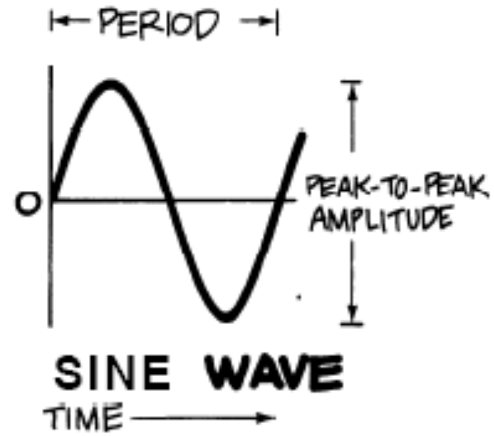
ELE 215
Linear Circuits Laboratory

Recitation 6

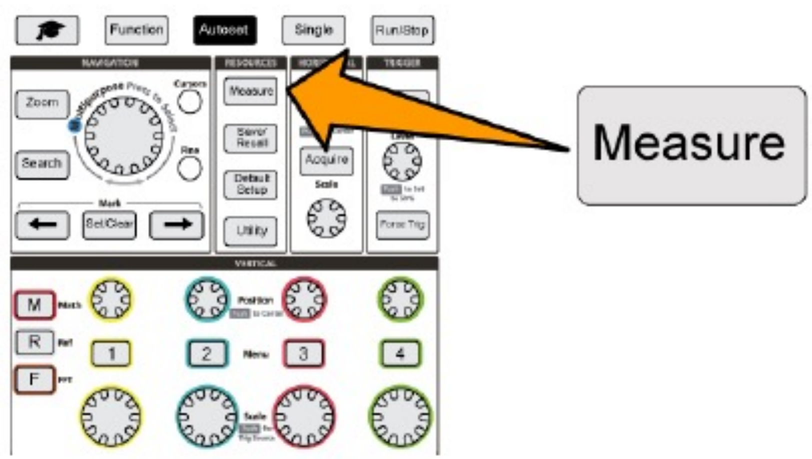
scope measurements; application to op amps

Scope Measurements

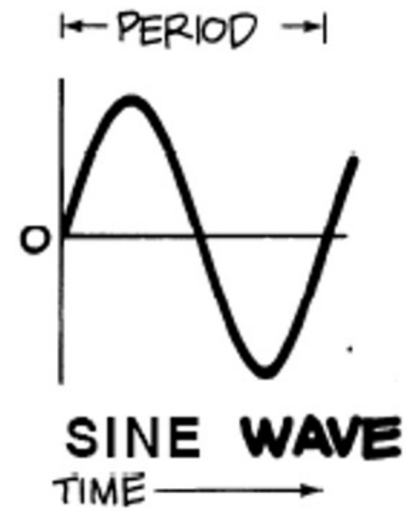
- SigGen settings allow us to control the inputs to circuits
  - Frequency
  - Amplitude
  - Other



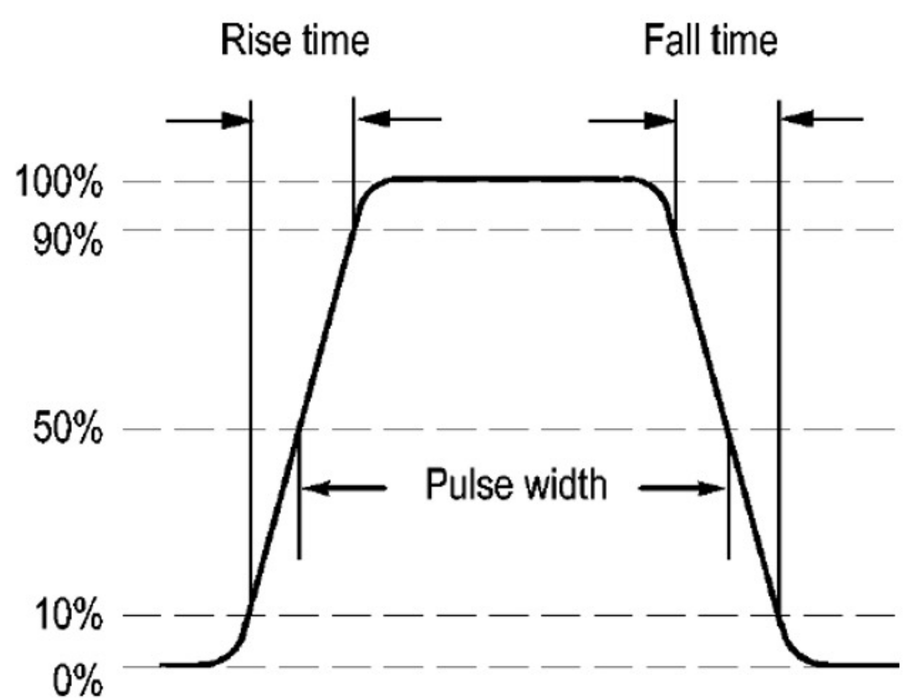
- How about measurement within the circuit?
  - Scope is the tool



