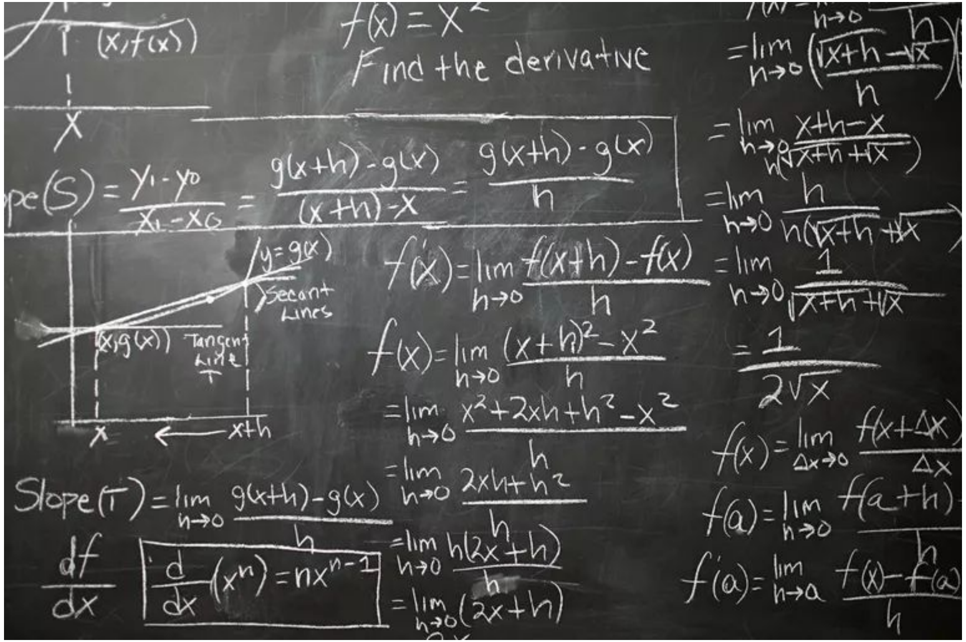

Operational Amplifiers

John R. Leeman

GEARS 2023

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Image: ThoughtCo

Op-Amps have just a few basic terminals, some with other features

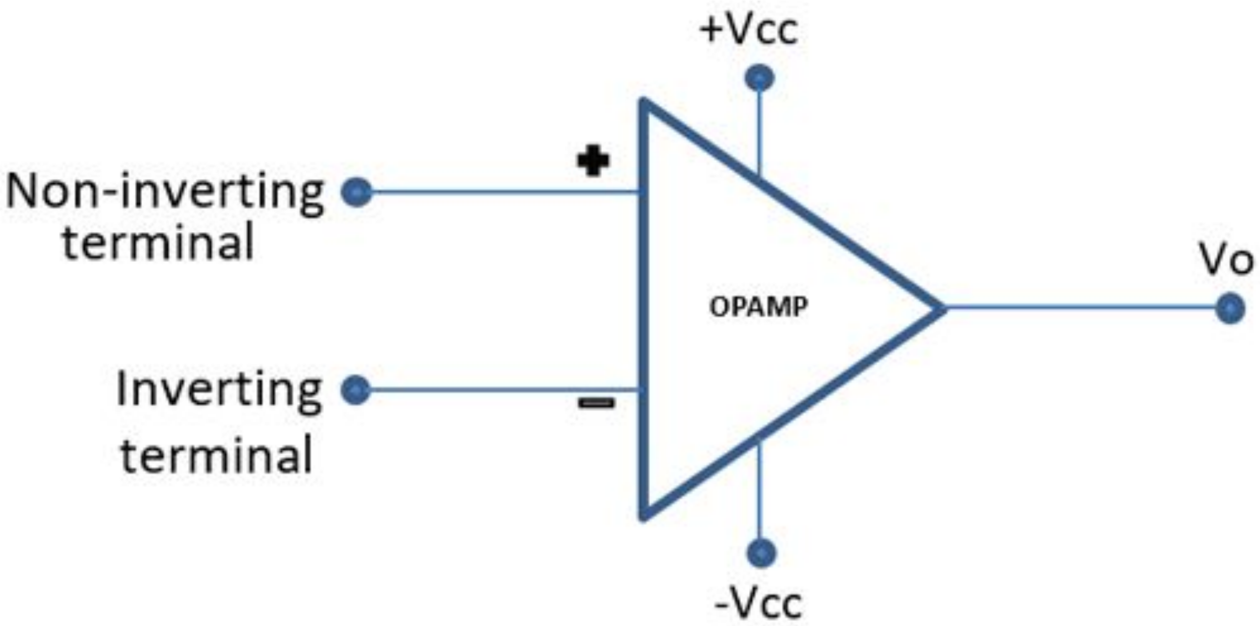

Image: Circuit Digest

A few rules let us understand ANY Op-Amp circuit

1) No current flow into/out of the input terminals (high impedance)
2) Op Amp will do whatever is necessary to keep the inputs at the same voltage (when feedback is used)
3) The output can source any current (low impedance)
4) Open loop gain is large

