Active Circuits: Life gets interesting

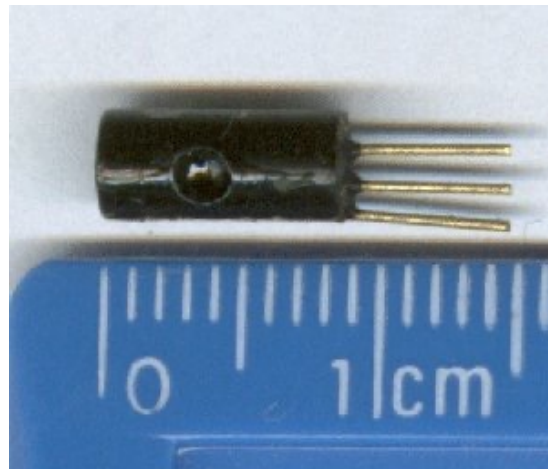## Active cct elements – transistors and operational amplifiers (OP-AMPS)

Devices which can inject power into the cct

External power supply – normally comes from connection to the voltage supply "rails"

Capable of linear operation – amplifiers

and nonlinear operation – typically switches

Triodes, pentodes, transistors

MAE40 Linear Circuits

Active Cct Elements

Amplifiers – linear & active

Signal processors

Stymied until 1927 and Harold Black

Negative Feedback Amplifier

Control rescues communications

Telephone relay stations manageable

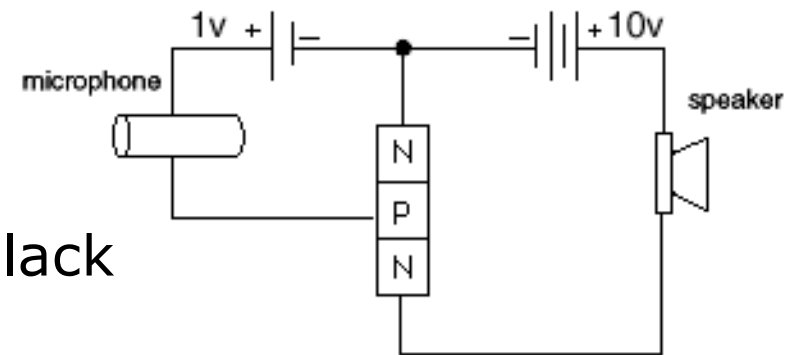against manufacturing variability

Linearity

Output signal is proportional to the input signal

Note distinction between signals and systems which transform them

Yes! Just like your stereo amplifier

Idea – controlled current and voltage sources

A Brief Aside - Transistors

A semiconductor sometimes conducts and sometimes does not – conductivity controlled by applied voltage

Commonly made of silicon doped w/ other elements:
- Doping mixes traces of dopant elements into semiconductor materials
- These elements add "donor atoms" to substrate material, encouraging conductivity

p-doping (mobile holes): Si doped w/ B, Ga, In
n-doping (mobile electrons): Si doped w/ Sb, P, As
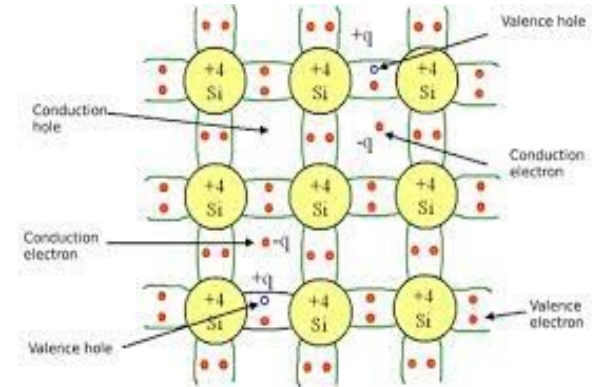
Bipolar Junction Transistors

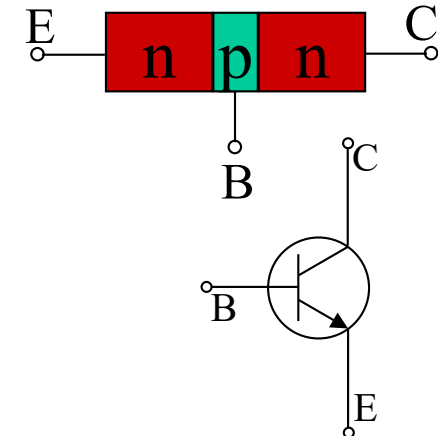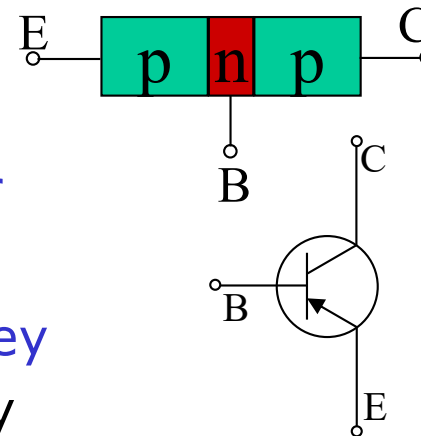Two types npn and pnp
    Heavily doped Collector and Emitter
    Lightly doped Base and very thin
   Collector and Emitter thick and dopey
Need to bias the two junctions properly
    Then the base current modulates a strong C→E current

MAE40 Linear Circuits   Amplification $i_C = \beta i_B$

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Transistor Switch

The transistor is an active component:

a device that can produce an output signal with more power in it than the input signal. The additional power comes from external power supply.
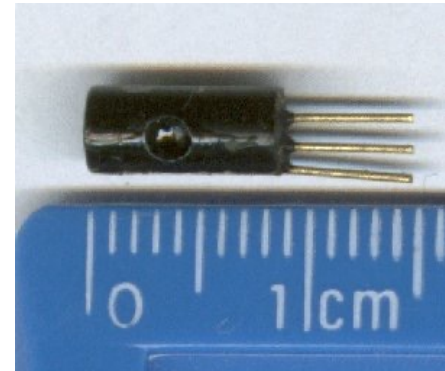
The Arduino digital output asserts a voltage on the pin and this causes a small current to flow through R1 into the base of the transistor. This then makes the transistor conduct, which causes a much larger current to flow through the load.
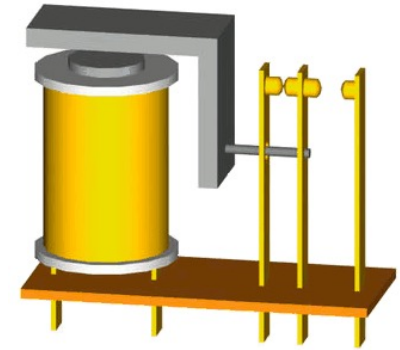

Amplification $i_C = \beta i_B$

Current gains in transistors typically range from 50 to 1000

MAE40 Linear Circuits
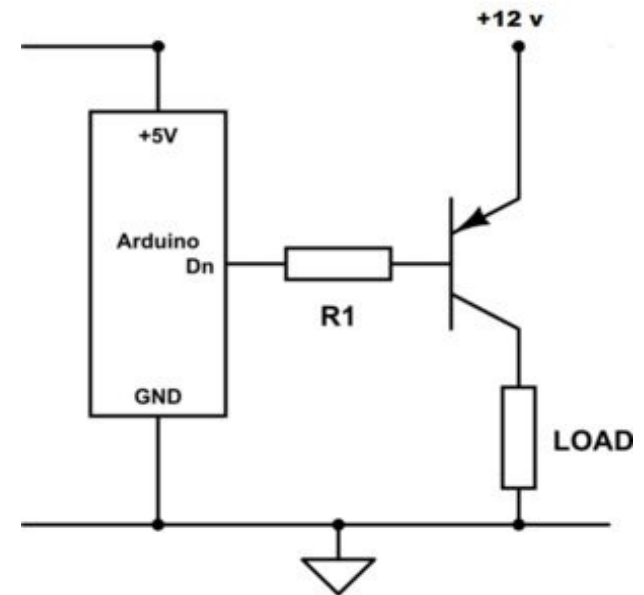
Alternative to transistors: mechanical relays

- A relatively small current powers an electromagnet that activates a switch
- Thus, a lower power signal can control a higher power device

Relay motion when coil is activated

What are the disadvantages of relays relative to transistors?

- Slower switching

- Wears out over time

Advantages?

- Full electrical isolation of controlled circuit to avoid frying circuits

- Can be built to control very large currents

Transistors

Common Emitter Amplifier Stage

Biasing resistors R_1 and R_2

- Keep transistor junctions biased in amplifying range

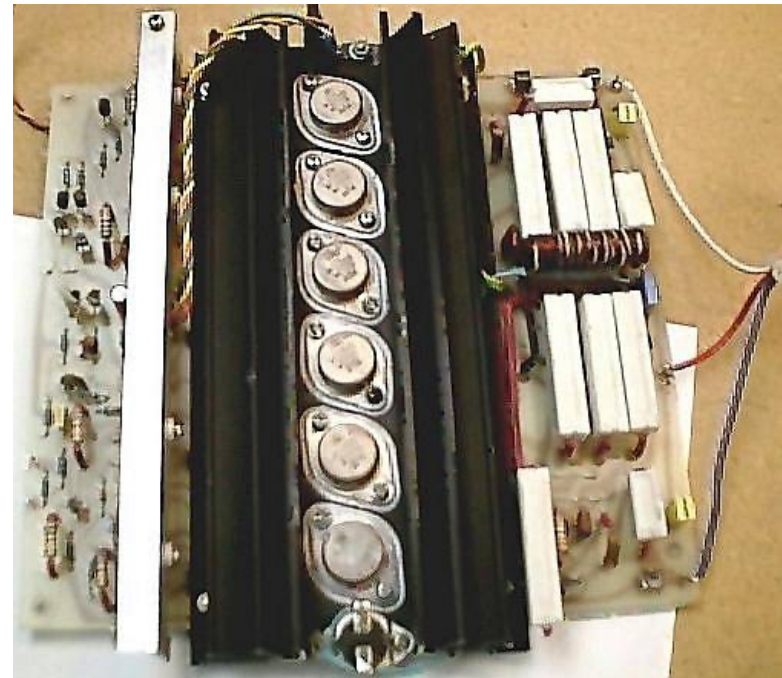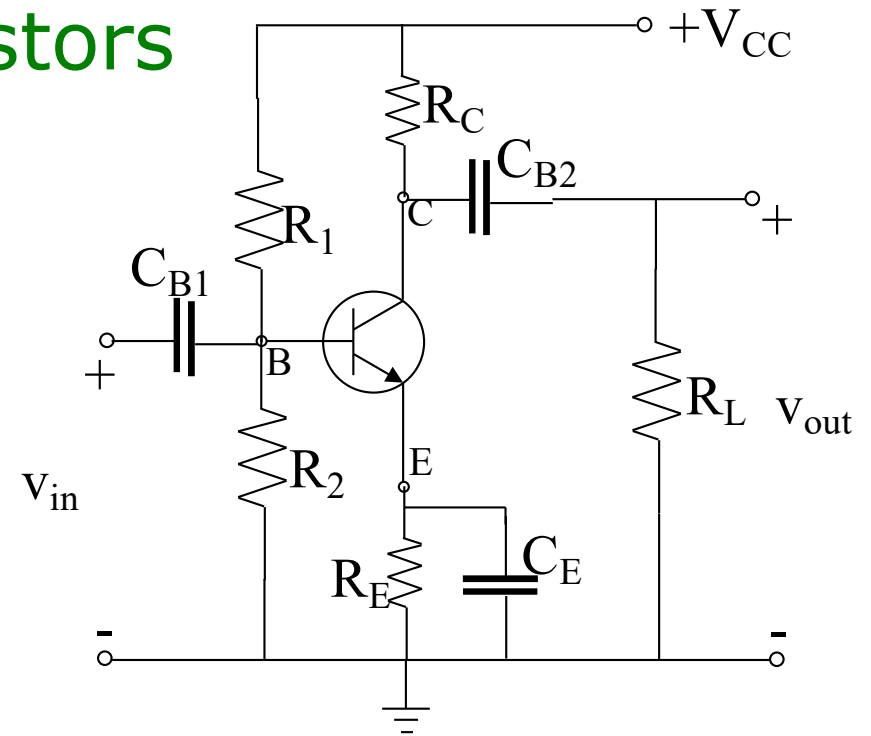Blocking capacitors C_{B1} and C_{B2}

- Keep dc currents out

Feedback capacitor C_E

- Grounds emitter at high frequencies

Small changes in v_{in}
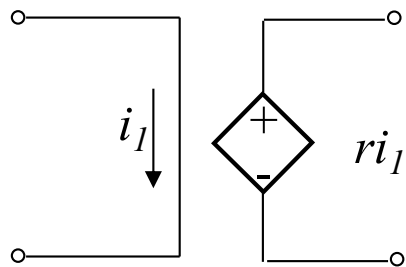Produce large changes in v_{out}
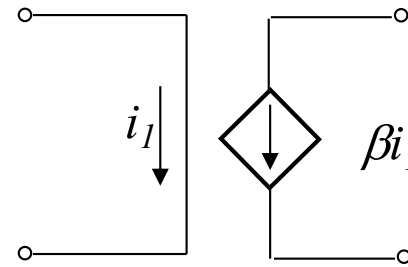
Linear Dependent Sources

Active device models in linear mode

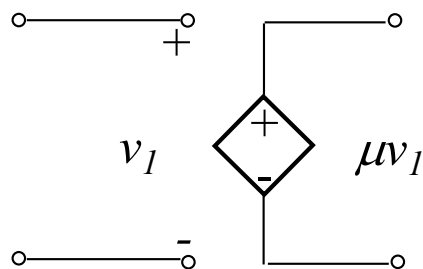Transistor takes an input voltage v_i and produces an output current $i_0 = g v_i$ where g is the gain

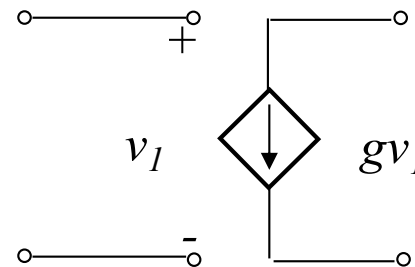This is a linear voltage-controlled current source VCCS

CCVS r transresistance

CCCS β current gain

VCVS μ voltage gain

VCCS g transconductance

Linear dependent source (contd)

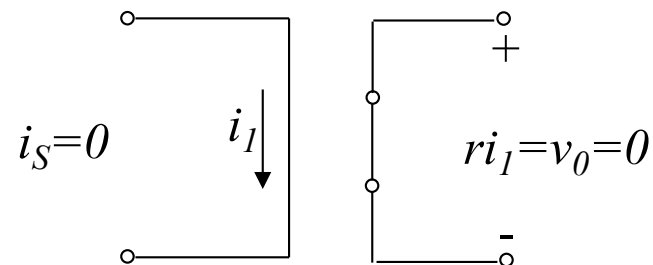Linear dependent sources are parts of active cct models – they are not separate components

But they allow us to extend our cct analysis techniques to really useful applications

This will become more critical as we get into dynamic ccts

Dependent elements change properties according to the values of other cct variables
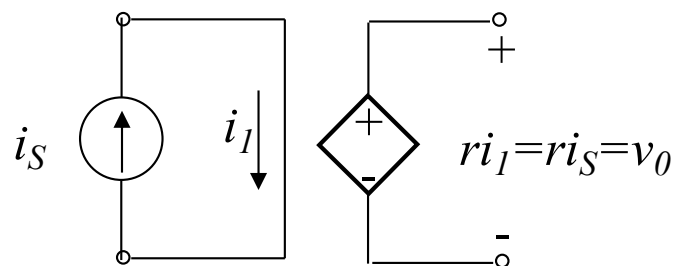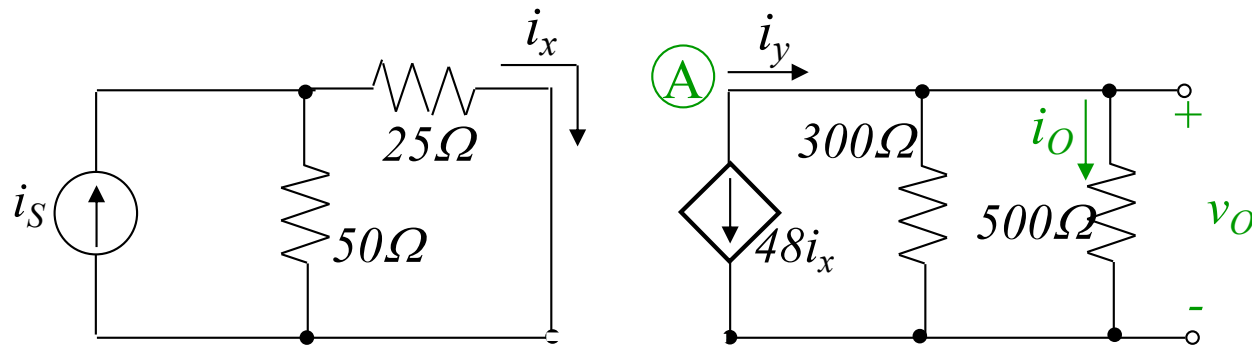

