Some chapter 4 Notes Shoeberth

4-1 Linear Dependent Sources

Design of circuits containing devices like transistors or op amps (are active devices)

active device is a component that requires an external power supply to operate correctly.

active circuit; a circuit is one that contains one or more active devices.

Active circuits are capable of providing signal amplification

→ recall the proportionallity property,

$$y = kx$$

Signal amplification means $k > 1$ when x and y have the same dimensions

→ active circuits can deliver more signal

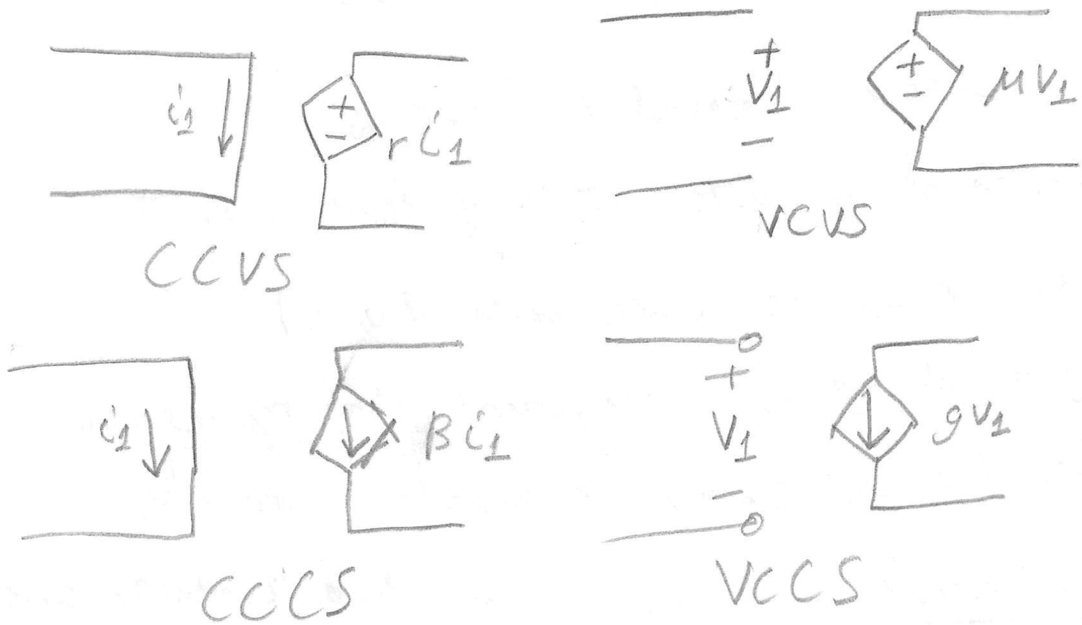
→ active devices operating in a linear mode are modeled using resistors and one or more dependent sources

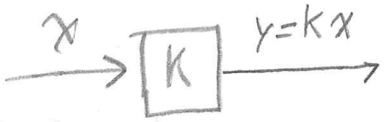
Dependent sources; is a voltage or current source whose output is controlled by a voltage or current in a different part of the circuit

4 Types

1.) Current controlled Voltage source (CCVS)
2.) Voltage controlled Voltage source (VCVS)
3.) current controlled current source (CCCS)
4.) Voltage controlled current source (VCCS)

Fig 4-1





Block Diagram of a gain stage

linear dependent source: output is proportional to the controlling voltage or current.

Proportionality factor: $\mu, \beta, r, g \rightarrow$ gain

Voltage gain: μ

Current gain: β

trans-resistance: r Ω

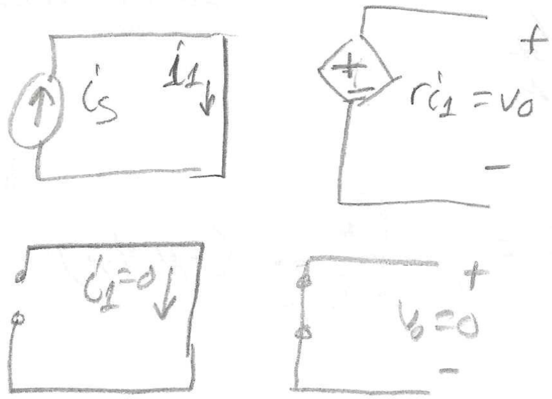
transconductance: g Ω^{-}

Dependent sources aren't physical devices, they are used in combination with other circuit elements to create models of active devices

Voltage source shorts when it turns off
Current source open circuit when its off

Dependent sources that turn off behave the same
→ They don't turn off individually
→ They depend on excitation supplied by independent sources

Fig 4-2



KCL
$i_s = i_1$
$v_0 = ri_1 = ri_s$

$i_s = 0 \rightarrow v_0 = ri_1 = 0$

Because of this, be careful of superposition and Thévenin's theorem

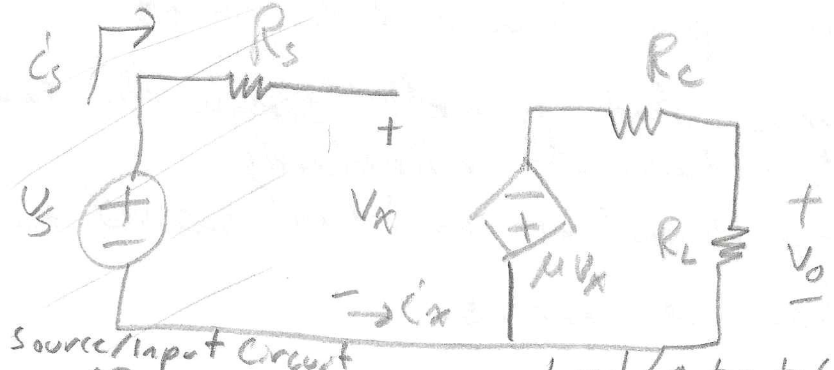
Superposition: responses due to all independent sources acting simultaneously is equal to the sum of the responses due to each independent source acting at one time.

[Difference? only at one time a signal!
No half + half
$f(x) + f(y+z) = f(x+y) + f(z)$ X for Dependent sources

p156 4-2 Analysis of Circuits with Dependent Sources
for dependent sources, we cannot lose the controlling signal in our analysis methods
→ we can do source transformation on dependent sources

(4)

Fig 4-3



Whats $K = \frac{V_o}{V_s}$

Voltase divider

$$V_o = \frac{R_L}{R_L + R_c}(-\mu V_x)$$

whats the relationship between V_x and V_s?

KVL: $-V_s + i_s R_s + V_x = 0$

open circuit, $i_s \rightarrow 0$

$V_x = V_s$

So $V_o = \frac{R_L}{R_L + R_c}(-\mu V_s)$ V $\rightarrow K = \frac{V_o}{V_s} = \frac{R_L}{R_L + R_c}(-\mu)$

Some observations

$R_s = R_c = R_L = 1\ k\Omega$, $\mu = 10^5$

So $K \rightarrow -50000$, Big

And $i_s = 0$, $i_x = 0$ → The source isn't supplying power

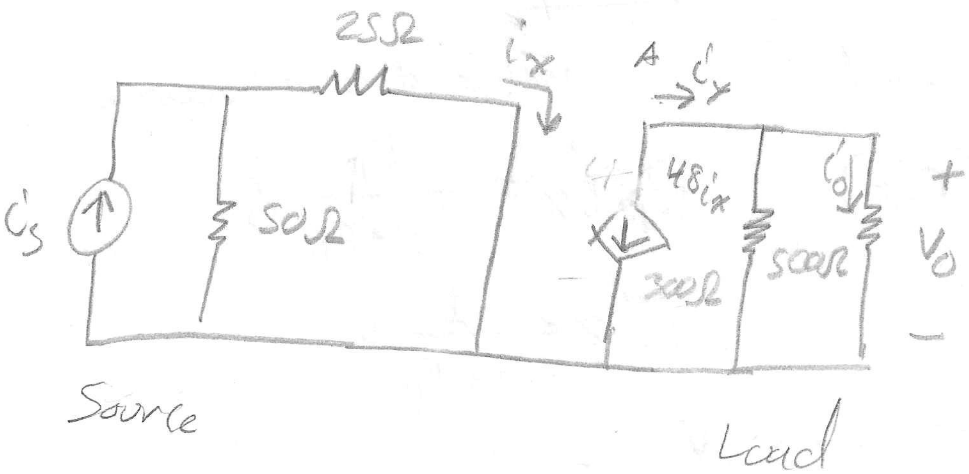
→ The Dependent Source doesn't rely on the input for power output

Pg 157

Ex) 4-1

i_o? V_o? P? and $K = \frac{P_o}{P_s}$, Power Gain

Fig 4-4



Current division: Load

$$i_o = \frac{300}{300+500} i_y$$

$$i_y = -48 i_x$$

Current division: Source

$$i_x = \frac{50}{50+25} i_s$$

So then,

$$i_o = \frac{300}{300+500}(-48)\frac{50}{50+25} i_s$$

$$i_o = -12 i_s \text{ A} \quad (4\text{-}3)$$

$$V_o = 500(i_o) = -6000 i_s \text{ V} \quad (4\text{-}4)$$

often, active circuits produce negative Ks

K < 0 → Signal Inversions

$$P_o = i_o V_o = 72{,}000\, i_s^2 \text{ W}$$

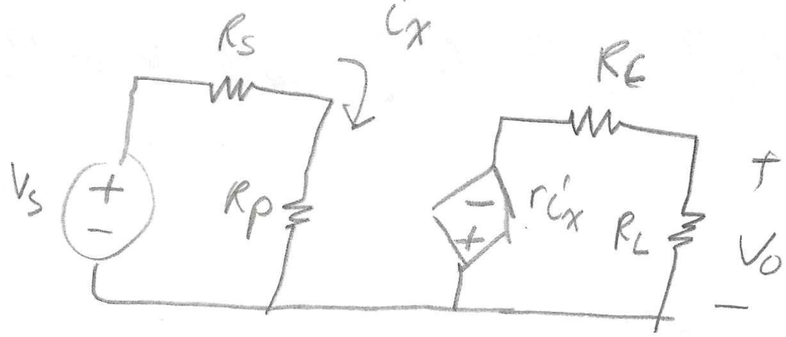
$$P_s = R_N i_s^2 = \overset{50/3}{(50 \| 25)}\, i_s^2 \text{ W}$$

$$K = \frac{72{,}000}{\frac{50}{3}}$$

(6) Exercise 4-1

V_O?