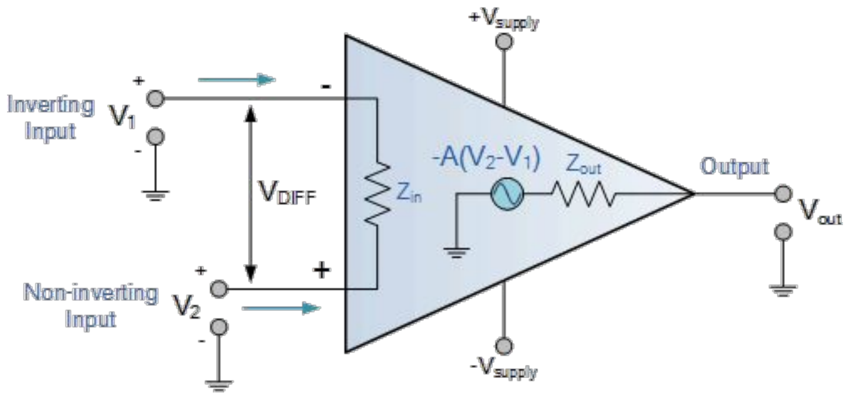

Image: Electronics Tutorials

The most straightforward circuit is a comparator

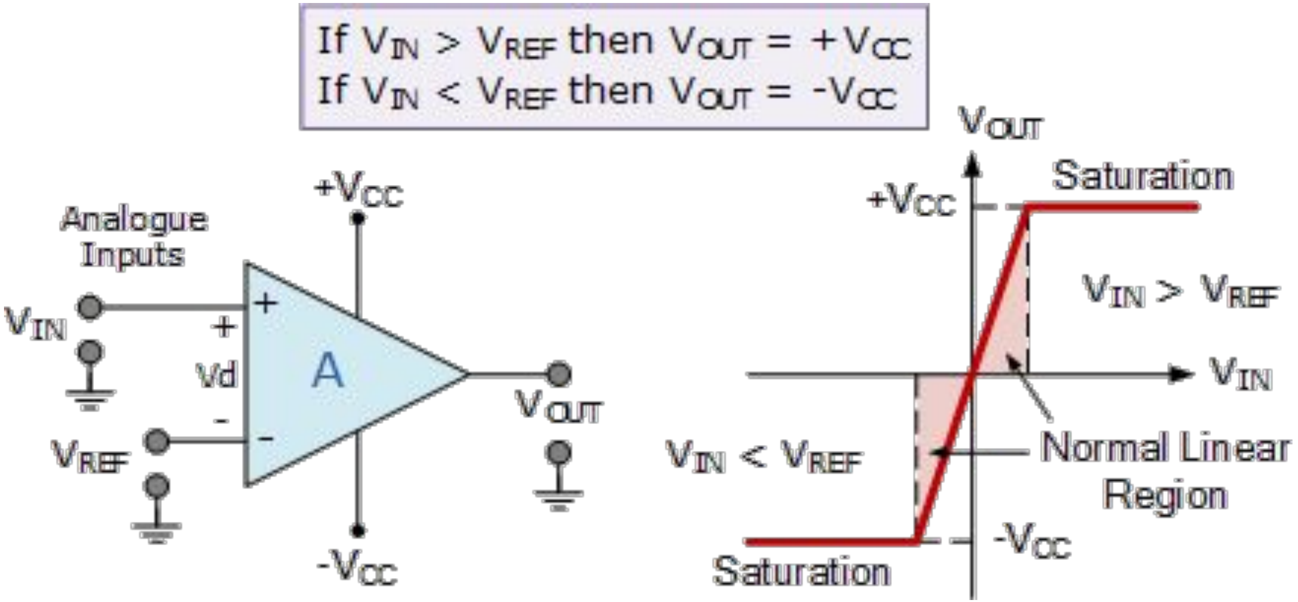

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Image: Electronics Tutorials

