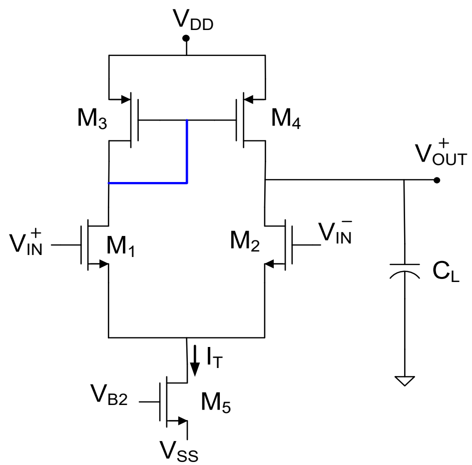
$$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

$$V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$$

Simple Expressions (7) in Practical Parameter Domain

Recall from Lecture 6

Design example for single-stage op amp



Performance Parameters in Practical Parameter Domain $\{ V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$:

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$$V_{OUT} < V_{DD} - |V_{EB3}|$$

$$V_{OUT} > V_{ic} - V_{T2}$$

$$V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$$

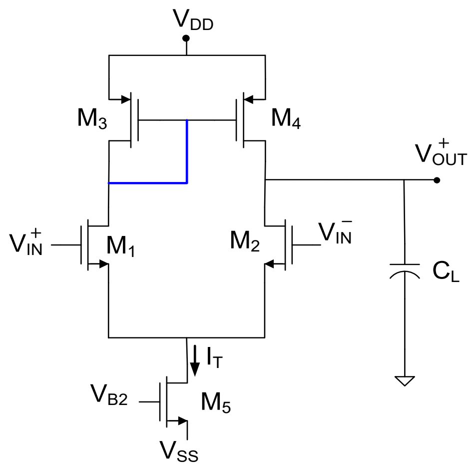
$$V_{ic} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$$

Assume design to meet A_0, GB and signal swing specs.

1. Select Parameter Domain (will use practical parameter domain) $\{ V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$
2. Pick V_{EB1} to meet gain requirement) $\{ \cancel{V_{EB1}}\ V_{EB3}\ V_{EB5}\ \ P\}$
$$V_{EB1} = \left[\frac{1}{\lambda_1+\lambda_3}\right]\left(\frac{2}{A_0}\right)$$
3. Pick P to meet GB requirement $\{ \cancel{V_{EB1}}\ V_{EB3}\ V_{EB5}\ \cancel{P}\}$
4. Pick V_{EB3} and V_{EB5} to meet signal swing requirements
5. Map back from the Practical Parameter Domain to the Natural Parameter domain (next page)

Recall from Lecture 6

Design example for single-stage op amp



Performance Parameters in Practical Parameter Domain $\{V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$:

Mapping from Practical Parameter Domain $\{V_{EB1}\ V_{EB3}\ V_{EB5}\ \ P\}$ to Natural Parameter Domain $\{W_1/L_1\ \ W_3/L_3\ \ W_5/L_5\ \ I_T\}$

From expression $I_{Dk} = \frac{\mu_k C_{ox} W_k}{2L_k} V_{EBk}^2$ it follows that

$$\frac{W_1}{L_1} = \frac{1}{\mu_n C_{OX} V_{EB1}^2} \frac{P}{V_{DD} - V_{SS}}$$

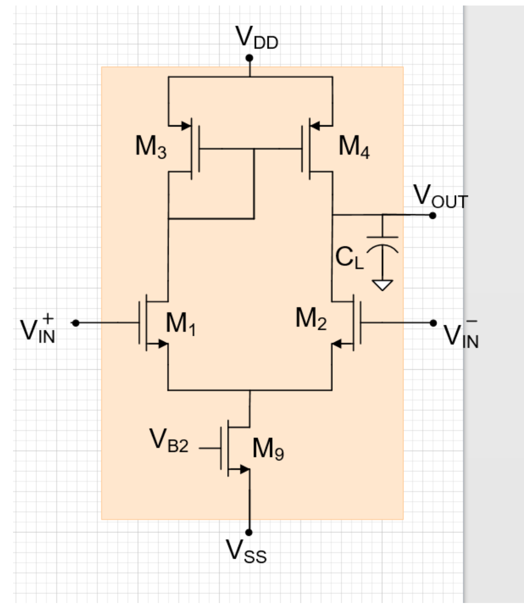
$$\frac{W_3}{L_3} = \frac{1}{\mu_p C_{OX} V_{EB3}^2} \frac{P}{V_{DD} - V_{SS}}$$

$$\frac{W_5}{L_5} = \frac{2}{\mu_n C_{OX} V_{EB5}^2} \frac{P}{V_{DD} - V_{SS}}$$

$$I_T = \frac{P}{V_{DD} - V_{SS}} \quad \text{or} \quad V_{B2} = V_{EB5} + V_{ss} + V_{THn}$$

Design Space Exploration

Consider the 5T Op Amp with CM Biasing



5T Op Amp Design

Process Paramaters

μnCOX	350	uAV^2
μpCOX	75	uAV^2
VTHn	0.4	V
VTHp	-0.4	V
λ	0.01	V^-1

Fixed Contraints

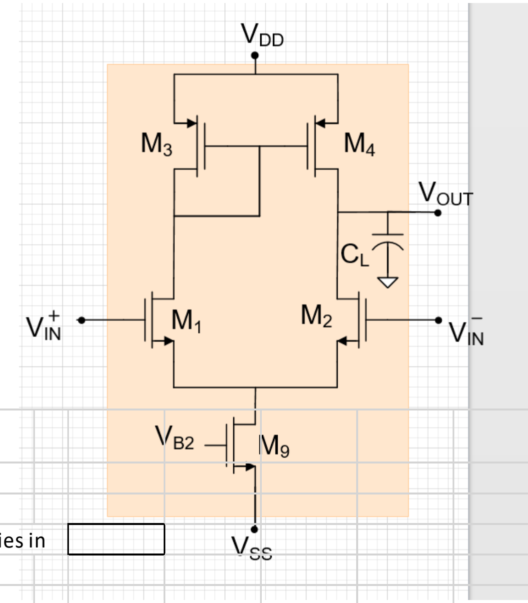
VDD	2	V
VSS	-2	V
CL	10	pf
L1=L2=…=L k	0.5	um
VB2	0.6	V

Input Quantities in

Op Amp	**Design Variables**				**Performance Characteristics**								**Practical Design Values in um**					**Small Signal Parameters (if desired)**					
No	**VEB1**	**VEB3**	**VEB9**	**P (mw)**	**A0**	**BW (MHz)**	**GB (MHz)**	**SR (V/uS)**	**Vomax**	**Vomin**	**VCM**	**IT (mA)**	**W1**	**W2**	**W3**	**W4**	**W9**	**gm1**	**gm3**	**gm9**	**go1**	**go3**	**go9**
1	0.1	-0.1	0.1	5	1000	0.20	199.04	0.125	1.9	0	0.1	1.25	357.1	357.1	1666.7	1666.7	714.3	0.0125	0.0125	0.025	6.25E-06	6.25E-06	1.3E-05
2	0.2	-0.2	0.1	5	500	0.20	99.52	0.125	1.8	-0.1	0.1	1.25	89.3	89.3	416.7	416.7	714.3	0.00625	0.00625	0.025	6.25E-06	6.25E-06	1.3E-05
3	0.4	-0.1	0.1	5	250	0.20	49.76	0.125	1.9	-0.3	0.1	1.25	22.3	22.3	1666.7	1666.7	714.3	0.003125	0.0125	0.025	6.25E-06	6.25E-06	1.3E-05
4	0.05	-0.1	0.1	5	2000	0.20	398.09	0.125	1.9	0.05	0.1	1.25	1428.6	1428.6	1666.7	1666.7	714.3	0.025	0.0125	0.025	6.25E-06	6.25E-06	1.3E-05
5	0.1	-0.1	0.1	1	1000	0.04	39.81	0.025	1.9	0	0.1	0.25	71.4	71.4	333.3	333.3	142.9	0.0025	0.0025	0.005	1.25E-06	1.25E-06	2.5E-06
6	0.1	-0.1	0.1	10	1000	0.40	398.09	0.25	1.9	0	0.1	2.5	714.3	714.3	3333.3	3333.3	1428.6	0.025	0.025	0.05	1.25E-05	1.25E-05	2.5E-05
7	0.1	-0.1	0.1	0.1	1000	0.00	3.98	0.0025	1.9	0	0.1	0.025	7.1	7.1	33.3	33.3	14.3	0.00025	0.00025	0.0005	1.25E-07	1.25E-07	2.5E-07
8	0.1	-0.1	0.1	20	1000	0.80	796.18	0.5	1.9	0	0.1	5	1428.6	1428.6	6666.7	6666.7	2857.1	0.05	0.05	0.1	0.000025	0.000025	0.00005
9	0.1	-0.1	0.2	1	1000	0.04	39.81	0.025	1.9	0	0.1	0.25	71.4	71.4	333.3	333.3	35.7	0.0025	0.0025	0.0025	1.25E-06	1.25E-06	2.5E-06
10	0.1	-0.2	0.1	0.1	1000	0.00	3.98	0.0025	1.8	0	0.1	0.025	7.1	7.1	8.3	8.3	14.3	0.00025	0.000125	0.0005	1.25E-07	1.25E-07	2.5E-07

Design Space Exploration

Embedded Spreadsheet



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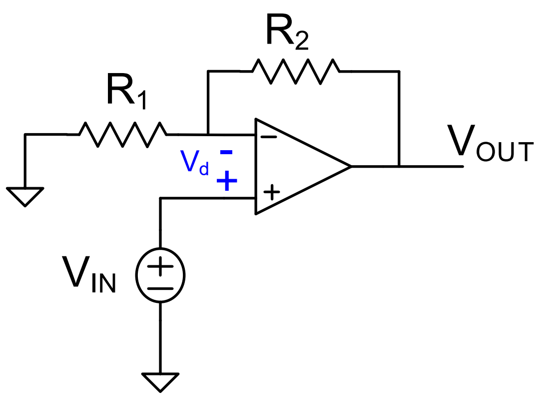
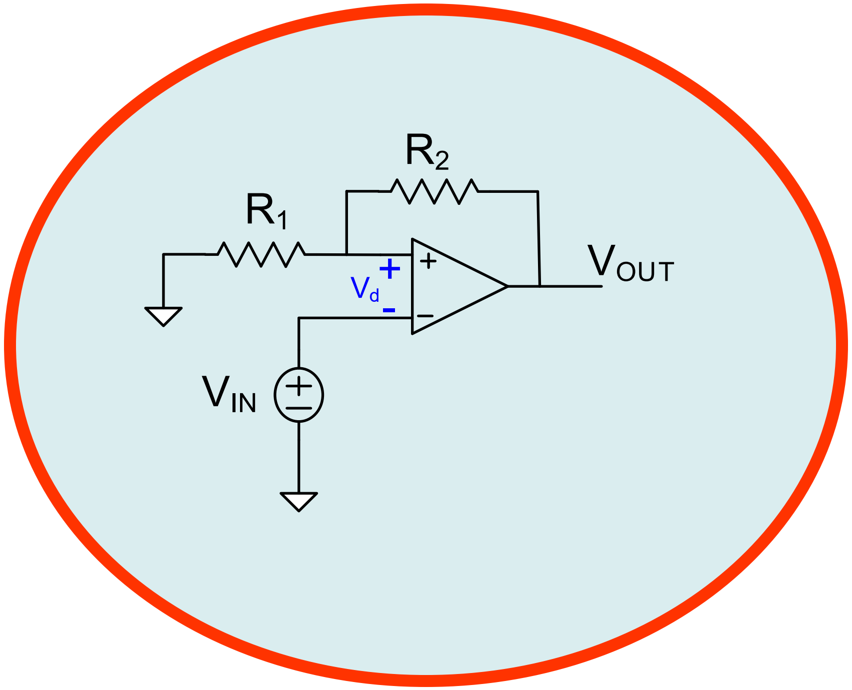
8	0.1	-0.1	0.1	20	1000	0.80	796.18	0.5	1.9	0	0.1	5	1428.6	1428.6	6666.7	6666.7	2857.1
9	0.1	-0.1	0.2	1	1000	0.04	39.81	0.025	1.9	0	0.1	0.25	71.4	71.4	333.3	333.3	35.7
10	0.1	-0.2	0.1	0.1	1000	0.00	3.98	0.0025	1.8	0	0.1	0.025	7.1	7.1	8.3	8.3	14.3

Positive Feedback Amplifiers

- Some Basic Observations
- More Detailed Discussions will be presented later

From homework Problem 7 Assignment 1

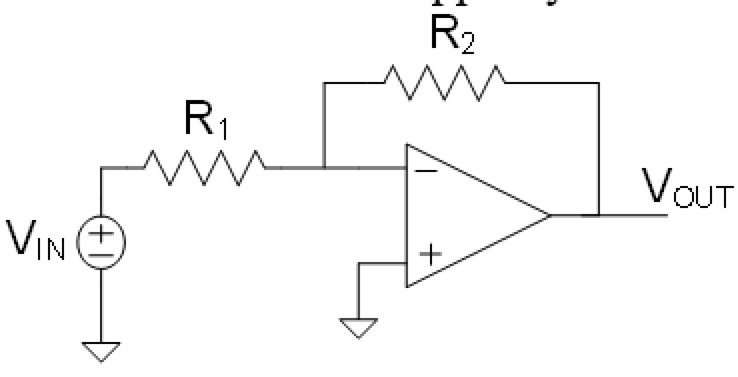


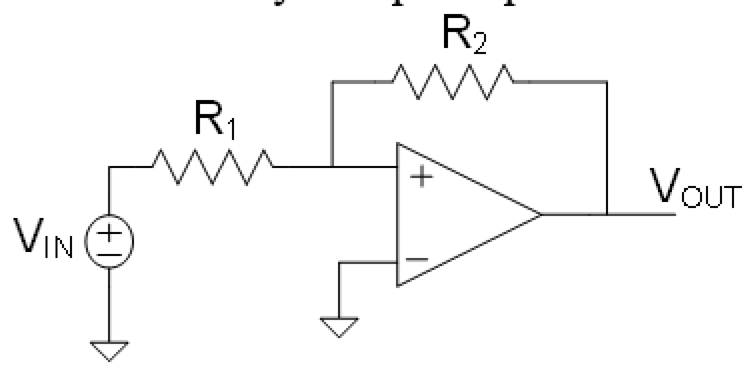


Homework Problem 7 Assignment 1

Problem 7 Two circuits that use a single operational amplifier are shown below.

a) Using the model of the standard model of the operational amplifier that appears in the Sedra/Smith book, analyze the two circuits under the assumption that the voltage gain of the op amp, A_V, is finite.
b) Compare the voltage gain of the two circuits as the voltage gain A_V goes to ∞
c) Although an engineer should be able to analyze any interconnection of basic devices and components, almost all basic electronics textbooks are silent on the existence of the simple circuit on the right. Why is this circuit is seldom discussed? Support your answer with sound analytical principles or concepts.

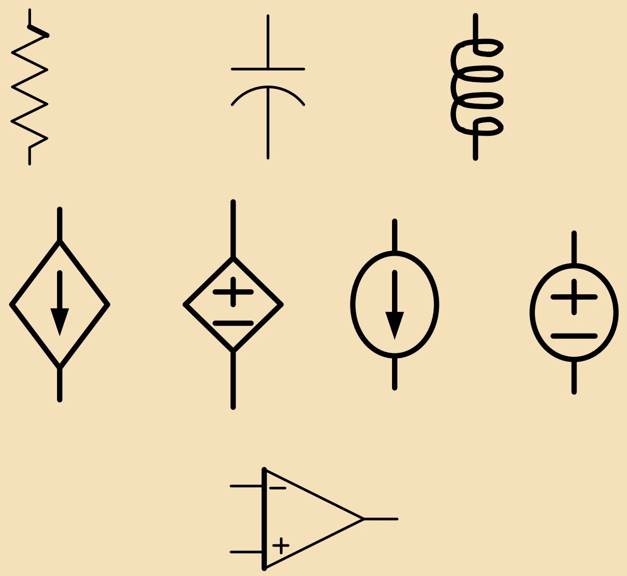




Most got the first parts right but only two rigorously assessed the performance of the circuit with positive feedback

This is an improvement ! Last year nobody correctly assessed the performance with positive feedback.

Are engineers expected to know how interconnections of basic circuit elements perform?