Fig 4-5



Voltage division: Load

$$V_O = \frac{R_L}{R_L + R_C}(-ri_x)$$

Voltage division: Source

$$R_P i_x = \frac{R_P}{R_S + R_P} V_S$$

$$i_x = \frac{1}{R_S + R_P} V_S$$

$$\rightarrow V_O = \frac{-R_L r}{(R_L + R_C)(R_S + R_P)} V_S$$

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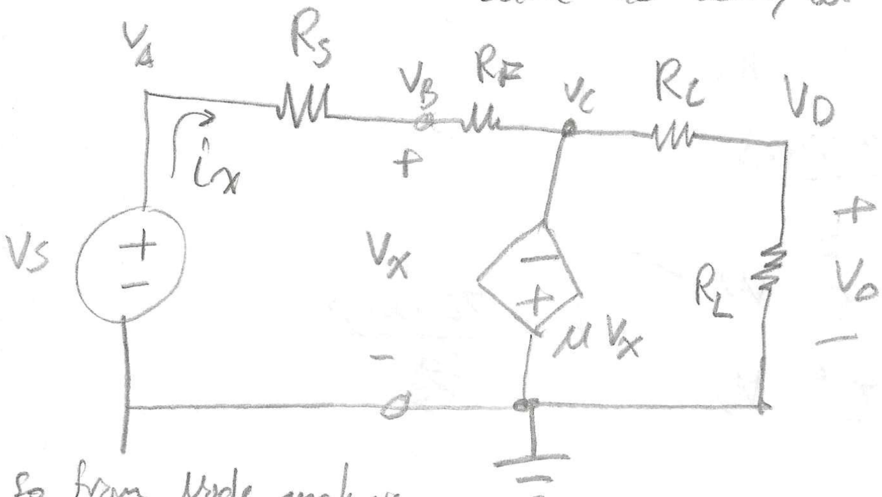
p159 Node-Voltage Analysis w/ Dependent Sources

Same as before, but we have another constraint

what's $K = V_O / V_S$



Node Voltage KCL Node B

$$\rightarrow \quad i_x = \frac{V_B - V_C}{R_F}$$

Remember Passive Sign Con.

$$\frac{V_A - V_B}{R_S} - \frac{(V_B - V_C)}{R_F} = 0$$

So from Node analysis

$V_A = V_S$, $V_B = V_x$, $V_C = -\mu V_x$, $V_D = V_O$

$$\frac{V_S - V_x}{R_S} - \frac{V_x - (-\mu V_x)}{R_F} = 0$$

Node D

$$\frac{V_C - V_D}{R_C} = \frac{V_D}{R_L}$$

$$\frac{-\mu V_x - V_O}{R_C} - \frac{V_O}{R_L} = 0$$

$$\frac{V_s}{R_s} - \frac{\mu V_x}{R_F} = V_x\left(R_s^{-1} + R_F^{-1}\right) \rightarrow V_x = \frac{v_s}{1 + \frac{(1+\mu) R_s}{R_F}}$$

for D

$$V_O\left(R_L^{-1} + R_c^{-1}\right) = \frac{-\mu V_x}{R_c} \rightarrow V_O = \frac{-\mu V_x R_L}{R_L + R_c}$$

So we have $V_O = \dfrac{-\mu R_L}{R_L + R_c}\left[\dfrac{v_s}{1 + \frac{(1+\mu) R_s}{R_F}}\right]$

Then we have $K = \dfrac{V_O}{V_s} = \left[\dfrac{-\mu R_L}{R_L + R_c}\right]\left[\dfrac{1}{1 + \frac{(1+\mu) R_s}{R_F}}\right]$

If we get rid of R_F, $R_F \longrightarrow \infty$

so now $K = \dfrac{-\mu R_L}{R_L + R_c}$, if all $R_s = 1\ k\Omega$

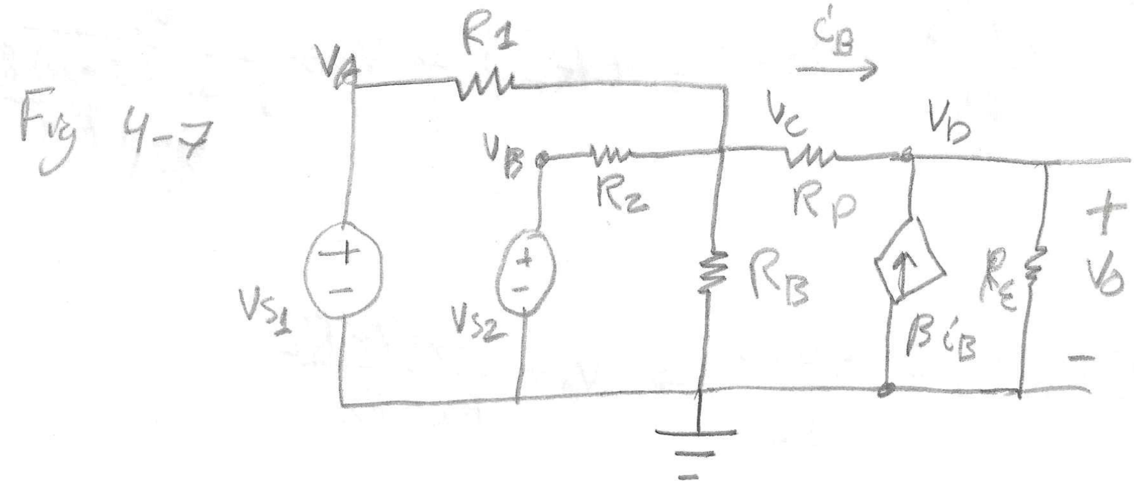
$\mu = 10^5$

R_F	k
∞	$-50{,}000$
$1\ M\Omega$	-495.05
$100\ k\Omega$	-49.9
$10\ k\Omega$	-4.99

R_F = Feedback Resistor but $i_x \neq 0$

⑧ Example 4-2 p160

Fig 4-7



from inspection, Node C

$$V_C(R_P^{-} + R_B^{-} + R_2^{-} + R_1^{-}) - V_A R_1^{-} - V_B R_2^{-} - V_D R_P^{-} = 0$$

Node D

$$V_D(R_P^{-} + R_E^{-}) - V_C R_P^{-} - \underline{\beta i_B} = 0$$

recall, we subtract incoming currents, add outgoing currents when doing Inspection

Note: KCL at D!

$$\frac{V_C - V_D}{R_P} + \beta i_B - \frac{V_D}{R_E} = 0$$

$$\frac{V_C}{R_P} + \beta i_B = V_D(R_E^{-} + R_P^{-})$$

We can write $i_B = \frac{1}{R_P}(V_C - V_D)$

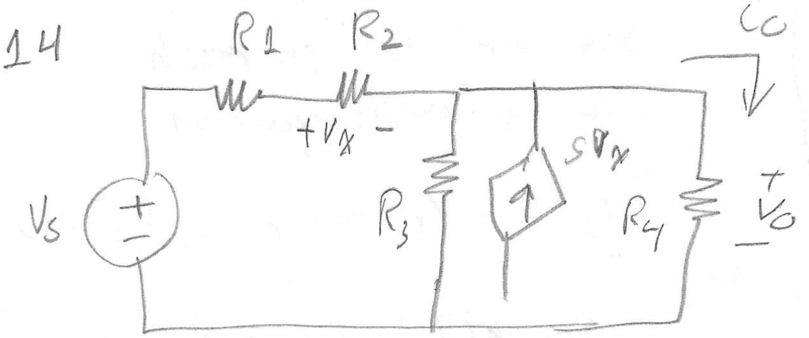
→ To write node-voltages equations for circuits with dependent sources. Use the Inspection method like normal, we get a system of equations that's matrix symmetrical, then express the Dependent source in terms of the unknown node voltages, then those terms are now arranged in the matrix

→ No Longer symmetrical, but we have a system p167 Mesh-Current Analysis w/ Dependent Sources ④

Same for node-voltage analysis

just do mesh analysis, and then deal with the Dependent constraint, matrix won't be symmetrical after this

Fig 4-14



for v_o? R_{IN}?

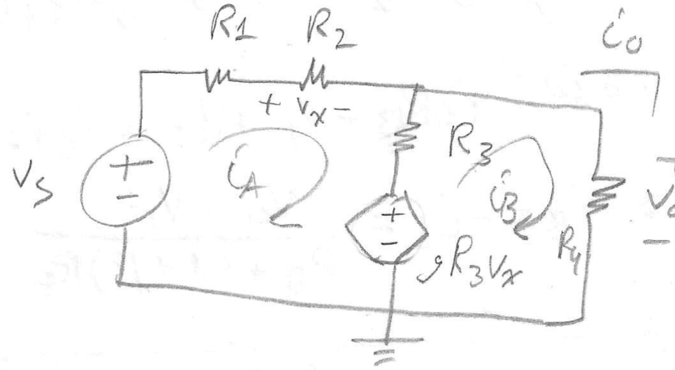
$R_1 = 50\,\Omega$

$R_2 = 1\,k\Omega$

$R_3 = 100\,\Omega$

$R_4 = 5\,k\Omega$

$g = 100\,mS$



A

$-V_s + R_1 i_A + i_A R_2 + R_3(i_A - i_B) + gR_3 v_x = 0$

B

$-R_3(i_A - i_B) + i_B R_4 - gR_3 v_x = 0$

Ohm's Law $\rightarrow$ $i_A R_2 = v_x$

So now we have

$$(R_1 + R_2 + R_3 + gR_2R_3)\, i_A - R_3 i_B = V_s$$

$$-(R_3 + gR_2R_3)\, i_A + (R_3 + R_4)\, i_B = 0$$

$$\rightarrow (1.115 \times 10^4)\, i_A - (10^2)\, i_B = V_s$$

$$-1.01 \times 10^4\, i_A + (5.1 \times 10^3)\, i_B = 0$$

Cramer's rule

$$i_A = \frac{\begin{vmatrix} V_s & -10^2 \\ 0 & 5.1\times10^3 \end{vmatrix}}{\det} \qquad i_B = \frac{\begin{vmatrix} 1.115\times10^4 & V_s \\ -1.01\times10^4 & 0 \end{vmatrix}}{\det}$$

$V_O = i_B R_4$ $\qquad R_{IN} = \frac{V_S}{i_A} = 10.95\,k\Omega$

$= 0.904\,V_S$

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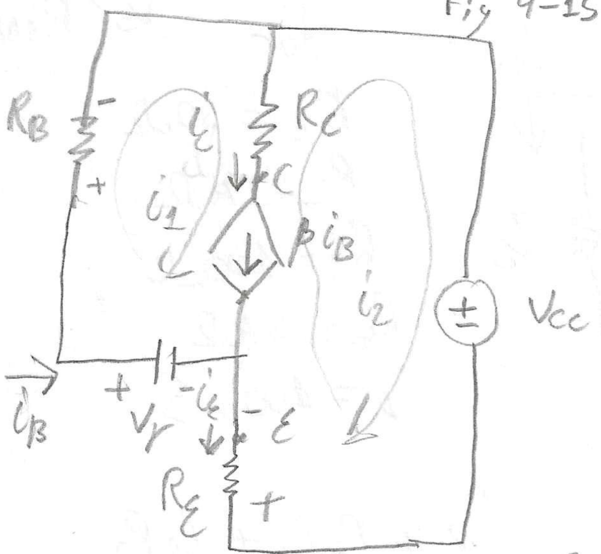
p169 4-7, bipolar junction transistor operating in the active mode