Two comparators can make a window comparator

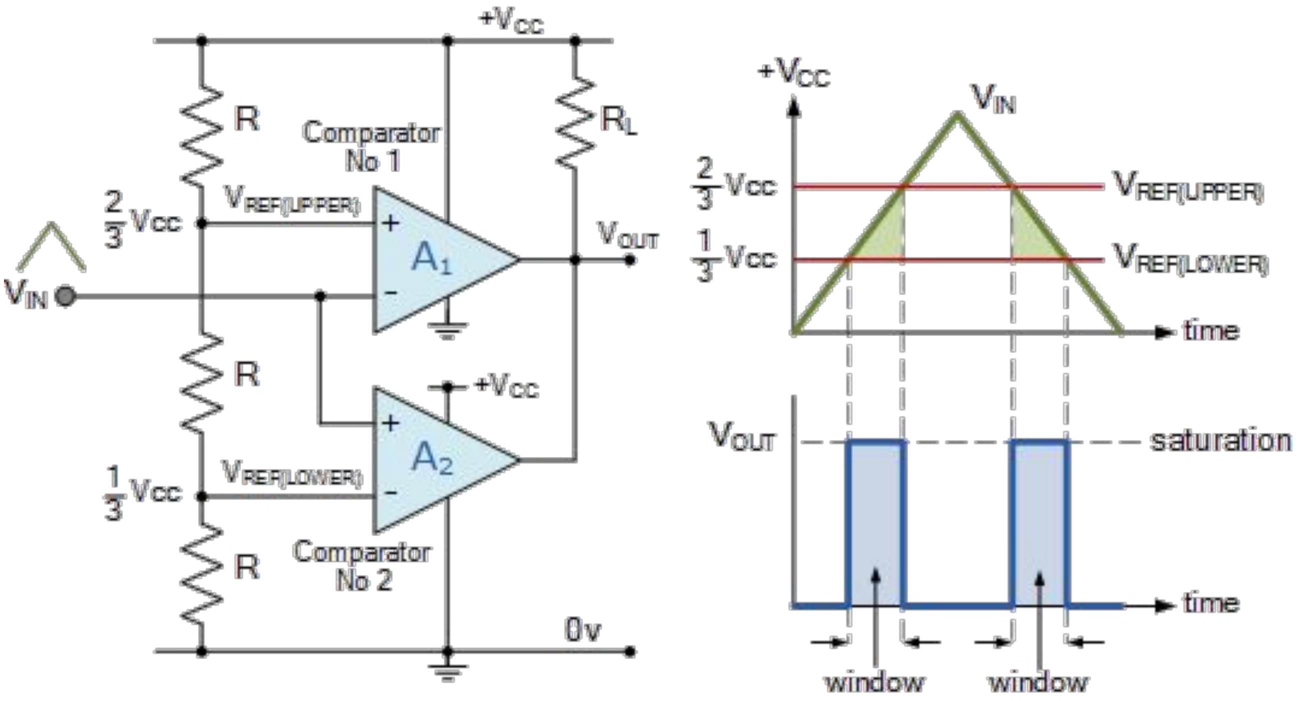
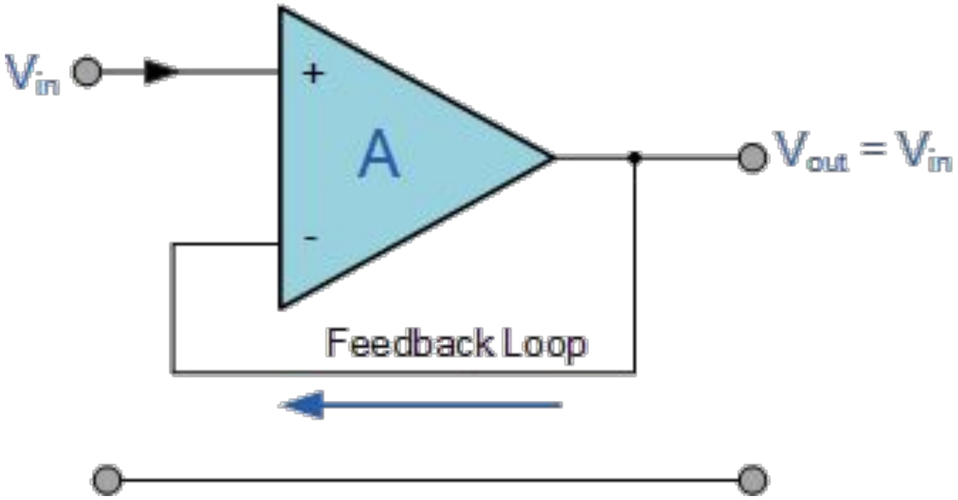