- Common attributes of interest
  - Time axis
    - **Frequency**
    - Period

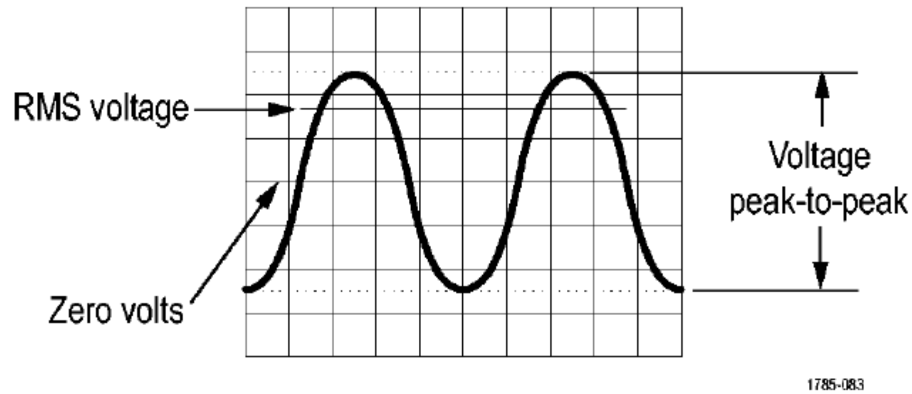


- Rise time
- Fall time
- Width
- Duty cycle



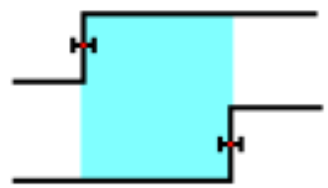
– Amplitude axis

- Peak-to-peak
- **Amplitude**
- Mean
- Max
- Min



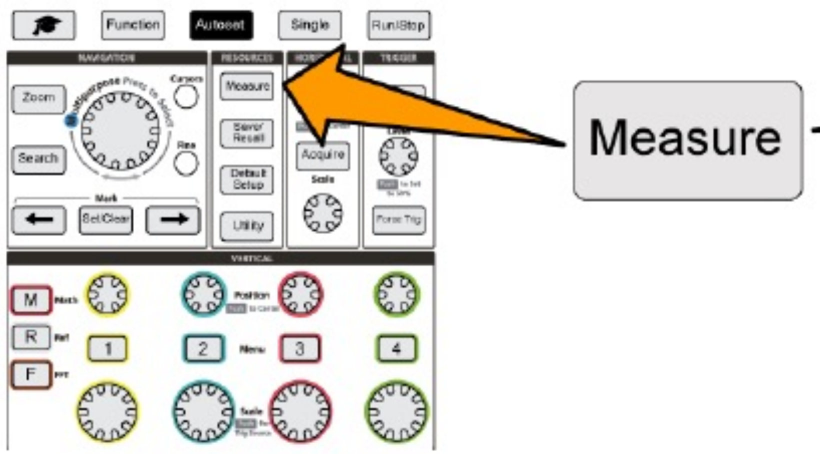
– Between channels

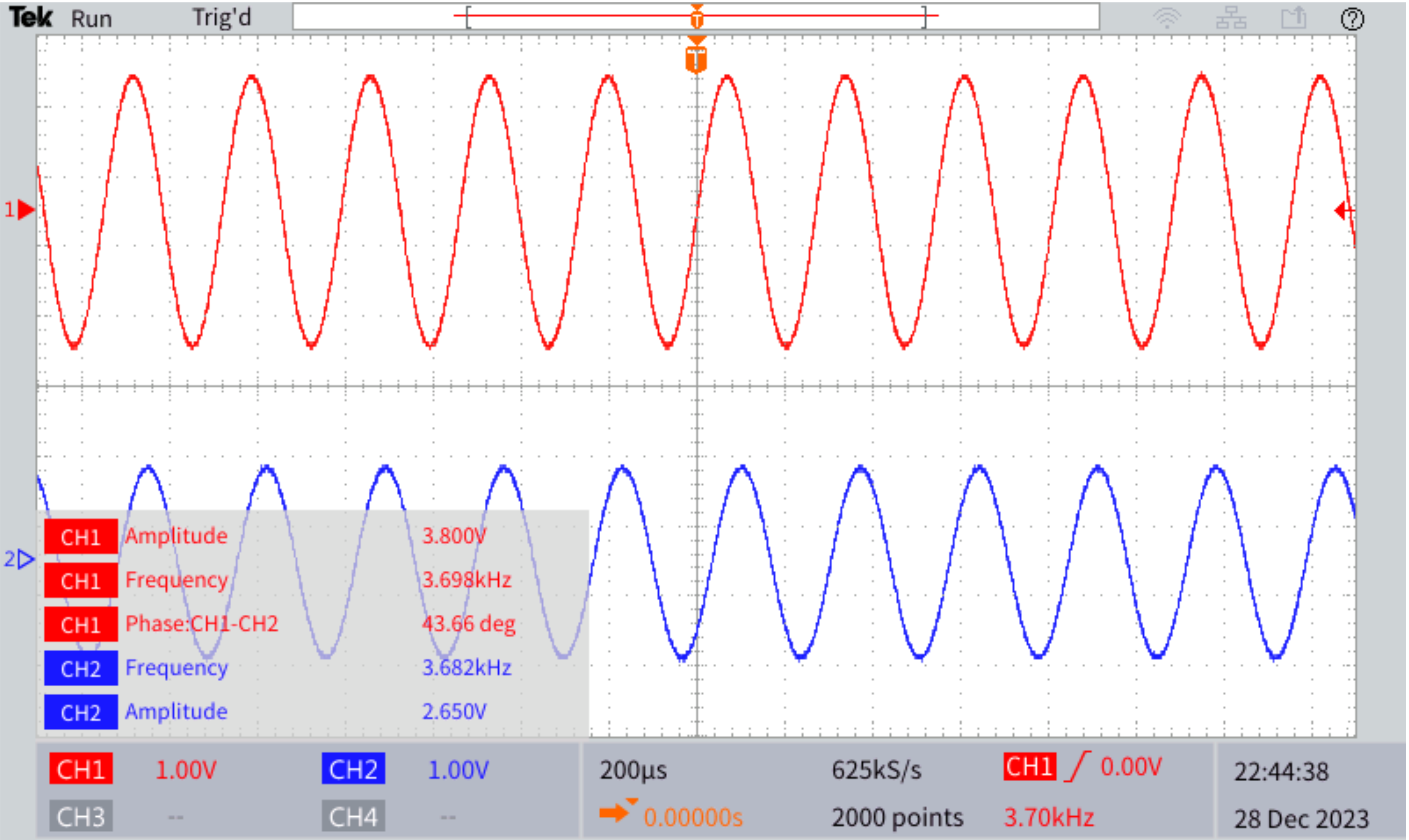
- Delay
- **Phase**



- How to choose?