Fig 4-15



find transistor base current i_B

→ we need a supermesh

KVL supermesh equation

$+i_1 R_B - V_r + V_{cc} + i_2 R_E = 0$

from KCL: $\beta i_B = i_1 - i_2$

And $i_B = -i_1$ So → $i_2 = i_1(1+\beta)$

So now: $i_1 R_B - V_r + V_{cc} + i_1(1+\beta) R_E = 0$

$$i_1 = \frac{V_r - V_{cc}}{R_B + (1+\beta)R_E} \rightarrow i_B = -i_1 = \frac{V_{cc} - V_r}{R_B + (1+\beta)R_E}$$

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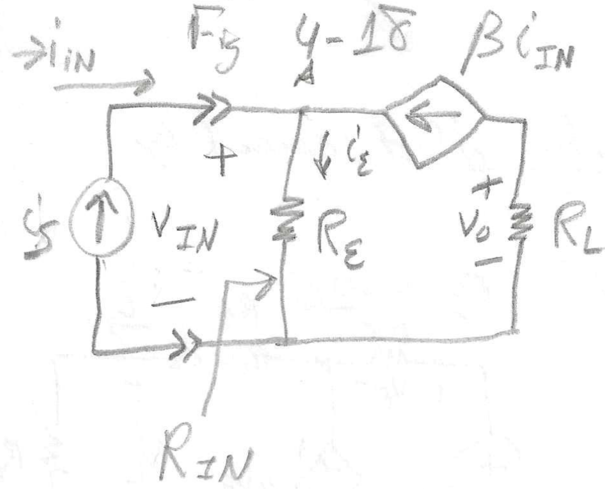
p171 Thévenin Equivalent Circuit w/ Dependent Sources

To find the Thévenin equivalent of an active circuit, we must leave the independent sources on or else supply excitation from an external source. So the Thévenin resistance cannot be found by the <u>Look back method</u> (all independent sources must be turned off)

→ Turning off independent sources turns off dependent sources which changes the characteristics of input/output p172 Example 4-9 whats the input R?

Fig 4-18



for $i_{IN}=0$, $\beta i_{IN}=0$

So $R_{IN}=R_E$

KCL at Node A

$$i_E = i_{IN} + \beta i_{IN}$$
$$= (1+\beta) i_{IN}$$

Ohm's Law, $\rightarrow V_{IN} = i_E R_E = R_E(1+\beta) i_{IN}$

So we have $R_{IN} = \dfrac{V_{IN}}{i_{IN}} = R_E(1+\beta)$

NOTES:

4-18 models a transistor circuit in which the gain parameter β typically lies between $50 \sim 250$

The Input Resistance w/external excitation is $(\beta+1)R_E$, which is significantly higher than R_E alone,

Bigger R_{IN} helps reduce the effects of loading on the input source

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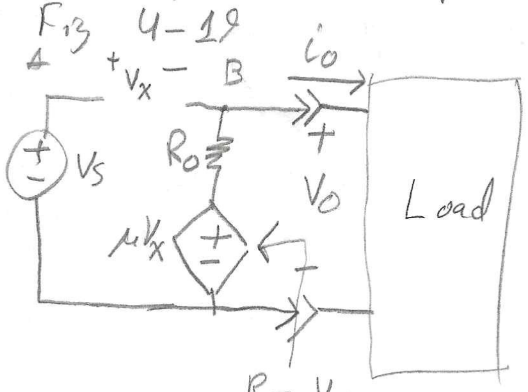
Example 4-10 p172 What's the Thévenin Equivalent?

Fig 4-19



KVL

$V_x + V_o - V_s = 0 \rightarrow V_x = V_s - V_o$

Look back resistance would be R_o

KCL at B

$$\frac{\mu V_x - V_o}{R_o} = i_o \rightarrow \frac{\mu V_s - \mu V_o - V_o}{R_o} = i_o$$

$$\frac{-V_o(\mu+1)}{R_o} = i_o - \frac{\mu V_s}{R_o} \rightarrow V_o = -\frac{i_o R_o}{\mu+1} + \frac{\mu V_s}{\mu+1}$$

So KVL of a Thévenin circuit i-v relationship is $iR_T + V_o - V_T = 0$

$\rightarrow V_o = V_T - i R_T$

Therefore $V_o = \dfrac{\mu V_s}{\mu+1} - \dfrac{i_o R_o}{\mu+1}$

So $V_T = \dfrac{\mu V_s}{\mu+1}$ $\quad R_T = \dfrac{R_o}{\mu+1}$

(12) This is a model of an op-amp circuit called Voltage follower

$R_O = 100\Omega$ for general purpose OP AMP as $\mu = 10^5$

So active resistance is $1\ m\Omega$

Low output resistance reduces the loading effect caused by connecting a load to the output

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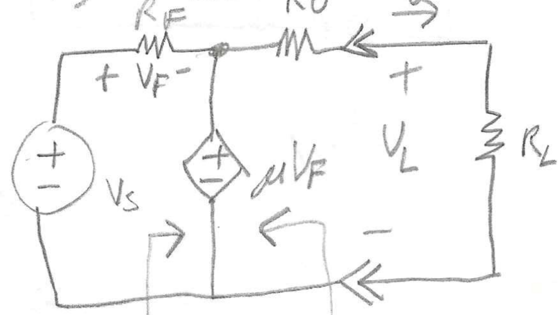
Exercise 4-12 R_{IN}? V_T? R_T?

Fig 4-20



$$i_{IN} = \frac{V_S - \mu V_F}{R_F} \quad \cancel{V_{IN} = \mu V_F}$$

KVL

$$V_F + \mu V_F = V_S \rightarrow V_S = V_F(1+\mu)$$

$$\text{So } V_{IN} = \frac{\mu V_S}{1+\mu} \quad i_{IN} = \frac{1}{R_F}\left[V_S - \frac{\mu V_S}{1+\mu}\right]$$

$$i_{IN} = \frac{V_S}{R_F}\left[\frac{1+\mu-\mu}{1+\mu}\right] = \frac{V_S}{R_F(1+\mu)}$$

$$R_{IN} = \frac{V_{IN}}{i_{IN}} = R_F(1+\mu) \text{ if } V_{IN} = V_S$$

$$V_T = \mu V_F \qquad R_T = \frac{\mu V_F}{\mu V_F} R_O = R_O$$

$$V_T = \frac{\mu V_S}{1+\mu}$$

$$i_N = \frac{\mu V_F}{R_O} \quad \text{Source transformation}$$

$$V_T = i_N R_T$$

Example 4-11, Notes on BJTs

→ dependent sources are used to model semiconductor devices like transistors and OP Amps

The model describes Voltages + currents at exit terminals

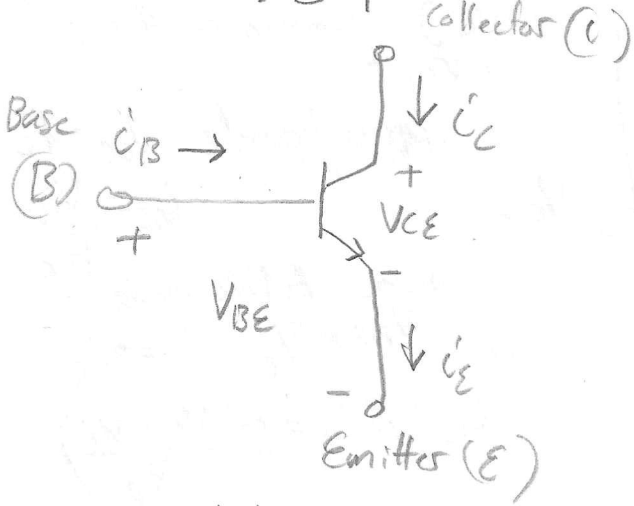
Bipolar junction transistor (BJT)

Field Effect transistor (FET)

→ They have operating modes with different i-V characteristics

These can change

BJT



V_{BE}: Base-Emitter Voltage

V_{CE}: Collector-emitter Voltage

KCL: $i_E = i_B + i_C$

i_B, V_{BE} This model can't have these variables be negative

i_C, V_{CE}

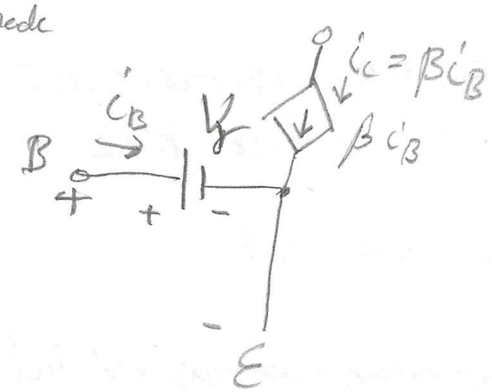
Active Mode: i_C is controlled by i_B, V_{BE} is constant

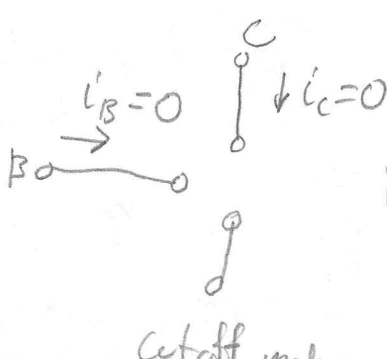
$$i_C = \beta i_B, \quad V_{BE} = V_\gamma$$

Proportionality factor β ~ forward gain 50 ~ 300

V_γ ~ threshold Voltage $V_\gamma < 1$ V

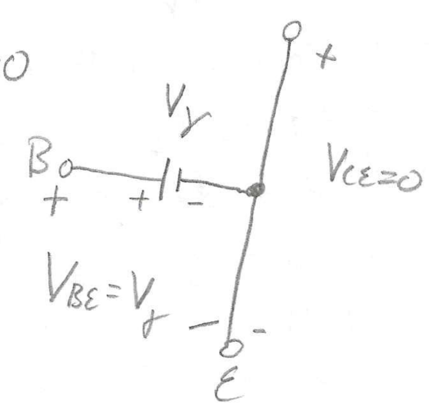
active mode





Cutoff mode

Saturation mode



(14) In saturation mode, $i_C = i_{SC}$ = short-circuit current from external circuit.