Image: Electronics Tutorials

One of the most useful circuits is a voltage follower or buffer



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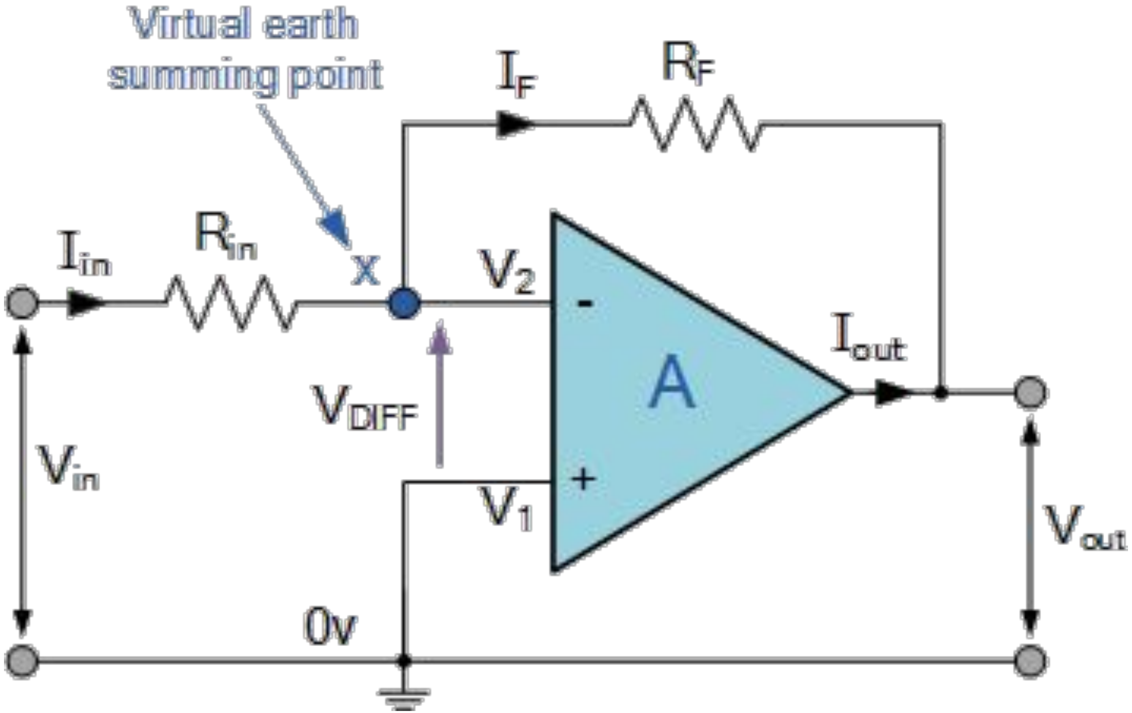
Inverting amplifiers have a simple gain formula, but some caveats



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Non-inverting amplifiers are modified voltage followers