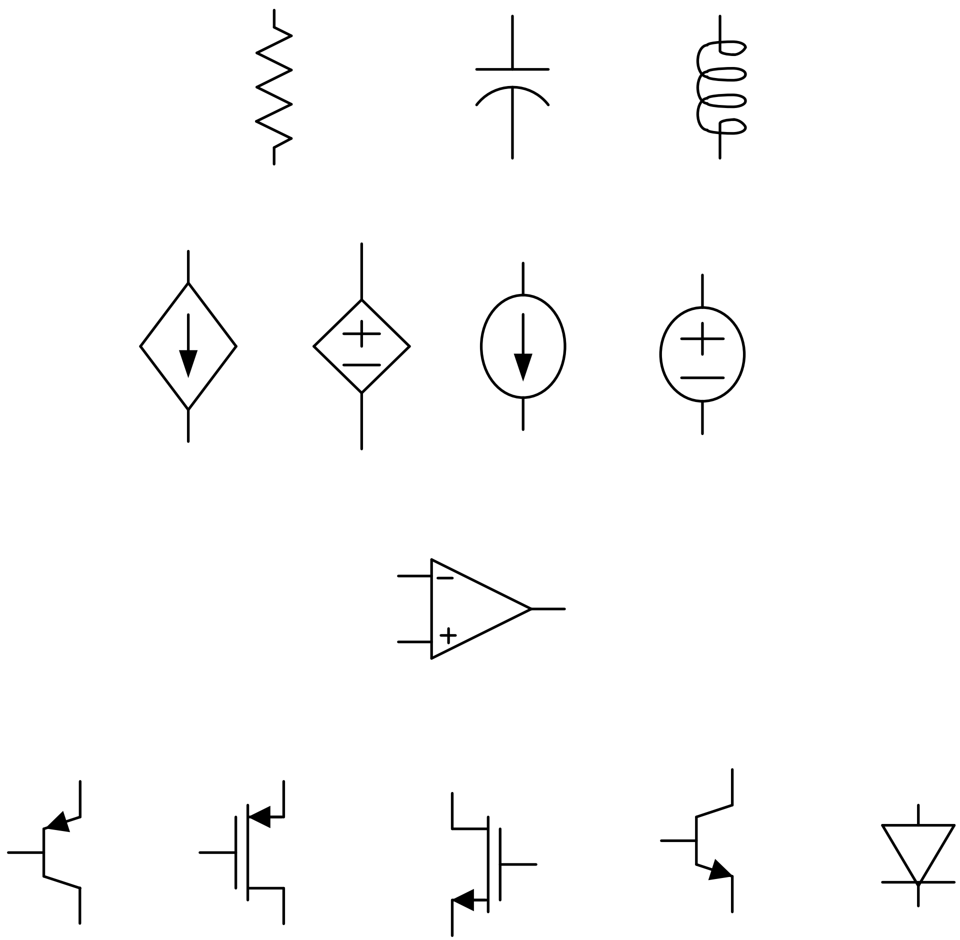


Basic Circuit Components
Discussed in EE 201 and EE 230 in our curriculum

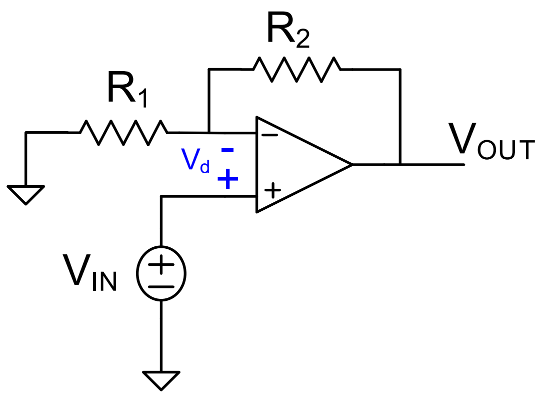
Design engineers are invariably and routinely required to create new interconnections of these basic components to solve existing problems

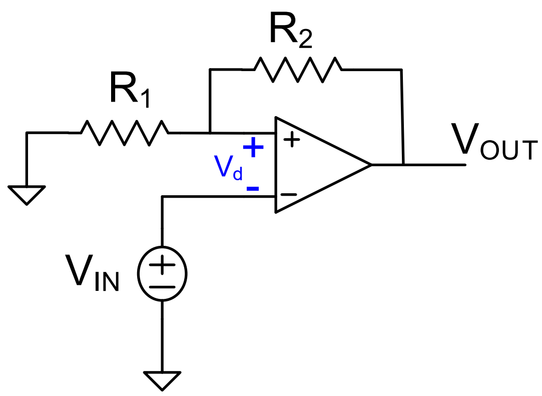
Designers are often guided by previous design that often appears in text books or other literature

Are engineers expected to know how interconnections of basic circuit elements perform?



Homework Problem 6 Assignment 1





Sedra Smith Analysis
(for circuit on left)

1. Assume Op Amp operating linearly (not stated)
2. Since A_V large, conclude V_d=0
3. Apply KCL at node between resistors

$$V_{IN}\frac{1}{R_1}+\left(V_{IN}-V_{OUT}\right)\frac{1}{R_2}=0$$

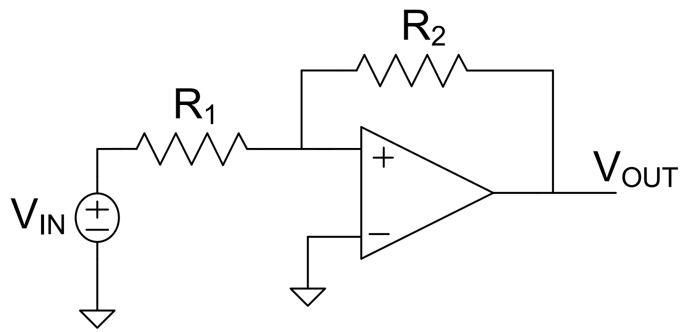
4. Solve to obtain

$$V_{OUT}=\left(1+\frac{R_2}{R_1}\right)V_{IN}$$

Identical analysis applies for circuit on right so get identical results

If op amps are ideal based upon the models introduced in most texts, and based upon the analysis presented in the most recent edition of the Sedra Smith test, both circuits have the same input-output relationship

Homework Problem 6 Assignment 1



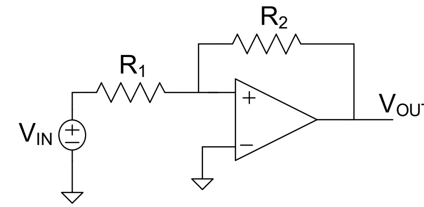
c) Although an engineer should be able to analyze any interconnection of basic devices and components, almost all basic electronics textbooks are silent on the existence of the simple circuit on the right. Why is this circuit seldom discussed? **Support your answer with sound analytical principles or concepts.**

Why is this issue important?

How can you trust or be confident in your analysis and understanding if the principles you use to analyze even some of most basic circuits fail in slightly different circuits?

Why is this circuit is seldom discussed?

Support your answer with sound analytical principles or concepts.



Selected Answers from Students

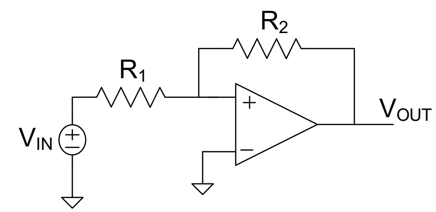
For the circuit on the right, if a finite Av value is employed, the gain increases. This raises the possibility of an undefined gain. Un-like the negative feedback system of the left circuit, the positive feedback loop of the right is lacking in stability, difficult to analyse, and all round un-desirable.

The circuit on the right is seldom dissussed because it is not practical to use.

Although the circuit on the right has some use cases, it is not used as much because it has no gain region.

Why is this circuit is seldom discussed?

Support your answer with sound analytical principles or concepts.



Selected Answers from Students

a) $A_{v_1} = -\frac{R_2}{R_1}$, $A_{v_2} = 1 + \frac{R_2}{R_1}$

b) As $A_{v_1} \to \infty$ $R_2 \to \infty$ $R_1 \to 0$

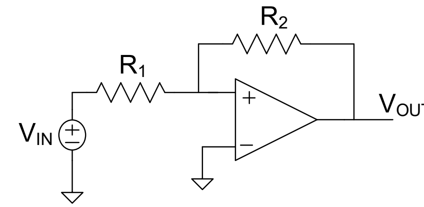
As $A_{v_2} \to \infty$ $R_2 \to \infty$ $R_1 \to 0$

c) because gain is limited a non inverting amplifier is not as useful since it will max out quickly

The voltage gain of the two circuits for $A \to \infty$ is the same $(-R_2/R_1)$.

Why is this circuit is seldom discussed?

Support your answer with sound analytical principles or concepts.



Selected Answers from Students

a.) Positive feedback increases the gain and negative feedback decreases the gain. The negative feedback adds phase shift to the system.

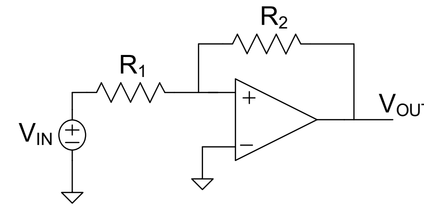
b.) The voltage gain of negative feedback is stable and easy to control. The gain of positive feedback is not stable and highly non-linear.

c.) Positive feedback is not stable and easily leads to a runaway. Positive feedback is really only used when oscillation is desired, but in most cases oscillation is a bad thing.

The secondary circuit is seldom discussed because it is not nearly as useful in analog circuits. This is because of the positive feedback in the design. We can see in the equation that the only difference between the two circuit gain equations is the bottom term $R_1 + R_2$, it is either added or subtracted. When it is added it reduces the overall gain and slightly lowers the output voltage. If it is subtracted then it will be slightly greater. This is the problem. If it is slightly greater than the equation for V_+ shows that VOUT is linearly related. Any increase in this output voltage increases the input which in turn increases the output more. In the end the output voltage will clip at the rails at the slightest input. This small change ruins the stability of the circuit. What's actually very interesting is that we have proved that an ideal operational amplifier would not have a positive feedback issue because the infinite gain would remove this slight increase in gain.

Why is this circuit is seldom discussed?

Support your answer with sound analytical principles or concepts.



Selected Answers from Students

b. negative feedback: $A = -\frac{R_2}{R_1}$

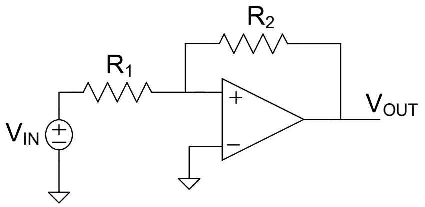
Positive feedback: $A = -\frac{R_2}{R_1}$

c. Positive feedback loops cause a chain reaction with a positive input into Ve causing the output to quickly raise to VDD and a negative causing a drop to Vss.

7. C. Positive feedback tends to amplify noise and disturbances, making the circuit less predictable and more challenging to control. In a positive feedback configuration it can lead to unwanted consequences like sustained oscillations. Stability is a crucial consideration in electronic circuits, and the inverting amplifier configuration is more commonly used because it provides stable and controllable operation.

Why is this circuit is seldom discussed?

Support your answer with sound analytical principles or concepts.

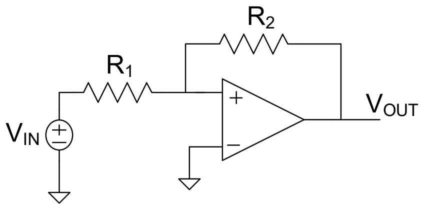


Selected Answers from Students

Probably the Best Answer!

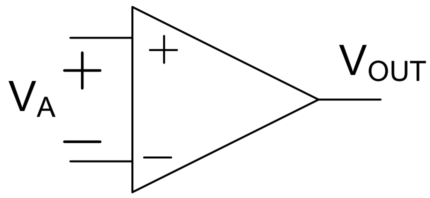
Why is this circuit is seldom discussed?

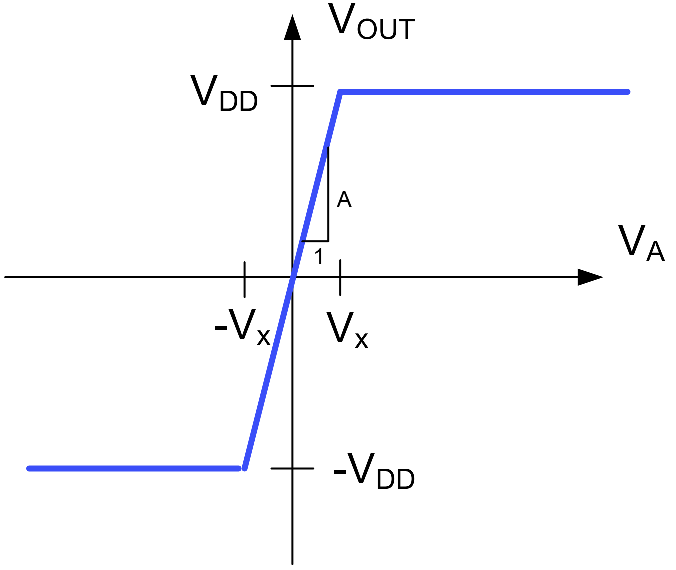
Support your answer with sound analytical principles or concepts.



Is positive feedback bad?

DC model of actual op amp

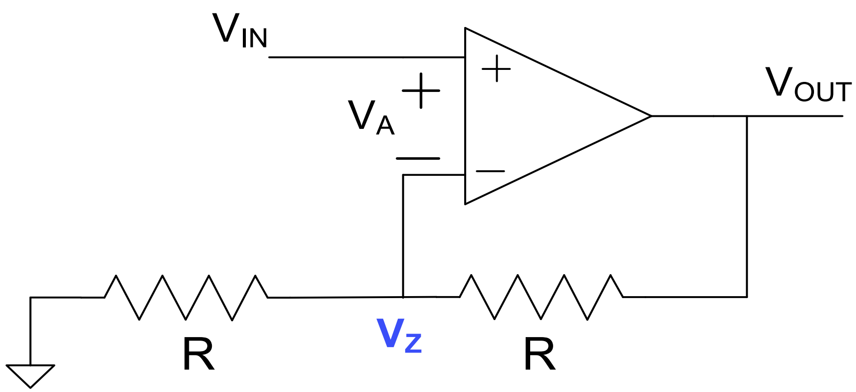




$$V_{OUT} = \begin{cases} V_{DD} & V_A > V_X \\ AV_A & -V_X < V_A < V_X \\ -V_{DD} & V_A < V_X \end{cases}$$

Consider the negative feedback configuration

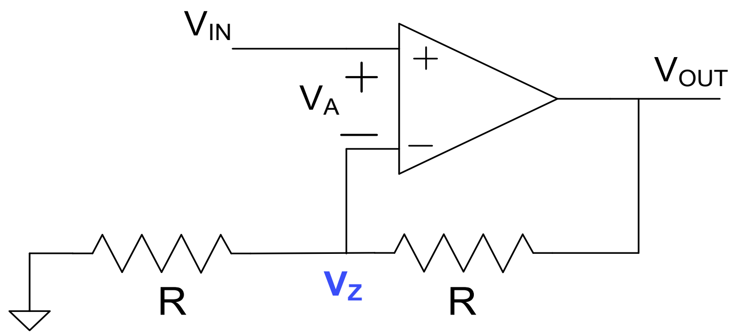
For convenience, assume $R_1=R_2=R$



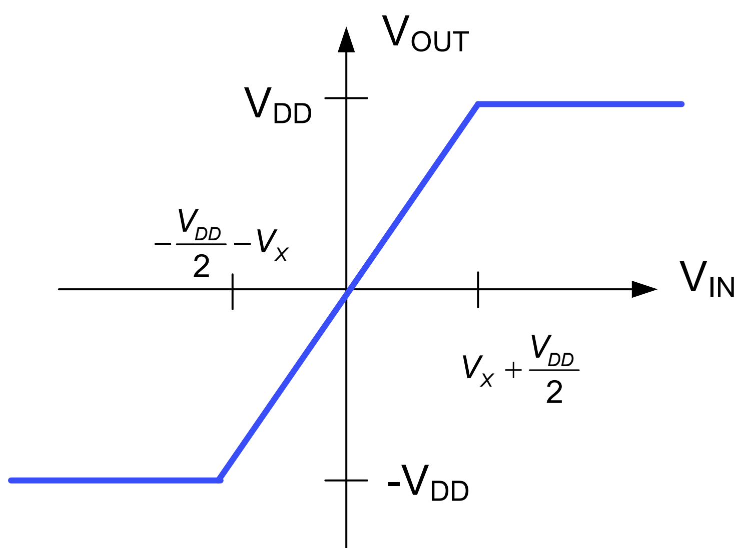
$$\left.\begin{aligned} V_Z &= \frac{V_{OUT}}{2} \\ V_{IN} &= V_A + V_Z \end{aligned}\right\} \Rightarrow \quad V_A = V_{IN} - \frac{V_{OUT}}{2}$$

$$V_{OUT} = \begin{cases} V_{DD} & V_A > V_X \\ AV_A & -V_X < V_A < V_X \\ -V_{DD} & V_A < -V_X \end{cases} \Rightarrow \quad V_{OUT} = \begin{cases} V_{DD} & V_{IN} - \frac{V_{DD}}{2} > V_X \\ \frac{2A}{2+A} V_{IN} \cong 2V_{IN} & -V_X - \frac{V_{DD}}{2} < V_{IN} < V_X + \frac{V_{DD}}{2} \\ -V_{DD} & V_{IN} + \frac{V_{DD}}{2} < -V_X \end{cases}$$