- “Measure” button opens a window of choices
  - Use multipurpose knob to scroll to desired one; press multipurpose knob to select (or deselect)
  - Appears on the screen

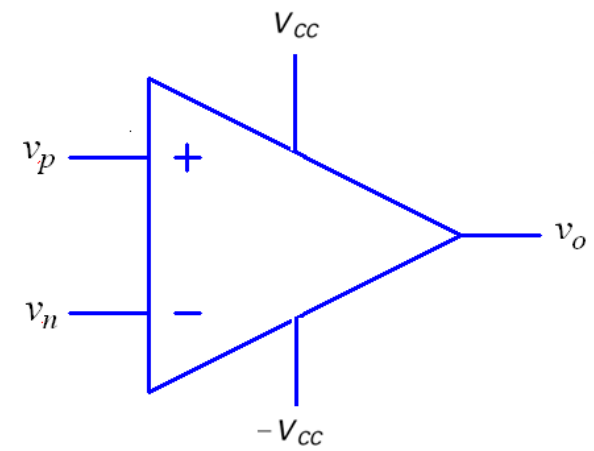


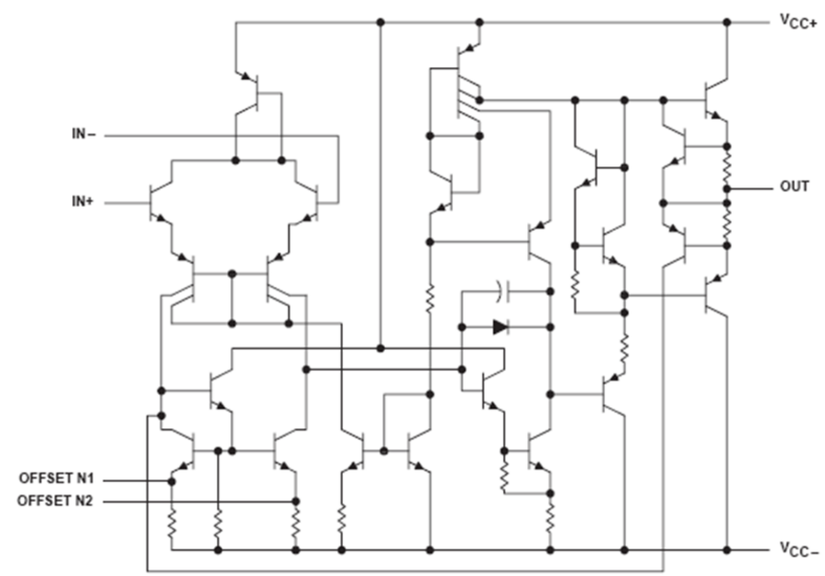


Tek
Run
Trig'd
1
2
CH1 Amplitude 3.800V
CH1 Frequency 3.698kHz
CH1 Phase:CH1-CH2 43.66 deg
CH2 Frequency 3.682kHz
CH2 Amplitude 2.650V
CH1 1.00V
CH2 1.00V
CH3 --
CH4 --
200µs
0.00000s
625kS/s
2000 points
CH1 0.00V
3.70kHz
22:44:38
28 Dec 2023

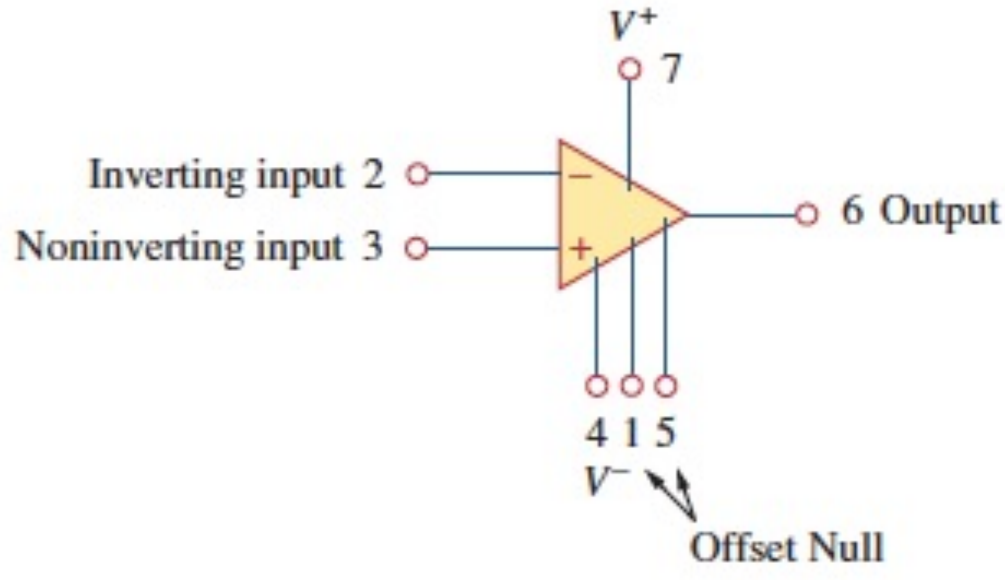
Op Amps

- A 3-terminal device (plus power connections)
- Introduced in the 1960's
- Commonly used to build amplifiers, math circuits, and filters
- Many versions exist:
  - 741
  - Low noise
  - …