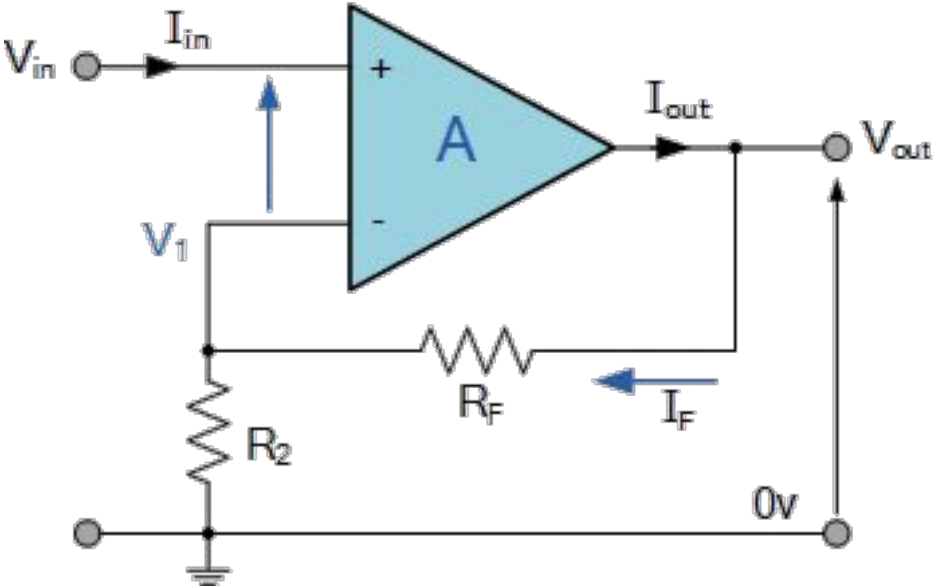

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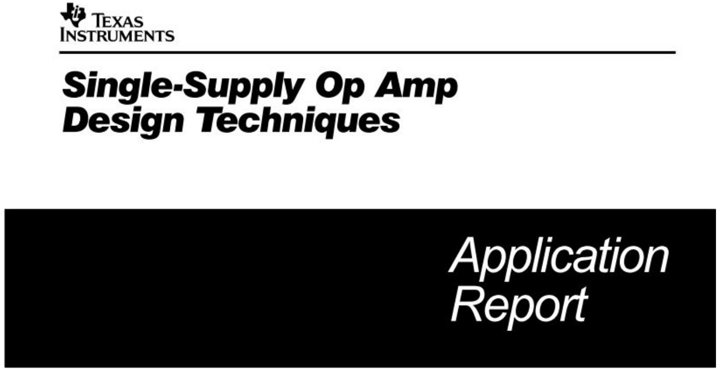
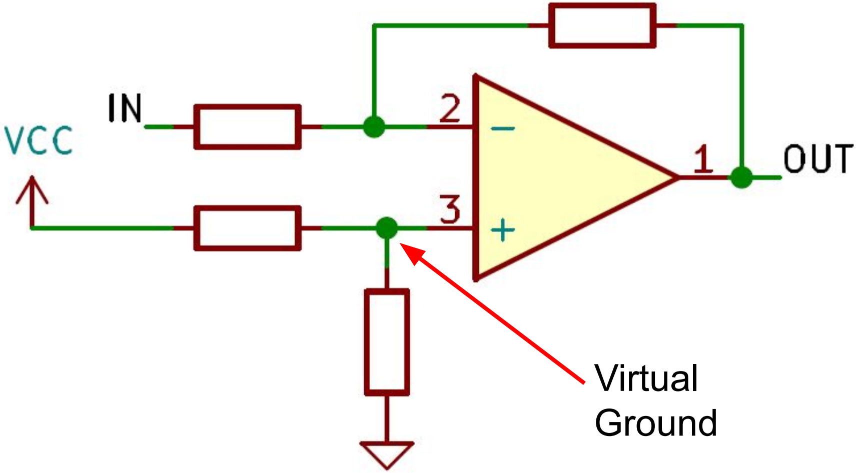
Image: Electronics Tutorials

Amplifiers don’t have to operate from a bipolar supply

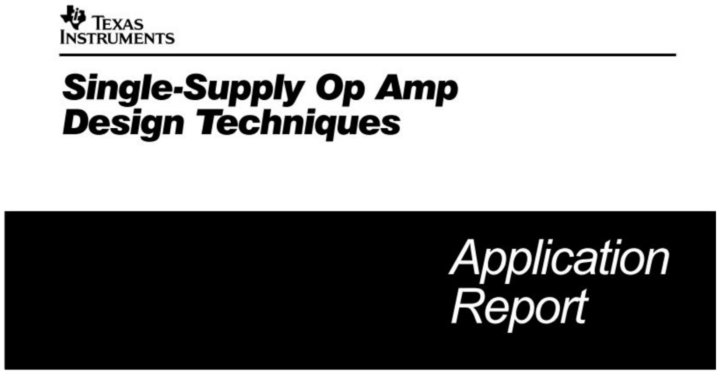

Texas Instruments

Single-Supply Op Amp Design Techniques

Application Report



Amplifiers don’t have to operate from a bipolar supply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Single-Supply Op Amp Design Techniques