BJT output variables

cutoff bounds		saturation bounds

V_{OC} = open circuit voltage

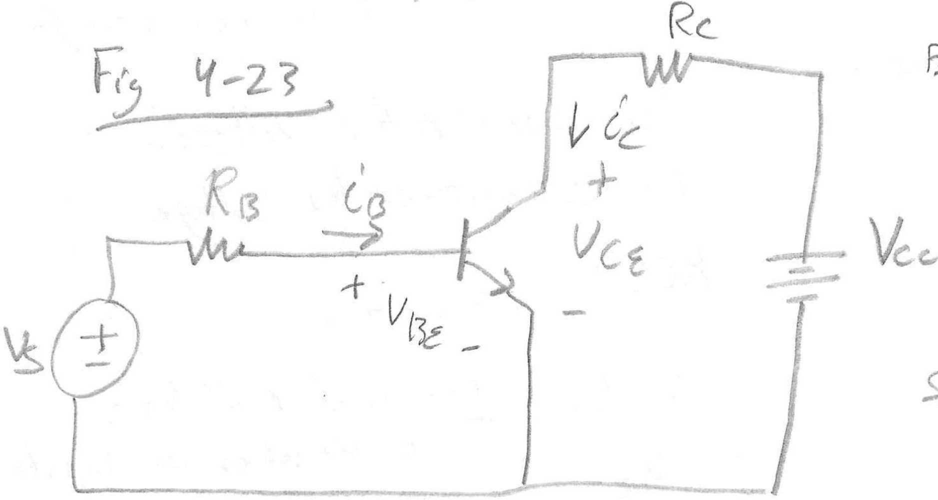
$$0 \le i_C \le i_{SC}$$
$$V_{OC} \ge V_{CE} \ge 0$$

Assume

1) i_C, V_{CE} cannot be '$-$'

2) V_{OC}, i_{SC} depend on the rest of the circuit

Fig 4-23



BJT common emitter circuit

upper bounds $V_{OC} = V_{CC}$

$i_{SC} = \frac{V_{CC}}{R_C}$

Assume Active mode

So $V_{BE} = V_\gamma$, $i_C = \beta i_B$

$$i_C = \beta i_B = \beta\left(\frac{V_S - V_\gamma}{R_B}\right) \quad (4\text{-}11)$$

for $V_S > V_\gamma$, then $i_C > 0$

if $V_S < V_\gamma$, $i_C < 0$ → BJT is in cutoff mode

cutoff bounds

$i_C = 0$, $V_{CE} = V_{OC} = V_{CC}$

When $V_S > V_\gamma$, $i_C = \beta\left(\frac{V_S - V_\gamma}{R_B}\right)$ predicts positive collector current that increases linearly with V_S. To set collector-emitter voltage, KVL

$V_{CE} = V_{CC} - i_C R_C \quad (4\text{-}12)$

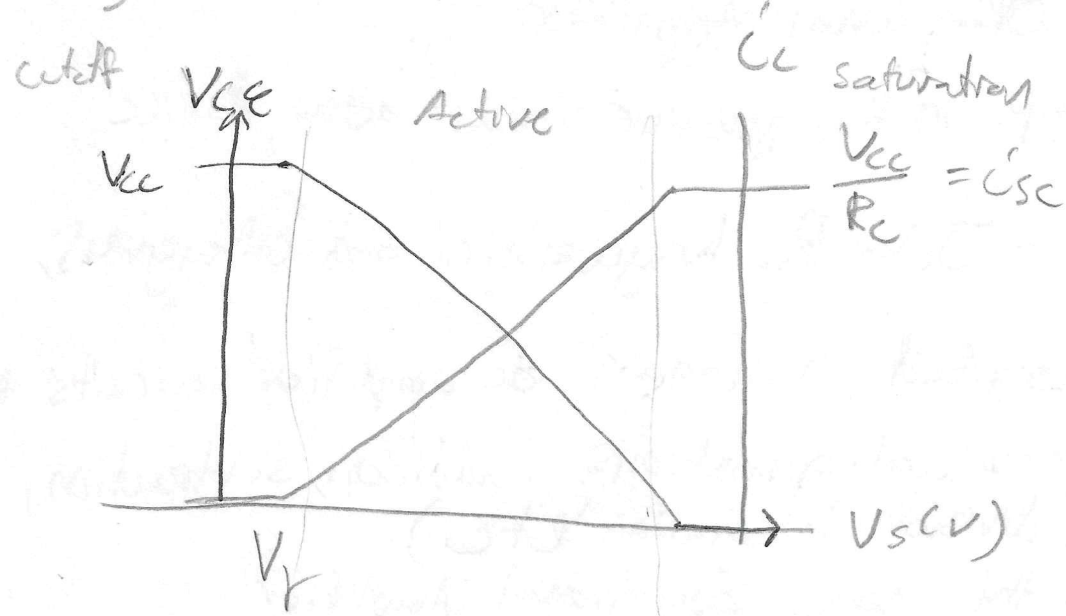
So $V_{CE} > 0$ for $i_C < \frac{V_{CC}}{R_C}$, b/c $\frac{V_{CC}}{R_C}$ is i_{SC} (short circuit)

Thus $V_S > V_\gamma$, $i_C < i_{SC}$ → BJT is active

if (4-11) predicts $i_C > i_{SC}$ then $V_{CE} < 0$ → saturation conditions violated

But we are still saturated $i_C = i_{SC} = V_{CC}/R_C$ and $V_{CE} = 0$

Fig 4-24 p175



when $V_S < V_r$, cutoff

$i_C = 0 \quad V_{CE} = V_{OC} = V_{CC}$

for $V_S > V_r$

$i_C = \beta i_B = \beta\left(\frac{V_S - V_r}{R_B}\right)$

$V_{CE} = V_{CC} - i_C R_C$

as V_S increases, i_C increases, V_{CE} decreases

i_C increases until it reaches saturation

$i_C = i_{SC}$

Transistor reaches saturation and the constant are;

$i_C = i_{SC} = \frac{V_{CC}}{R_C}$

$V_{CE} = 0$

→ Sunny V2, gammy utubers fall

Note; In digital applications, the input voltage drives the transistor between the cutoff and saturation modes passing through the active mode as quickly as possible.

In analog application, the transistor remains in the active mode where the slope of the transistor characteristic provides voltage amplification

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4-3 The Operational Amplifier

IC OP AMP is the premier linear active device

1947 - John R. Ragazzini and colleagues,

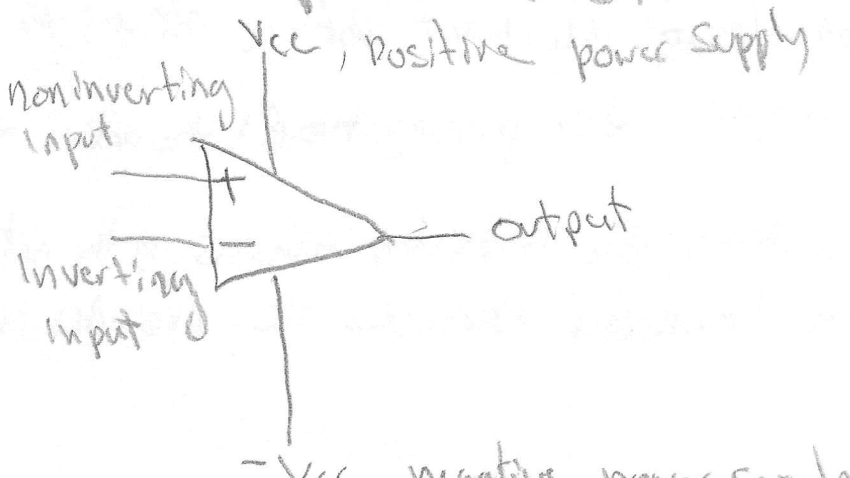
paper described high-gain dc amplifier circuits that perform mathematical operations (addition, subtraction, multiplication, division, integration etc)
hence the name operational Amplifier

general- and special-purpose analog computers using vacuum tubes

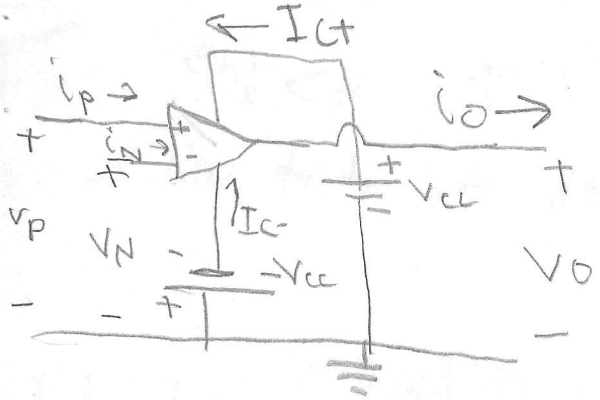
The Device itself is a complex array of transistors, resistors, diodes, and capacitors, all fabricated and interconnected on a tiny silicon chip.

The device can be modeled by i-v characterist-ics

OP AMP Notation



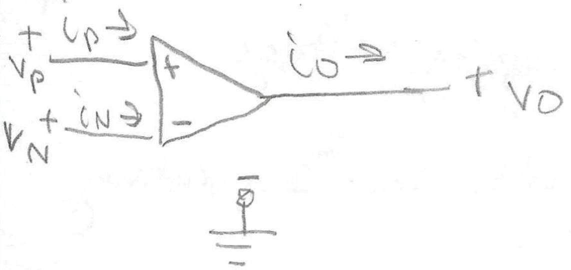
power supply may not be seen, but they are there



all voltages are defined to a common reference node

Note the direction of currents

$$i_P + i_N + I_{C+} + I_{C-} = i_O$$

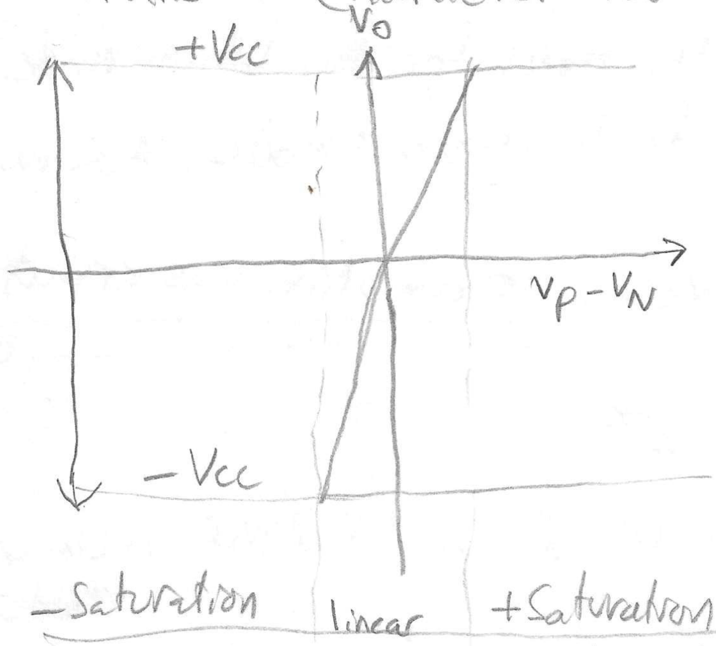


→shorthand Notation

$$i_O = i_N + i_P$$

This is very wrong, The output current does not come from the input current. Input currents are very small output current comes from the supply voltages