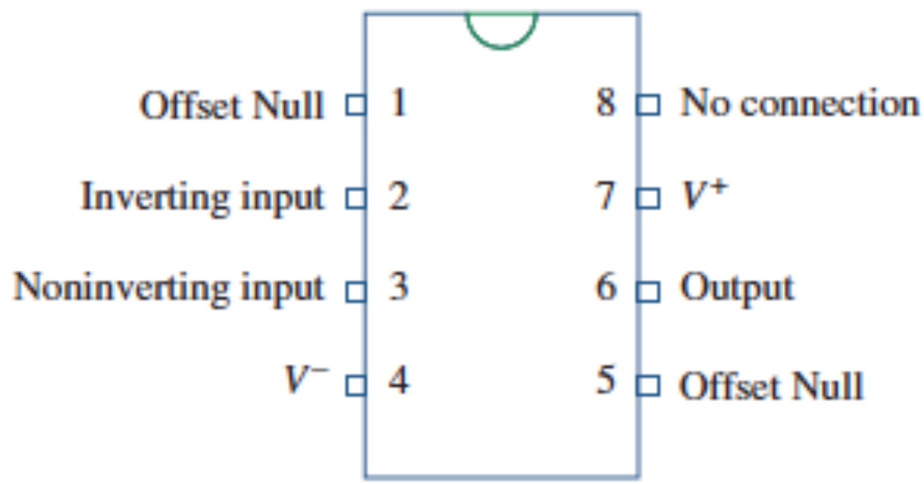




- Connections:
  - + power ($+\mathrm{V}_{\mathrm{cc}}$)
  - – power ($-\mathrm{V}_{\mathrm{cc}}$)
  - Inverting input v_n
  - Non-inverting input v_p
  - Output v_o

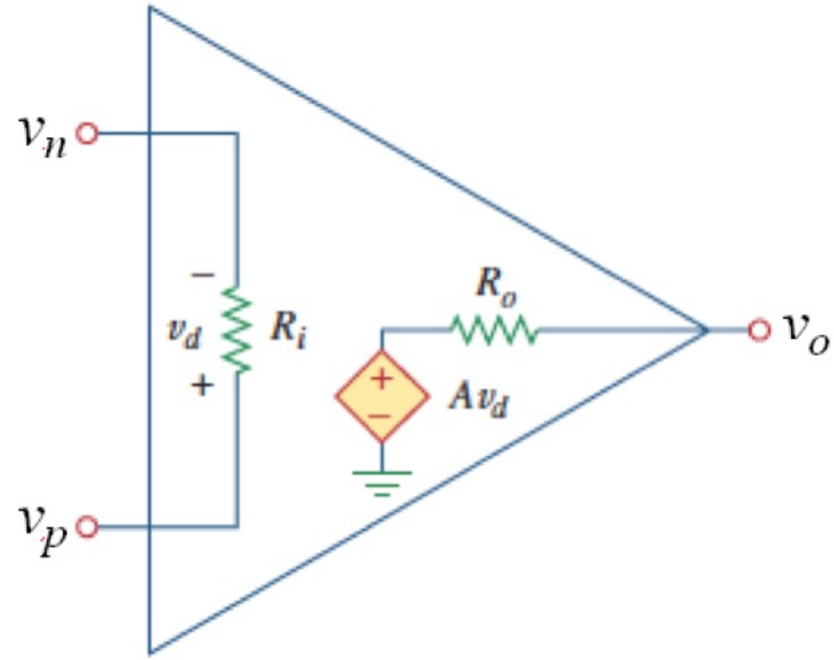


circuit symbol



pin configuration

- Nominally behaves like a voltage dependent voltage source



- Simplest circuit model:
  – Dependent voltage source
    - Control voltage is $v_d = v_p - v_n$
    - "Open loop" gain: A (is large, 10^5 or more)

  – Two resistors
    - "Input resistance" R_i : large (10^5 Ω or more)
    - "Output resistance" R_o : small (100 Ω or less)

From the 741 Spec Sheet

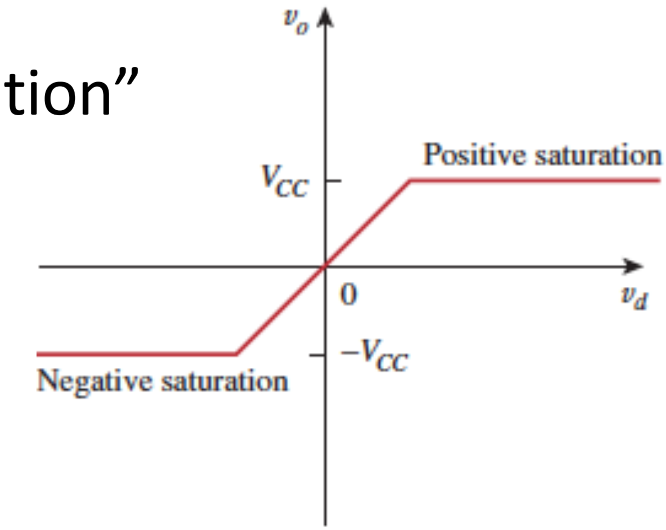
electrical characteristics at specified free-air temperature, $V_{CC\pm} = \pm15$ V, T_A = 25°C (unless otherwise noted)

PARAMETER		TEST CONDITIONS	µA741Y MIN	µA741Y TYP	µA741Y MAX	UNIT
V_{IO}	Input offset voltage	$V_O = 0$		1	6	mV
$\Delta V_{IO(adj)}$	Offset voltage adjust range	$V_O = 0$		±15		mV
I_{IO}	Input offset current	$V_O = 0$		20	200	nA
I_{IB}	Input bias current	$V_O = 0$		80	500	nA
V_{ICR}	Common-mode input voltage range		±12	±13		V
V_{OM}	Maximum peak output voltage swing	R_L = 10 kΩ	±12	±14		V
		R_L = 2 kΩ	±10	±13		
A_{VD}	Large-signal differential voltage amplification	$R_L \geq 2$ kΩ	20	200		V/mV
r_i	Input resistance		0.3	2		MΩ
r_o	Output resistance	$V_O = 0$, See Note 5		75		Ω
C_i	Input capacitance			1.4		pF
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}$min	70	90		dB
k_{SVS}	Supply voltage sensitivity ($\Delta V_{IO}/\Delta V_{CC}$)	$V_{CC} = \pm9$ V to ±15 V		30	150	µV/V
I_{OS}	Short-circuit output current			±25	±40	mA
I_{CC}	Supply current	$V_O = 0$, No load		1.7	2.8	mA
P_D	Total power dissipation	$V_O = 0$, No load		50	85	mW