Source on

Source off

Cct Analysis with Dependent Sources

Golden rule – do not lose track of control variables
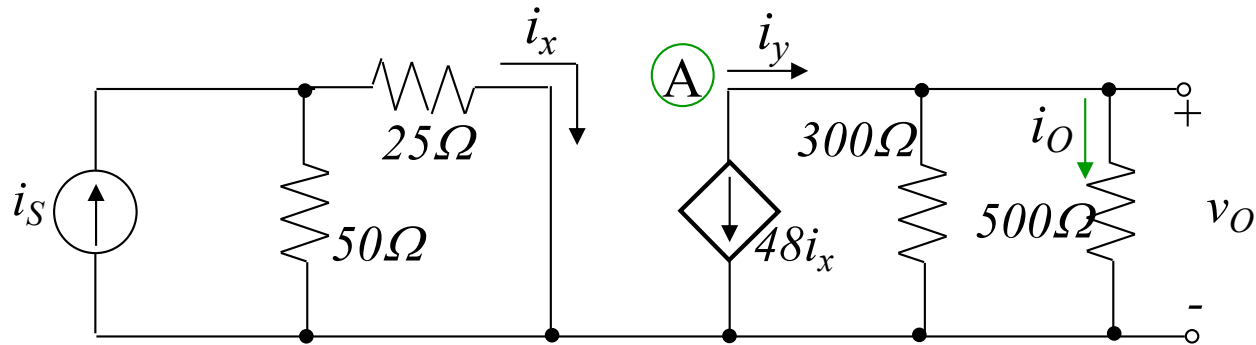
Find i_O, v_O and P_O for the 500Ω load

Current divider on LHS $i_x = \frac{2}{3} i_S$

Current divider on RHS $i_O = \frac{3}{8}(-48)i_x = -18i_x = -12i_S$

Ohm's law $v_O = i_O 500 = -6000i_S$

Power $p_O = i_O v_O = 72,000 i_S^2$

Analysis with dependent sources

Power provided by ICS

$$p_S = (50\|25)i_S^2 = \frac{50}{3}i_S^2$$
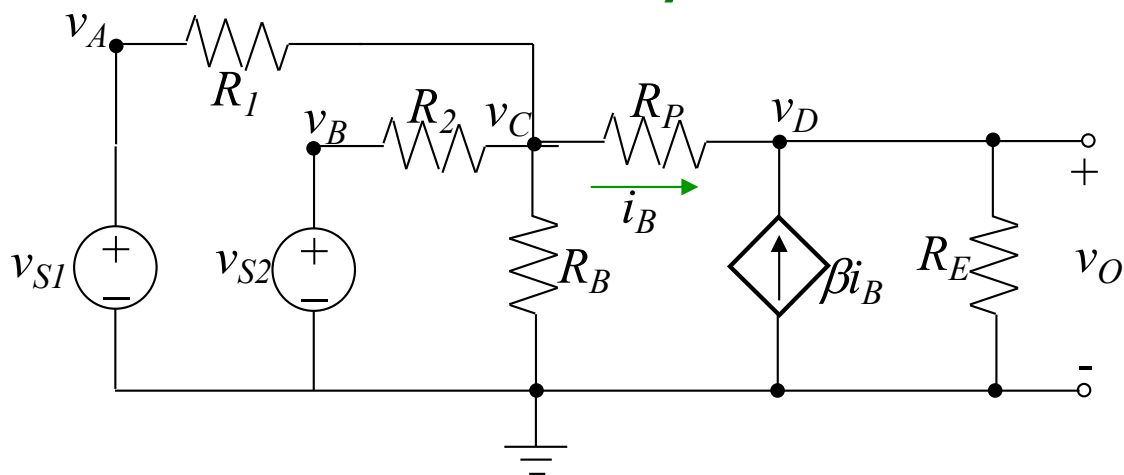
Power delivered to load

$$72000i_S^2$$

Power gain

$$G = \frac{p_O}{p_S} = \frac{72000i_S^2}{\frac{50}{3}i_S^2} = 4320$$

Where did the energy come from?

External power supply

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Nodal Analysis with Dependent Source

KCL at node C $\quad G_1(v_C - v_{S1}) + G_2(v_C - v_{S2}) + G_B v_C + G_P(v_C - v_D) = 0$

KCL at node D $\quad G_P(v_D - v_C) + G_E v_D - \beta i_B = 0$
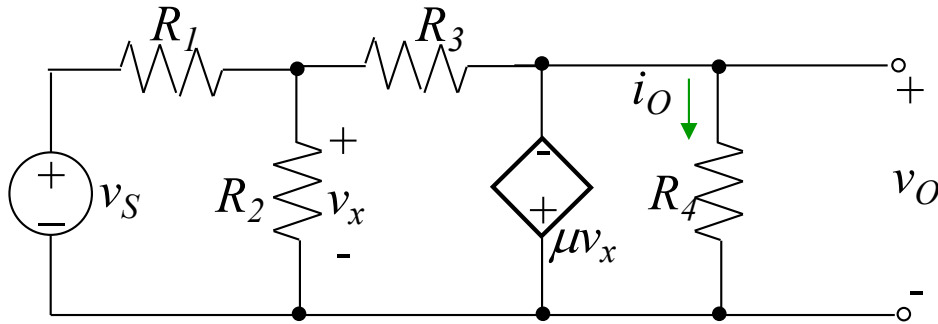
CCCS element description $\quad i_B = G_P(v_C - v_D)$
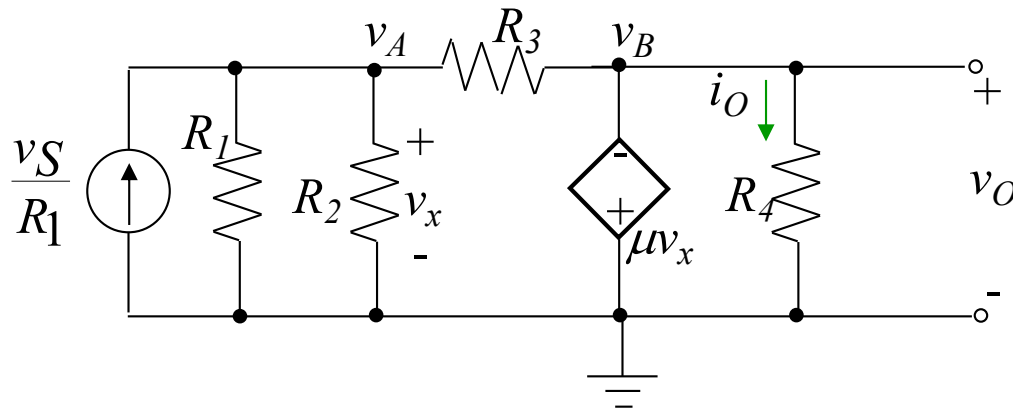
Substitute and solve

$$(G_1 + G_2 + G_B + G_P)v_C - G_P v_D = G_1 v_{S1} + G_2 v_{S2}$$

$$-(\beta + 1)G_P v_C + \left[(\beta + 1)G_P + G_E\right]v_D = 0$$

T&R, 5th ed, Example 4-3 p 148

Find v_O in terms of v_S
What happens as $\mu \to \infty$?

Node A:

$$(G_1 + G_2 + G_3)v_A - G_3 v_B = G_1 v_S$$

Node B:

$$v_B = -\mu v_x = -\mu v_A$$

Solution:

$$v_O = v_B = -\mu v_A = \left(\frac{-\mu G_1}{G_1 + G_2 + (1+\mu)G_3} \right) v_S$$

For large gains μ: $(1+\mu)G_3 >> G_1 + G_2$

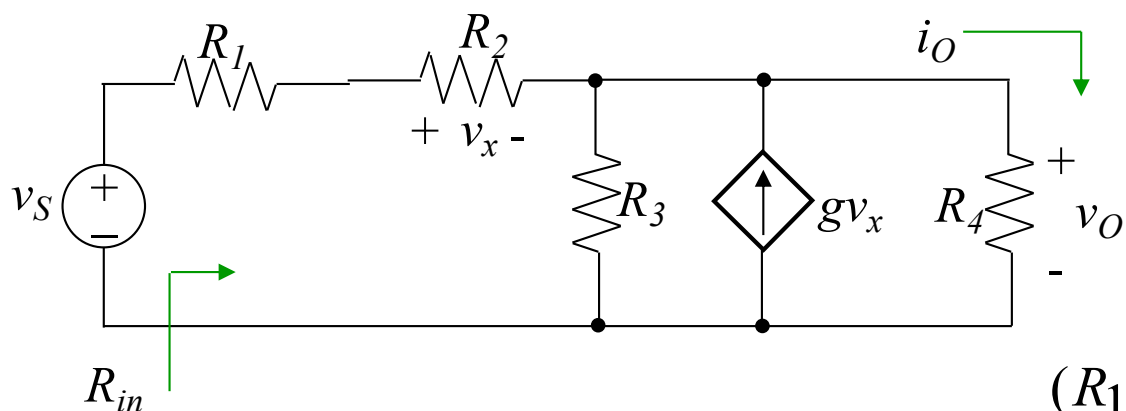$$v_O \approx \left[\frac{-\mu G_1}{(1+\mu)G_3} \right] v_S \approx -\frac{R_3}{R_1} v_S$$

This is a model of an inverting op-amp

Mesh Current Analysis with Dependent Sources
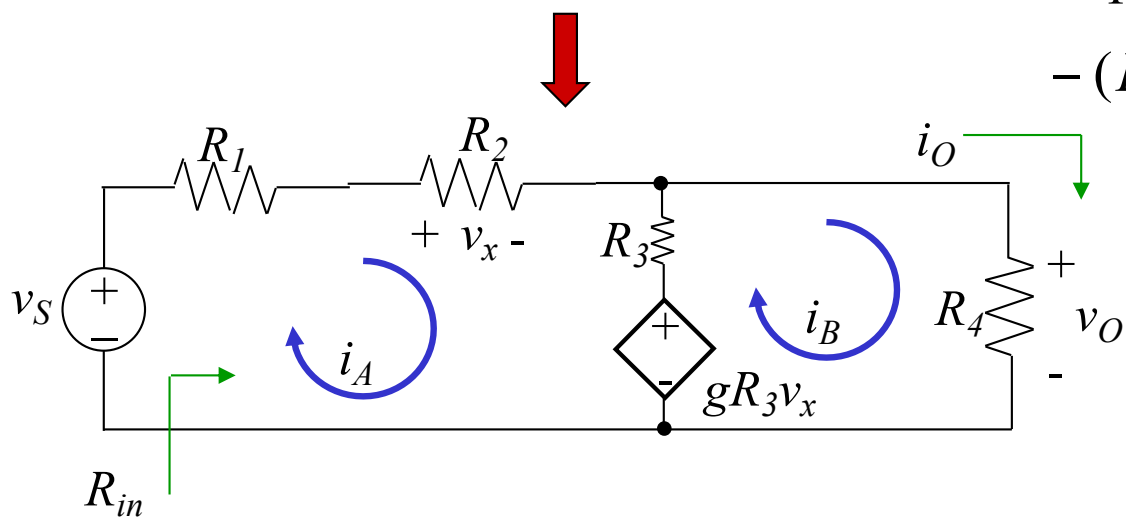
Dual of Nodal Analysis with dependent sources

Treat the dependent sources as independent and sort out during the solution

$$(R_1 + R_2 + R_3 + gR_2R_3)i_A - R_3i_B = v_S$$

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

T&R, 5th ed, Example 4-5 BJTransistor
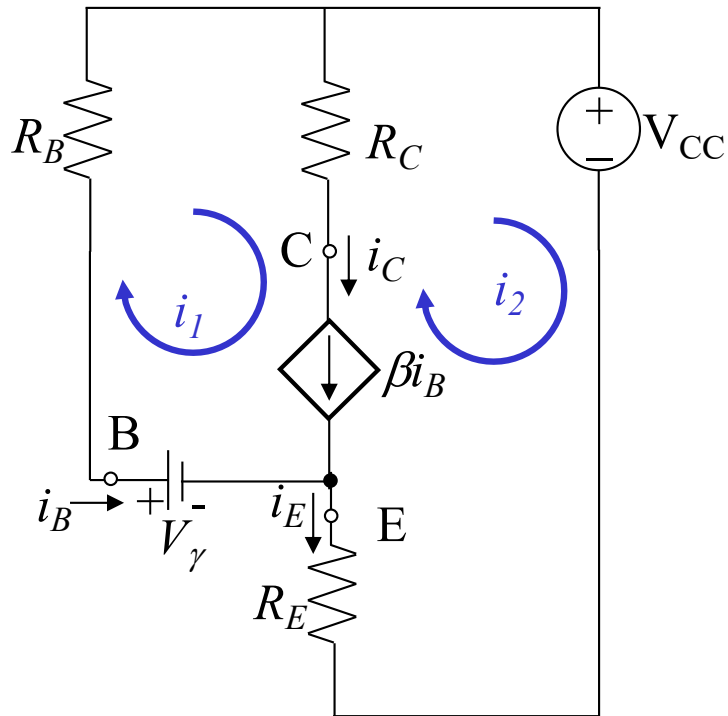
Needs a supermesh