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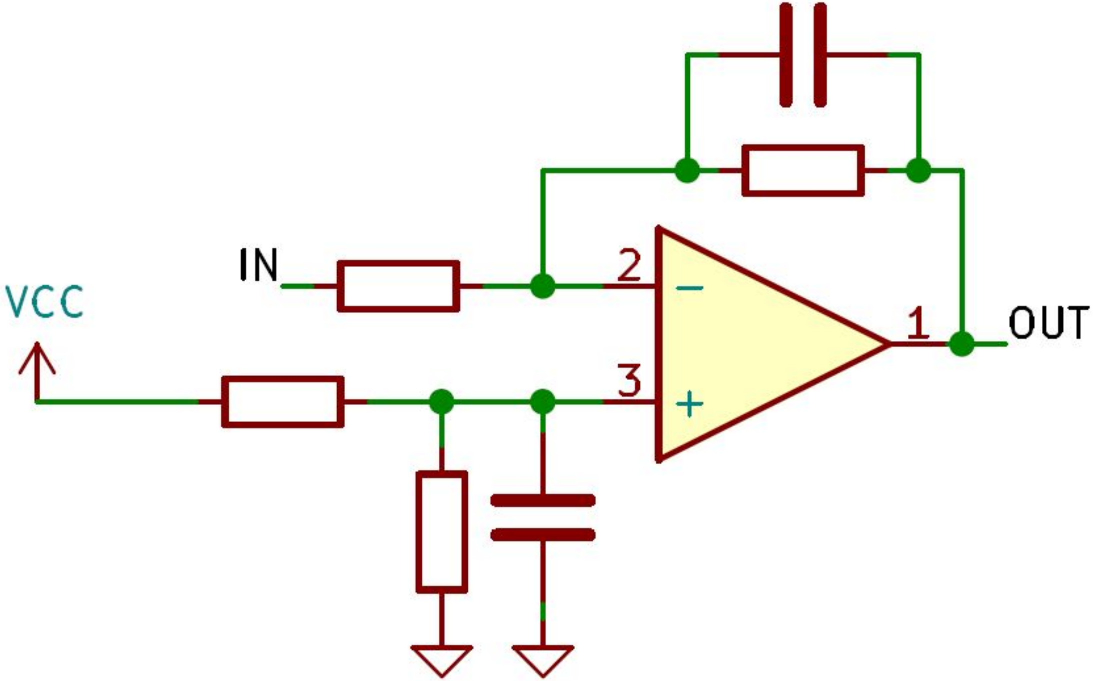
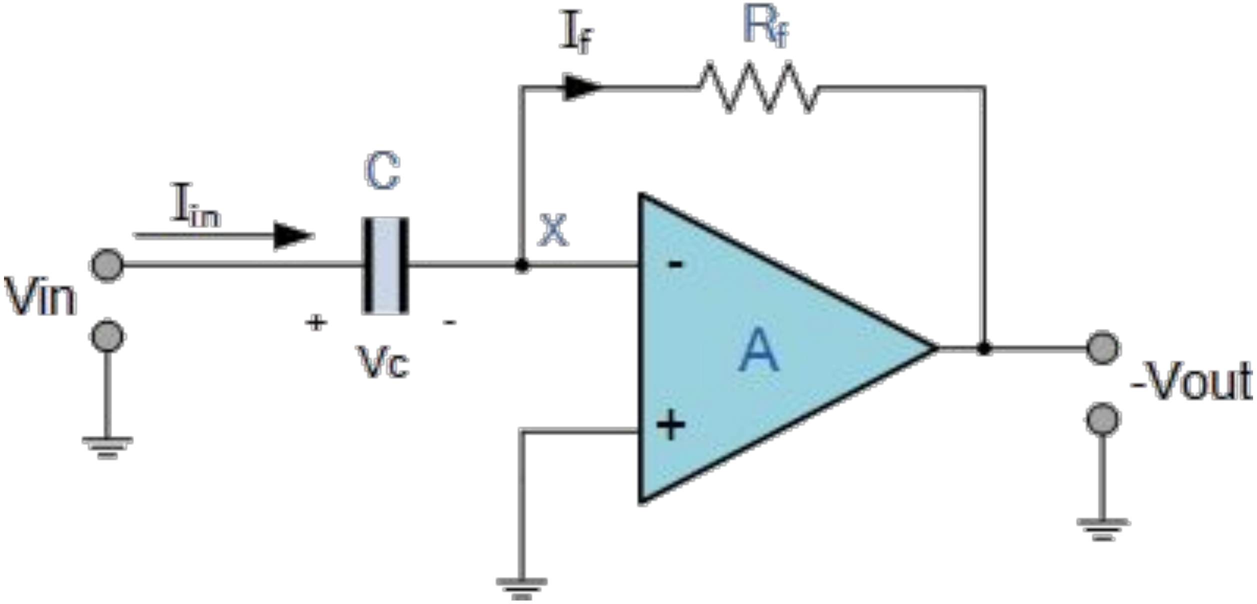


Differentiators output the rate of change of the input



$$V_{OUT} = -R_F C \frac{dV_{IN}}{dt}$$

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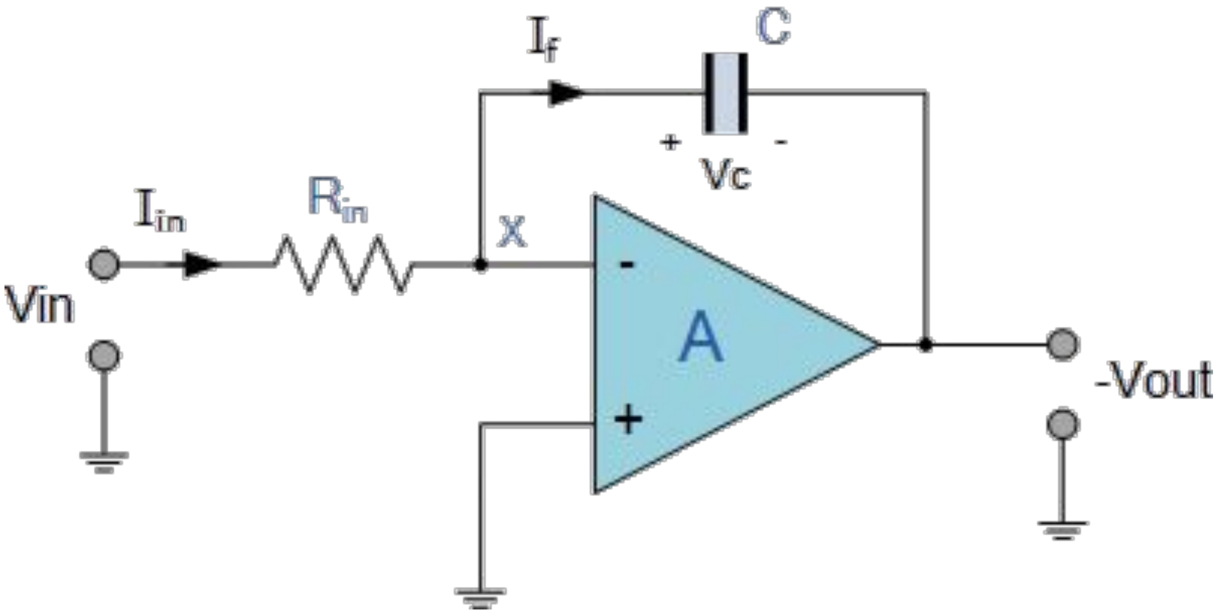
Image: Electronics Tutorials