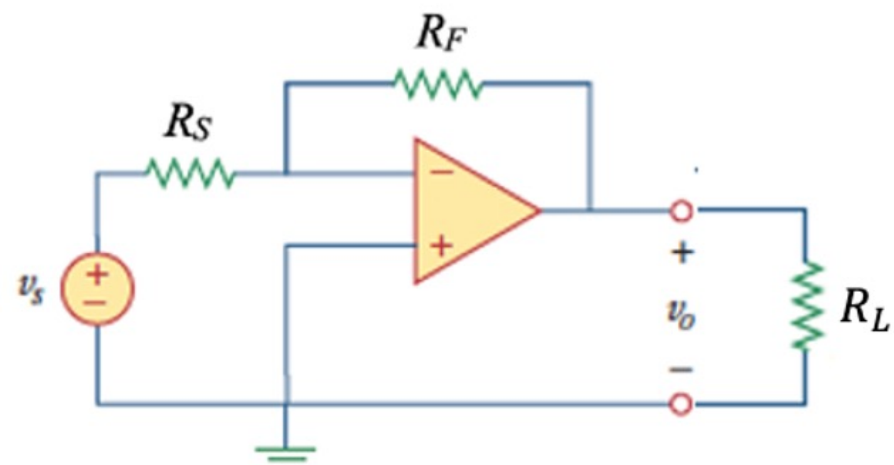
† All characteristics are measured under open-loop conditions with zero common-mode voltage unless otherwise specified.

NOTE 5: This typical value applies only at frequencies above a few hundred hertz because of the effects of drift and thermal feedback.

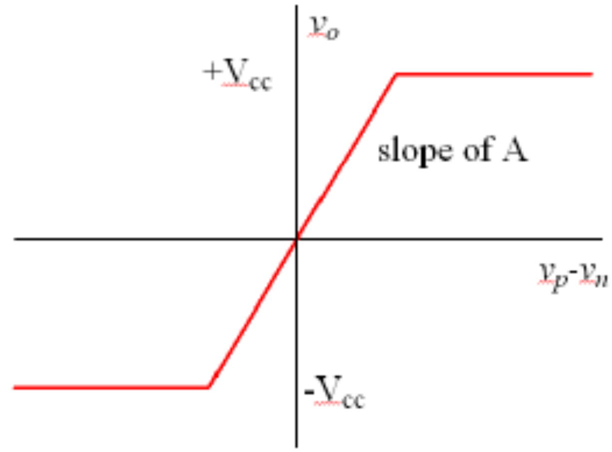
- Experiences open loop “saturation”



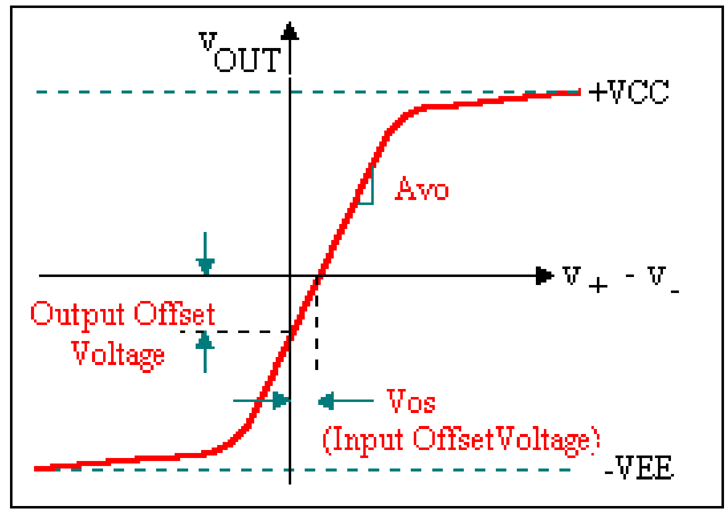
  – Usually configured with “negative feedback”

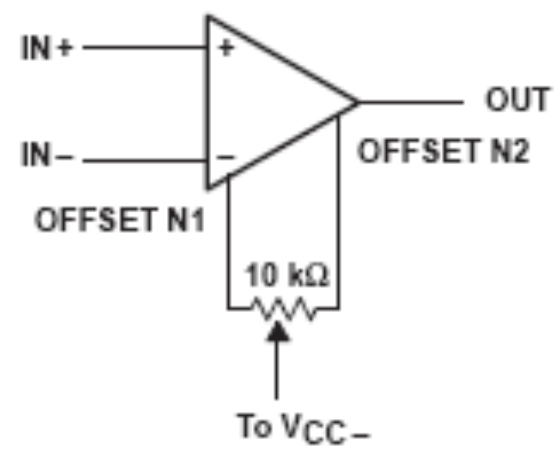


Non-Ideal Characteristics



- Issue 1 – DC offset voltage
  - Equal input voltages yield non-zero output
  - Large enough to saturate an open loop circuit
  - External compensation is possible
  - 1 mv typical for 741