Current source in two loops
without R in parallel

Supermesh = entire outer loop

Supermesh equation

$$i_2 R_E - V_\gamma + i_1 R_B + V_{CC} = 0$$
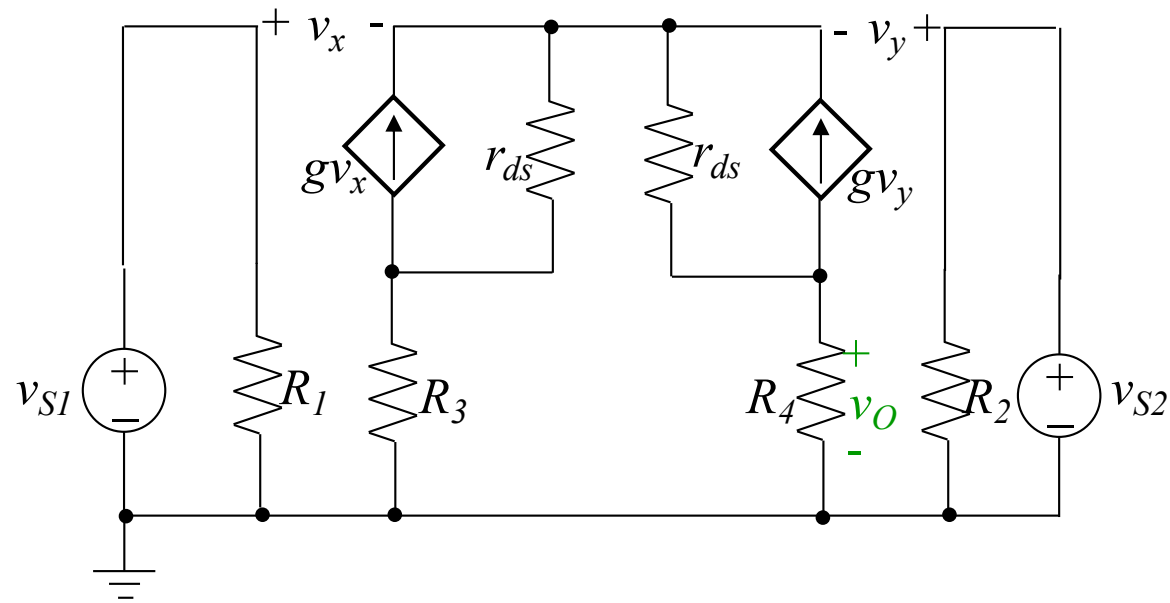
Current source constraint

$$i_1 - i_2 = \beta i_B$$

Solution

$$i_B = -i_1 = \frac{V_{CC} - V_\gamma}{R_B + (\beta + 1)R_E}$$

T&R, 5th ed, Example 4-6 Field Effect Transistor

Since cct is linear $v_O = K_1 v_{S1} + K_2 v_{S2}$

Solve via superposition

First *v_{S1} on* and *v_{S2} off*, then *v_{S1} off* and *v_{S2} on*

This gives *K_1* and *K_2*

Operational Amplifiers - OpAmps

Basic building block of linear analog circuits

Package of transistors, capacitors, resistors, diodes in a chip

Five terminals

- Positive power supply V_{CC}
- Negative power supply - V_{CC}
- Non-inverting input v_p
- Inverting input v_n
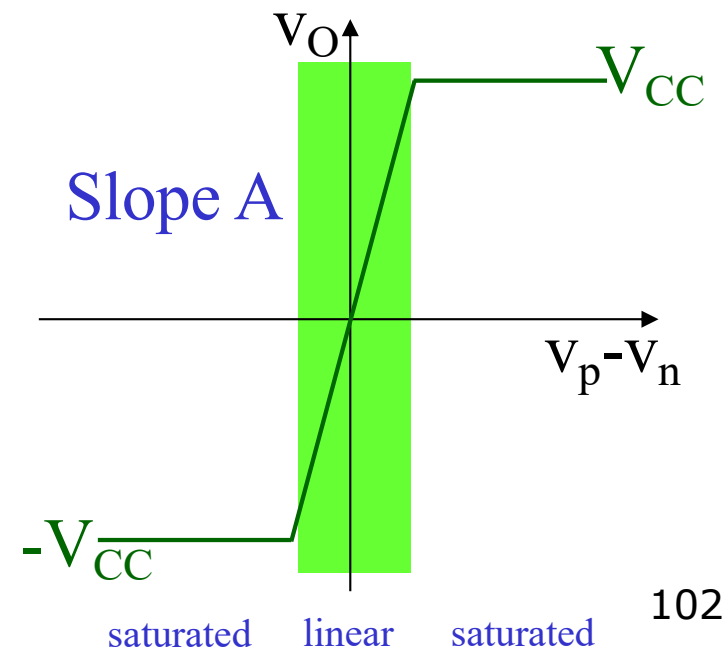
- Output v_O
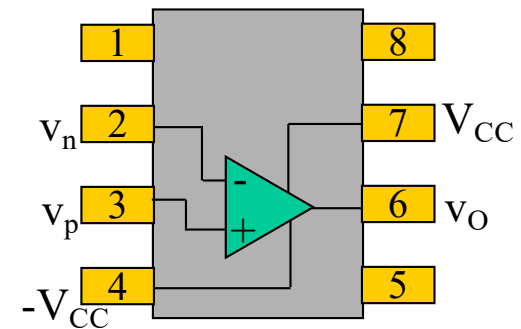
Linear region of operation

$$v_O = A(v_p - v_n)$$

Ideal behavior

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

Saturation at V_{CC}/-V_{CC} limits range

Real OpAmp (u741)
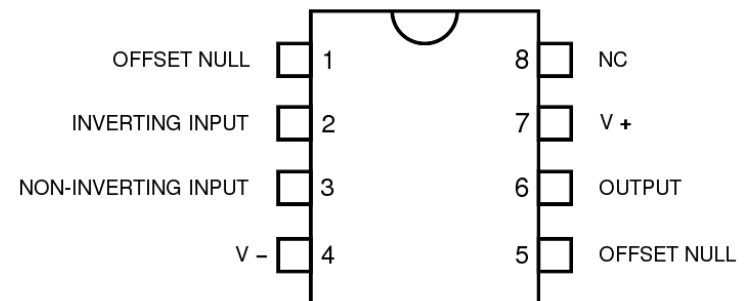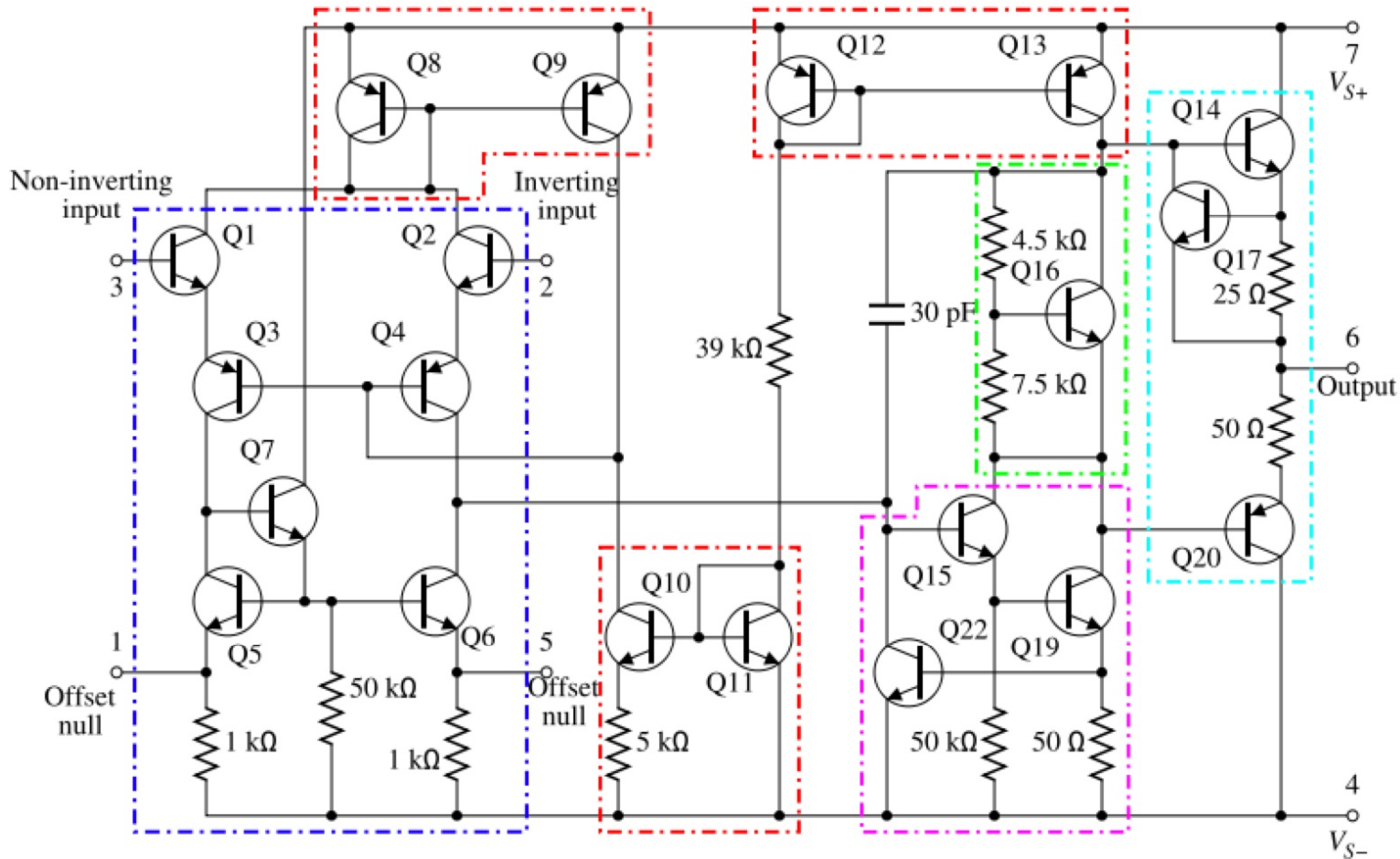
Ideal OpAmp

Equivalent linear circuit

Dependent source model

$$10^6 < R_I < 10^{12}\,\Omega \qquad \infty\Omega$$

$$10 < R_O < 100\,\Omega \qquad 0\Omega$$

$$10^5 < A < 10^8 \qquad \infty$$

Need to stay in linear range

$$-V_{CC} \le v_O \le V_{CC}$$

$$-\frac{V_{CC}}{A} \le v_p - v_n \le \frac{V_{CC}}{A}$$

Ideal conditions

$$v_p = v_n$$

$$i_p = i_n = 0$$

MAE40 Linear Circuits

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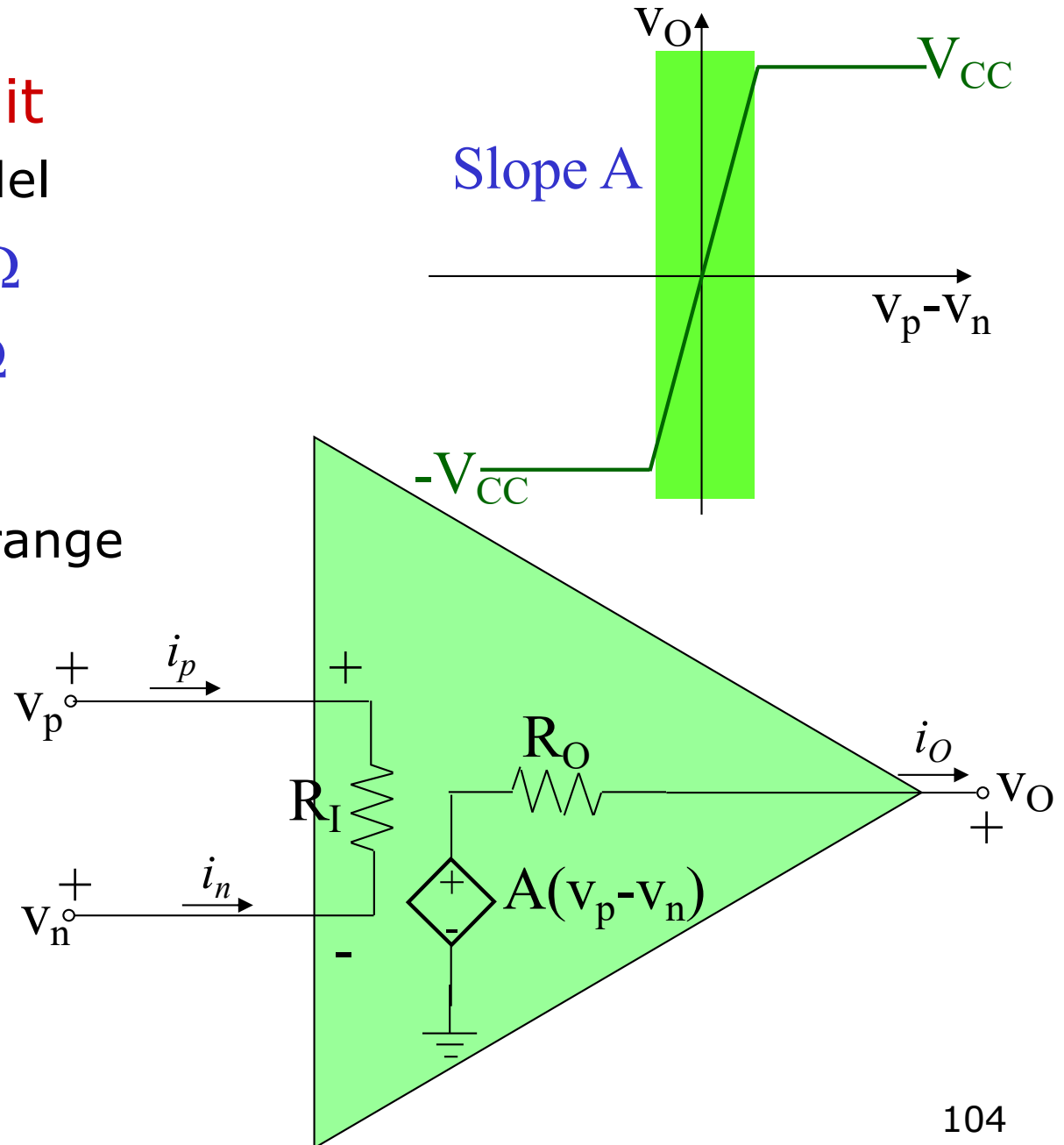
Non-inverting OpAmp - Feedback

What happens now?

Voltage divider feedback

$$v_n = \frac{R_2}{R_1 + R_2} v_O$$

Operating condition $v_p = v_S$

$$v_O = \frac{R_1 + R_2}{R_2} v_S$$

Linear non-inverting amplifier

Gain K$= \dfrac{R_1 + R_2}{R_2}$

With dependent source model

$$v_O = \frac{R_I A (R_1 + R_2) + R_2 R_O}{R_I (A R_2 + R_O + R_1 + R_2) + R_2 (R_1 + R_O)} v_S$$

T&R, 5th ed, Example 4-13

Analyze this

$$i_p = 0$$

$$K_S = \frac{v_p}{v_S} = \frac{R_2}{R_1 + R_2}$$

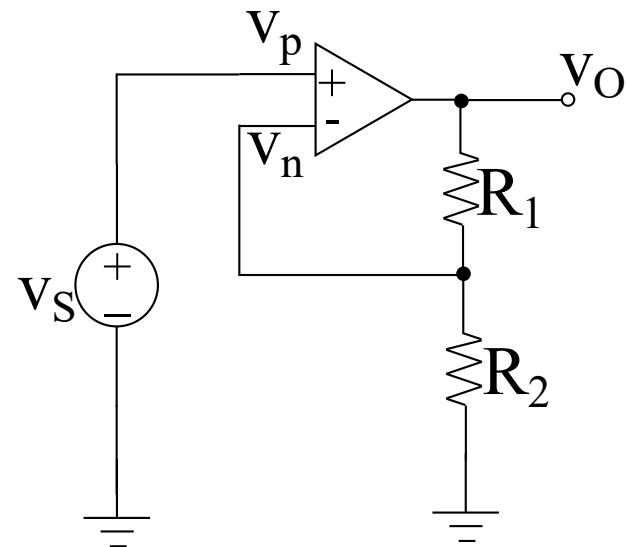Ideal OpAmp has zero output resistance

R$_L$ does not affect v_O

$$K_{AMP} = \frac{v_O}{v_p} = \frac{R_3 + R_4}{R_4}$$

$$K_{Total} = K_S K_{AMP} = \frac{v_O}{v_S} = \left[\frac{R_2}{R_1 + R_2} \right]\left[\frac{R_3 + R_4}{R_4} \right]$$

MAE40 Linear Circuits
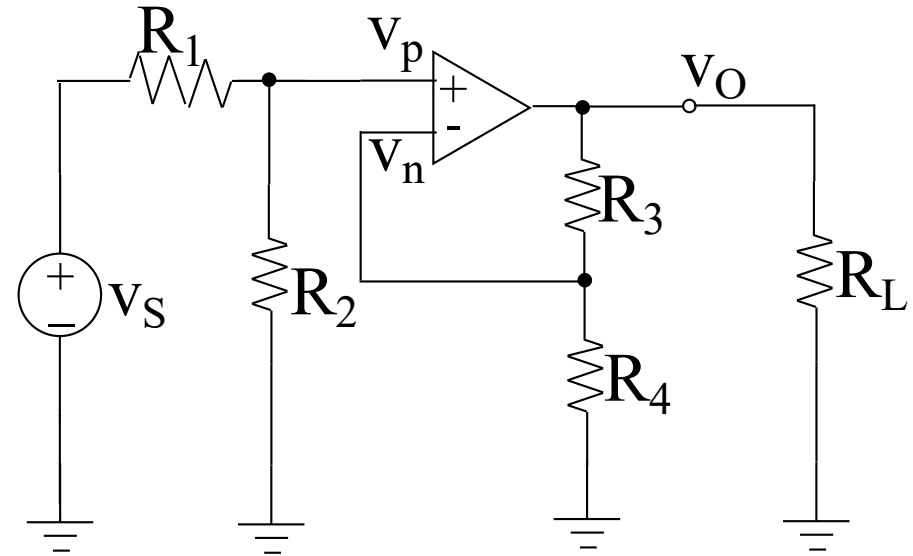
Voltage Follower - Buffer