Consider the negative feedback configuration

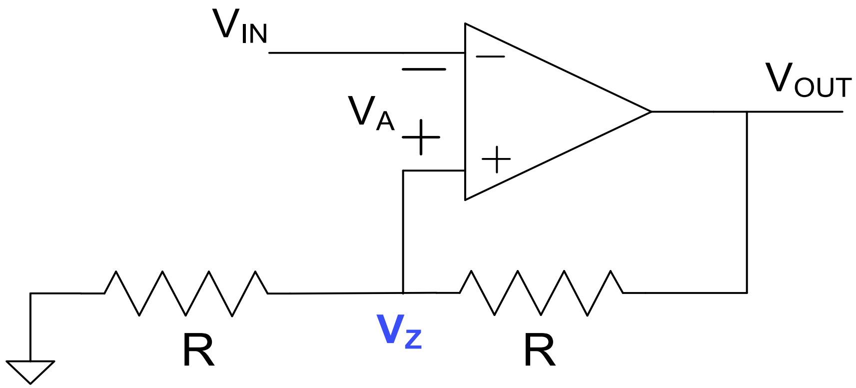


$$V_{OUT} = \begin{cases} V_{DD} & V_{IN} - \frac{V_{DD}}{2} > V_X \\ \frac{2A}{2+A}V_{IN} \cong 2V_{IN} & -V_X - \frac{V_{DD}}{2} < V_{IN} < V_X + \frac{V_{DD}}{2} \\ -V_{DD} & V_{IN} + \frac{V_{DD}}{2} < -V_X \end{cases}$$



Consider the positive feedback configuration

For convenience, assume R_1=R_2=R

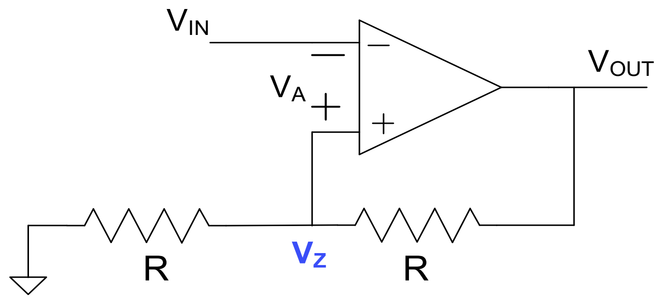


$$\left.\begin{array}{l} V_Z = \dfrac{V_{OUT}}{2} \\ V_{IN} = -V_A + V_Z \end{array}\right\} \Rightarrow V_A = -V_{IN} + \frac{V_{OUT}}{2}$$

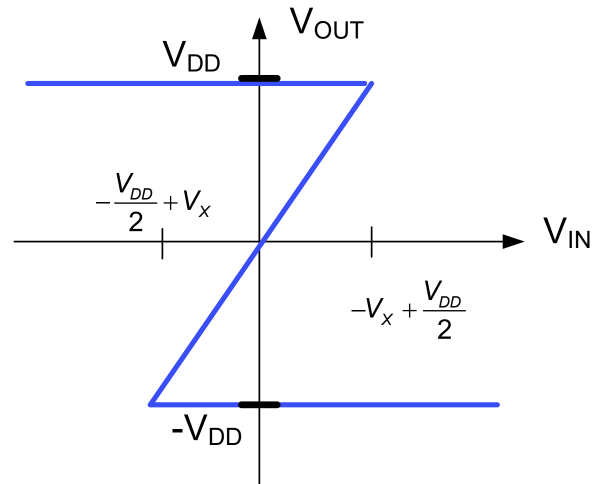
$$V_{OUT} = \begin{cases} V_{DD} & V_A > V_X \\ AV_A & -V_X < V_A < V_X \\ -V_{DD} & V_A < -V_X \end{cases} \Rightarrow V_{OUT} = \begin{cases} V_{DD} & -V_{IN} + \dfrac{V_{DD}}{2} > V_X \\ \dfrac{2A}{2+A} V_{IN} \cong 2V_{IN} & -V_{IN} + \dfrac{V_{DD}}{2} < V_X \text{ and } -V_{IN} + \dfrac{V_{DD}}{2} > -V_X \\ -V_{DD} & -V_{IN} - \dfrac{V_{DD}}{2} < -V_X \end{cases}$$

Consider the positive feedback configuration

For convenience, assume $R_1=R_2=R$



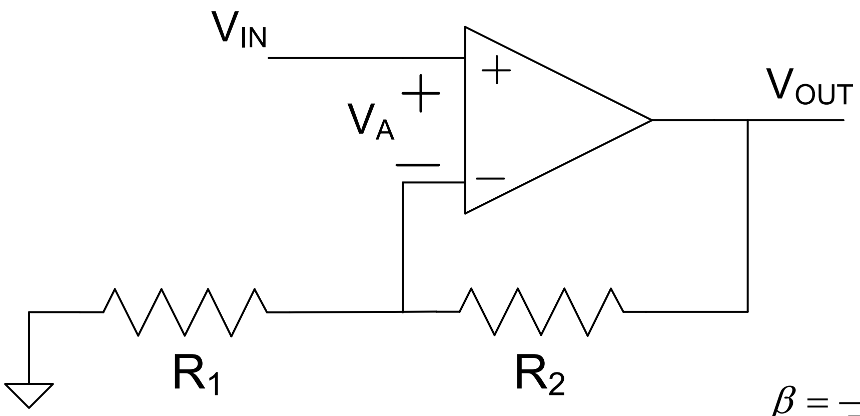
$$V_{OUT} = \begin{cases} V_{DD} & \frac{V_{DD}}{2} - V_X > V_{IN} \\ \frac{2A}{2+A} V_{IN} \cong 2V_{IN} & \frac{V_{DD}}{2} - V_X < V_{IN} < -\frac{V_{DD}}{2} + V_X \\ -V_{DD} & V_X - \frac{V_{DD}}{2} < V_{IN} \end{cases}$$



Note: Tripple-valued output in interval

So what will the output be?

Consider the negative feedback configuration



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

Assume single-pole amplifier model AND linear operation of the op amp

$$A(s) = \frac{pA_O}{s + p}$$

$$V_{OUT} = A(s)(V_{IN} - \beta V_{OUT})$$

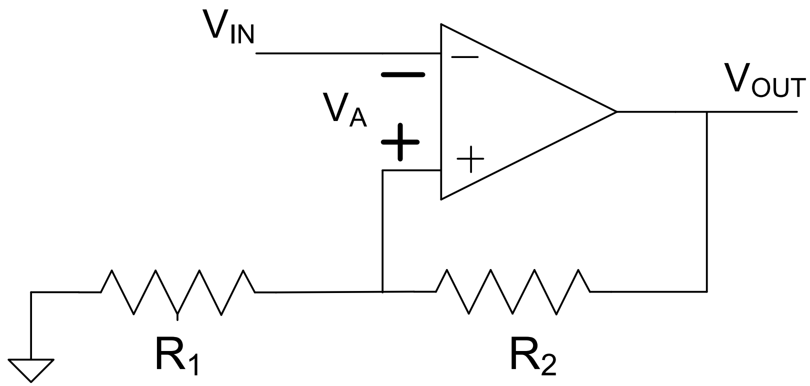
$$A_{CL}(s) = \frac{V_{OUT}}{V_{IN}} = \frac{pA_O}{s + p(1 + \beta A_O)}$$

Single pole p_1

$$p_1 = -p(1 + \beta A_O)$$

Note pole in LHP on negative real axis !

Consider the positive feedback configuration



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$$A(s) = \frac{pA_O}{s+p}$$

$$V_{OUT} = A(s)\left(\beta V_{OUT} - V_{IN}\right)$$

$$A_{CL}(s) = \frac{V_{OUT}}{V_{IN}} = \frac{-pA_O}{s + p\left(1 - \beta A_O\right)} \cong \frac{-pA_O}{s - p\beta A_O}$$

$$p_1 = p\left(1 - \beta A_O\right) \simeq -p\beta A_O$$

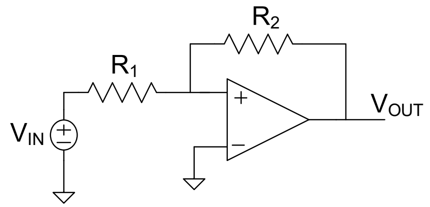
Note pole in RHP on positive real axis !

The circuit is unstable when operating linearly and output will be of form Ke^{-pt}

Does this mean this amplifier is not useful as an amplifier?

Why is this circuit is seldom discussed?

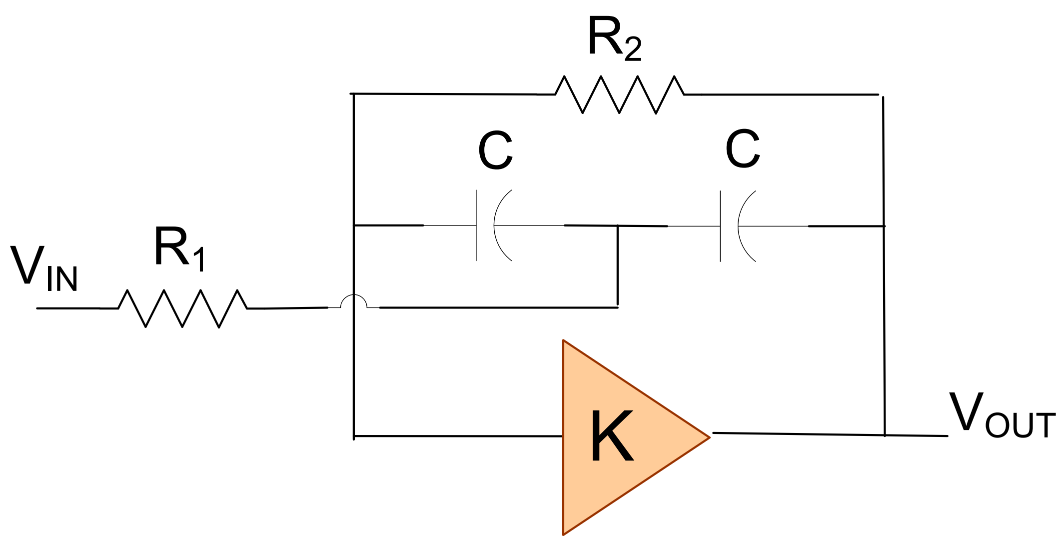
Support your answer with sound analytical principles or concepts.



Is positive feedback bad?

Consider: Filter Structure with Feedback Amplifier

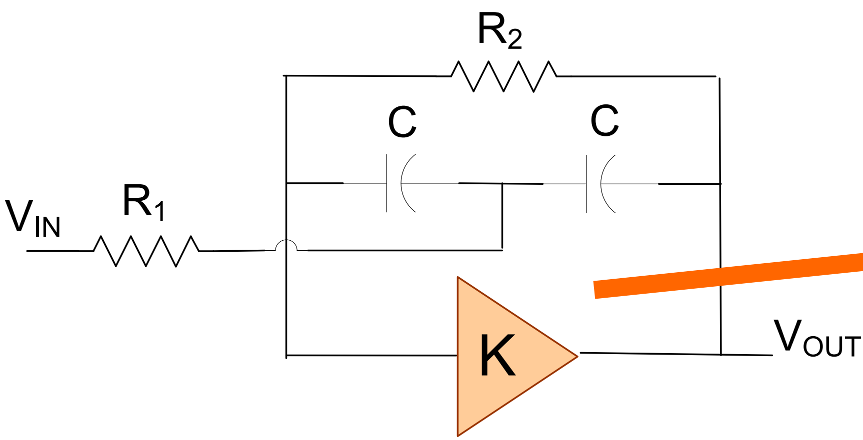
Bridged-T Feedback
(Termed SAB, STAR, Friend/Delyannis Biquad)

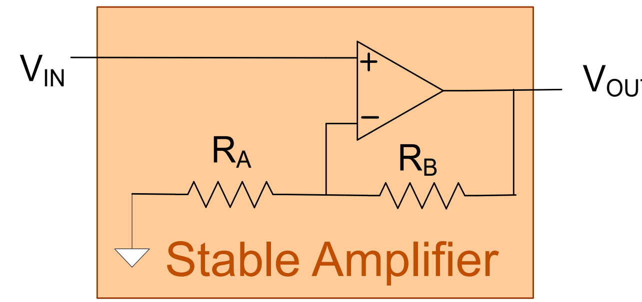


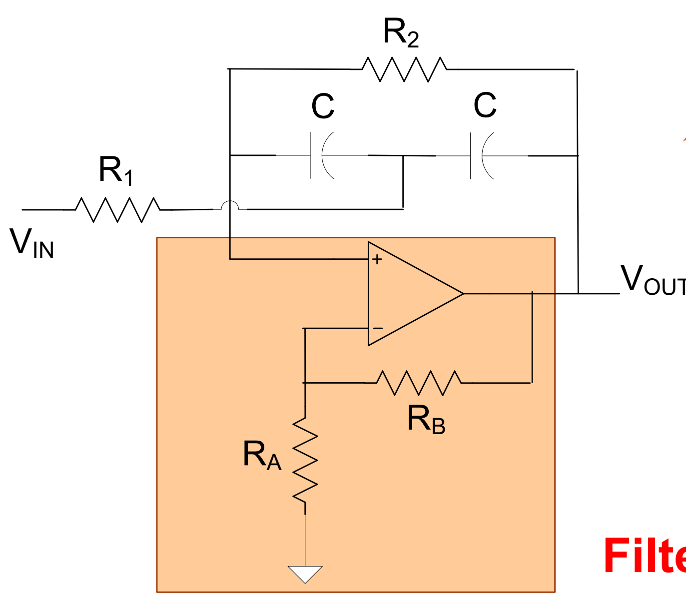
K is a small positive gain
want high input impedance on “K” amplifier

- Very popular filter structure
- One of the best 2nd-order BP filters
- Widely used by Bell System in 70’s

Example: Filter Structure with Feedback Amplifier



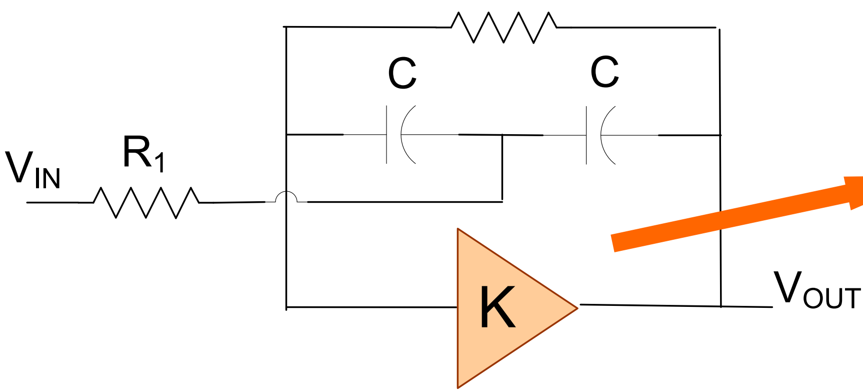


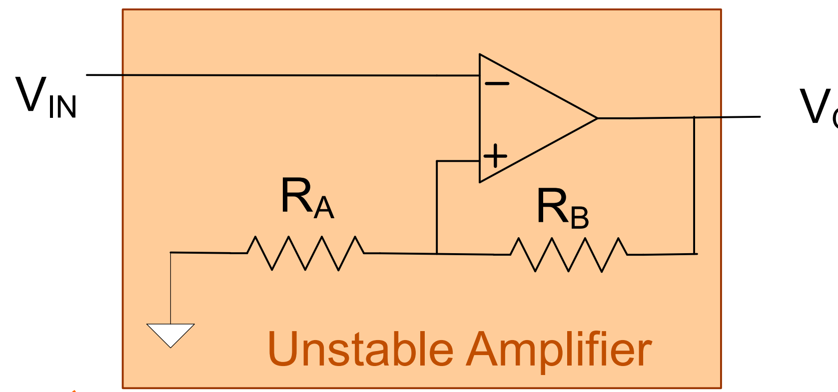


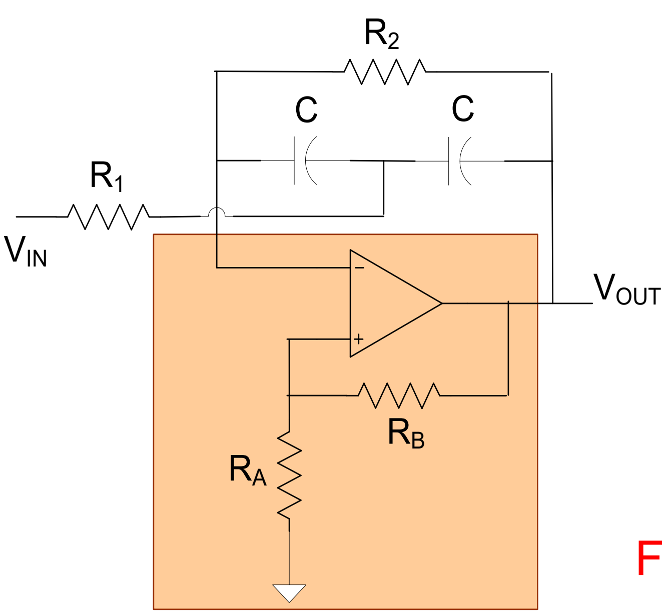
Filter is unstable !