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k_{SVS}	Supply voltage sensitivity ($\Delta V_{IO}/\Delta V_{CC}$)	V_{CC} = ±9 V to ±15 V		30	150	µV/V
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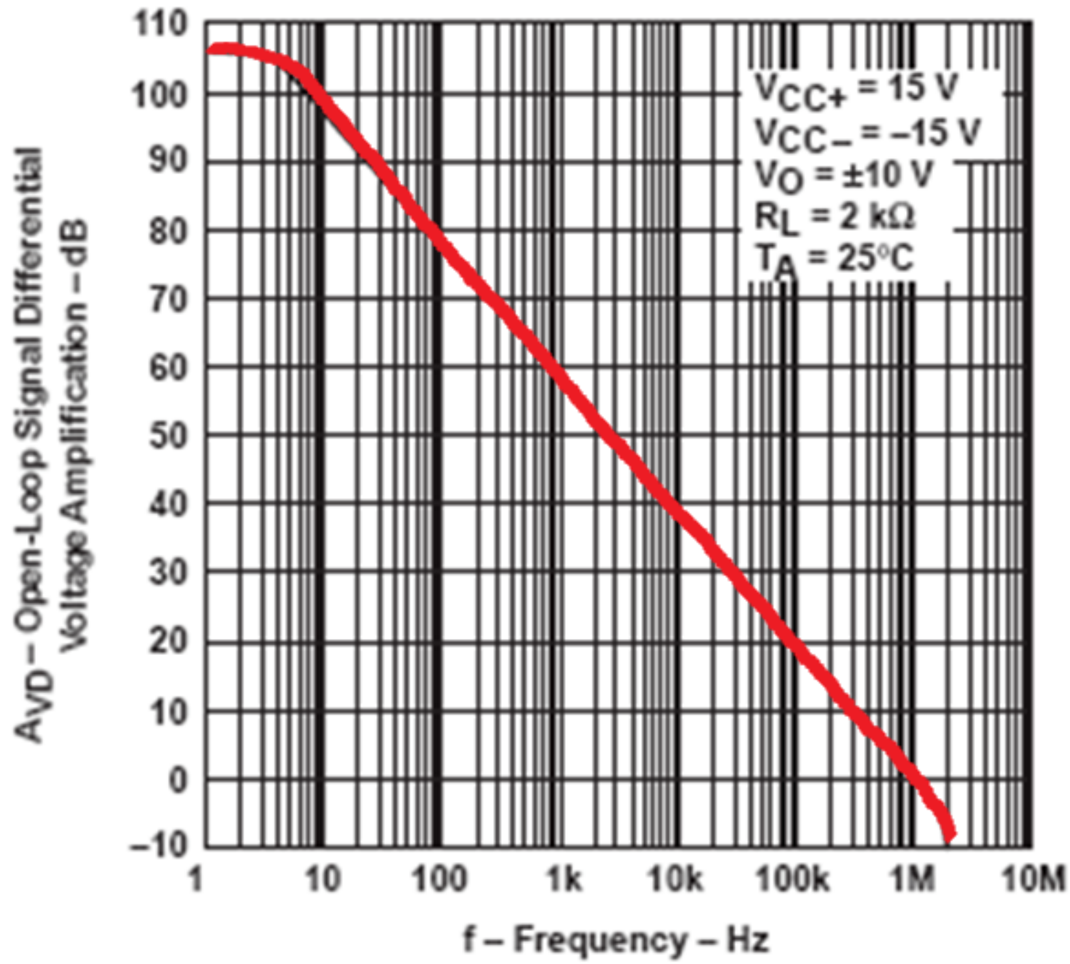
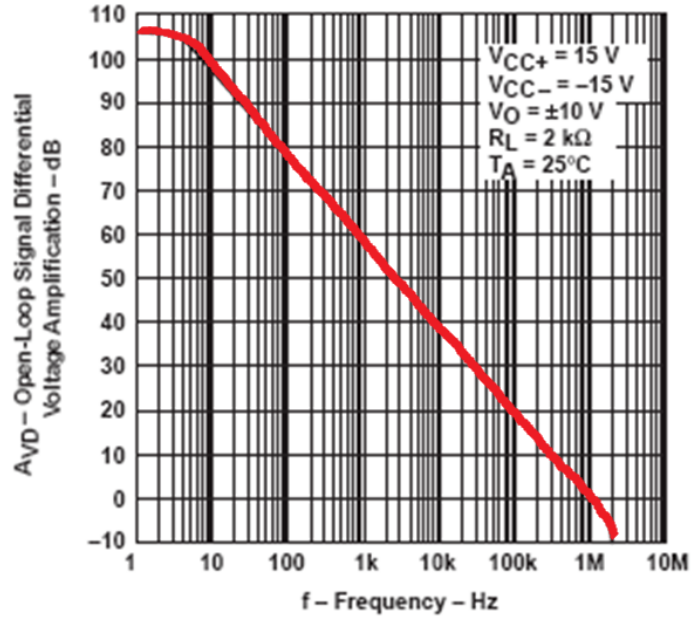
operating characteristics, $V_{CC\pm} = \pm15$ V, T_A = 25°C

PARAMETER		TEST CONDITIONS	µA741Y			UNIT
			MIN	TYP	MAX	
t_r	Rise time	V_I = 20 mV, R_L = 2 kΩ, C_L = 100 pF, See Figure 1		0.3		µs
	Overshoot factor			5%		
SR	Slew rate at unity gain	V_I = 10 V, R_L = 2 kΩ, C_L = 100 pF, See Figure 1		0.5		V/µs

- Issue 2 – Open loop gain, A, is finite
  - Decreases with frequency
  - 200,000 typical for a 741 op amp
  - Limits amplifier gain





- Notes on this plot:
  - Logarithmic scale for frequency
    - Factor of 10 called a "decade"
  - Gain A is plotted on the vertical scale using units of decibels

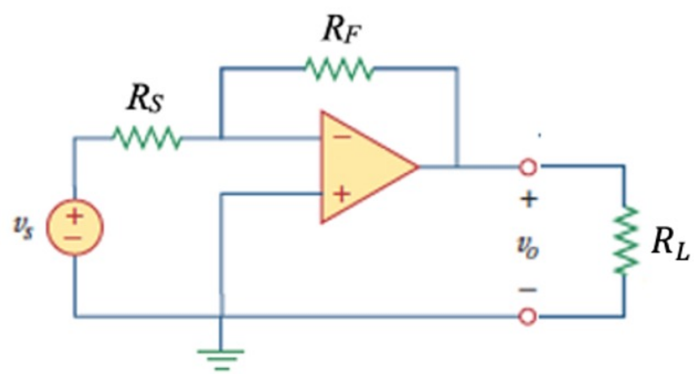
$$20\ \log_{10} A = 20\ \log_{10} 200{,}000 = 106\ \mathrm{dB}$$