Feedback path

$$v_n = v_O$$

Infinite input resistance

$$i_p = 0, \quad v_p = v_S$$

Ideal OpAmp

$$v_p = v_n$$

$$v_O = v_S \qquad i_O = \frac{v_O}{R_L}$$

Loop gain is 1

Power is supplied from the Vcc/-Vcc rails

MAE40 Linear Circuits

Blast from the past: Voltage Dividers

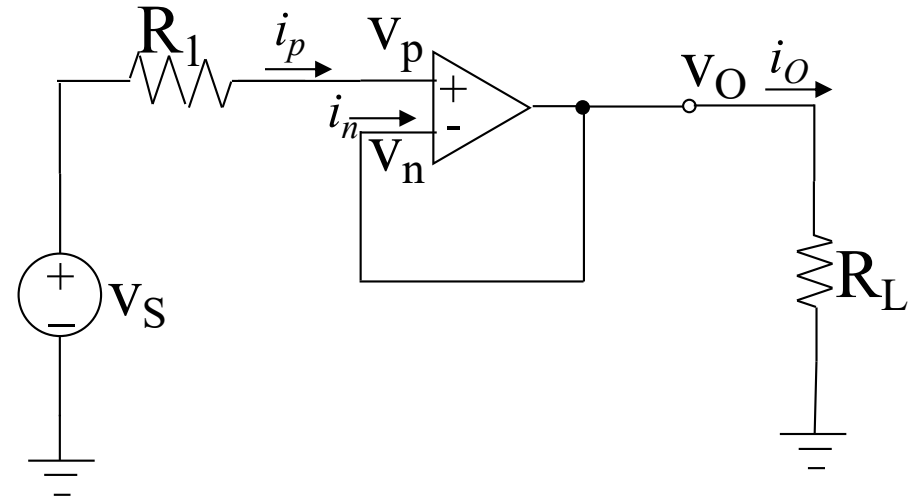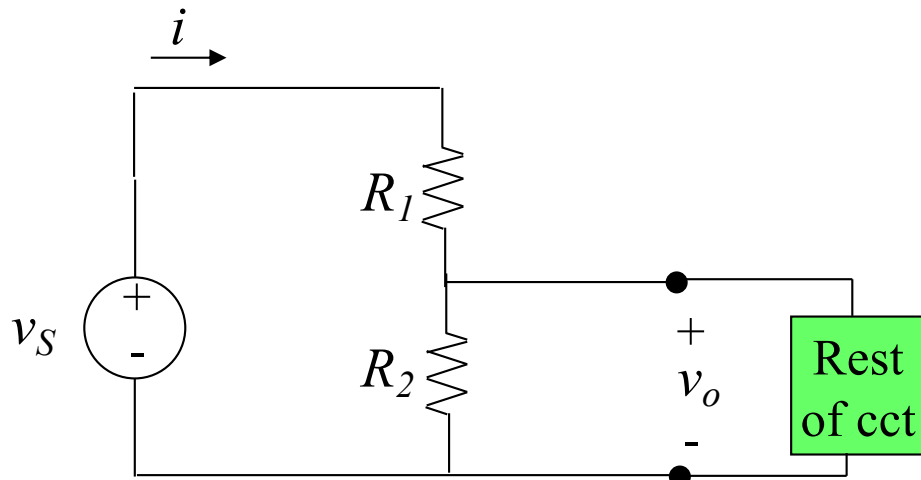Often we use a voltage divider to provide an input voltage to a cct element

When would this work?

When the "rest of cct" does not draw much current compared to R_2

Why is this?

What is it asking of the equivalent of the rest of cct?
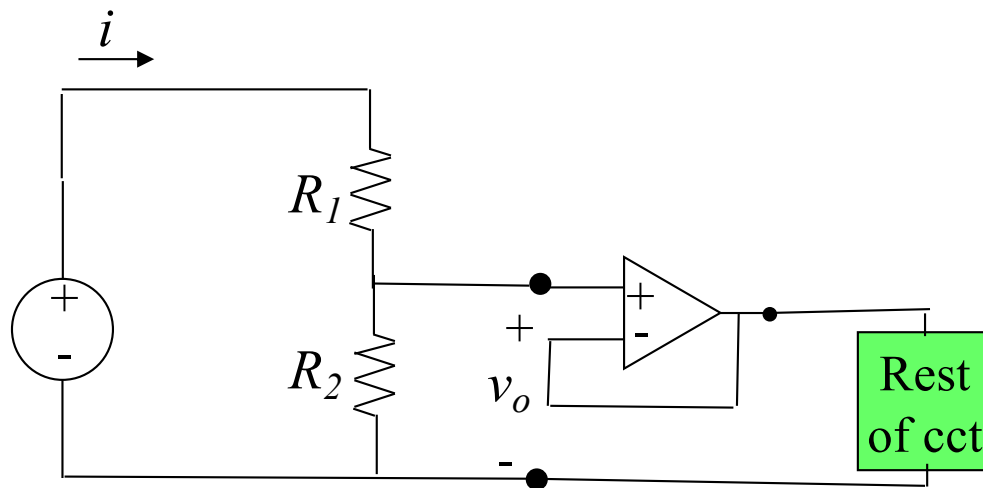
Note that this is a very common circuit used to "bias" a transistor to an operating voltage

OpAmp Ccts – inverting amplifier

Input and feedback applied at same terminal of OpAmp

Inverting amp

R_2 is the feedback resistor

So how does it work?

KCL at node A

$$\frac{v_N - v_S}{R_1} + \frac{v_N - v_O}{R_2} + i_N = 0$$

$$i_N = 0, \quad v_N = v_p = 0$$

$$v_O = -\frac{R_2}{R_1} v_S$$

Non-inverting amp

$v_O = -K v_S$ hence the name
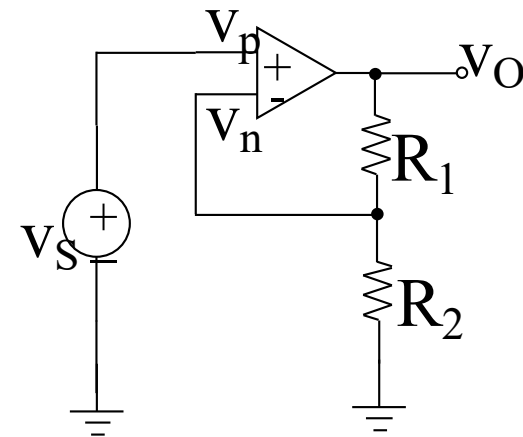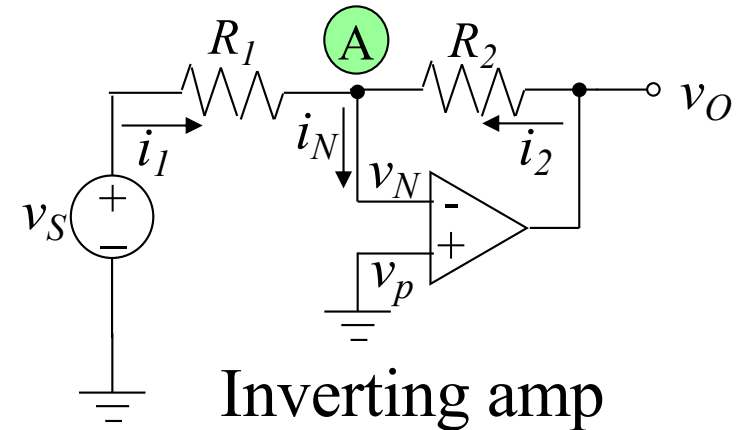
Inverting Amplifier (contd)

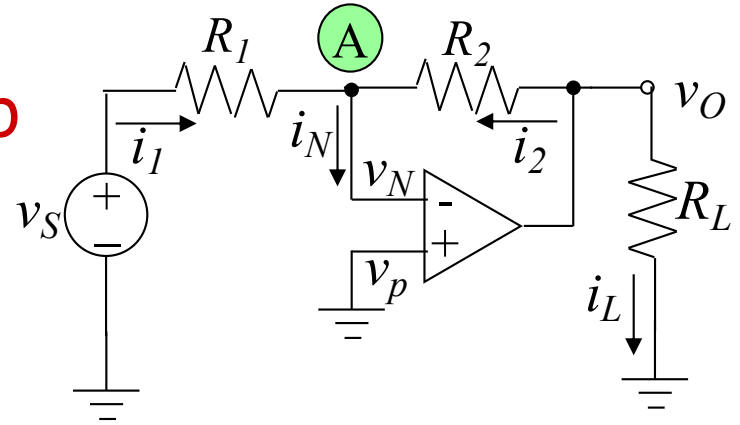Current flows in the inverting amp

$$i_1 = \frac{v_S}{R_1}, \quad R_{in} = R_1$$

$$i_2 = \frac{v_O}{R_2} = \frac{-v_S}{R_1} = -i_1$$

$$i_L = \frac{v_O}{R_L} = -\frac{R_2}{R_1} \times \frac{1}{R_L} \times v_S$$

OpAmp Analysis – T&R, 5th ed, Example 4-14

Compute the input-output relationship of this cct

Convert the cct left of the node A to its Thévenin equivalent

$$v_T = v_{OC} = \frac{R_2}{R_1 + R_2} v_S$$

$$R_T = R_{in} = R_3 + \frac{R_1 R_2}{R_1 + R_2} = \frac{R_1 R_2 + R_1 R_3 + R_2 R_3}{R_1 + R_2}$$

Note that this is not the inverting amp gain times the voltage divider gain

There is interaction between the two parts of the cct (R_3)

This is a feature of the inverting amplifier configuration
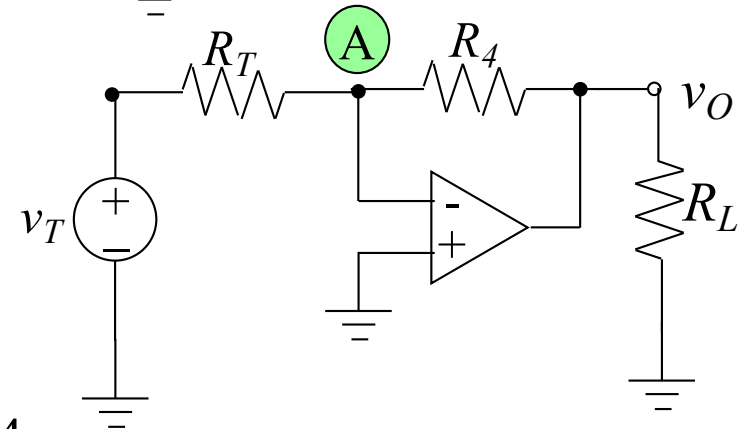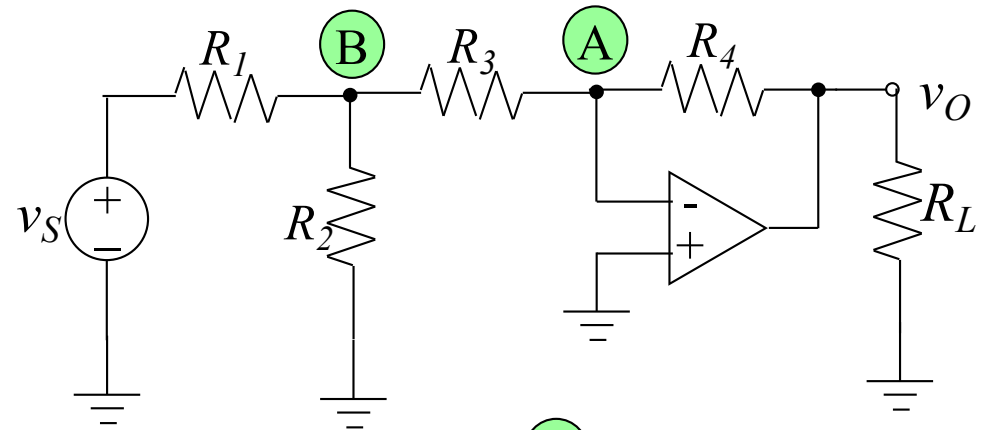
$$v_O = -\frac{R_4}{R_T} v_T$$

$$= -\left[\frac{R_4(R_1 + R_2)}{R_1 R_2 + R_1 R_3 + R_2 R_3} \right]\left[\frac{R_2}{R_1 + R_2} \right] v_S$$

$$= -\frac{R_2 R_4}{R_1 R_2 + R_1 R_3 + R_2 R_3} v_S$$

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Summing Amplifier - Adder

So what happens?

Node A is effectively grounded

$$v_n = v_p = 0$$

Also $i_N = 0$ because of R_{in}

So

$$i_1 + i_2 + i_F = 0$$

$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_O}{R_F} = 0$$

This is an inverting summing amplifier
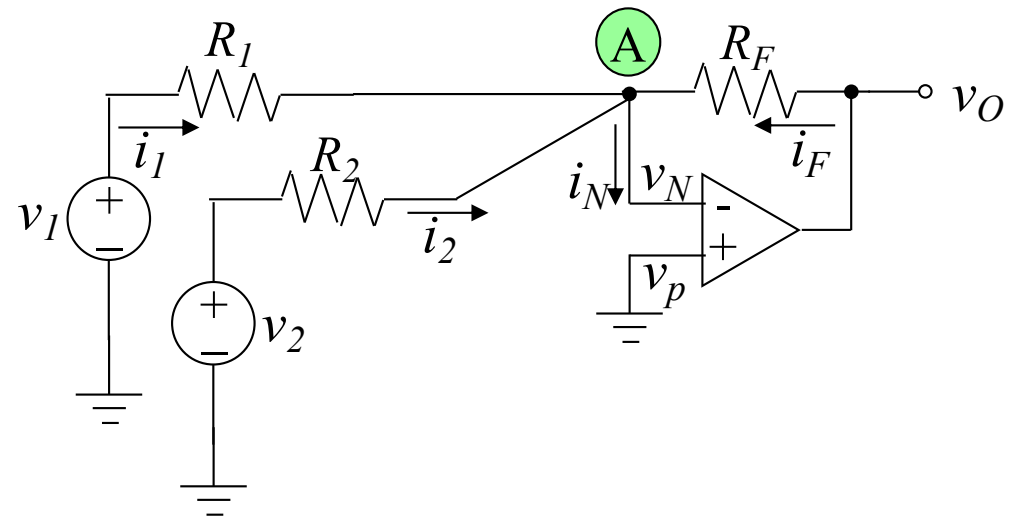
$$v_O = \left(-\frac{R_F}{R_1}\right)v_1 + \left(-\frac{R_F}{R_2}\right)v_2$$

$$= -K_1 v_1 - K_2 v_2$$

Ever wondered about audio mixers? How do they work?