Example: Filter Structure with Feedback Amplifier

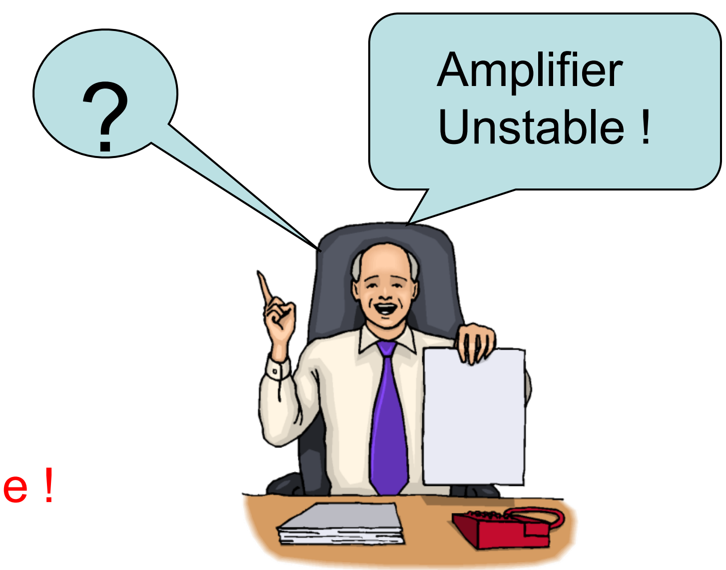
Bridged-T Biquad
(with feed-forward)







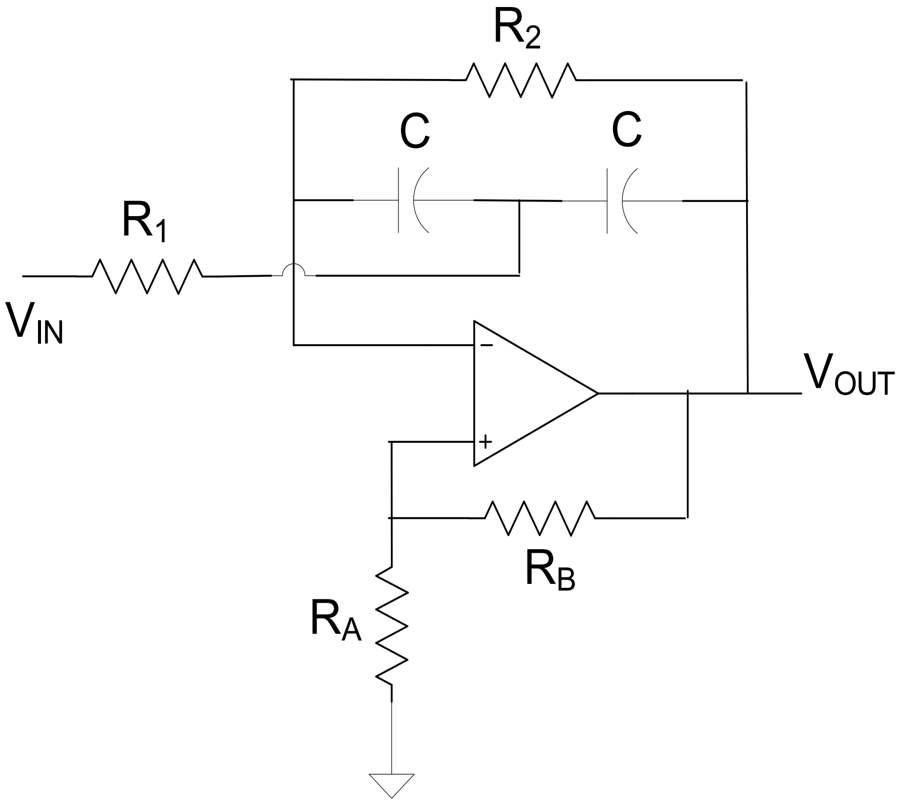
Friend/Deliyannis Biquad



Filter is stable !

Very Popular Bandpass Filter

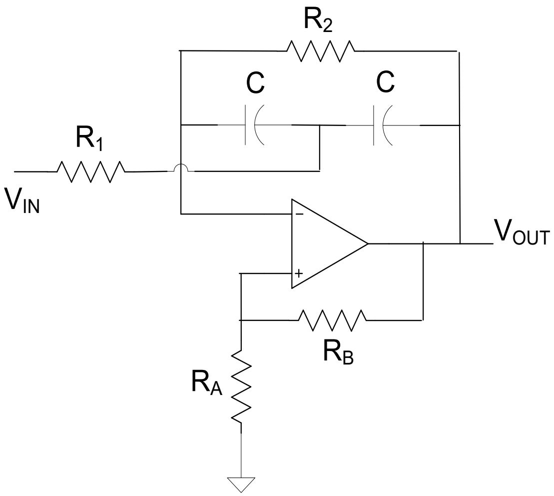
Friend-Deliyannis Biquad



One of the best bandpass filters !!

Embedded finite gain amplifier is unstable!!

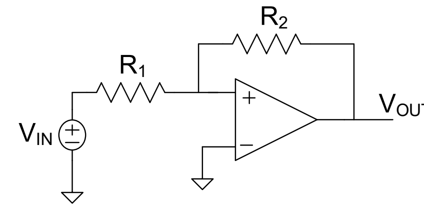
Stability of embedded amplifier is not necessary (or even desired)



- Filter structure unstable with stable finite gain amplifier
- Filter structure stable with unstable finite gain amplifier
- Stability of feedback network not determined by stability of amplifier!

Why is this circuit is seldom discussed?

Support your answer with sound analytical principles or concepts.

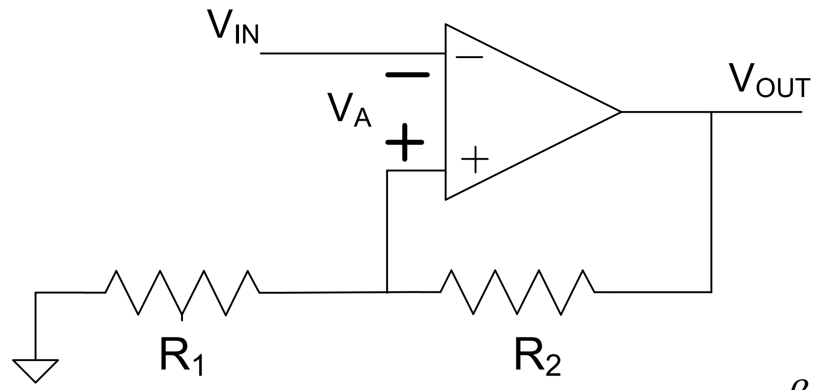


Is positive feedback bad?

Why is this issue important?

How can you trust or be confident in your analysis and understanding if the principles you use to analyze even some of most basic circuits fail in <u>slightly</u> different circuits?

Consider the positive feedback configuration



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

Assume single-pole amplifier model

$$A(s) = \frac{pA_O}{s+p}$$

$$V_{OUT} = A(s)\left(\beta V_{OUT} - V_{IN}\right)$$

$$\Rightarrow \quad A_{CL}(s) = \frac{V_{OUT}}{V_{IN}} = \frac{-pA_O}{s + p\left(1 - \beta A_O\right)} \cong \frac{-pA_O}{s - p\beta A_O}$$

$$p_1 = p\left(1 - \beta A_O\right) \simeq -p\beta A_O$$

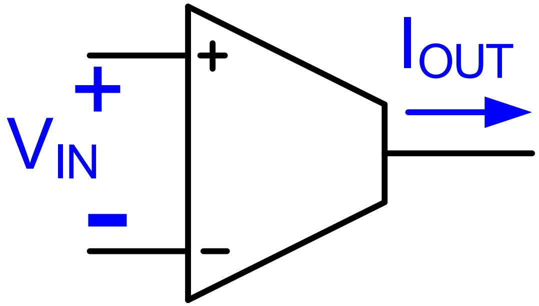
Note pole in RHP on positive real axis !

The circuit is unstable when operating linearly and output will be of form Ke^{-pt}

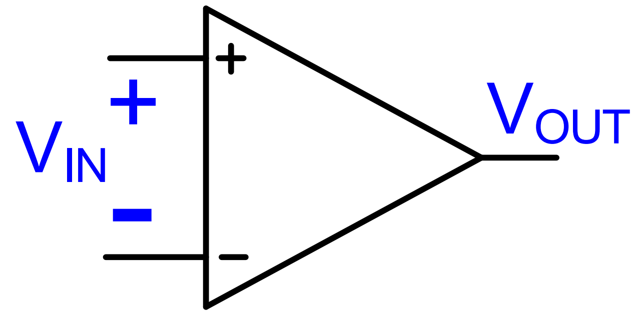
Does this mean this amplifier is not useful?

This circuit is widely used as a comparator with hysteresis, but it is not a stand-alone amplifier!

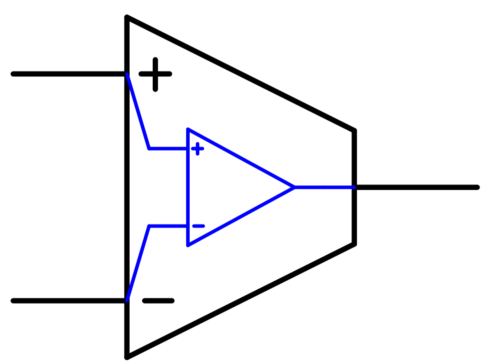
Transconductance vs Voltage Gain



$$I_{OUT} = g_m V_{IN}$$



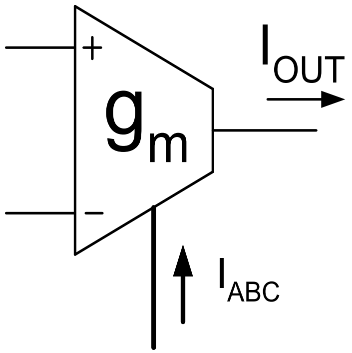
$$V_{OUT} = A_V V_{IN}$$



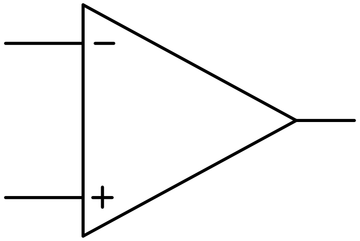
Same Circuit – Two Perspectives

OTA Circuits

OTA often used open loop



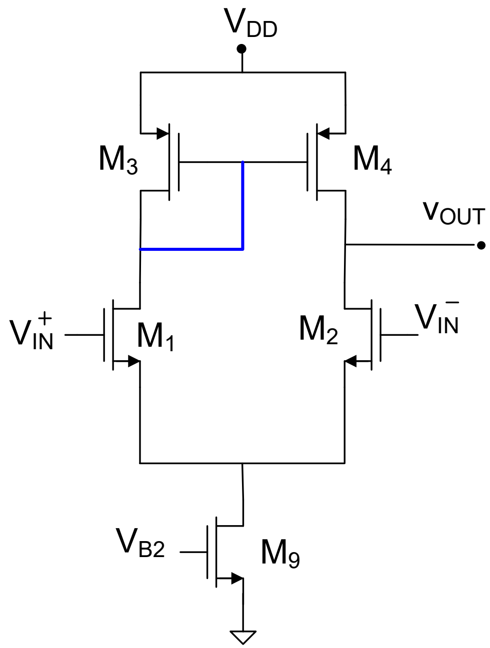
Recall: Op Amp almost never used open loop

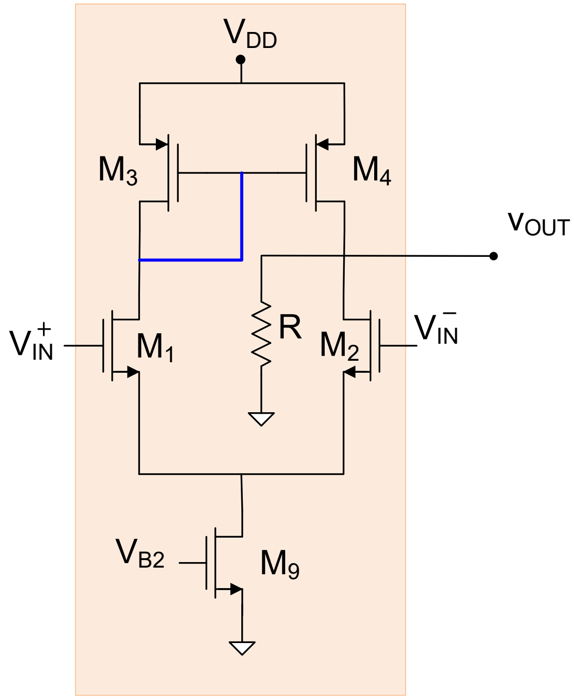


Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

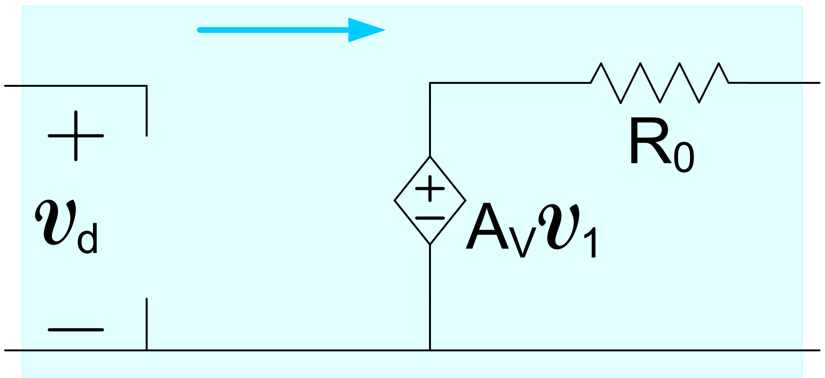
Challenge to students: Resolve what may appear to be conflicting statements.