Transfer characteristic



This characteristic provides the relationship between noninverting input: v_P inverting input: v_N and the output voltage v_O

3 regions
+saturation
-saturation
linear

In the linear Region, the OP AMP is a differential amplifier

output is proportional to the difference of the inputs

$$V_O = A(v_P - v_N) \quad (4\text{-}15)$$

Slope is the Voltage Gain

(18) The voltage Gain is very Large, $A > 10^5$

as long as $(V_P - V_N)$ is very small, the output will be proportional to the input

when $A|V_P - V_N| > V_{CC}$, OPAMP is saturated
→ output voltage is limited by supply voltage

Like the transistor, the OP AMP also has 3 operating modes

1.) +Saturation $A(V_P - V_N) > V_{CC}$; $V_O = +V_{CC}$

2.) -Saturation $A(V_P - V_N) < -V_{CC}$; $V_O = -V_{CC}$

3) Linear mode $A|V_P - V_N| < V_{CC}$; $V_O = A(V_P - V_N)$

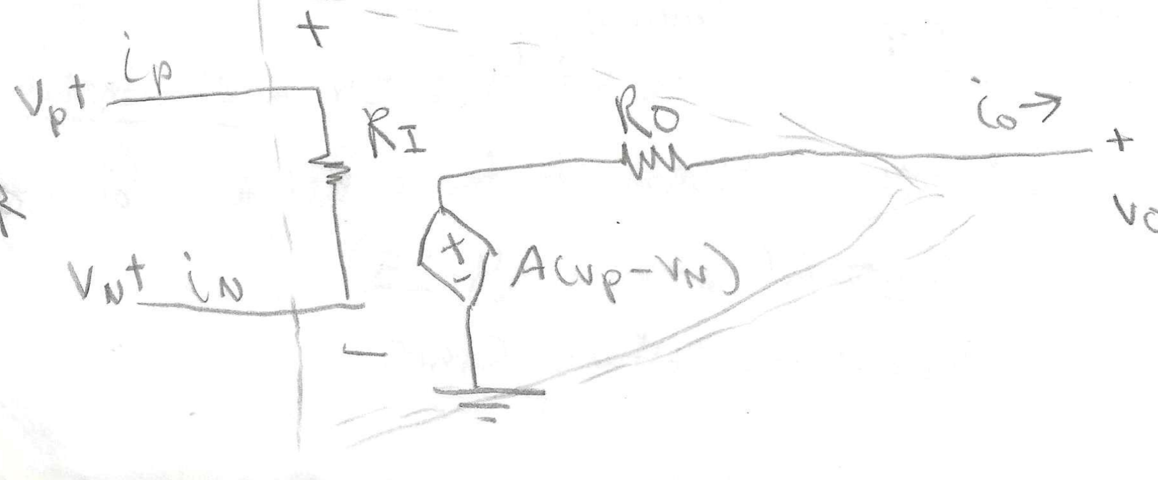
Usually, OP AMP circuits use the model for the Linear mode.
If the op-amp is not specified to be linear mode, Assume it is,
and if $-V_{CC} < V_O < V_{CC}$, assumption was correct

Ideal OP AMP Model p178

Dependent-Source Model of an OP AMP in Linear Mode

R_I: input R

R_O: output R



typically

$10^6 < R_I < 10^{12}\ \Omega$ High R_I

$10 < R_o < 100\ \Omega$ Low R_o

$10^5 < A < 10^8$ High A

Key attributes to OP AMPS

Typically $V_{cc} \sim 15\ V$, A is very Large $\sim 10^5$

we can write $-V_{cc} \leq V_O \leq +V_{cc}$, $V_O = A(V_P - V_N)$

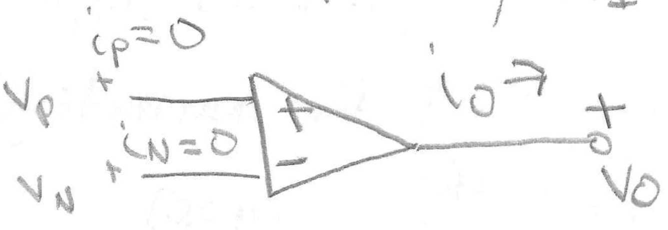
$$\frac{-V_{cc}}{A} \leq (V_P - V_N) \leq +\frac{V_{cc}}{A}$$

Lyz $V_{cc} \sim 15V$, $A \sim 10^5$, It comes to be $V_P \approx V_N$

This is a practical op-amp Model

for Ideal OP-AMP $A \to \infty$

and thus, $V_P = V_N$, $R_I \to \infty$, so $i_P = 0, i_N = 0$

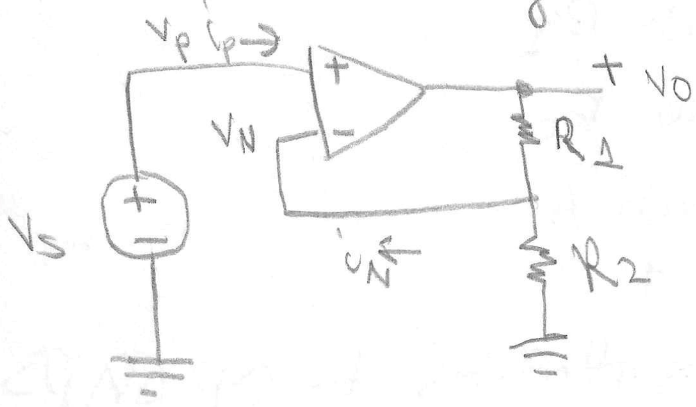


It's necessary to have a feedback path from the output to the input (one or both) to ensure $V_P \approx V_N$

with proper feedback we can get an Ideal Model

20

Noninverting OP AMP p180



Ideal OP AMP, $i_p = 0$

$i_N = 0$

for the Inverting Input (Voltage Division)

$$V_N = \frac{R_2}{R_1+R_2} V_O \quad (4\text{-}17)$$

$$V_s \longrightarrow \boxed{K} \xrightarrow{V_O}$$

$V_O = K V_S$

Fig 4-32

noninverting input

$V_p = V_s$

Ideal OP AMP constraints demand

$V_p = V_N$, so $V_N = V_s \rightarrow V_s = \dfrac{R_2}{R_1+R_2} V_O \rightarrow V_O = \dfrac{R_1+R_2}{R_2} V_s$

Strategy:

1) use circuit analysis methods to express the OP AMP input voltages V_p and V_N in terms of circuit parameters,

2) use Ideal OP AMP constraint $V_p = V_N$ to solve input-output relationship

Input-output relationship for noninverting amplifier

$$V_O = K V_S, \quad K = \frac{R_1+R_2}{R_2} \quad (4\text{-}20)$$

K is a proportionality constant and closed loop gain K

It defines input-output relationship when the feedback loop is connected (closed) for OP AMPs we have two types of Gains

1.) The Large open-loop gain from the Op Amp itself

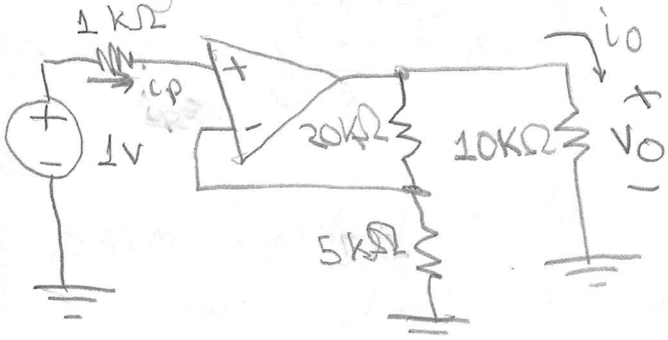
2.) The closed-loop voltage gain of the OP Amp circuit with a negative feedback path. [Not by the OP AMP Gain]

This gain is determined by the resistors

K is smaller than A, but defined and usable

Fig 4-33 p181 whats V_O? i_O? K? P_O? P_K?

Voltage gain — Power gain



We Know $K = \frac{R_1 + R_2}{R_2} = \frac{20K + 5K}{5K} = 5$

But there's now a 1KΩ Resistor

$V_S \rightarrow \boxed{K=5} \rightarrow V_O$ KVL: $-V_S + (1k\Omega) i_p + V_N = 0$

But recall for an Ideal OP AMP, $i_p = 0$, so there's no voltage drop across the resistor.

So $V_O = \frac{R_1 + R_2}{R_2} V_S \rightarrow V_O = 5V$, $K = 5$

$i_O = \frac{5V}{10k\Omega} = 500\,\mu A$, $P_O = i_O V_O = 2.5\,mW$

There's no power gain, $i_p = 0$, source doesn't supply power.

22 Design Example 4–12 p181

Design an amplifier with a gain, $K=10$

for $R_2 = 10\,k\Omega$, then $R_1 = 90\,k\Omega$ (These resistors normally have low tolerances $\pm 1\%$)

we usually limit ourselves to the range $1\,k\Omega$ to $1\,M\Omega$, we need to think about the power dissipation in the resistors. we usually use resistors with 1/4 W rating. we remember the maximum voltage is 15 V

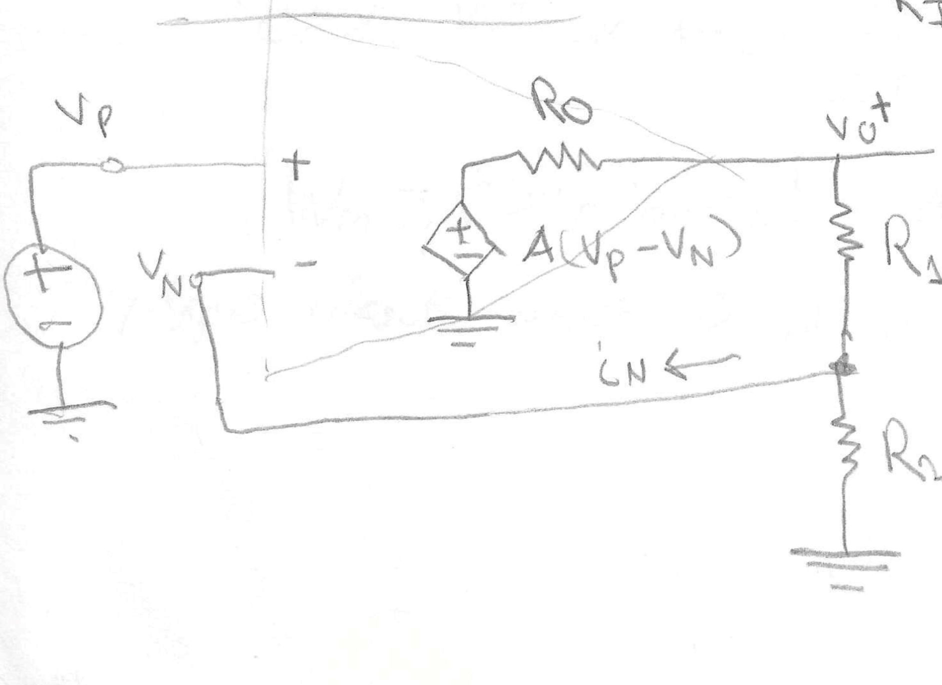
So the smallest 1/4 W R is $R_{min} \geq \frac{(15)^2}{0.25}$