Mixing desk – Linear ccts
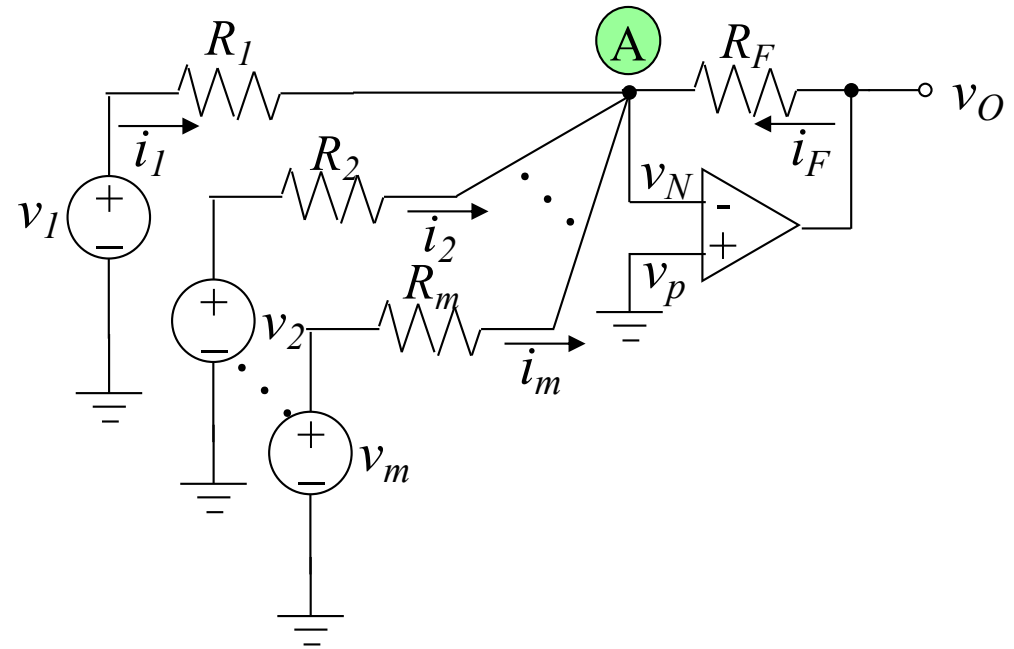
Virtual ground at v_n

Currents add

Summing junction

Permits adding signals to create a composite

Strings+brass+woodwind+percussion

Guitars+bass+drums+vocal+keyboards

$$v_O = \left(-\frac{R_F}{R_1}\right)v_1 + \left(-\frac{R_F}{R_2}\right)v_2 + \cdots + \left(-\frac{R_F}{R_m}\right)v_m$$

$$= K_1 v_1 + K_2 v_2 + \cdots + K_m v_m$$

T&R, 5th ed, Design Example 4-15

Design an inverting summer to realize $v_O = -(5v_1 + 13v_2)$

Inverting summer with $\dfrac{R_F}{R_1} = 5, \quad \dfrac{R_F}{R_2} = 13$
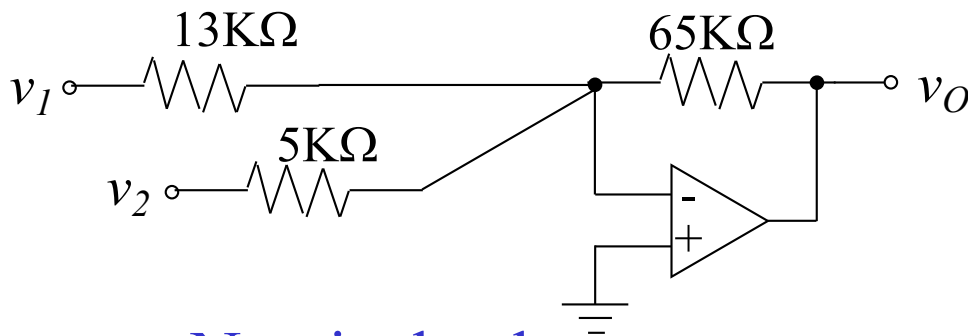
Nominal values
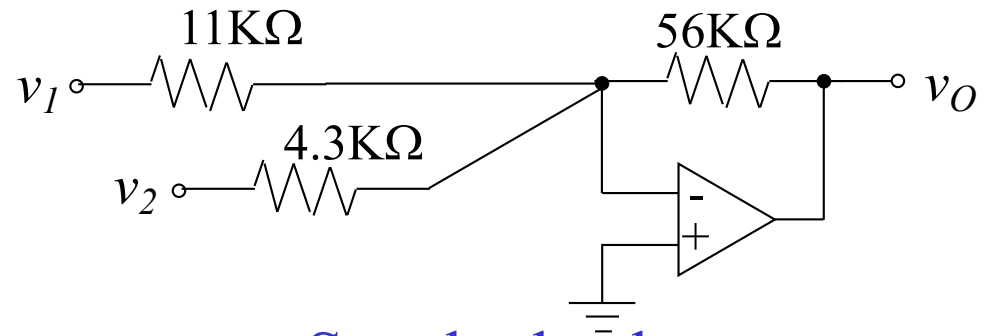
Standard values

If $v_1 = 400\text{mV}$ and $V_{CC} = \pm 15\text{V}$ what is max of v_2 for linear op^n?

Need to keep $v_O > -15\text{V}$

$$-15 < -(5v_1 + 13v_2)$$

$$15 > 5v_1 + 13v_2$$

$$v_2 < \frac{15 - 5 \times 0.4}{13} = 1\text{V}$$

OpAmp Circuits – Differential Amplifier
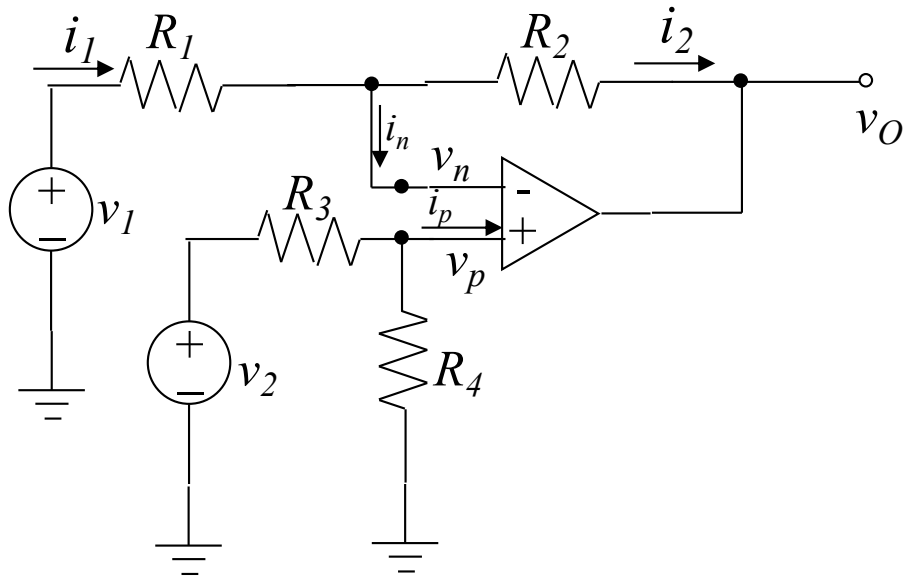
OpAmp Circuits – Differential Amplifier
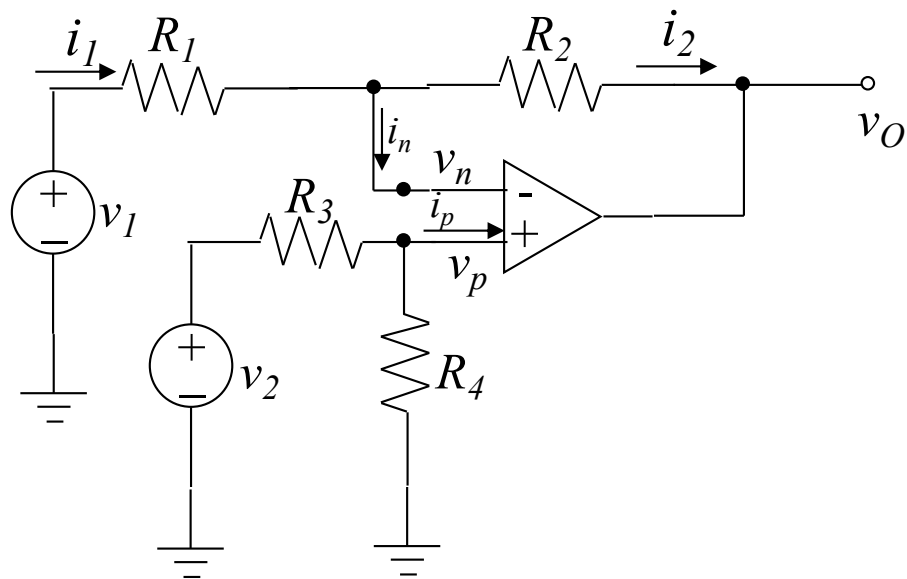
Use superposition to analyze

$v_2=0$: inverting amplifier

$$v_{O1} = -\frac{R_2}{R_1}v_1$$

$v_1=0$: non-inverting amplifier plus voltage divider

$$v_{O2} = \left[\frac{R_4}{R_3+R_4}\right]\left[\frac{R_1+R_2}{R_1}\right]v_2$$

$$v_O = v_{O1} + v_{O2}$$

$$= -\left[\frac{R_2}{R_1}\right]v_1 + \left[\frac{R_4}{R_3+R_4}\right]\left[\frac{R_1+R_2}{R_1}\right]v_2$$

$$= -K_1v_1 + K_2v_2$$

K_1 inverting gain

K_2 non-inverting gain

MAE40 Linear Circuits

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T&R, 5th ed, Exercise 4-13

What is v_O?

This is a differential amp

v_1 is 10V, v_2 is 10V

$R_1 = 1K\Omega || 1K\Omega = 500\Omega$

$R_2 = R_3 = R_4 = 1K\Omega$

$$v_O = K_1 v_1 + K_2 v_2$$

$$= -\frac{R_2}{R_1} v_1 + \left[\frac{R_1 + R_2}{R_1} \right\| \left[\frac{R_4}{R_3 + R_4} \right] v_2$$

$$= -20 + 3 \cdot \frac{1}{2} \cdot 10 = -5V$$

1KΩ

1KΩ

1KΩ

1KΩ

1KΩ

10V

v_O

Lego Circuits

v_1 o———[+ op-amp −]———o v_O

R_1

R_2

v_1 ——→ [K] ——→ v_Q
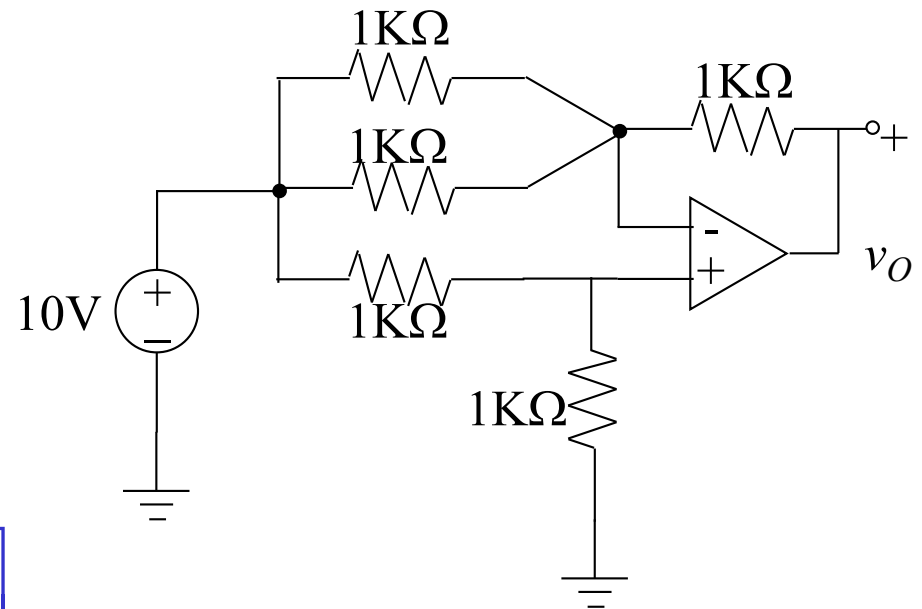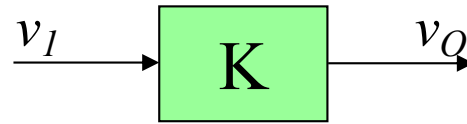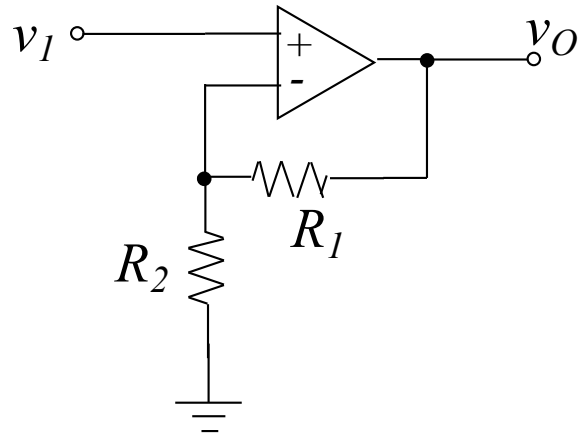
$$K = \frac{R_1 + R_2}{R_2}$$

Non-inverting amplifier

v_1 o——/\/\/\— R_1 ——/\/\/\— R_2 ——o v_O

[− op-amp +]

v_1 ——→ [K] ——→ v_Q
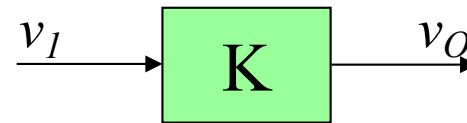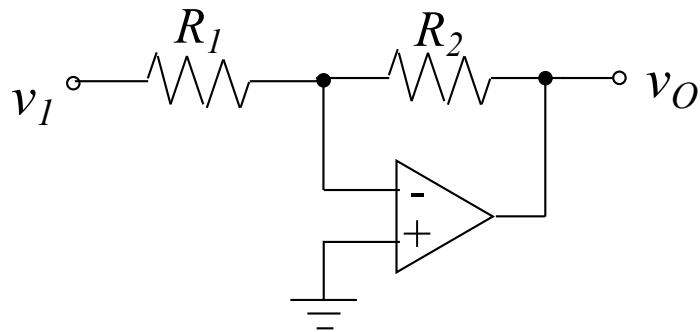
$$K = -\frac{R_2}{R_1}$$

Inverting amplifier

MAE40 Linear Circuits

Lego Circuits (contd)
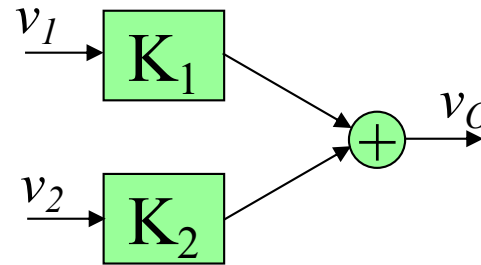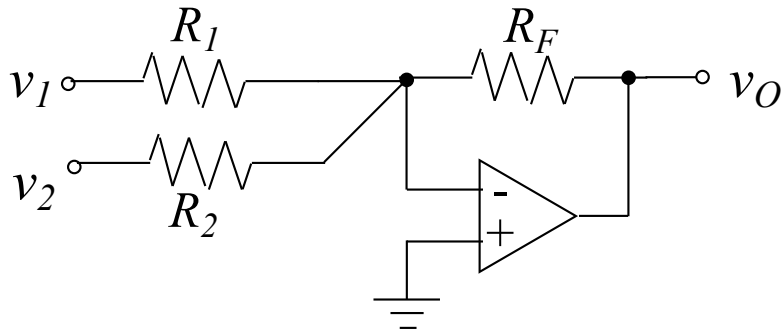
Inverting summer

$$K_1 = -\frac{R_F}{R_1}$$

$$K_2 = -\frac{R_F}{R_2}$$
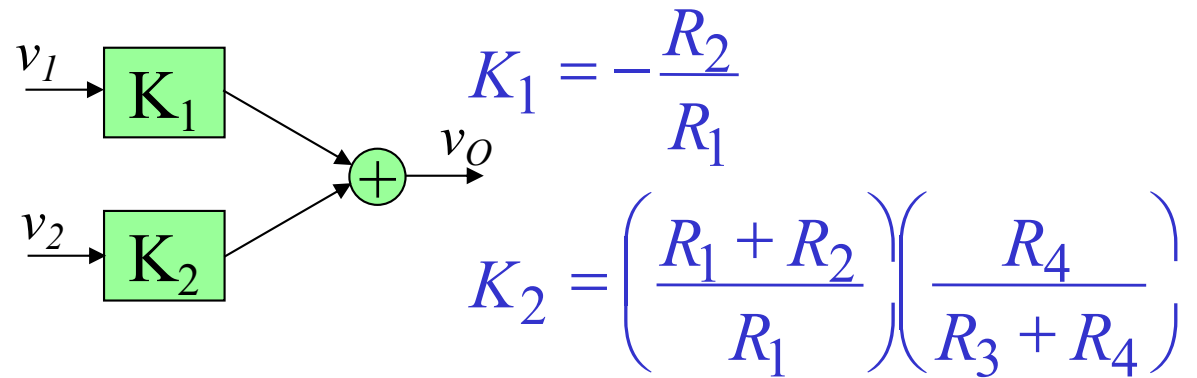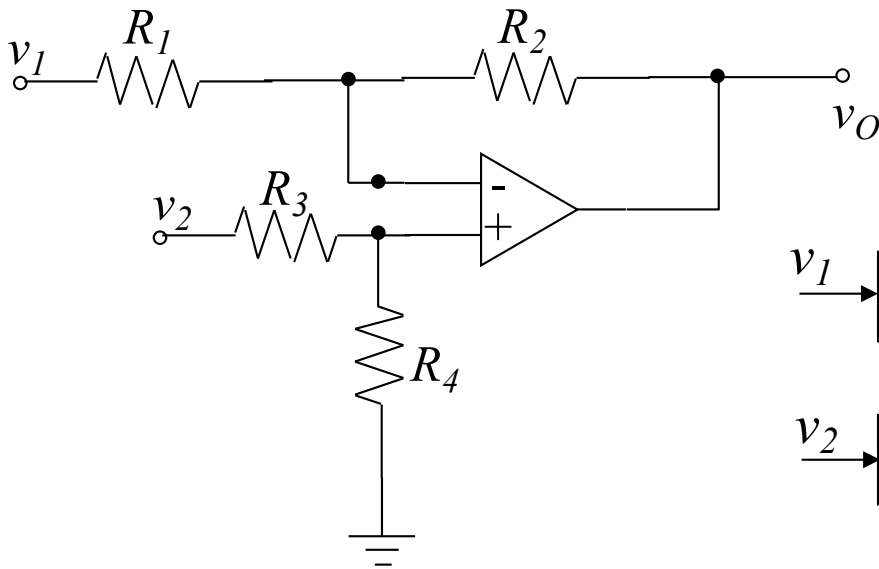
$$K_1 = -\frac{R_2}{R_1}$$