Compare the Gain and Output Impedance of These 2 Amplifiers





Both can be modeled as a two-port:



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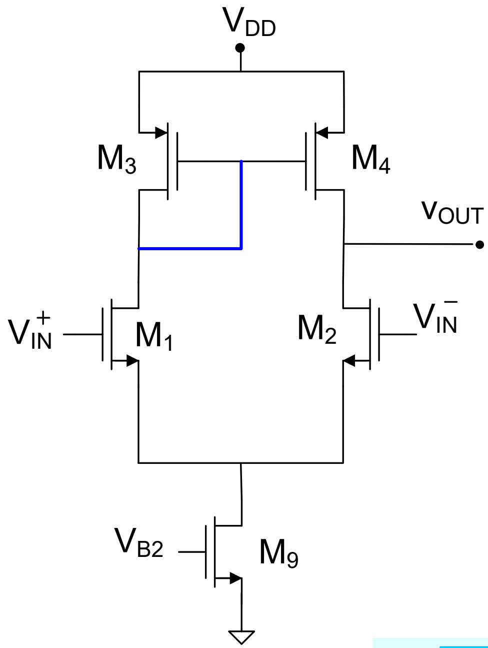
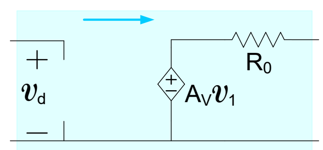
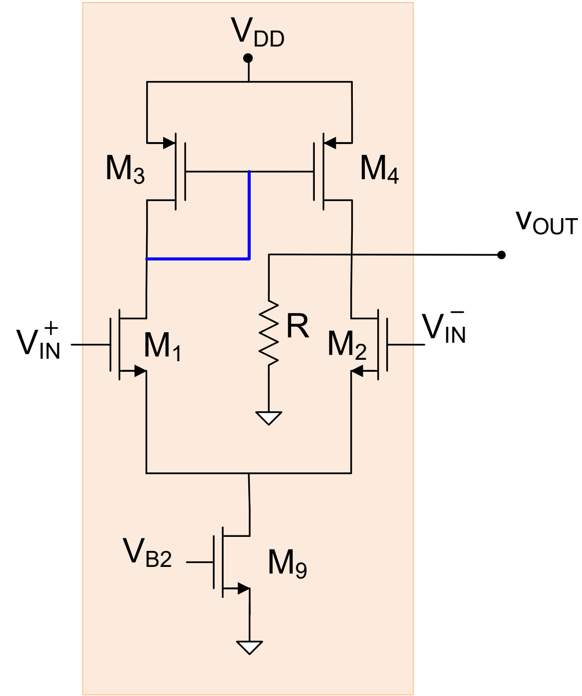






$$A_V = -\frac{g_{m1}}{2g_{01}} = \frac{1}{\lambda V_{EB1}}$$

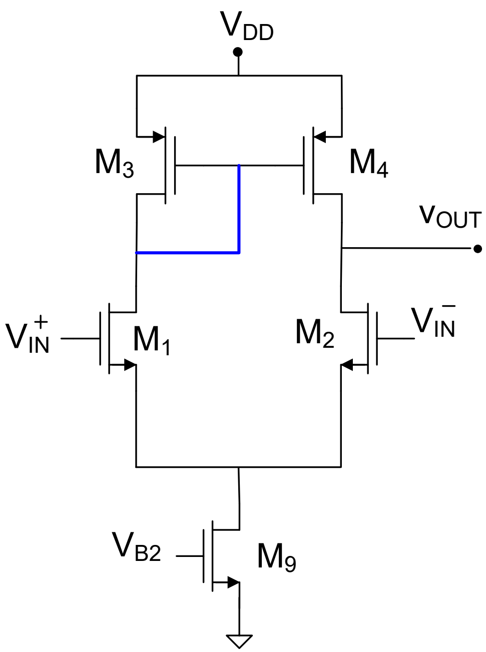
$$g_O = 2g_{01} = \lambda I_{TAIL}$$

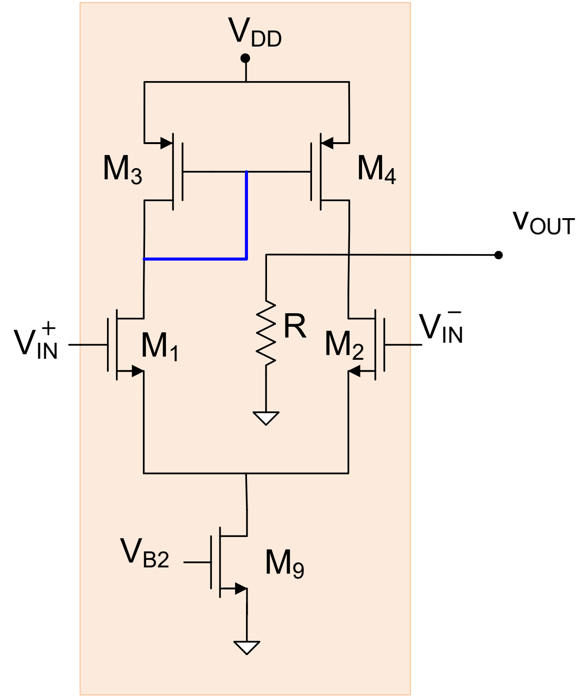
$$A_V = -g_{m1}\frac{R}{1+2Rg_{01}}$$

$$g_O = 2g_{01} + \frac{1}{R}$$

Compare the Gain and Output Impedance of These 2 Amplifiers

How do they compare if V_{EB1}=0.2V, R=1K, λ=0.01V^{-1} ,I_{TAIL}=1mA





$$A_V = -\frac{g_{m1}}{2g_{01}} = \frac{1}{\lambda V_{EB1}}$$

$$g_O = 2g_{01} = \lambda I_{TAIL}$$

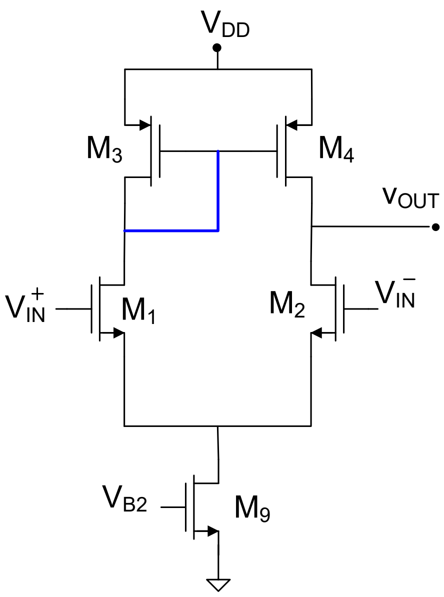
$$A_V = -g_{m1}\frac{R}{1+2Rg_{01}} = -\frac{I_{TAIL}}{V_{EB1}}\frac{R}{1+2Rg_{01}}$$

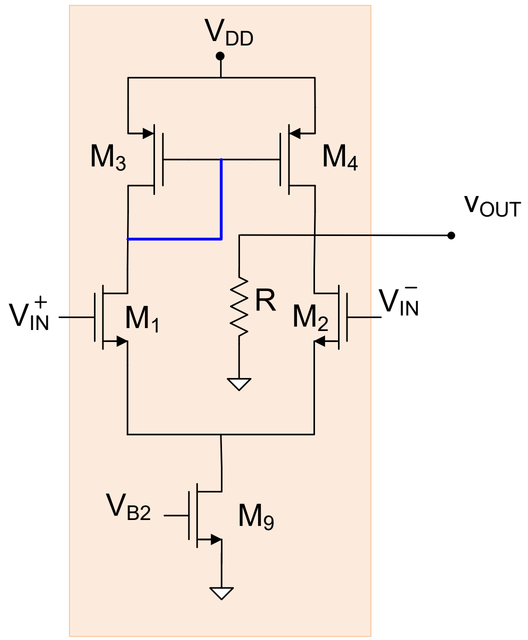
$$g_O = 2g_{01} + \frac{1}{R}$$

Compare the Gain and Output Impedance of These 2 Amplifiers

How do they compare if V_{EB1}=0.2V, R=1K, λ=0.01V^{-1} ,I_{TAIL}=1mA

- Is the open-loop op amp gain high?
- Is the output impedance low?





$$A_V = -\frac{1}{\lambda V_{EB1}} = -500$$

$$A_V = -\frac{I_{TAIL}}{V_{EB1}} \frac{R}{1+2Rg_{01}} = -4.95$$

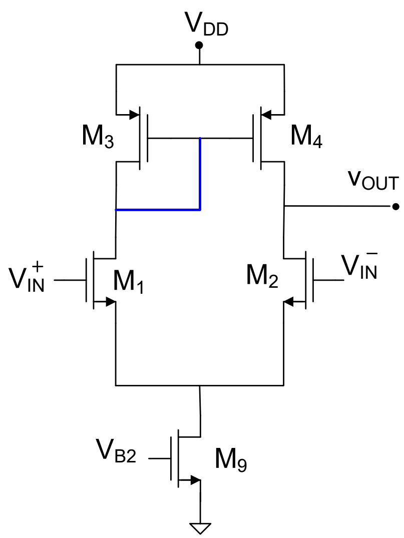
$$g_O = \lambda I_{TAIL} = 10^{-5}\Omega^{-1}$$

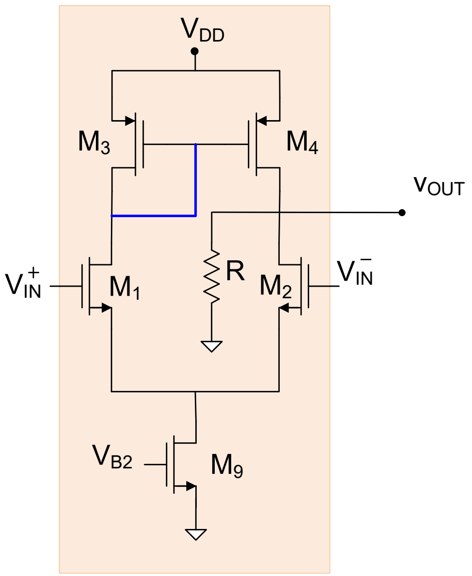
$$g_O = 2g_{01} + \frac{1}{R} = 1.02x10^{-3}\Omega^{-1}$$

Compare the Gain and Output Impedance of These 2 Amplifiers

Is the open-loop op amp gain high?

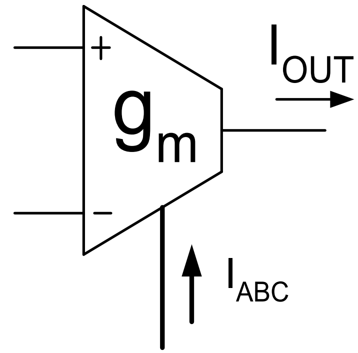
This effect will be much more dramatic for the other high gain op amps, including the Current Mirror Op Amp, that we have considered thus far!



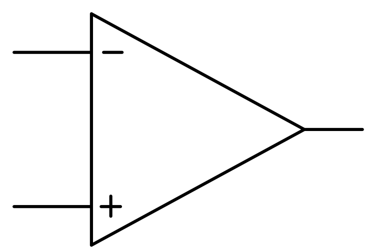


OTA Circuits

OTA often used open loop



Recall: Op Amp almost never used open loop

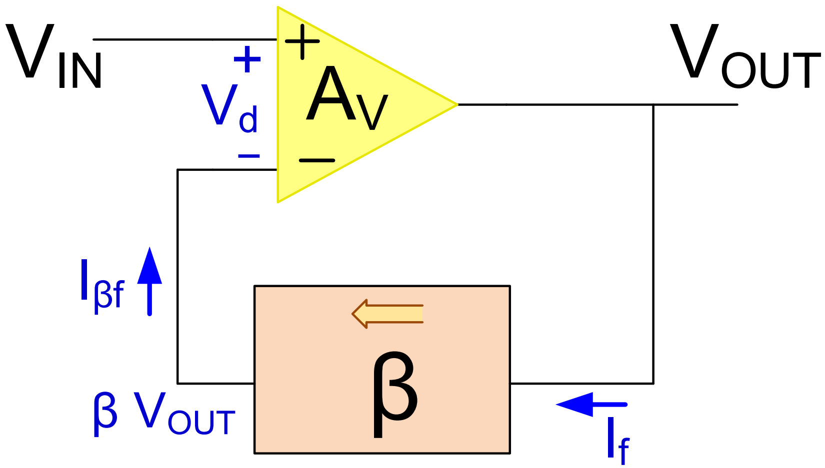


Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

Challenge to students: Resolve what may appear to be conflicting statements.

One Standard Feedback Configuration

Voltage-Series Feedback (one of the 4 most basic types)

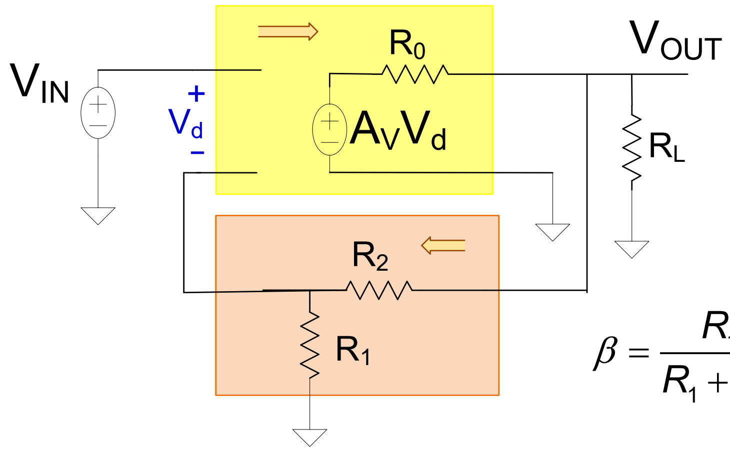


Assume ideal input and output impedance on A_V and β

$$\left.\begin{aligned} V_d &= V_{IN} - \beta V_{OUT} \\ V_{OUT} &= A_V V_d \end{aligned}\right\} \Rightarrow \quad A_{VF} = \frac{A_V}{1+\beta A_V} \underset{A_V \to \infty}{\simeq} \frac{1}{\beta}, \quad V_d \underset{A_V \to \infty}{\simeq} 0$$

One Standard Feedback Configuration

Voltage-Series Feedback (one of the 4 most basic types)



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

Define:

$$\theta = \frac{[R_1 + R_2]//R_L}{R_0 + [R_1 + R_2]//R_L}$$

Include Loading of nonideal A amplifier with β network

$$A_{VEFF} = \frac{V_{OUT}}{V_d}$$

$$V_d = V_{IN} - \beta V_{OUT}$$

⇒

$$V_{OUT} = A_{VEFF}\left(V_{IN} - \beta V_{OUT}\right)$$

$$V_d = V_{IN}\frac{1}{1+\beta A_{VEFF}}$$

⇓

$$A_{VF} = \frac{V_{OUT}}{V_{IN}} = \frac{A_{VEFF}}{1+\beta A_{VEFF}} \underset{A_{VEFF}\to\infty}{\simeq} \frac{1}{\beta}$$

$$V_d \underset{A_{VEFF}\to\infty}{\simeq} 0$$

$$V_{OUT} = A_V V_d \left(\frac{[R_1 + R_2]//R_L}{R_0 + [R_1 + R_2]//R_L}\right) = \theta A_V V_d$$

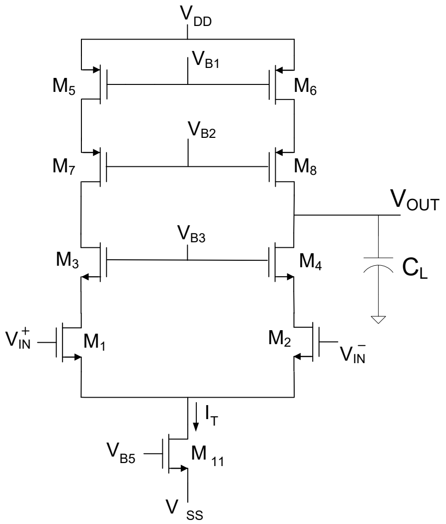
$$A_{VEFF} = \theta A_V$$

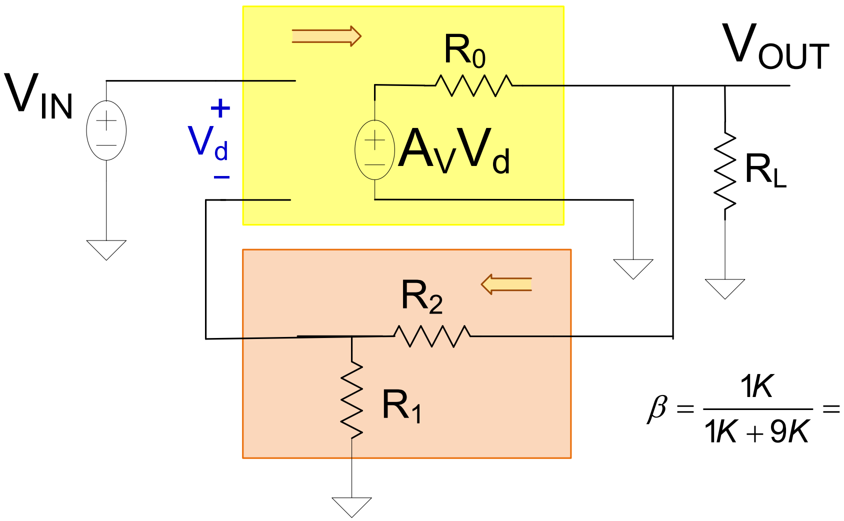
$$A_{VF} = \frac{A_{VEFF}}{1+\beta A_{VEFF}}$$

Example: Effects of Loading

Consider telescopic cascode op amp with $V_{EB1}=V_{EB3}=V_{EB5}=200mV$, $I_T=100uA$, $\lambda=.01V^{-1}$