$R_{min} \geq 900\,\Omega$

$1\,M\Omega$ is chosen because surface leakage makes it difficult to maintain the tolerance in a high-value resistance, High valued Rs are noisy

Effects of finite OP AMP Gain

Ideal OP AMP has infinite gain, but we have models for finite Gain



$R_I \sim 10^6\,\Omega \sim 10^{12}\,\Omega$

so we can treat it as an open circuit

non inverting (Vp) determined by source

Inverting can be found by circuit division

remember voltage division

$$V_O = \frac{(R_1+R_2)}{R_O+(R_1+R_2)} A(V_P - V_N)$$

recall from Non Inverting OP AMP

$$V_N = \frac{R_2}{R_1+R_2} V_O \quad , \quad V_P = V_S$$

$$V_O = \left[\frac{(R_1+R_2)}{R_O+(R_1+R_2)}\right] A \left[V_S - \frac{R_2}{R_1+R_2} V_O\right] \qquad [4\text{-}21]$$

from this relationship, we can see that the output V_o depends on the output V_o, So feedback is present

we now have

$$V_O = \frac{A(R_1+R_2)}{R_O+R_1+R_2(1+A)} V_S \qquad (4\text{-}22)$$

$$\lim_{A\to\infty} V_O = \lim_{A\to\infty} \frac{A(R_1+R_2)}{R_O+R_1+R_2(1+A)} V_S$$

$$\approx \lim_{A\to\infty} \frac{A(R_1+R_2)}{R_2(A)} V_S \quad \text{as A is very large}$$

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

So we have

$$V_O = \frac{R_1+R_2}{R_2} V_S = K V_S$$

K is the closed loop gain from the ideal OP AMP Model

<u>for finite A</u>, we ignore R_O as its small compared to R_1, R_2

eventually we get $V_O = \dfrac{K}{1+(K/A)} V_S$

So we get good approximation to Ideal OP AMP

as long as $K \ll A$

rule of thumb, $K < \frac{A}{100}$

Closed loop gain K must be less than 1% of OP AMP Gain A

Feed back Path also Affects output Resistance

To find the Thévenin circuit

open-circuit voltage, $v_o = v_{TH} = \frac{K}{1+(K/A)} v_S$

short-circuit current, $i_{SC} = i_N = \frac{A(v_P)}{R_O} = \frac{A v_S}{R_O}$

(No current goes thru R_1, R_2)

So R Thévenin

$$R_T = \frac{v_O}{i_{SC}} = \frac{v_{TH}}{i_N} = \frac{K}{1+(K/A)}\left(\frac{R_O}{A}\right) = \frac{(K/A)}{1+(K/A)} R_O$$

when $K \ll A$, $R_T = \frac{K}{A} R_O \approx 0\,\Omega$

~~wh~~ with feedback, $R_T \to 0$, or very small compared to R_T without feedback

Typically, $R_O < 100\,\Omega$, $A > 10^5$

So Typically in this course, we are dealing with Ideal OP AMP I-V characteristics (as long as conditions are met)

$\Rightarrow$ OP AMP circuits have essentially zero R_T p184

so then $\to$ output voltage does not change with different loads

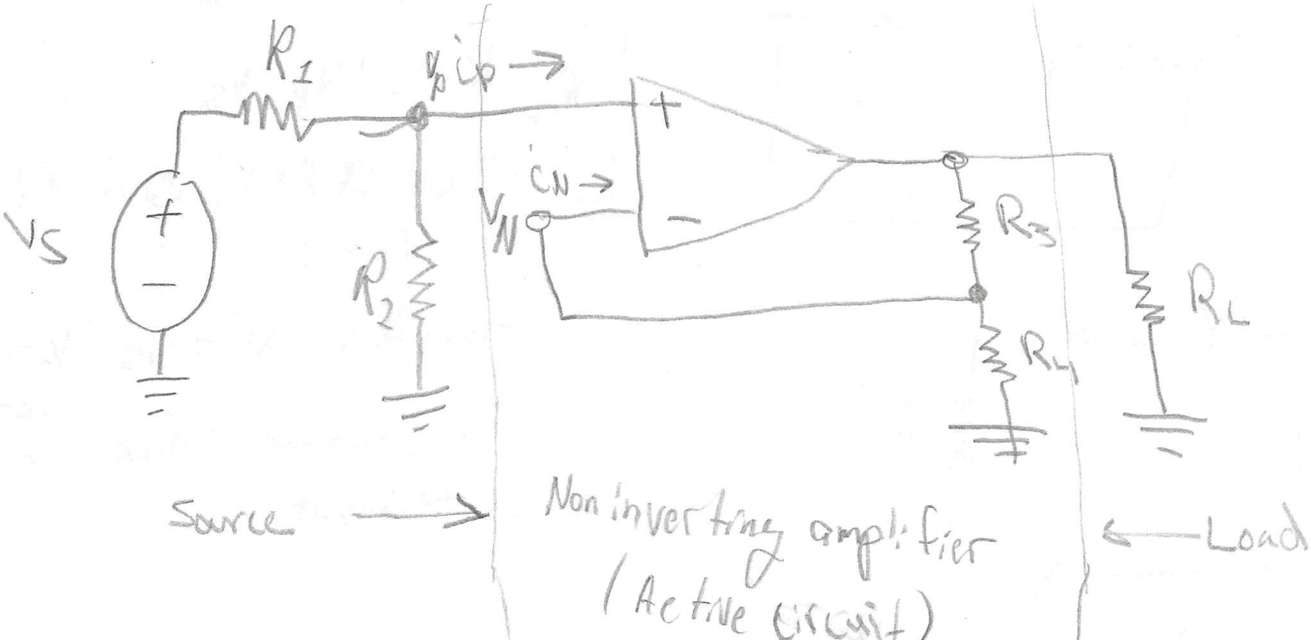
Thévenin output resistance of an OP AMP w/ feed back is essentially zero

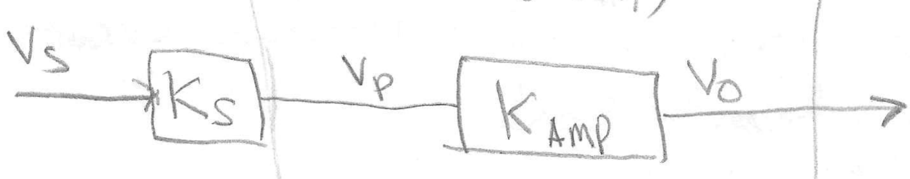
4-4 OP AMP Circuit Analysis p 184

This is useful for analog signal-processing systems
noninverting Amplifier
<u>plus:</u> voltage follower, the inverting amplifier, the summer, and the subtractor

→ recognize the feedback pattern,
→ isolate the basic circuit as a building block

Example 4-13, find the input-output relationship of the circuit





We have 2 building block gains
(1) Ks, the proportionality constant of the source circuit
(2) Kamp, gain of the noninverting amp

as $i_p = 0$, so $v_p = \frac{R_2}{R_1+R_2} v_s$, $K_s = \frac{v_p}{v_s} = \frac{R_2}{R_1+R_2}$

Ideal OP AMP constraints: $v_p = v_N = \frac{R_4}{R_3+R_4} v_o \rightarrow v_o = \frac{R_3+R_4}{R_4} v_p$ $K_{AMP} = \frac{v_o}{v_p} = \frac{R_3+R_4}{R_4}$

(26) The overall gain of the circuit

$$K_{circuit} = K_S K_{AMP} = \left(\frac{V_P}{V_S}\right)\left(\frac{V_O}{V_P}\right) = \frac{V_O}{V_S} = \left(\frac{R_2}{R_1+R_2}\right)\left(\frac{R_3+R_4}{R_4}\right)$$

we can do this because $i_P = 0$ and Ideal OP AMP non inverting constraints

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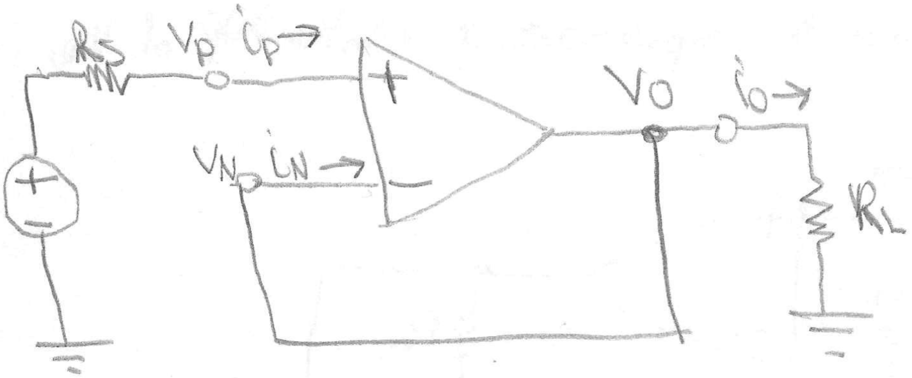
Voltage Follower



This forces $V_N = V_O$, they're connected

as $i_P = 0$, $V_{R_S} = 0$

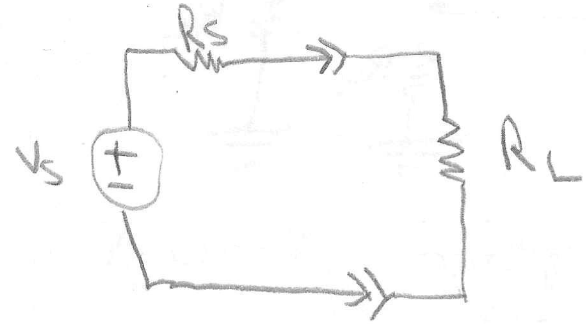
KVL: $V_P = V_S$

Ideal OP AMP constraint:

$V_P = V_N$

Therefore $V_O = V_S$, $K = 1$ also from inspection

The output follows the input



The voltage follower is used in interface circuits because it isolates the source from the Load

→ Note! the input-output relationship $V_O = V_S$ does not depend on R_S or R_L (source or load resistance)

→ The second circuit is a voltage divider depending on R_S and R_L → This Limits the signals that can be transfered across the Interface