$$K_2 = \left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right)$$

Differential amplifier

MAE40 Linear Circuits

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T&R, 5th ed, Example 4-16: OpAmp Lego

v_F $+$ 10KΩ

9.7V   10KΩ   3.3KΩ   10KΩ   10KΩ   9KΩ   5KΩ v_C

$V_{CC}=\pm15V$
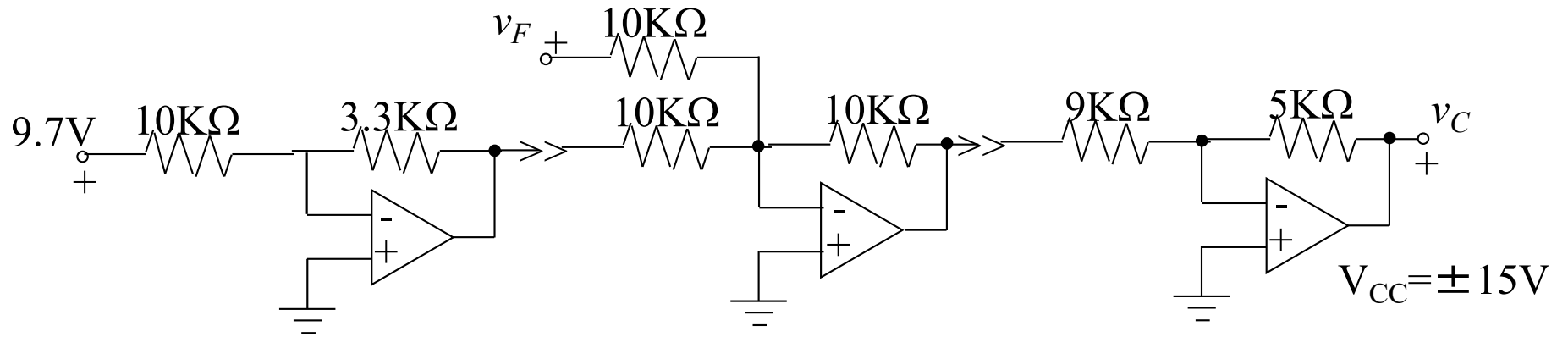
So what does this circuit do?

Example 4-16: OpAmp Lego
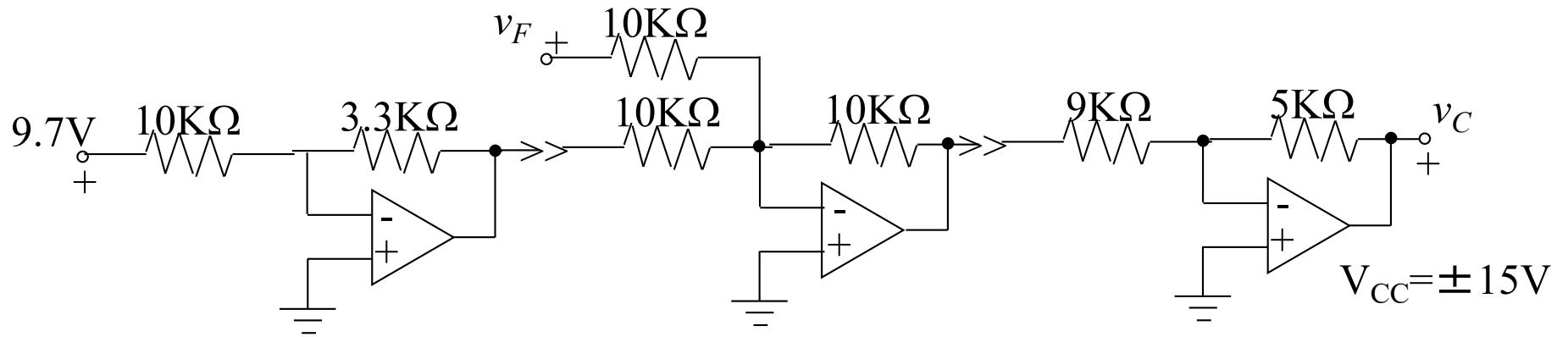
So what does this circuit do?
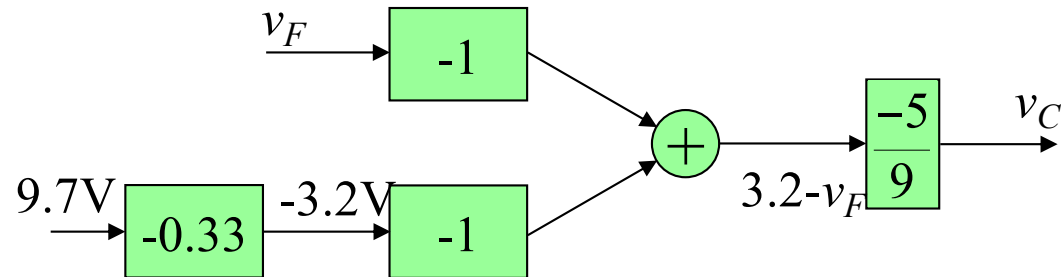
It converts tens of °F to tens of °C

Max current drawn by each stage is 1.5mA

OpAmp Cct Analysis

What if circuit is not simple interconnection of basic building blocks? OpAmp Nodal Analysis

Use dependent voltage source model

Identify node voltages

Formulate input node equations

Solve using ideal characteristic $v_p=v_n$

Rest of circuit v_p+ i_p +

Rest of circuit v_n+ i_n - $+$ $A(v_p-v_n)$

i_O+v_O Rest of circuit
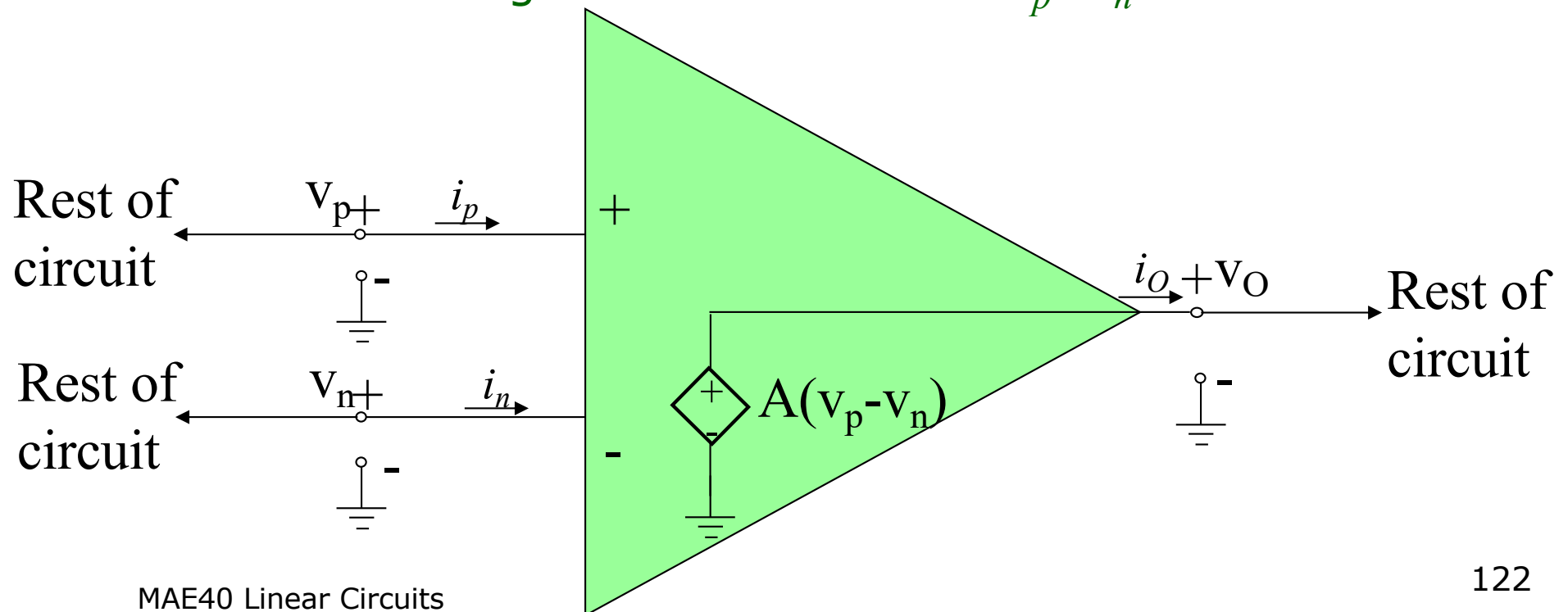
OpAmp Analysis – T&R, 5th ed, Example 4-18
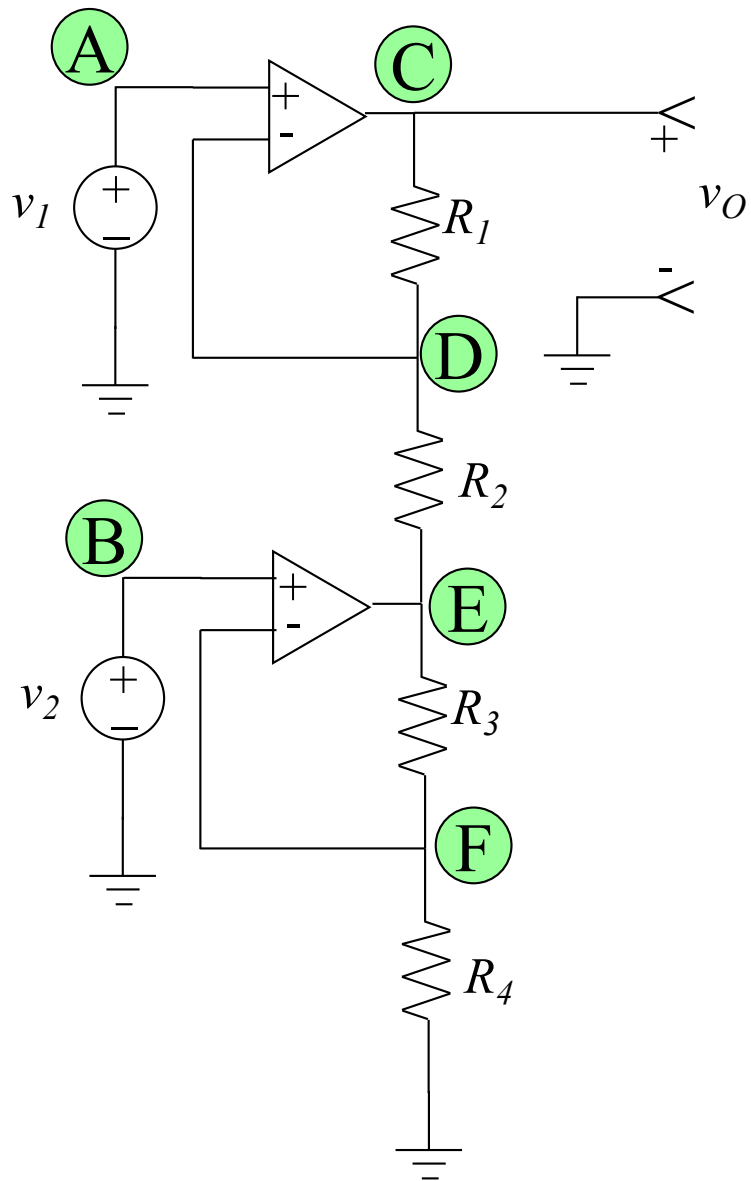
OpAmp Analysis – T&R, 5th ed, Example 4-18
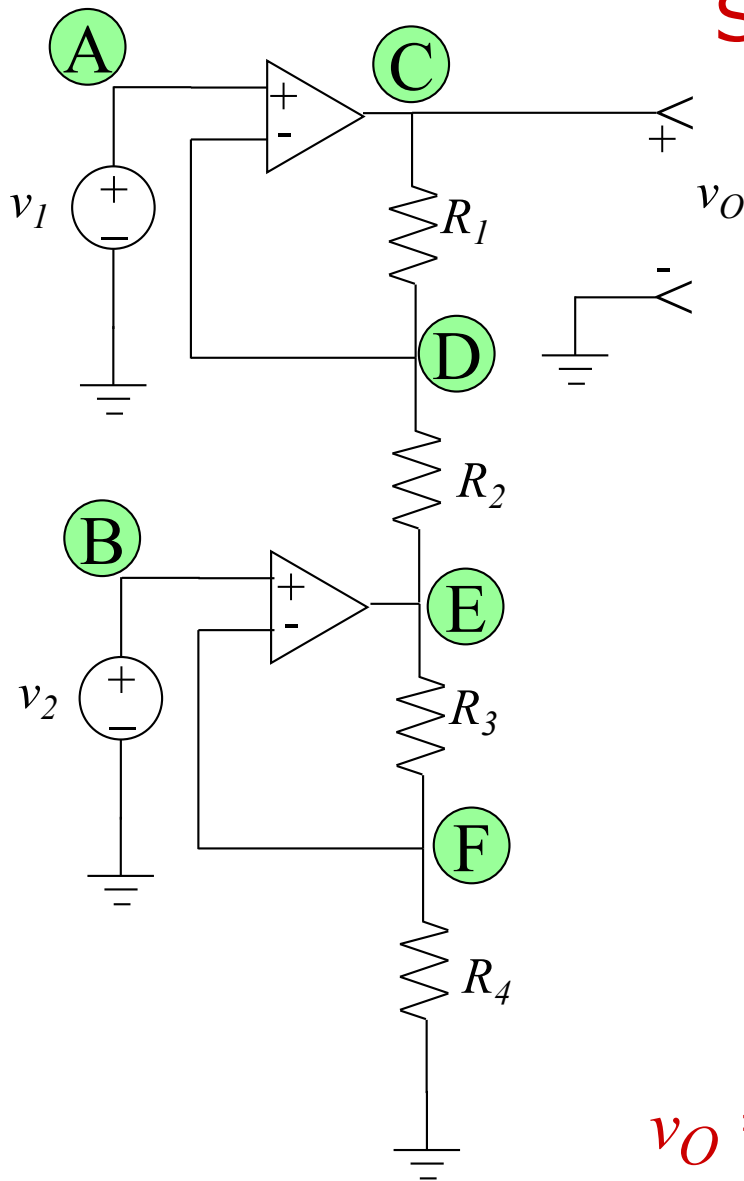
Seemingly six non-reference nodes: A-E

Nodes A, B: connect to reference voltages v_1 and v_2

Node C, E: connected to OpAmp outputs (forget for the moment)

Node D: $(G_1 + G_2)v_D - G_1 v_C - G_2 v_E = 0$

Node F: $(G_3 + G_4)v_F - G_3 v_E = 0$

OpAmp constraints

$$v_A = v_1 = v_D, \quad v_B = v_2 = v_F$$

$$G_1 v_C + G_2 v_E = (G_1 + G_2)v_1$$

$$G_3 v_E = (G_3 + G_4)v_2$$

$$v_O = v_C = \left[\frac{G_1 + G_2}{G_1}\right]v_1 - \frac{G_2}{G_1}\left[\frac{G_3 + G_4}{G_3}\right]v_2$$