Assume $R_1=1K$, $R_2=9K$, $R_L=10K$





$$\theta = \frac{[R_1+R_2]//R_L}{R_0+[R_1+R_2]//R_L}$$

$$\beta = \frac{1K}{1K+9K} = 0.1$$

Without considering loading, it follows that for dc input:

$$A_{V0} = \frac{2}{V_{EB1}\left(\lambda_1\lambda_3 V_{EB3} + \lambda_5\lambda_7 V_{EB5}\right)}$$

$$g_{OUT} = g_{02}\frac{g_{04}}{g_{m4}} + g_{06}\frac{g_{08}}{g_{m8}}$$

$$A_{VF} = \frac{A_{V0}}{1+\beta A_{V0}} = \frac{2.5x10^6}{1+2.5x10^6 x0.1} = 9.999960$$

A_{VF} very close to the ideal value of $\frac{1}{\beta} = 10.000$

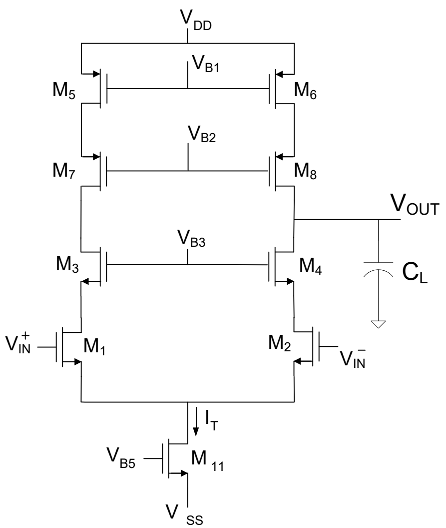
$$A_{V0} = \frac{1}{V_{EB1}^2\lambda^2} = 2.5x10^6$$

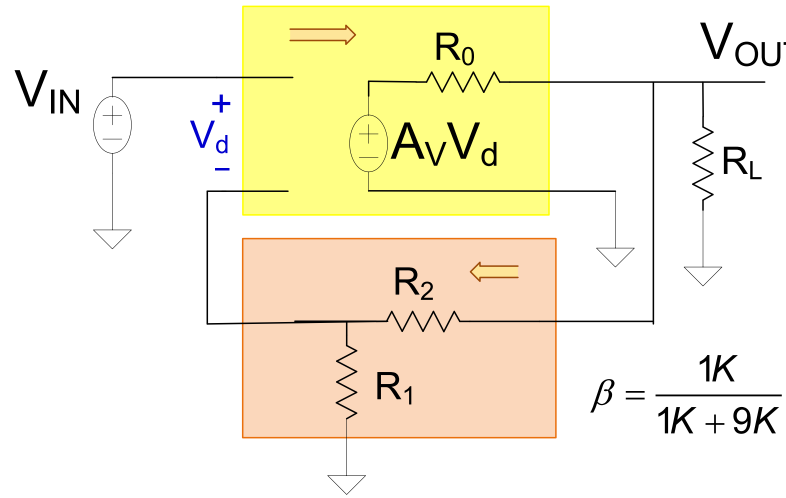
$$g_{OUT} = 2\lambda I_{D2Q}\frac{\lambda I_{D4Q}}{2\frac{I_{D4Q}}{V_{EB4}}} = \lambda^2 I_{D2Q}V_{EB4} = \lambda^2\frac{I_T}{2}V_{EB4} = 10^{-9}$$

Example: Effects of Loading

Consider telescopic cascode op amp with $V_{EB1}=V_{EB3}=V_{EB5}=200mV$, $I_T=100uA$, $\lambda=.01V^{-1}$

Assume $R_1=1K$, $R_2=9K$, $R_L=10K$





$$\theta = \frac{[R_1+R_2]//R_L}{R_0+[R_1+R_2]//R_L}$$

$$\beta = \frac{1K}{1K+9K} = 0.1$$

$$A_{V0} = \frac{2}{V_{EB1}\left(\lambda_1\lambda_3 V_{EB3} + \lambda_5\lambda_7 V_{EB5}\right)}$$

$$g_{OUT} = g_{02}\frac{g_{04}}{g_{m4}} + g_{06}\frac{g_{08}}{g_{m8}}$$

$$A_{V0} = \frac{1}{V_{EB1}^2\lambda^2} = 2.5x10^6$$

$$g_{OUT} = 2\lambda I_{D2Q}\frac{\lambda I_{D4Q}}{2\frac{I_{D4Q}}{V_{EB4}}} = \lambda^2 I_{D2Q}V_{EB4} = \lambda^2\frac{I_T}{2}V_{EB4} = 10^{-9}$$

With Loading for dc input:

$$R_0 = 10^9\Omega$$

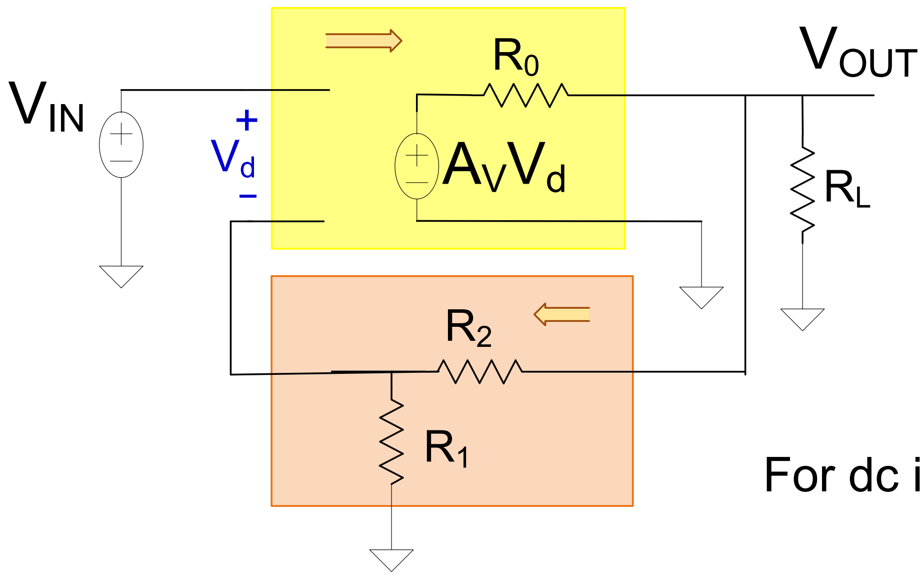
$$\theta = \frac{[R_1+R_2]//R_L}{R_0+[R_1+R_2]//R_L} = \frac{5K}{10^9+5K} \cong 5x10^{-6}$$

$$A_{VEFF} = \theta A_V = 5x10^{-6}x2.5x10^6 = 12.5$$

$$A_{VF} = \frac{A_{VEFF}}{1+\beta A_{VEFF}} = \frac{12.5}{1+1.25} = 5.\tilde{5}$$

Almost useless as a FB amplifier in this application !

Effective Gain of Operational Amplifiers



For dc input, $A_V = A_{V0}$

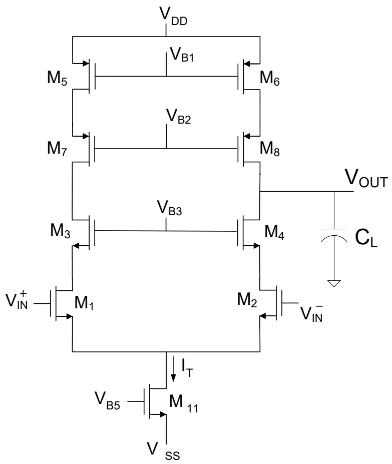
$$A_{VF} = \frac{A_{V0}}{1+\beta A_{V0}} \Rightarrow A_{VF} = \frac{A_{VEFF}}{1+\beta A_{VEFF}}$$

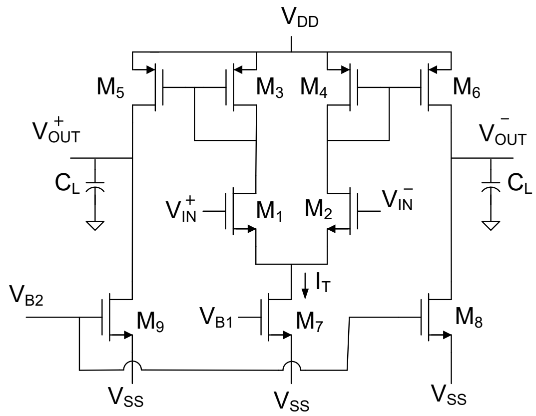
The open loop gain of an operational amplifier used in a FB configuration must include the loading of the feedback network and load resistor

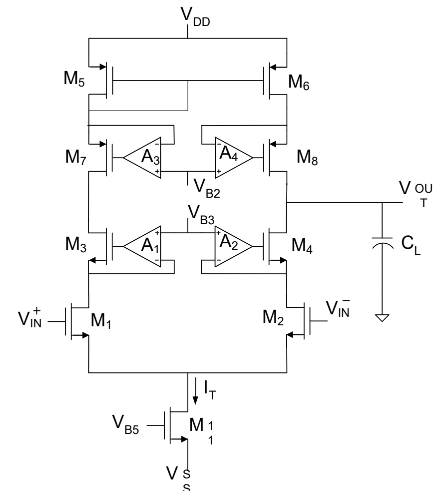
Some FB networks cause little or no loading and others can be significant

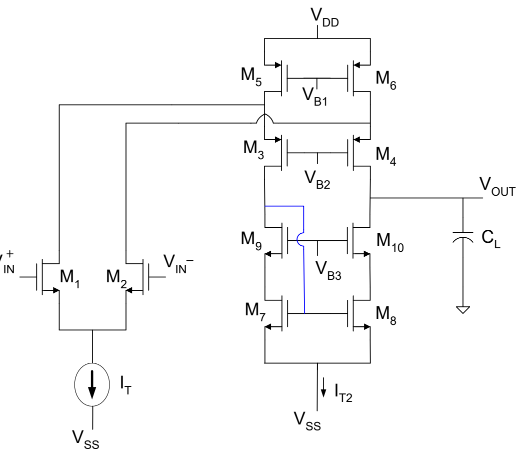
Often a buffer stage is added to the output of the op amp when used in FB applications driving “heavy” loads

Are these “high gain” amplifiers really high gain amplifiers?



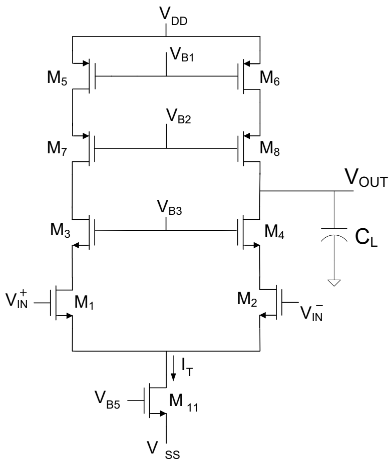


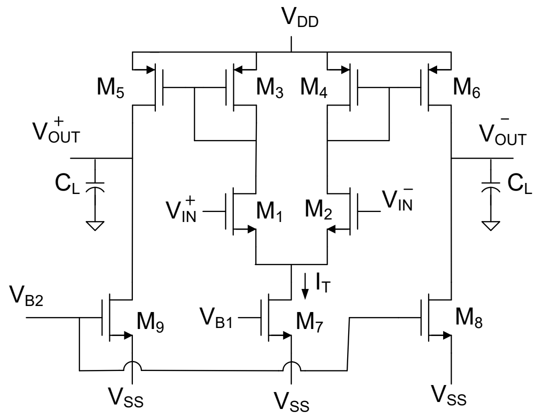


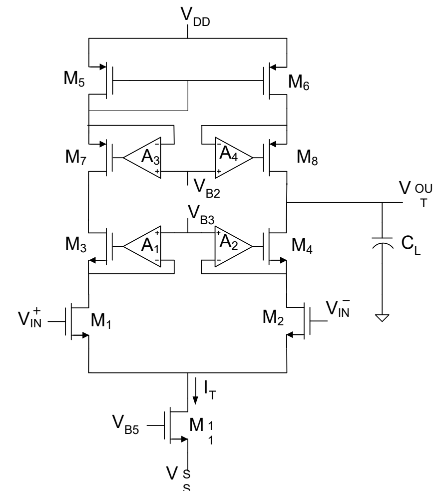


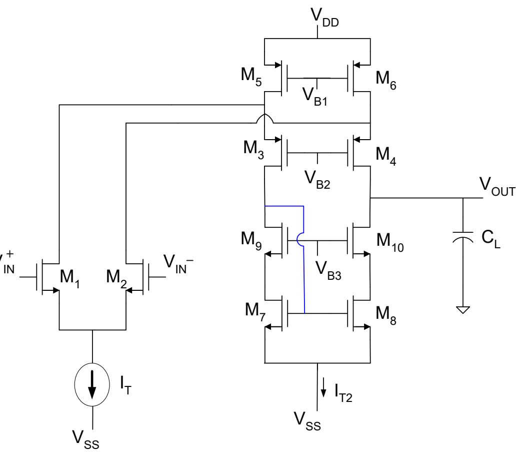
- All have high voltage gain if not driving heavy loads !
- Output buffer stage can be added to all to drive heavy loads and maintain high effective voltage gain
- All have very high output impedance so are inherently transconductance amplifiers
- None have large transconductance gain so are not good for feedback applications as transconductance amplifiers

Are these “high gain” amplifiers really high gain amplifiers?



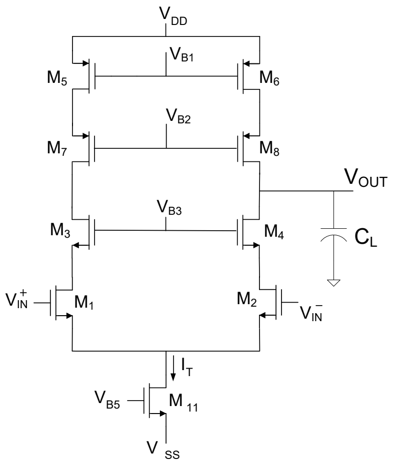


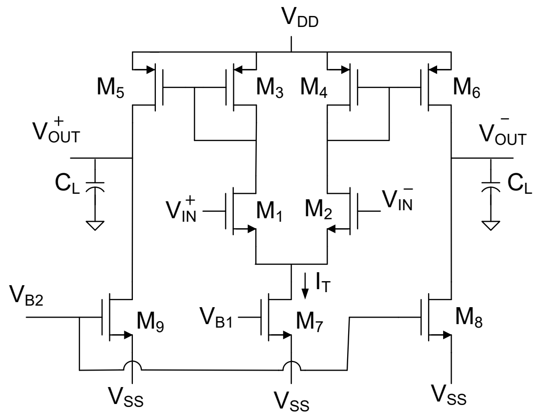


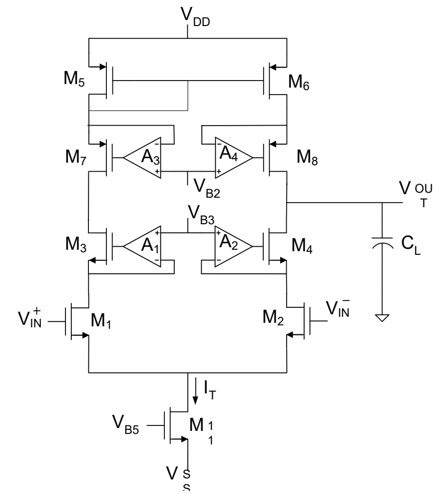


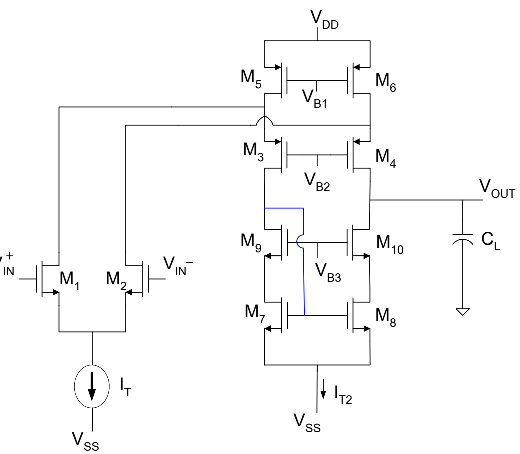
- High voltage gain op amps are seldom used open loop to build voltage amplifiers
- Since all have low transconductance gains, can be used open-loop in transconductance applications
- When used in transconductance applications, often termed Operational Transconductance Amplifiers (OTAs)
- When intended to be used as OTAs, voltage or current control input often added to electrically control the gain.

Are these “high gain” amplifiers really high gain amplifiers?