→ when a voltage follower is being used, between Source and Load, the signal Levels are limited by the OP AMP

So the current delivered to the Load, $i_0 = \frac{V_O}{R_L}$

as $V_O = V_S$, $i_O = \frac{V_S}{R_L}$

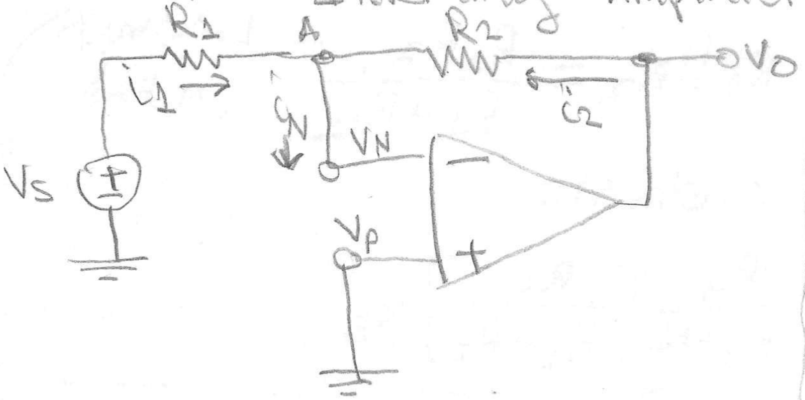
but what about $i_p = 0$? V_s isn't $\emptyset$

→ Supply terminals, output current comes from the power supply

Dont Do KCL at ground

p 186

The Inverting Amplifier



$V_s \to \boxed{K} \to V_o$

4-39 the inverting amplifier circuit

The input signal and the feedback are both applied at the inverting input

noninverting input is grounded so $V_p = 0$

KCL Node Analysis at A

$$\frac{V_s - V_N}{R_1} + \frac{V_O - V_N}{R_2} - i_N = 0$$

(4-24)

OP AMP Constraints: $V_p = V_N$, $i_p = 0 = i_N$

as $V_p = 0$, $V_N = 0$

so $\frac{V_s - 0}{R_1} + \frac{V_O - 0}{R_2} - 0 = 0 \rightarrow V_O = -\frac{R_2}{R_1} V_s$ (4-25)

we have $V_O = K v_s$, $K = -\frac{R_2}{R_1}$ the closed-loop gain, it's negative hence inverting amplifier.

$V_s \to \boxed{K} \to V_O$, this block Diagram indicates inverting or non inverting op AMP configuration

28 4-15 Example p189 whats input-output relationship?

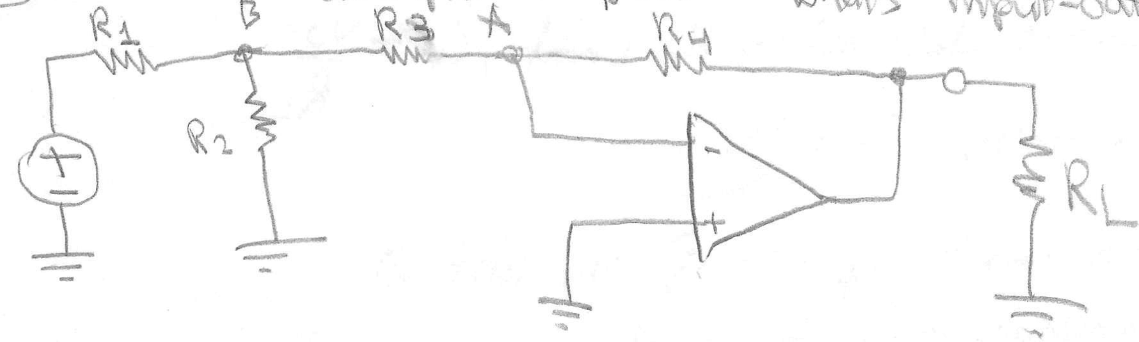


Fig 4-41

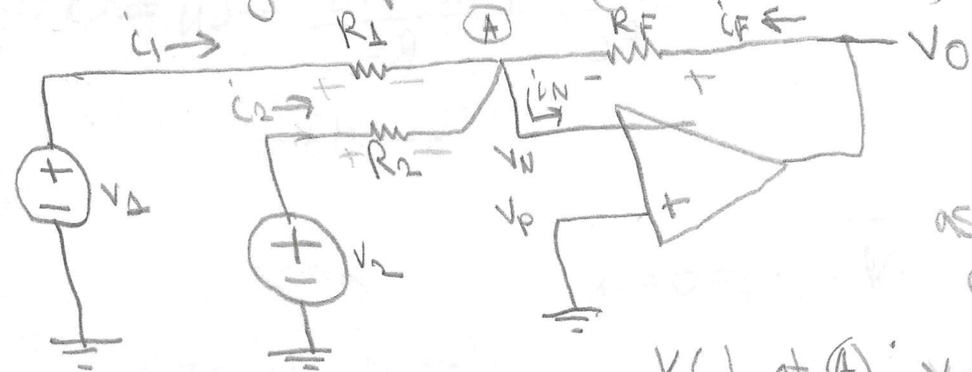
The input resistance is affected by the source circuit, find the Thévenin equivalent

$$V_T = \frac{R_2}{R_1 + R_2} V_S \qquad R_T = R_1 \| R_2 = \frac{R_1 R_2}{R_1 + R_2}$$ (Look back method)

KCL at A and Ideal OP AMP constraints

$$V_O = -\frac{R_4}{R_3 + R_T} V_T = -\frac{R_4}{R_3 + R_T}\left[\frac{R_2}{R_1 + R_2}\right] V_S$$

The Summing Amplifier (adder circuit)



2 inputs connected to Node A, A is the summing point as $V_P = 0$, similar to inverting amplifier

KCL at A: $\frac{V_1 - V_N}{R_1} + \frac{V_2 - V_N}{R_2} + \frac{V_O - V_N}{R_F} = i_N$

As $V_P = 0$, $V_N = 0$, $i_N = 0$

$$\rightarrow \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_O}{R_F} = 0$$

$$\rightarrow V_O = -\frac{R_F}{R_1} V_1 - \frac{R_F}{R_2} V_2 \qquad (4\text{-}28)$$

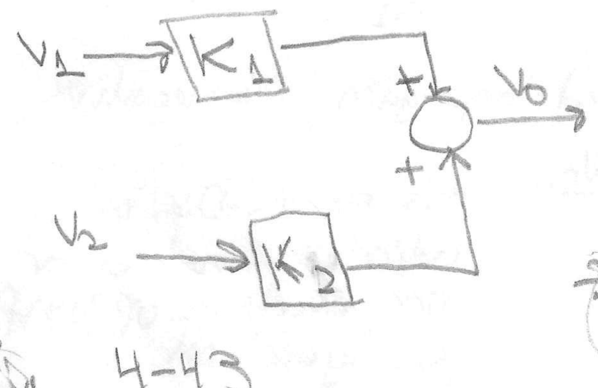


Fig 4-43

$K_1 = -\frac{R_F}{R_1}$ $K_2 = -\frac{R_F}{R_2}$ These are the gains if $R_1 = R_2 = R$

Summing Amplifier

Inverting Summer

$$v_O = -\frac{R_F}{R}(v_1 + v_2)$$

for n inputs,

$$v_O = \left(-\frac{R_F}{R_1}\right)v_1 + \left(-\frac{R_F}{R_2}\right)v_2 + \dots + \left(-\frac{R_F}{R_n}\right)v_n \quad (4\text{-}29)$$

$$= K_1 v_1 + K_2 v_2 + \dots + K_n v_n$$

Note for Non-inverting summer, $v_P \neq 0$ so the Ks at the summing point are influenced by the R's associated for each input. The Example on p142 shows that getting good Ks can be tricky, easier to keep Rs the same

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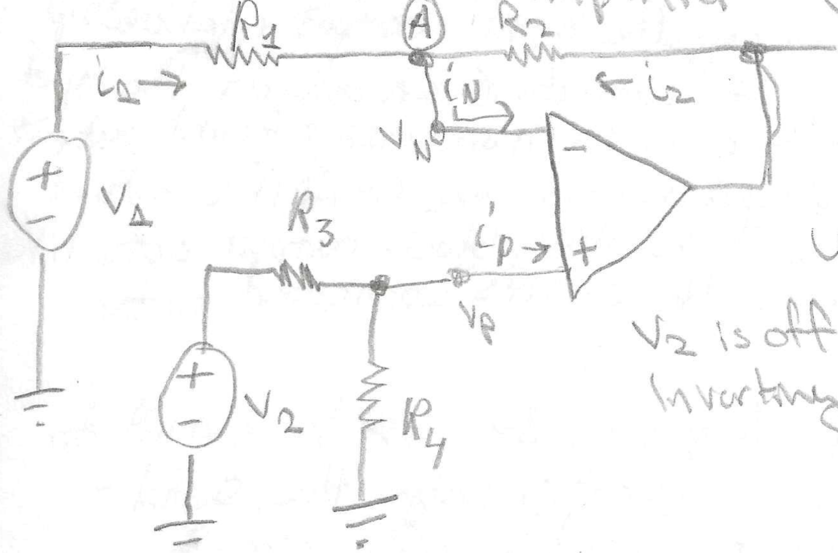
The Differential Amplifier (subtractor circuit) p144

2 inputs, one at inverting input node other at noninverting input node



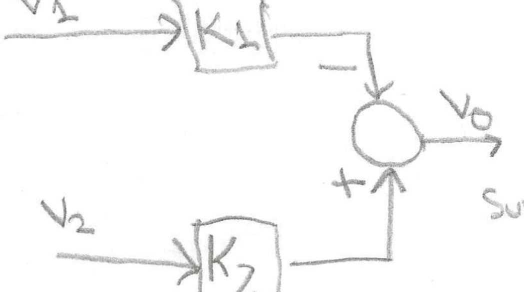
Use superposition

V_2 is off → $v_p = 0$ → circuit acts Like inverting Amplifier so

$$v_{O1} = -\frac{R_2}{R_1} v_1 \quad (4\text{-}30)$$

v_1 is off (v_2 on) → noninverting amp w/ voltage divider input so write

$$v_{O2} = \left[\frac{R_1 + R_2}{R_1}\right]\left[\frac{R_4}{R_3 + R_4}\right] v_2 \quad (4\text{-}31)$$



Superposition: $v_O = v_{O1} + v_{O2} = \left(-\frac{R_2}{R_1}\right)v_1 + \left(\frac{R_1 + R_2}{R_1}\frac{R_4}{R_3 + R_4}\right)v_2$

$$v_O = [-K_1]\, v_1 + [K_2]\, v_2$$

for $(R_3/R_1) = (R_4/R_2)$ → $v_O = \frac{R_2}{R_1}(v_2 - v_1)$

(30) Fig 4-48, Summary of Basic OP AMP signal-processing circuits p 195

Basic OP AMP Building Blocks

The noninverting and inverting amplifiers are represented as gain blocks.