OpAmp Analysis – T&R, 5th ed, Exercise 4-14
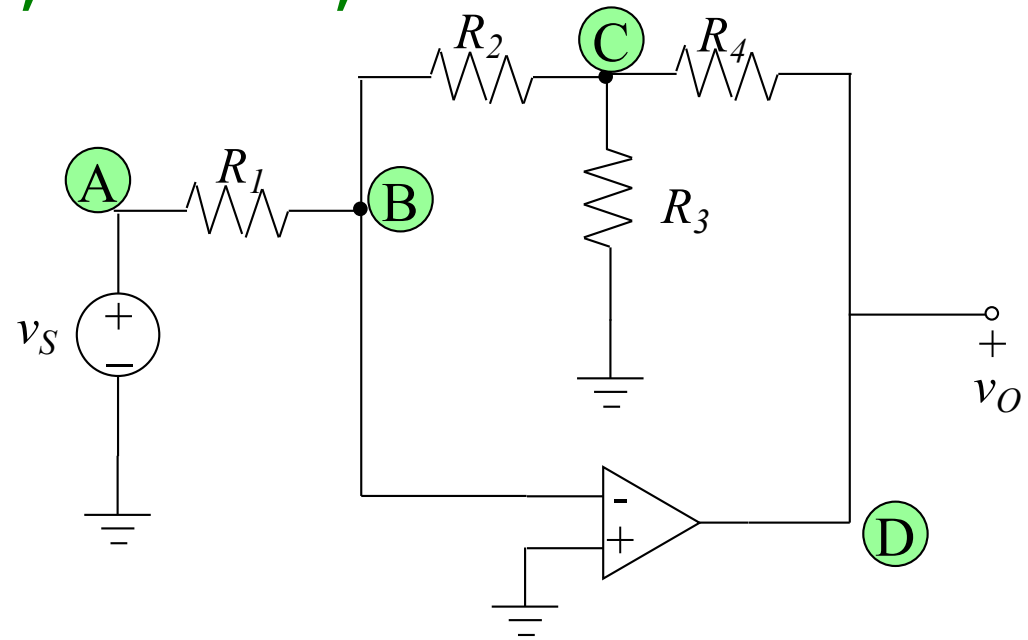
OpAmp Analysis – T&R, 5th ed, Exercise 4-14

Node A: $v_A = v_S$

Node B:

$(G_1 + G_2)v_B - G_1 v_A - G_2 v_C = 0$

Node C:

$(G_2 + G_3 + G_4)v_C - G_2 v_B - G_4 v_D = 0$

Constraints

$v_B = v_p = v_n = 0$

Solve

$v_C = -\dfrac{G_1}{G_2} v_S$

$v_O = v_D$
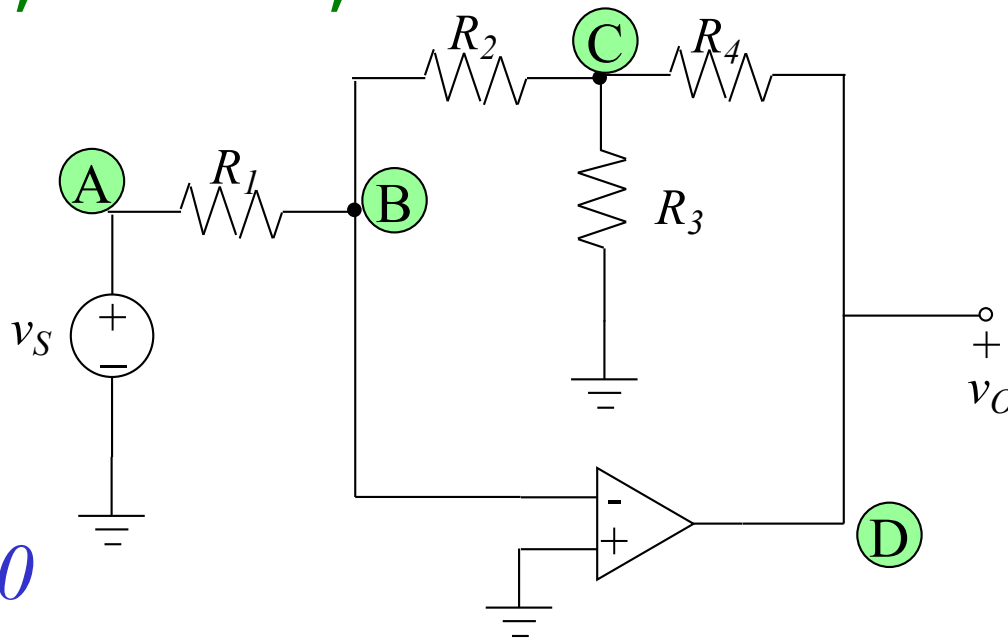
$$v_O = \frac{(G_2 + G_3 + G_4)}{G_4} \cdot \frac{-G_1}{G_2} v_S$$

$$= -\frac{(R_2 R_3 + R_2 R_4 + R_3 R_4)}{R_1 R_3} v_S$$

OpAmp Circuit Design – the whole point

Given an input-output relationship design a cct to implement it

Build a cct to implement $v_O = 5v_1 + 10v_2 + 20v_3$

OpAmp Circuit Design – the whole point

Given an input-output relationship design a cct to implement it

Build a cct to implement $v_O = 5v_1 + 10v_2 + 20v_3$

Inverting summer followed by an inverter

20KΩ

10KΩ

100KΩ   100KΩ   100KΩ v_O

5KΩ

v_1

v_2

v_3

←——— Summer ———→   ←——— Inverter ———→
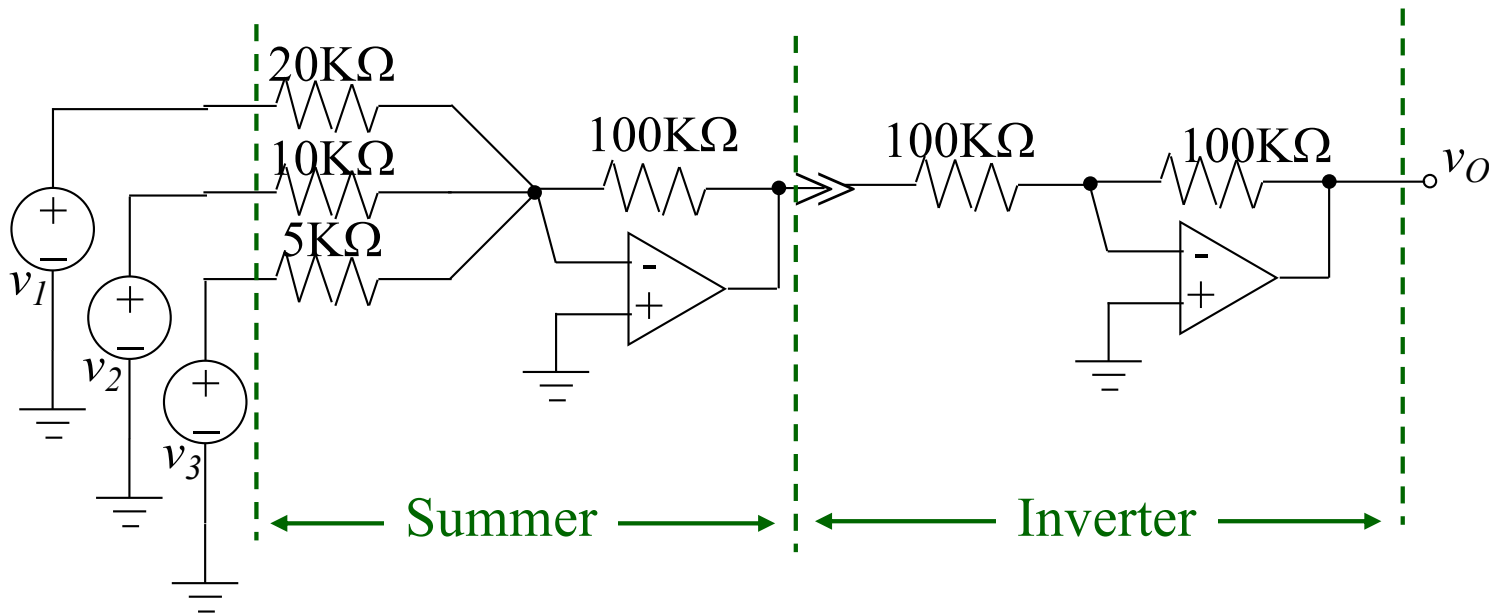
T&R, 5th ed, Example 4-21
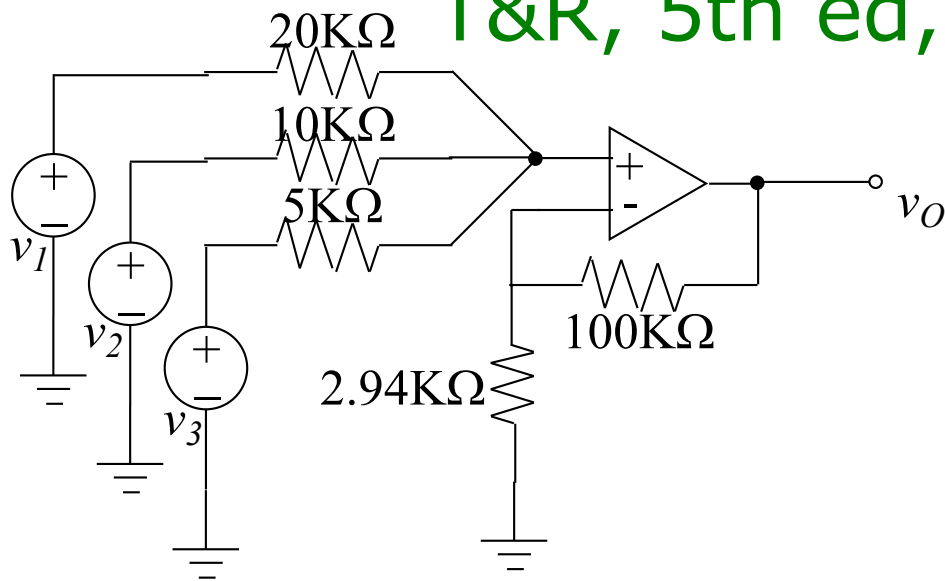
How about this one?

v_O

20KΩ

10KΩ

5KΩ

100KΩ

2.94KΩ

v_1

v_2

v_3

Example 4-21

20KΩ

10KΩ

5KΩ

v_1

v_2

v_3

v_O

100KΩ

2.94KΩ
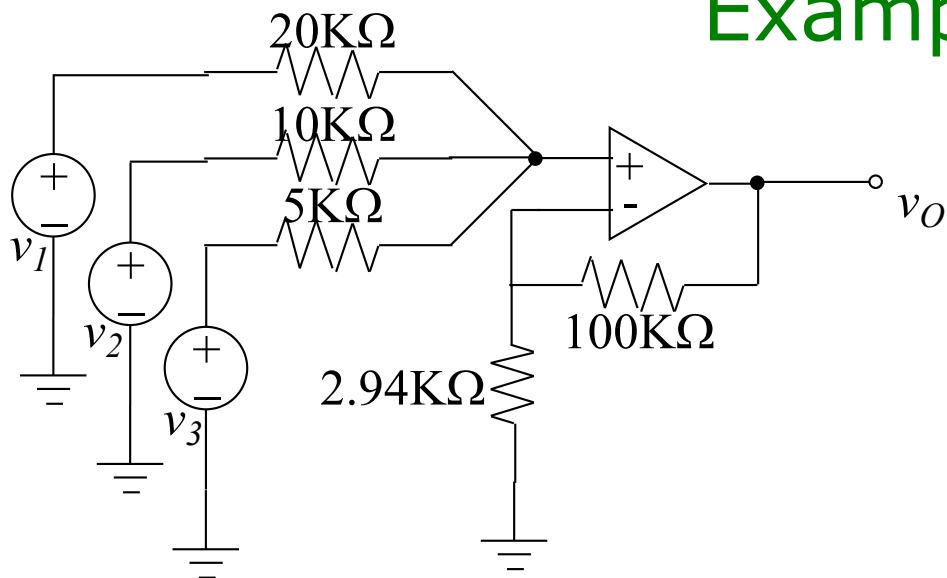
How about this one?

Non-inverting amp $v_p \rightarrow v_O$

$$v_O = K v_p = \frac{100 \times 10^3 + 2.94 \times 10^3}{2.94 \times 10^3} v_p = 35 v_p$$

KCL at p-node with $i_p = 0$

$$\frac{v_1 - v_p}{2 \times 10^4} + \frac{v_2 - v_p}{10^4} + \frac{v_3 - v_p}{0.5 \times 10^4} = 0$$

$$3.5 v_p = 0.5 v_1 + v_2 + 2 v_3$$

v_1 — R_1

v_2 — R_2

v_m — R_m

v_O

$(K-1)R$

R

Non-inverting summer

Fewer elements than inv-summer + inverter
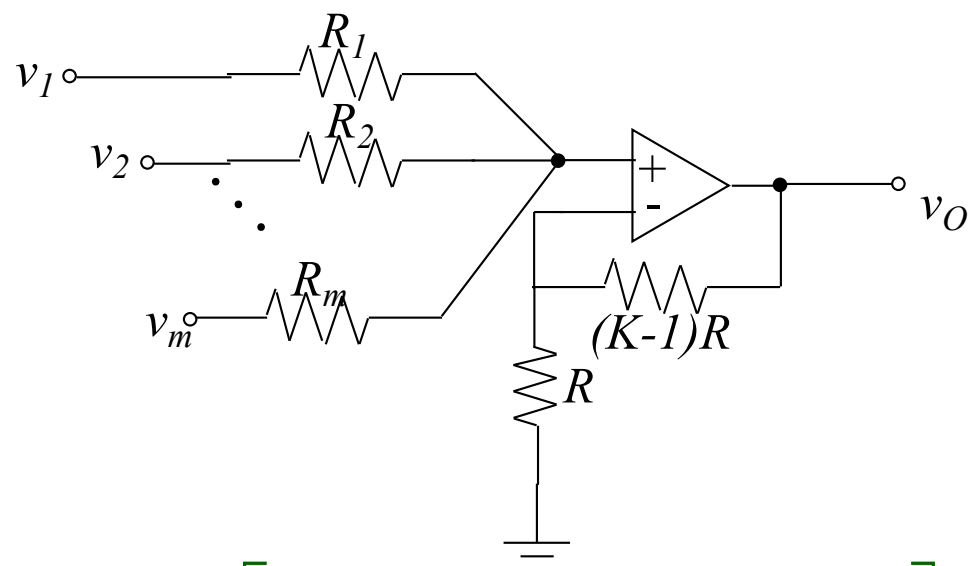
$$v_O = K\left[\frac{R_{eq}}{R_1} v_1 + \frac{R_{eq}}{R_2} v_2 + \dots + \frac{R_{eq}}{R_m} v_m\right] \qquad R_{eq} = R_1 \| R_2 \| R_3 \| \dots R_m$$

MAE40 Linear Circuits

Comparators – A Nonlinear OpAmp Circuit

We have used the ideal OpAmp conditions for the analysis of OpAmps in the linear regime

$$v_n = v_p, \quad i_n = i_p = 0 \quad \text{if} \quad A\left|v_p - v_n\right| \leq V_{CC}$$

What about if we operate with $v_p \neq v_n$?

That is, we operate outside the linear regime. We saturate!!

$$v_O = +V_{CC} \quad \text{if} \quad v_p > v_n$$

$$v_O = -V_{CC} \quad \text{if} \quad v_p < v_n$$

Without feedback, OpAmp acts as a comparator

- one of the terminal inputs, say v_n, is a sensor signal
- other terminal v_p is a threshold voltage
- value of the sensor signal can flip v_{out} between $+V_{cc}$ and $-V_{cc}$

Sensor resolution

Sensor resolution is the is the smallest increment a system can display or measure

Related to number of significant digits on a sensor readout

This scale has resolution of 0.1 grams

Sensor accuracy is how close a measured value is to the true quantity of what is being measured.

Resolution: with +Vcc = 5V and -Vcc = 0V, then v_o is 0 or 5V

Computers' logic is binary (0/1's), so we can use:
　　　　0V => Logical 0　　and　　5V => Logical 1

This is a very low resolution: can we do better?