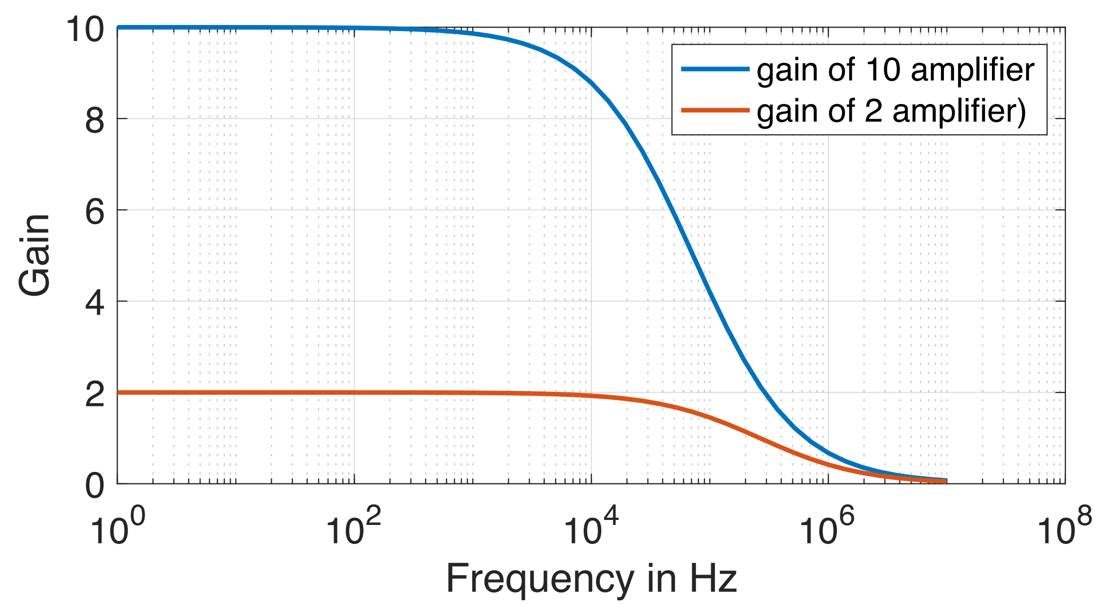
- Note: decibel scale

mag	dB	mag	dB
1	0		
2	3	0.5	-3
10	20	0.1	-20
100	40	0.01	-40

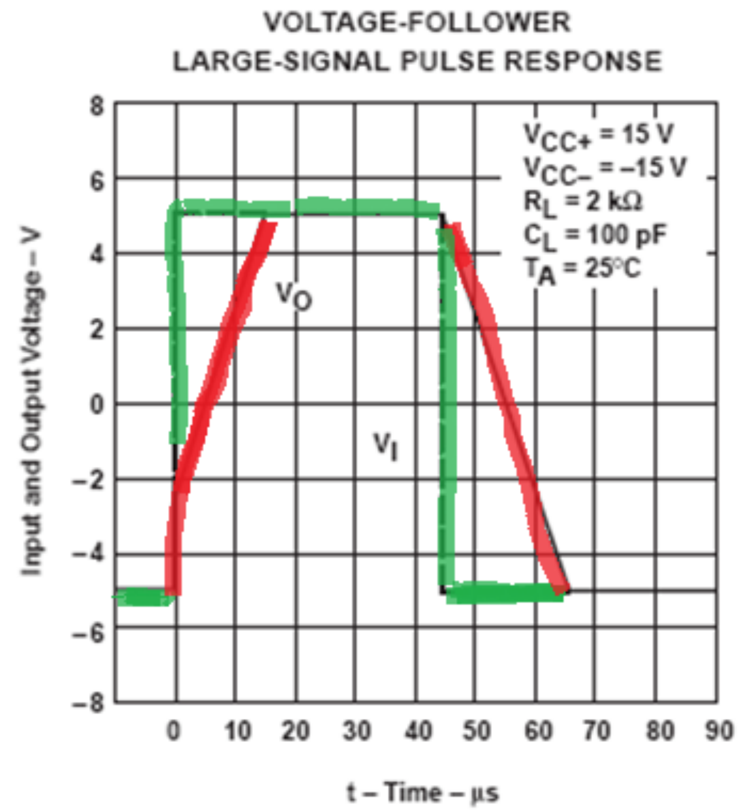
For audio sound levels, whisper to normal conversation to a motorcycle are 30 dB jumps each

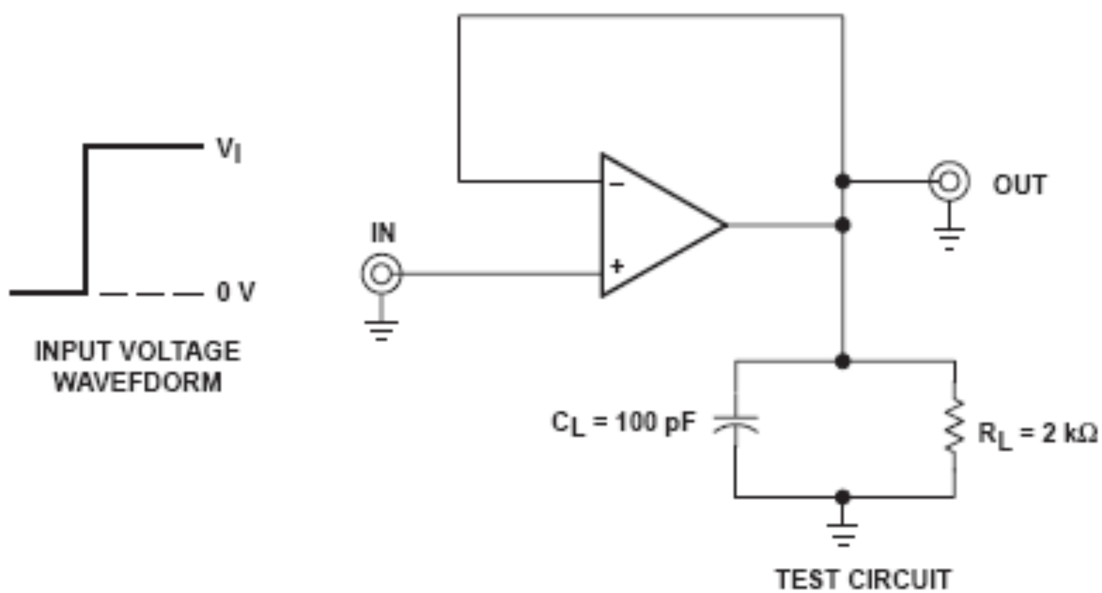
- Impact of decreasing A on the gain of an inverting amplifier:





- Issue 3 – slow response to voltage jumps: "slew rate"
  - Essentially the slope of the response
  - Measured in V/µs, 0.5 typical for 741





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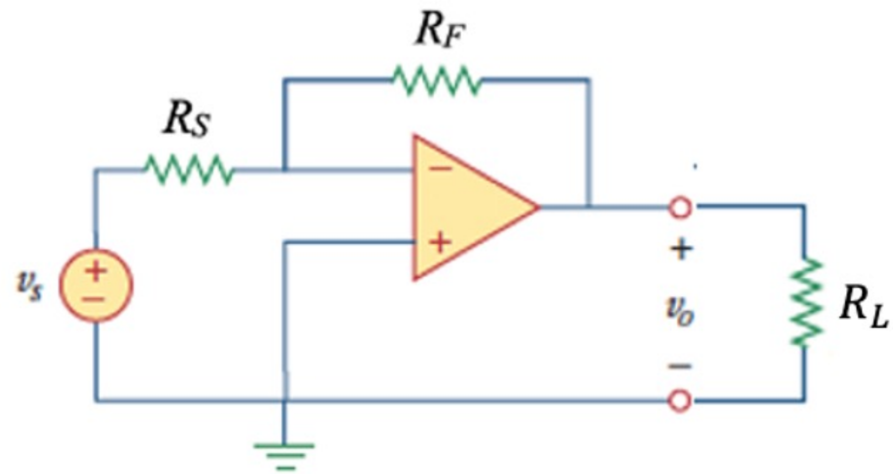
The Inverting Amplifier

- Detailed analysis yields (ELE 212 lecture):



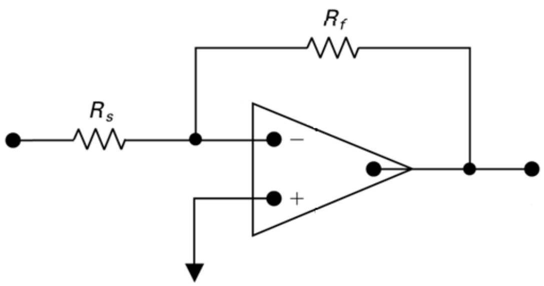
$$\frac{v_o}{v_s} = -\frac{R_i R_L (R_F\, A - R_o)}{R_L (R_S + R_i)(R_F\ + R_o) + (A+1) R_S\, R_i\, R_L + R_o (R_S R_i + R_F R_i + R_S R_F)}$$

- Under normal conditions, approximate result

$$\frac{v_o}{v_s} \approx -\frac{R_F}{R_S}$$

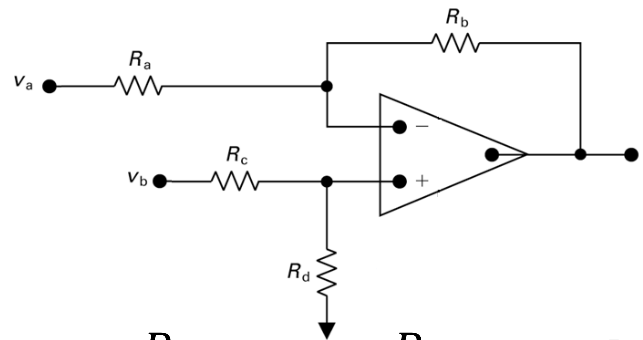
Other Op Amp Uses

- Inverting amplifier



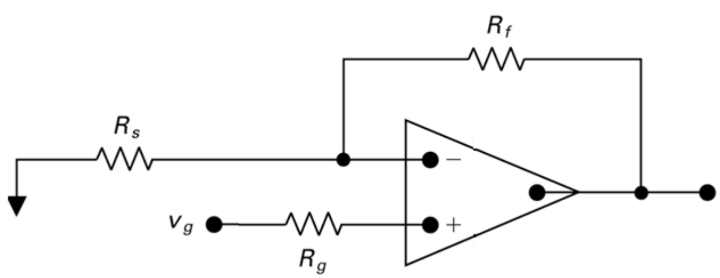
$$v_o = -\frac{R_F}{R_S} v_s$$

- Difference amplifier



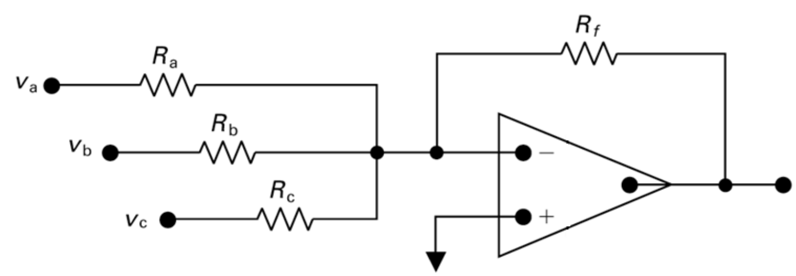
$$v_o = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right) v_2 - \frac{R_2}{R_1} v_1$$

- Non-inverting amplifier



$$v_o = \left(1 + \frac{R_F}{R_1}\right) v_s$$

- Summing amplifier



$$v_o = -\left(\frac{R_F}{R_1} v_1 + \frac{R_F}{R_2} v_2 + \frac{R_F}{R_3} v_3\right)$$

Specifics for next week

- Continue work on Exercise 1 (programming) and Exercise 3 (simulation)

- Lab 4 – 75 points (pairs)
  - Instructions and pairings posted on ELE 215 website
  - Summary sheets available in lab rooms and on website
  - Due by 5 PM Wednesday Mar 11