Integrators integrate the input over a time window



$$V_{out} = -\frac{1}{R_{in}C}\int_0^t V_{in}\,dt = -\int_0^t V_{in}\frac{dt}{R_{in}.C}$$

Image: Electronics Tutorials

Differential amplifiers work with "double ended" signals, but aren't commonly implemented

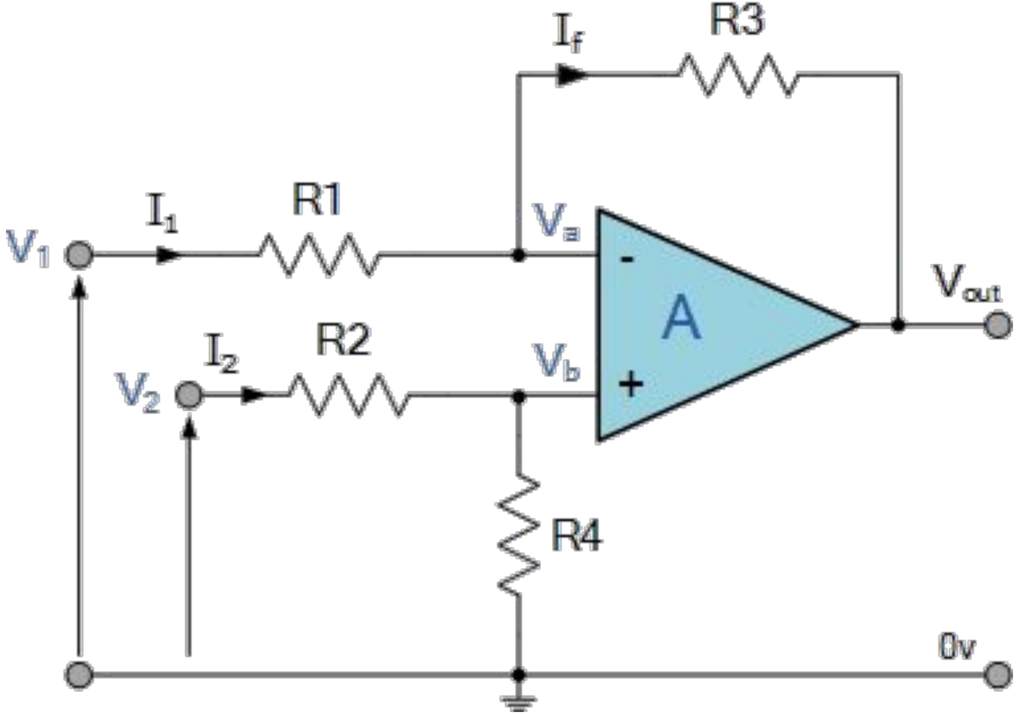


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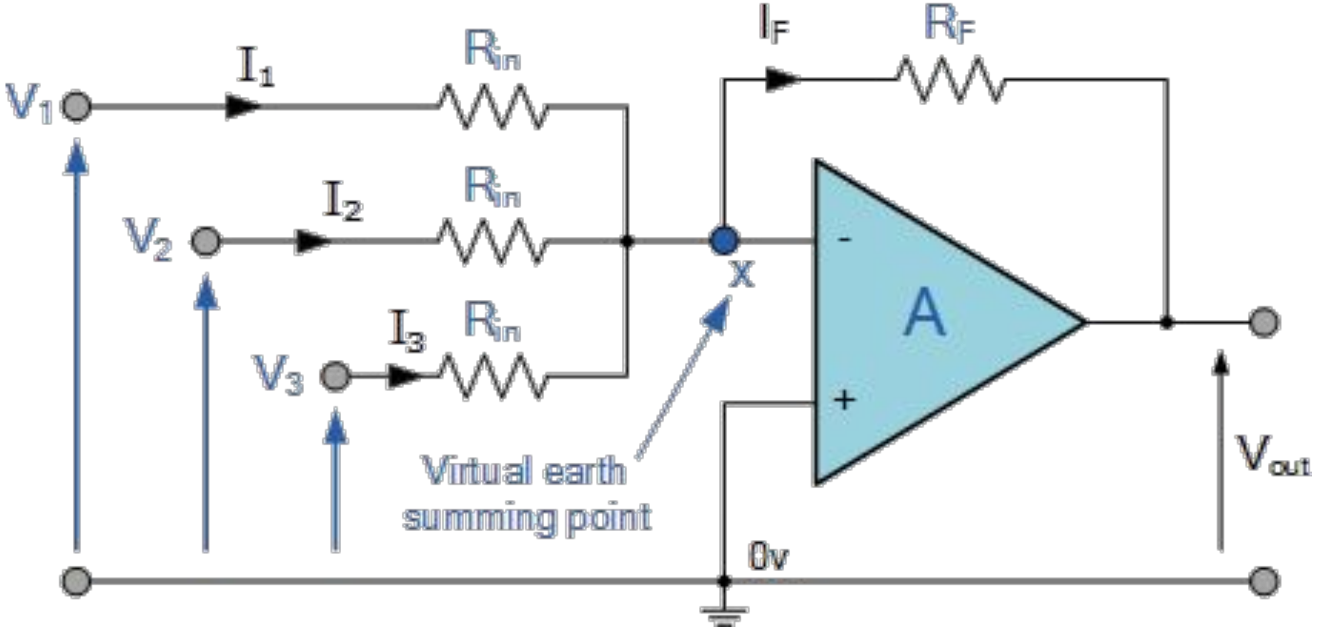
Image: Electronics Tutorials

Summing amplifiers can be handy as well



$$-Vout = \left[\frac{R_F}{Rin} V1 + \frac{R_F}{Rin} V2 + \frac{R_F}{Rin} V3 \right]$$

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Image: Electronics Tutorials

There are a lot of traps out there that can surprise even experienced electrical engineers

1) Input Bias Current
2) Input Offset Voltage