"Analog-to-digital converter" - comparators

8V

3R

v_{O3}

2R

v_{O2}

2R

v_{O1}

v_S

R

+V$_{CC}$=5V
-V$_{CC}$=0V
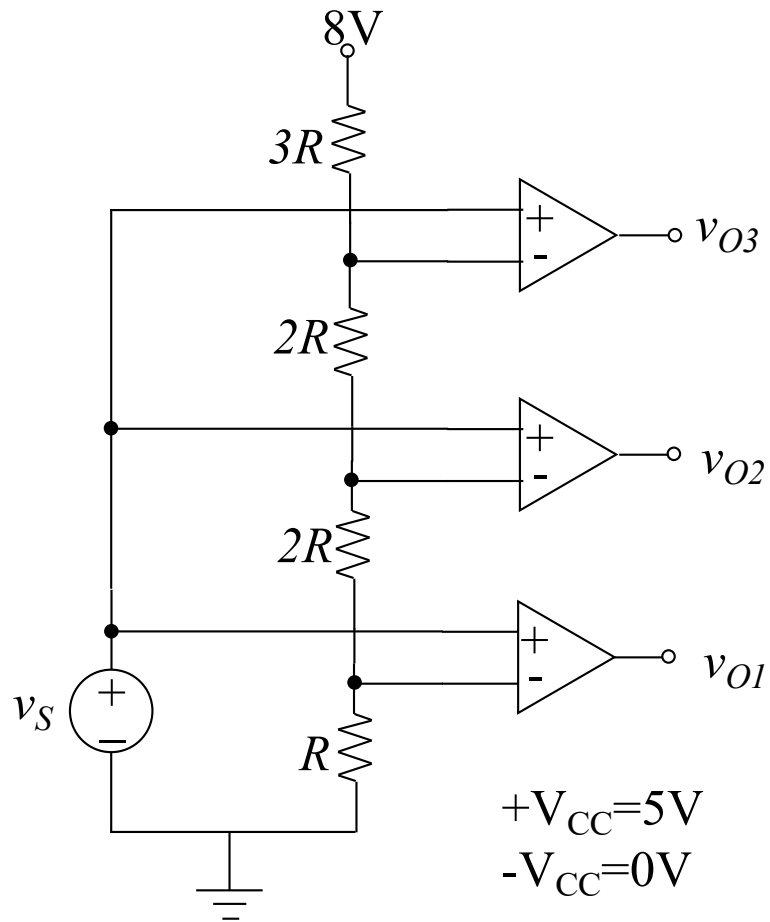
"Analog-to-digital converter" - comparators

Current laws still work

$$i_p = i_n = 0$$

Parallel comparison

Flash converter

"3-bit" output

Not really how it is done

Voltage divider switched

8V

3R

v_{O3}

2R

v_{O2}

2R

v_{O1}

v_S

R

+V_{CC}=5V
-V_{CC}=0V
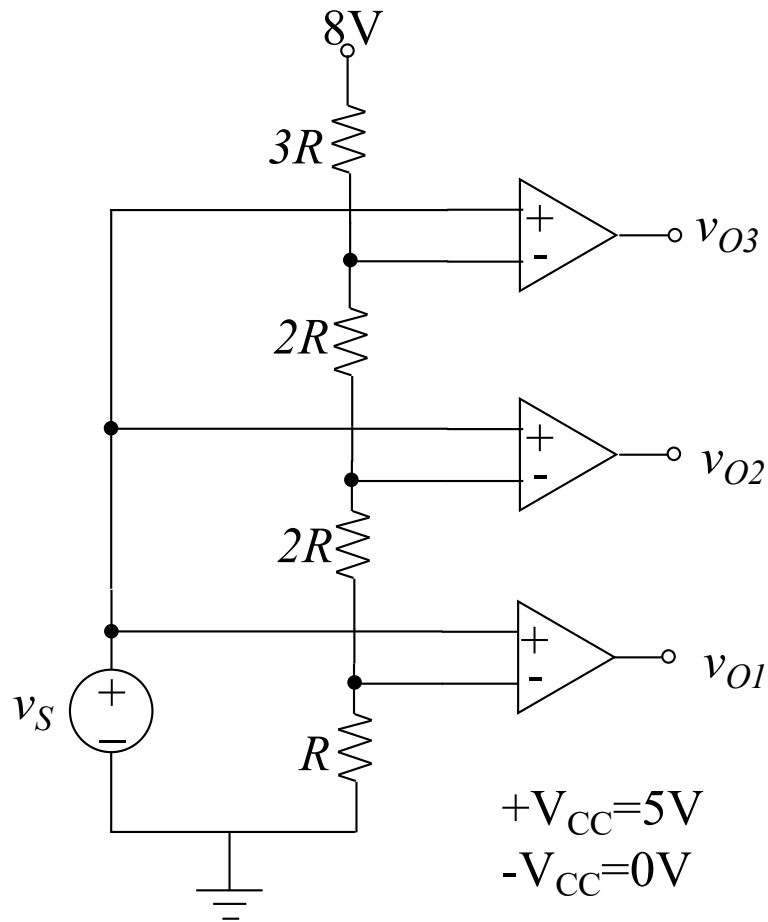
Input	v_{O1}	v_{O2}	v_{O3}
$1 > v_S$	0	0	0
$3 > v_S > 1$	5	0	0
$5 > v_S > 3$	5	5	0
$v_S > 5$	5	5	5

ADC Resolution

- An Arduino has 10 bit ADCs, providing $2^{10} = 1024$ bins (0 to 1023)

- Default ADC input voltage range is 0 to 5V

- Resolution of measured voltage:
  $$\Delta V = 5/2^{10} = 0.0049 \text{ V}$$

- Paying for more bits on ADC can lead to higher resolution measurements

- But using OpAmps customized to your sensing needs can increase resolution too
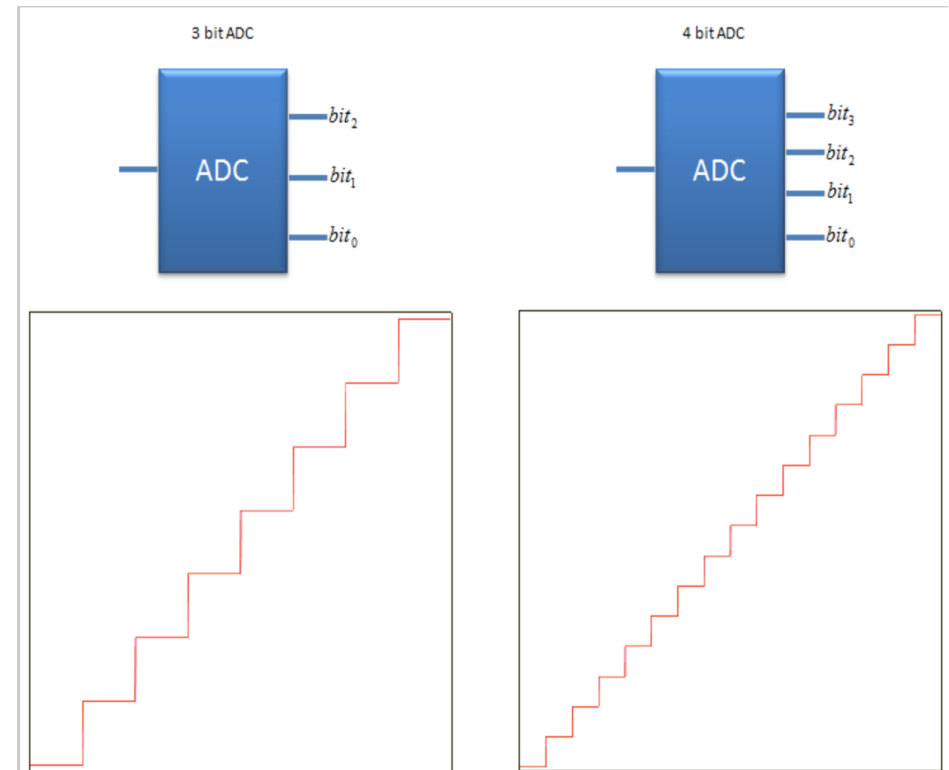
Resolution of 3 vs 4 bit ADC

Upcoming HW6 Problem

- Your experiment will measure a force load between 8N and 15N
- You buy a linear force sensor with range of 0 to 50N* that outputs 0 to 5 V
- You are using an Arduino with a 10 bit ADC with input of 0 to 5 V
- Case 1: Connect sensor voltage directly to ADC
- Case 2: Design an OpAmp circuit to maximize resolution for your experiment
  - You can use multiple OpAmps
  - You have power supplies of +5V, +15V, and -15V
- For each case:
  - Calculate the resolution in volts
  - Calculate the resolution Newtons
- What approach can you use to maximize resolution in Case 2?

*You often buy a sensor w/ higher range than expected to avoid damaging it

How to Tackle HW for Maximizing Sensor Resolution

- Determine sensor voltages corresponding to 8N and 15N loads

- Design OpAmp Circuit that will create linear transformation
  - Sensor output at 8N load results in 0 volt input to ADC
  - Sensor output at 15N load results in 5 volt input to ADC

- What math operations are needed?
  - Addition/Subtraction
  - Multiplication

- Enjoy designing your high-resolution circuit!

MAE40 Linear Circuits

Digital-to-analog converter
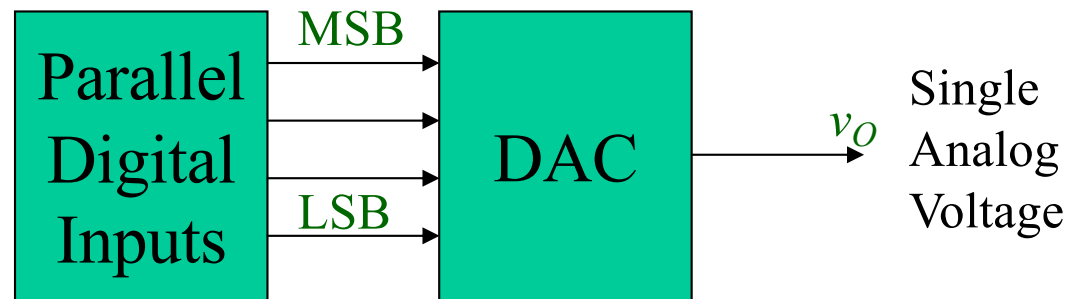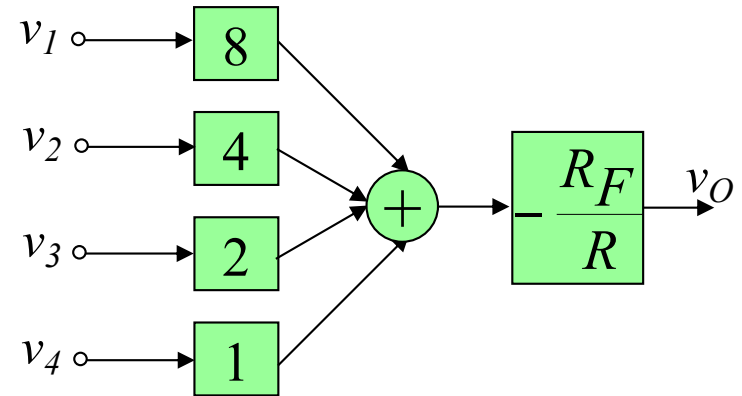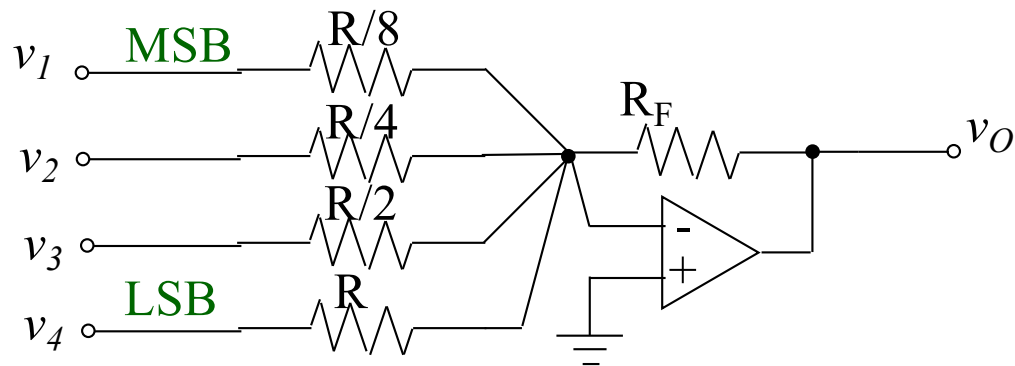
Conversion of digital data to analog voltage value

Bit inputs = 0 or 5V

Analog output varies between v_{min} and v_{max} in 16 steps

MAE40 Linear Circuits

Signal Conditioning

Your most likely brush with OpAmps in practice

Signal – typically a voltage representing a physical variable

Temperature, strain, speed, pressure

Digital analysis – done on a computer after

Anti-aliasing filtering – data interpretation

Adding/subtracting an offset – zeroing

Normally zero of ADC is 0V

Scaling for full scale variation – quantization

Normally full scale of ADC is 5V

Analog-to-digital conversion – ADC

Maybe after a few more tricks like track and hold

Offset correction: use a summing OpAmp
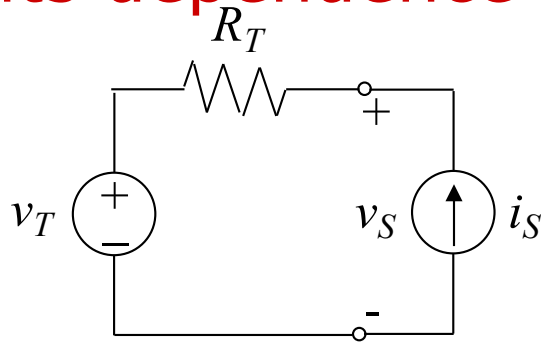
Scaling: use an OpAmp amplifier

Anti-aliasing filter: use a dynamic OpAmp cct

Thévenin and Norton for dependent sources

Cannot turn off the ICSs and IVSs to do the analysis
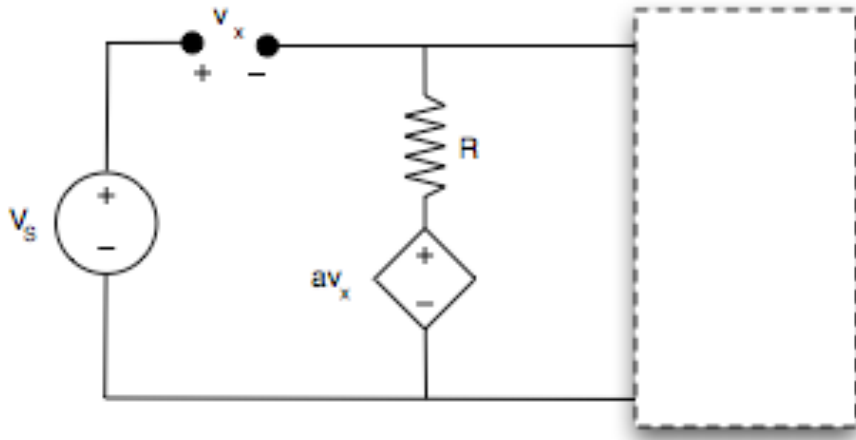
This would turn off DCSs and DVSs

Connect an independent CS or VS to the terminal and compute the resulting voltage or current and its dependence on the source

Compute v_S in response to i_S: $v_S = v_T + i_S R_T$

Or just compute the open-circuit voltage and the short-circuit current

Thévenin and Norton for dependent sources

Thevenin equivalent circuit?

Open-circuit voltage

$$\left.\begin{aligned} v_{OC} &= v_S - v_x \\ v_{OC} &= v_R + av_x = av_x \end{aligned}\right\} \Rightarrow v_T = v_{OC} = \frac{a}{1+a}v_S$$

Thevenin resistance

$$R_T = \frac{v_{OC}}{i_{SC}} = \frac{1}{1+a}R$$

Short-circuit current

$$\left.\begin{aligned} 0 &= v_S - v_x \\ 0 &= -Ri_{SC} + av_x \end{aligned}\right\} \Rightarrow i_{SC} = \frac{a}{R}v_S$$

What would instead be the resistance obtained by turning off IVS?

Where to now?

Where have we been?

- Nodal and mesh analysis
- Thévenin and Norton equivalence
- Dependent sources and active cct models
- OpAmps and resistive linear active cct design

Where to now?

- Capacitors and inductors (Ch.6)
- Laplace Transforms and their use for ODEs and ccts (Ch.9)
- s-domain cct design and analysis (Ch.10)
- Frequency response (Ch.12) and filter design (Ch.14)
  - We will depart from the book more during this phase