The Summing Amp and differential amp require a gain block and ~~the~~ summing point Symbol

Be careful when going from circuit to block diagram and block diagram to circuit. → Some gain blocks involve negative gains. Gains of inverting summer are negative.

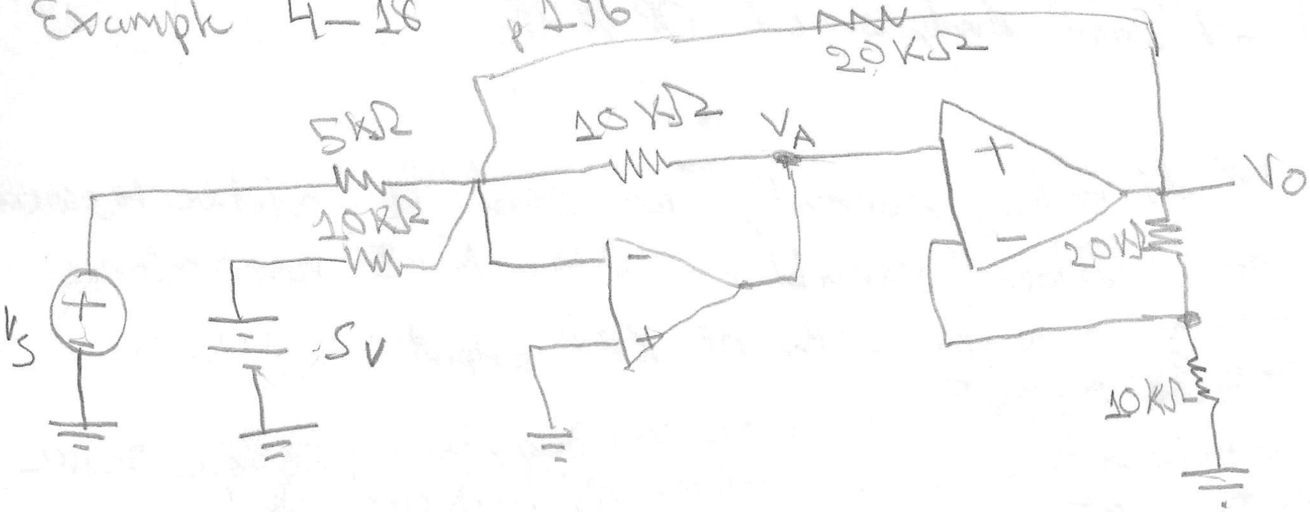
The required minus sign is sometimes moved to the summing point and the value of K in the gain block is changed to a positive number. There isn't a standard

The OP AMP circuits defined in 4-48 can be interconnected without changing the input-output relationship of each circuit (as long as the connections are between the input and output). These feedback circuits have insignificant output resistances and can drive any load within the OP AMP's output current capacity. OP AMP circuit building block output acts like ideal voltage sources just like the sources connected to the OP AMP circuit inputs.

→ Connecting the output of one building block circuit to an input of another does not change the signal-processing function performed by either circuit

Example 4-18 p196

expression for V_O, and a block diagram

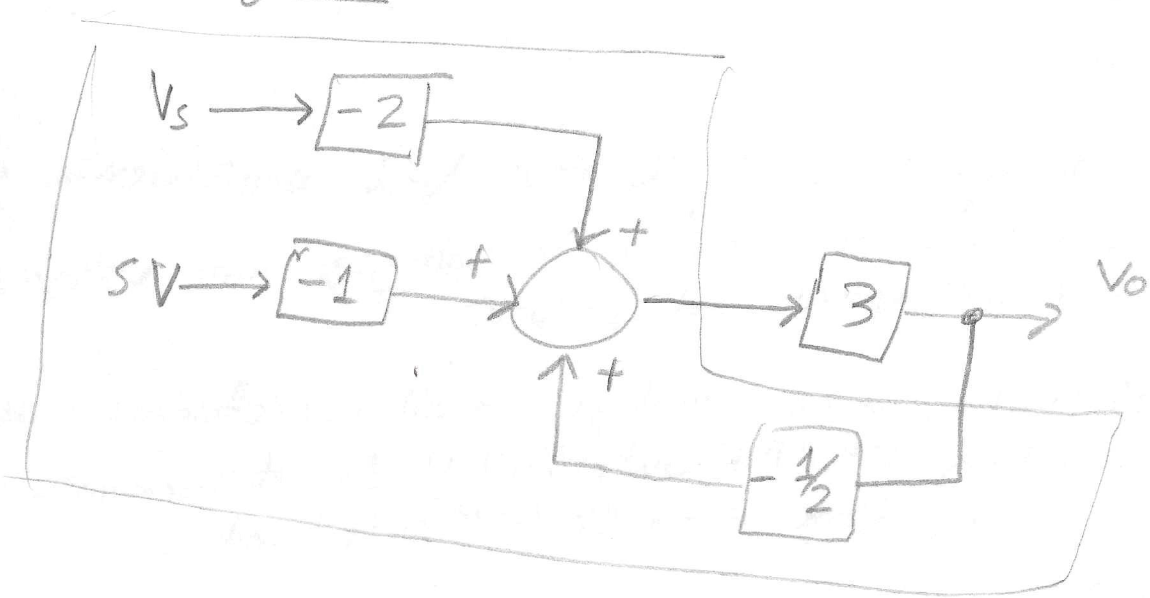


Solution: we have a 3 input summer, and a noninverting amplifier, V_A is the output of the summer.

Summer K: $K_n = -\frac{R_F}{R_n}$ → $V_A = -5 - 2V_S - \frac{1}{2}V_O$

noninverting K: $K = \frac{R_1 + R_2}{R_2}$ → $V_O = 3V_A$

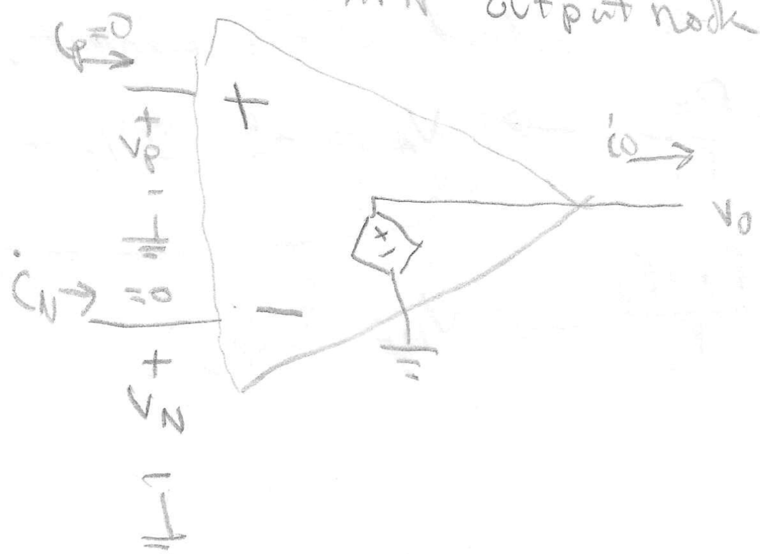
Block Diagram



(32) Node-Voltage Analysis w/ OP AMPs

circuit w/ N nodes, normally we find V_0 relative to ground
Now, assign node voltage variables to the N-1 nonreference nodes, including a variable at the OP AMP output.

→ Ideal OP AMP acts like a dependent voltage source between the output terminal and ground
→ The output node is determined by the other node voltages so we don't write a node equation at the OP AMP output node



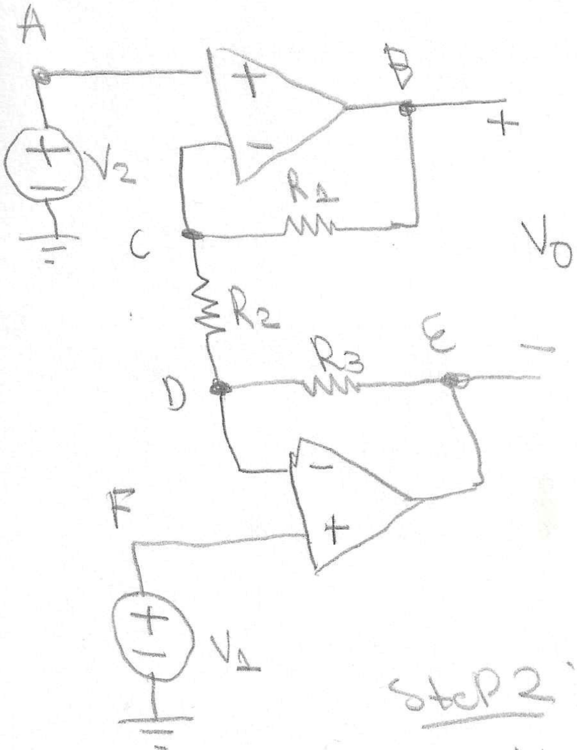
Formulate node equations at the other N-2 nonreference in the usual way. But there are N-1 node voltages, more unknowns than equations. recall $v_p = v_N$ and $i_p = i_N = 0$

steps

1) Identify a node voltage at all nonreference nodes, including OP AMP outputs, but do not formulate node equations at the OP AMP output nodes.

2) Formulate node equations at the remaining nonreference nodes and then use the ideal OP AMP voltage constraint $v_p = v_N$ to reduce the number of unknowns

Example 4-20



Derive an expression for Vo in terms of V_1 and V_2

This circuit is not an interconnection of OP AMP circuits (R_2 is connected between two inputs

Step 1: 6 non reference Nodes, B, E are output nodes, A, F are known. so C, and D

$$C: -\frac{V_C - V_B}{R_1} + \frac{V_D - V_C}{R_2} = 0$$

$$D: \frac{V_C - V_D}{R_2} - \frac{V_D - V_E}{R_3} = 0$$

Step 2: recall $V_P = V_N$ for Ideal OP AMP constraints

$$V_D = V_1, \quad V_C = V_2$$

$$\rightarrow C: -\frac{V_2 - V_B}{R_1} + \frac{V_1 - V_2}{R_2} = 0 \quad \text{find expression in terms of } V_B$$

$$D: \frac{V_2 - V_1}{R_2} - \frac{V_1 - V_E}{R_3} = 0 \quad \text{" for } V_E$$

$$\rightarrow V_B = \frac{R_1}{R_2}(V_2 - V_1) + V_2, \quad V_E = \frac{R_3}{R_2}(V_1 - V_2) + V_1$$

So we have $V_O = V_B - V_E = \left(\frac{R_1 + R_2 + R_3}{R_2}\right)(V_2 - V_1)$

These are 2 noninverting Amplifiers

I didn't Take notes for 4-5 OP AMP Circuit Design

4-6 OP AMP Circuit Applications.