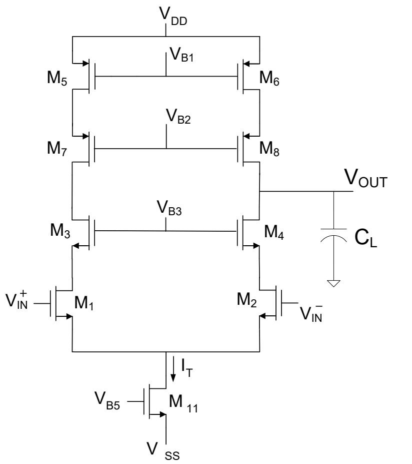
Are these high gain voltage amplifiers?

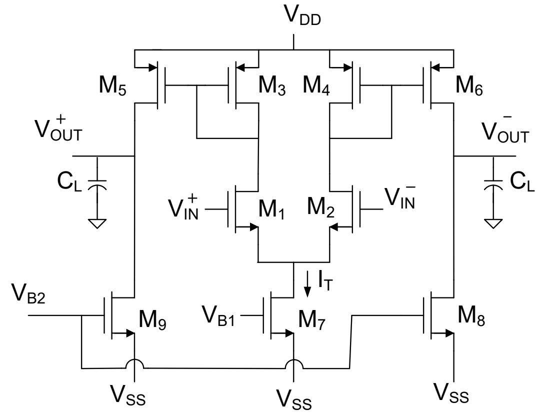
Are these high gain transconductance amplifiers?

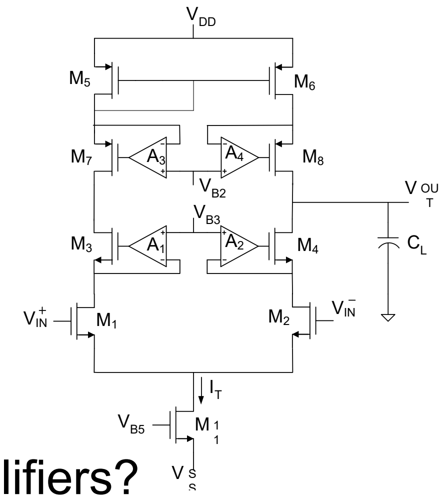
Are these high gain current amplifiers?

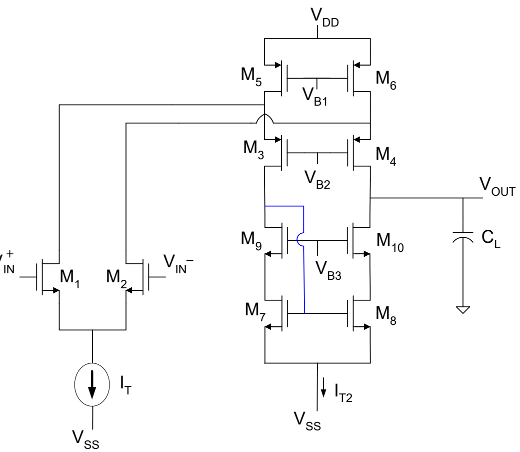
Are these high gain transresistance amplifiers?

Are these "high gain" amplifiers really high gain amplifiers?









Are these high gain voltage amplifiers?

Yes if loading ignored

Are these high gain transconductance amplifiers?

No!

Are these high gain current amplifiers?

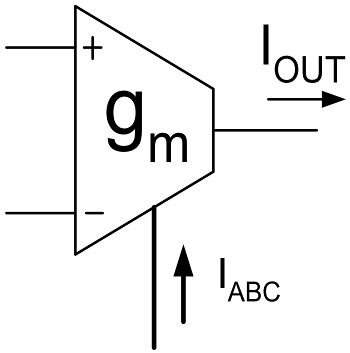
No input current but if modified with low impedance shunt at input, have low current gain

Are these high gain transresistance amplifiers?

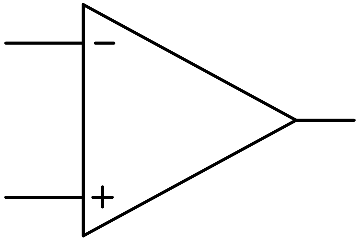
No input current but if modified with low impedance shunt at input, transresistance gain would not be high even if loading of output neglected

OTA Circuits

OTA often used open loop



Recall: Op Amp almost never used as an open amplifier

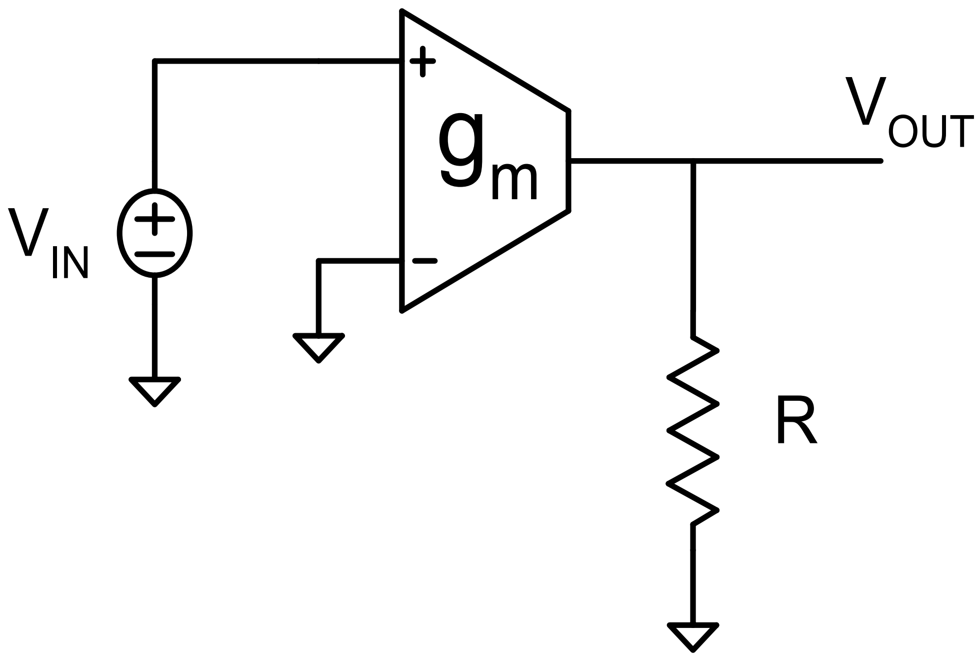


Since we just showed that the OTA is also a good high-gain op amp it seems there are conflicting statements

Challenge to students: Resolve what may appear to be conflicting statements.

OTA Applications

OTA Applications



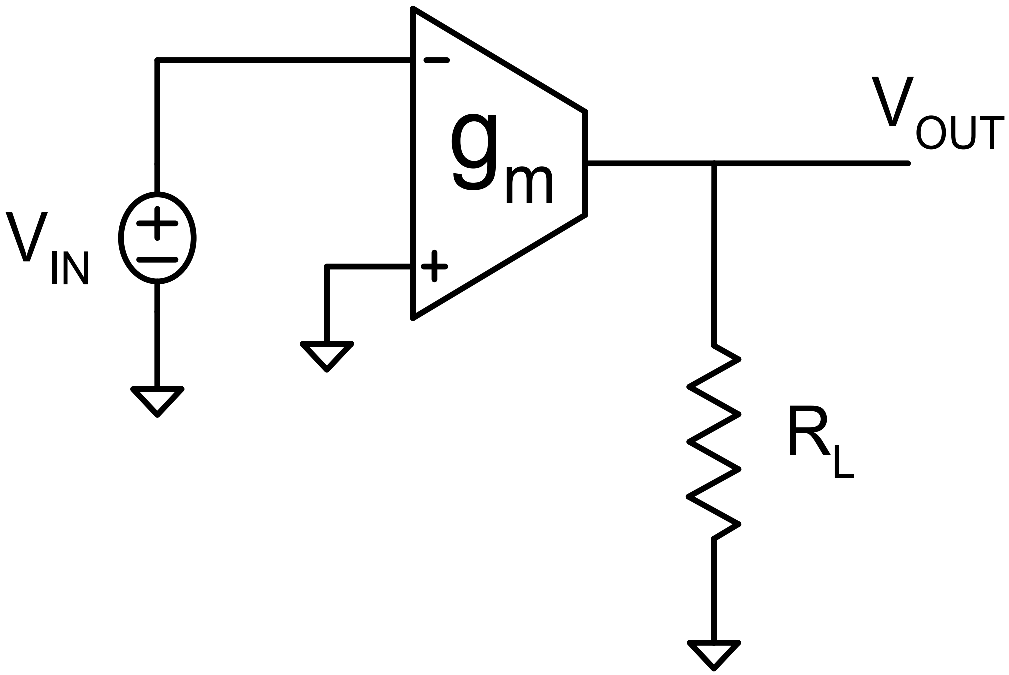
$$V_{OUT} = g_m R \bullet V_{IN}$$

g_m is controllable with I_{ABC}

Voltage Controlled Amplifier

Note: Technically current-controlled, control variable not shown here and on following slides

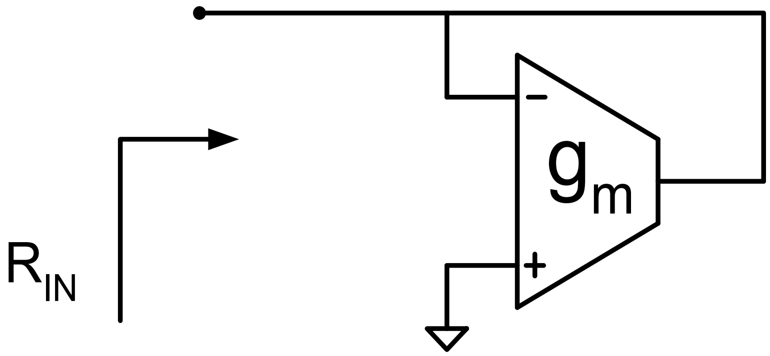
OTA Applications

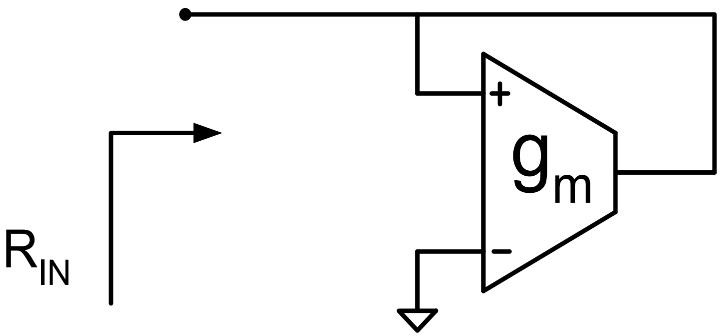


$$V_{OUT} = -g_m R \bullet V_{IN}$$

Voltage Controlled Inverting Amplifier

OTA Applications



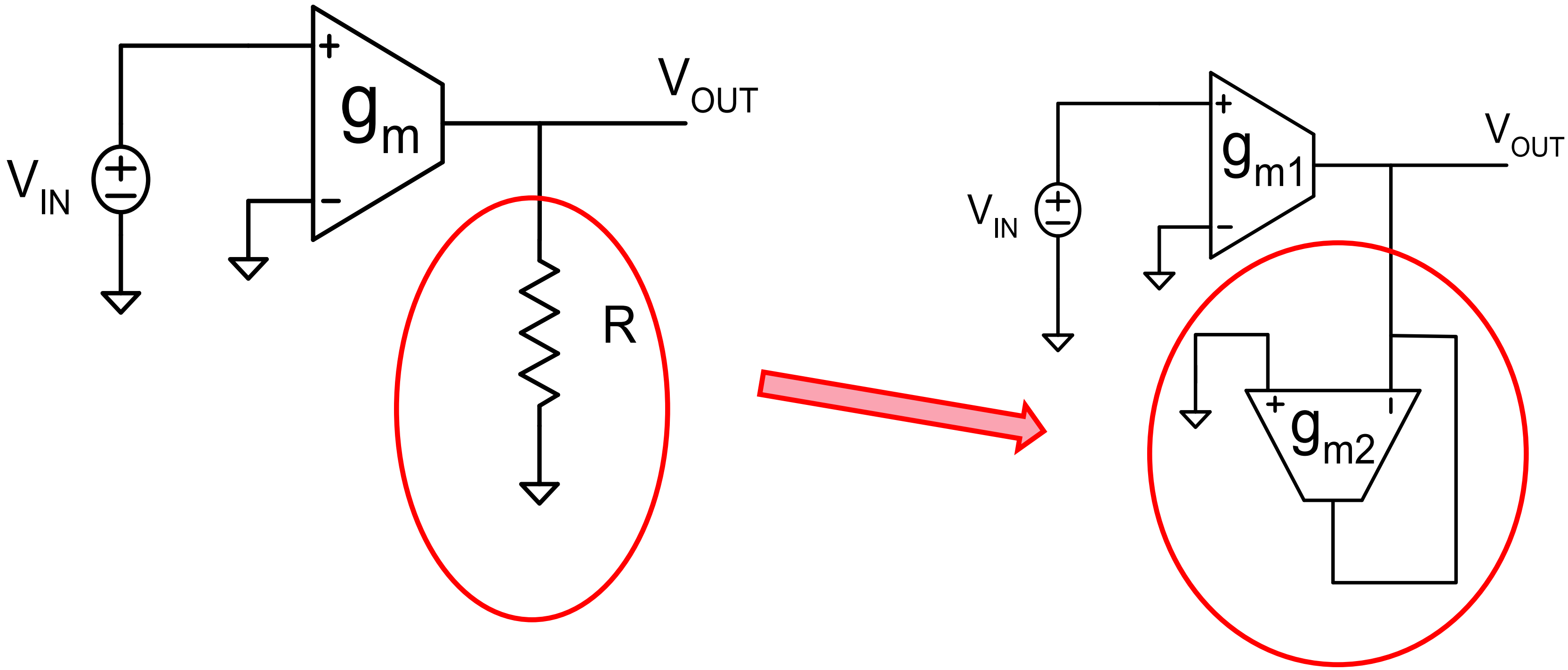


$$R_{IN} = \frac{1}{g_m}$$

$$R_{IN} = -\frac{1}{g_m}$$

Voltage Controlled Resistances

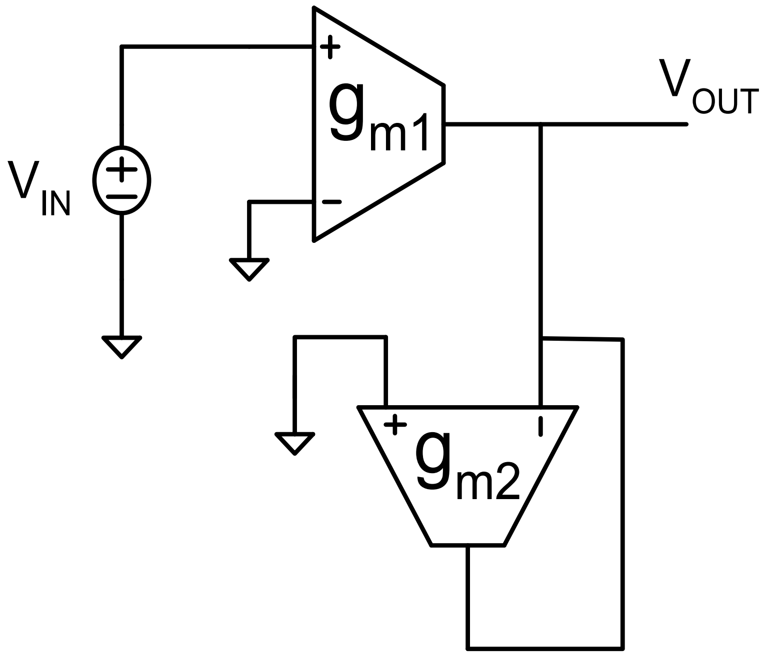
OTA Applications



Resistorless Amplifiers

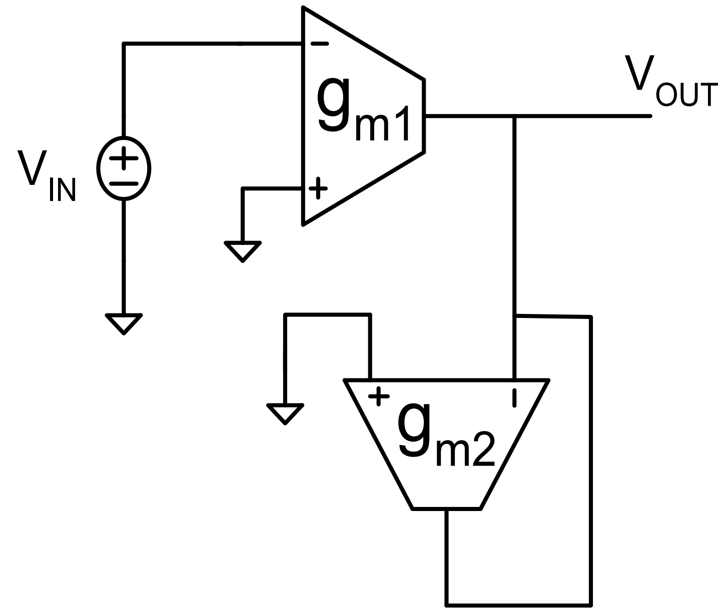
Would anyone ever do something like this ?

OTA Applications



$$V_{OUT} = \frac{g_{m1}}{g_{m2}} V_{in}$$

Noninverting Voltage Controlled Amplifier



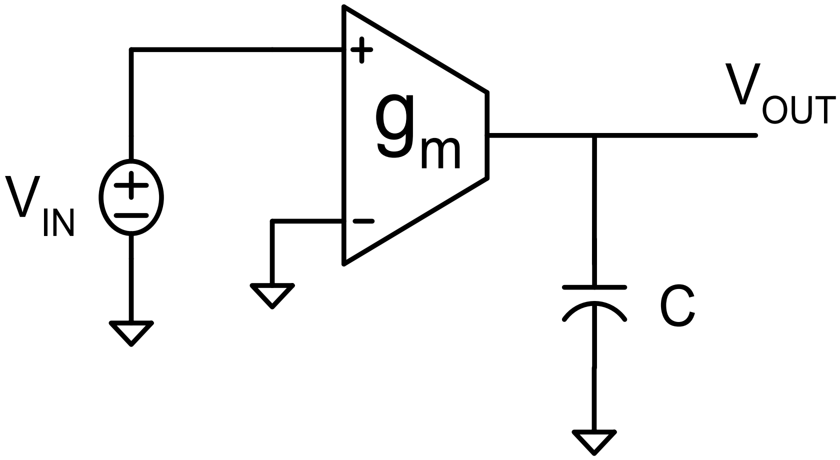
$$V_{OUT} = -\frac{g_{m1}}{g_{m2}} V_{in}$$

Inverting Voltage Controlled Amplifier

Extremely large gain adjustment is possible

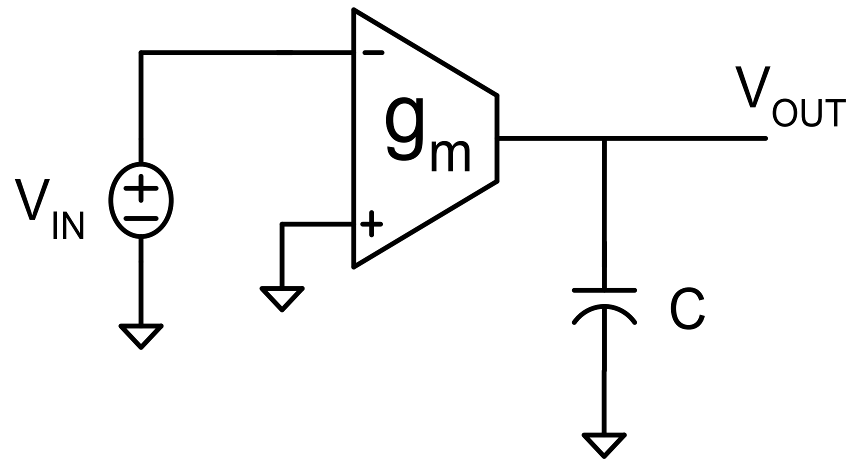
Voltage Controlled Resistorless Amplifiers

OTA Applications



$$V_{OUT} = \frac{g_m}{sC} V_{in}$$

Noninverting Voltage Controlled Integrator



$$V_{OUT} = -\frac{g_m}{sC} V_{in}$$

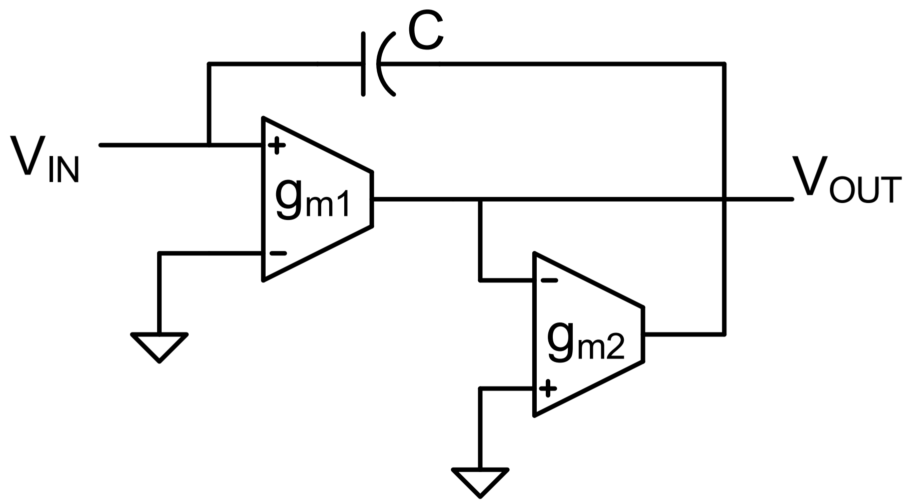
Inverting Voltage Controlled Integrator

Voltage Controlled Integrators

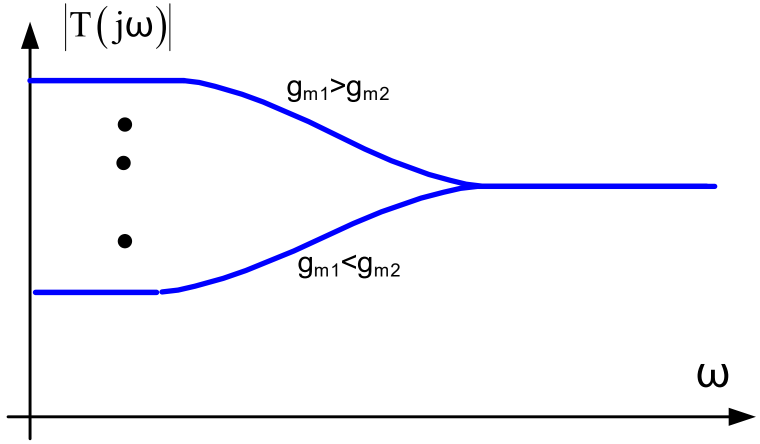
OTA Applications

Shelving Equalizer (First-order filter)

Programmable with g_{m1} or g_{m2}



$$T(s) = \frac{sC + g_{m1}}{sC + g_{m2}}$$

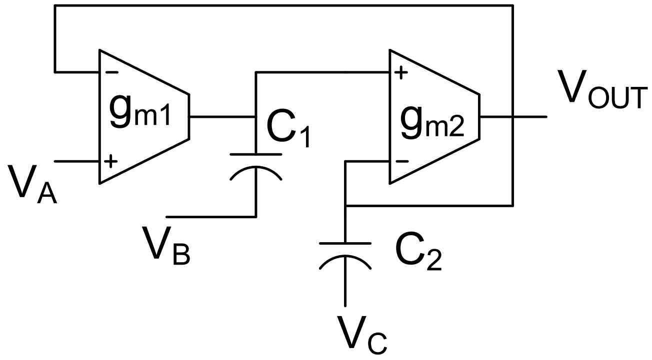


OTA Applications

Biquadratic Filter

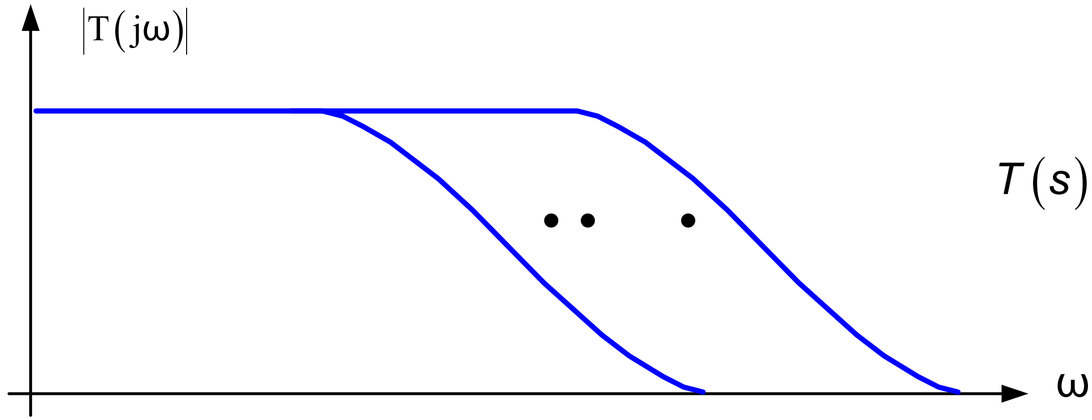
Programmable with g_{m1} or g_{m2}

Individual or Combined Inputs Can Be Used (Lowpass, Bandpass,Highpass, Notch,…)



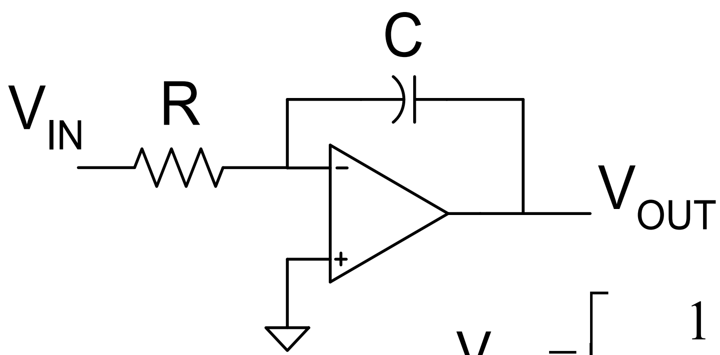
$$V_{OUT}(s)=\frac{V_C s^2+V_B s\frac{g_{m2}}{C_2}+V_A\frac{g_{m1}g_{m2}}{C_1C_2}}{s^2+s\frac{g_{m2}}{C_2}+\frac{g_{m1}g_{m2}}{C_1C_2}}$$

Lowpass response only shown (V_C=0, V_B=0, V_{IN}=V_A)

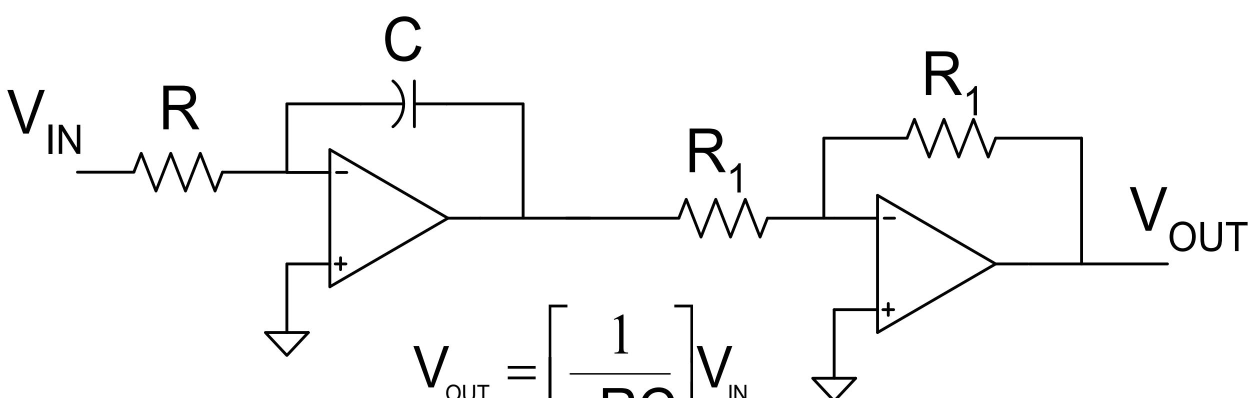


$$T(s)=\frac{V_{OUT}}{V_{IN}}=\frac{\frac{g_{m1}g_{m2}}{C_1C_2}}{s^2+s\frac{g_{m2}}{C_2}+\frac{g_{m1}g_{m2}}{C_1C_2}}$$

Comparison with Op Amp Based Integrators



$$V_{OUT} = \left[-\frac{1}{sRC} \right] V_{IN}$$



$$V_{OUT} = \left[\frac{1}{sRC} \right] V_{IN}$$

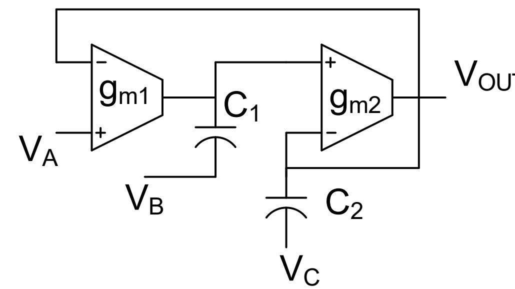
OTA-based integrators require less components and significantly less for realizing the noninverting integration function !

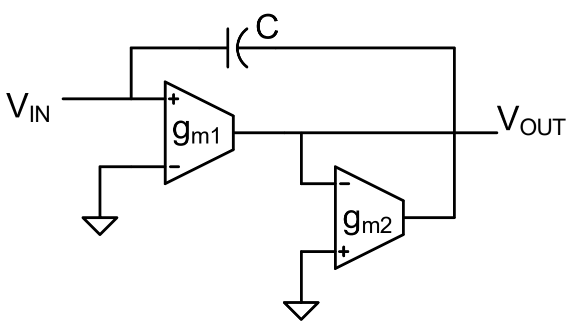
Properties of OTA-Based Circuits

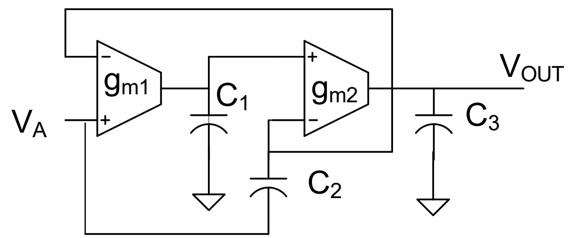
- Can realize arbitrarily complex functions
- Circuits are often simpler than what can be obtained with Op Amp counterparts
- Inherently offer excellent high frequency performance
- Can be controlled with a dc voltage or current
- Often used open-loop rather than in a feedback configuration (circuit properties depend directly on g_m)
- Other high output impedance op amps can also serve as OTA
- Linearity is limited
- Signal swing may be limited but can be good too
- Circuit properties process and temperature dependent

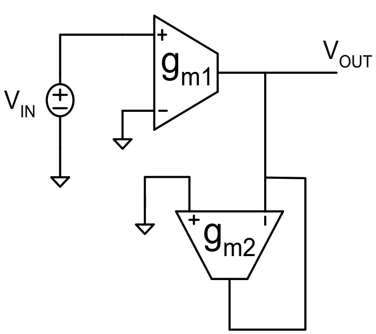
OTA Applications

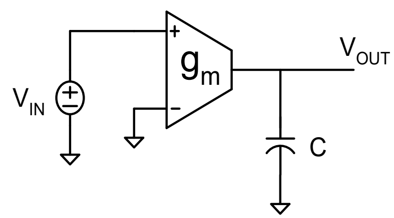
- OTA Applications are Extensive
- Programmable Features Are Attractive
- Can be Readily Integrated (often without resistors)
- Excellent high frequency performance

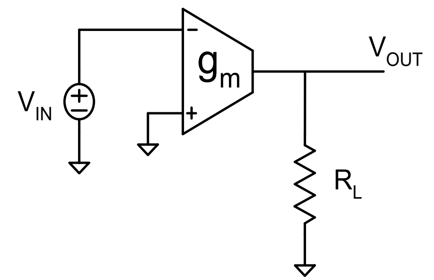


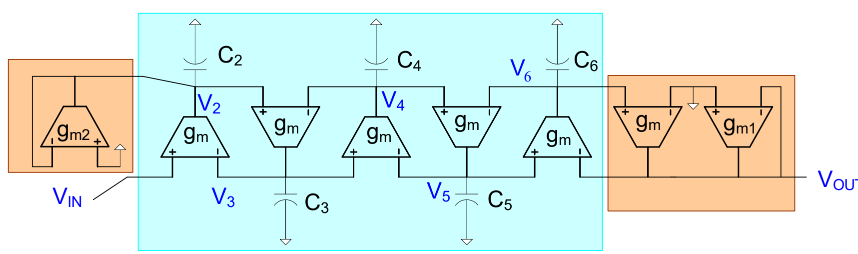












Stay Safe and Stay Healthy !

End of Lecture 10