3) Gain Bandwidth Product
4) Others!

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Image: istockphoto

Input bias current is current flowing into/out of the inputs

6.5 Electrical Characteristics, LM741[1]

PARAMETER	TEST CONDITIONS		MIN	TYP	MAX	UNIT
Input offset voltage	$R_S \leq 10\ k\Omega$	$T_A = 25°C$		1	5	mV
		$T_{AMIN} \leq T_A \leq T_{AMAX}$			6	mV
Input offset voltage adjustment range	$T_A = 25°C$, $V_S = \pm 20\ V$			±15		mV
Input offset current	$T_A = 25°C$			20	200	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$			85	500	nA
Input bias current	$T_A = 25°C$			80	500	nA
	$T_{AMIN} \leq T_A \leq T_{AMAX}$				1.5	μA

Input bias current also depends on everything else

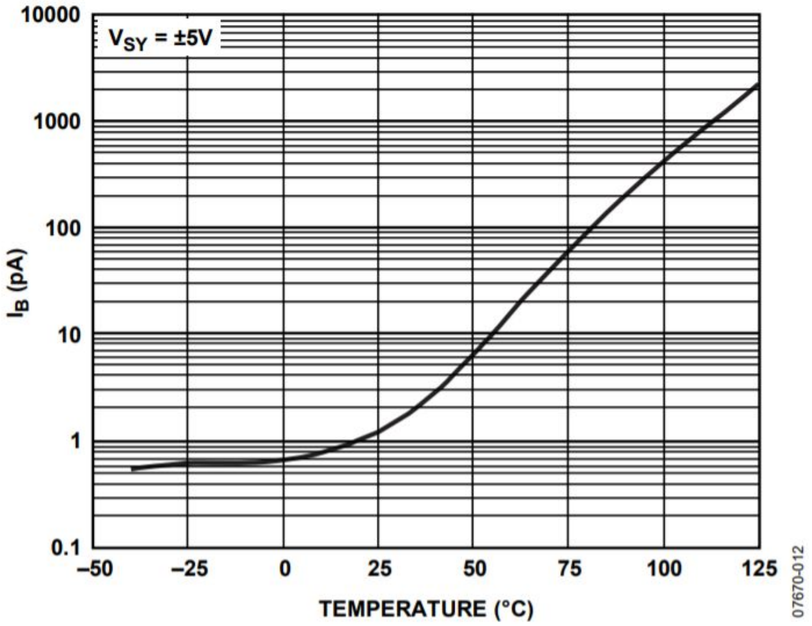


Figure 12. Input Bias Current vs. Temperature

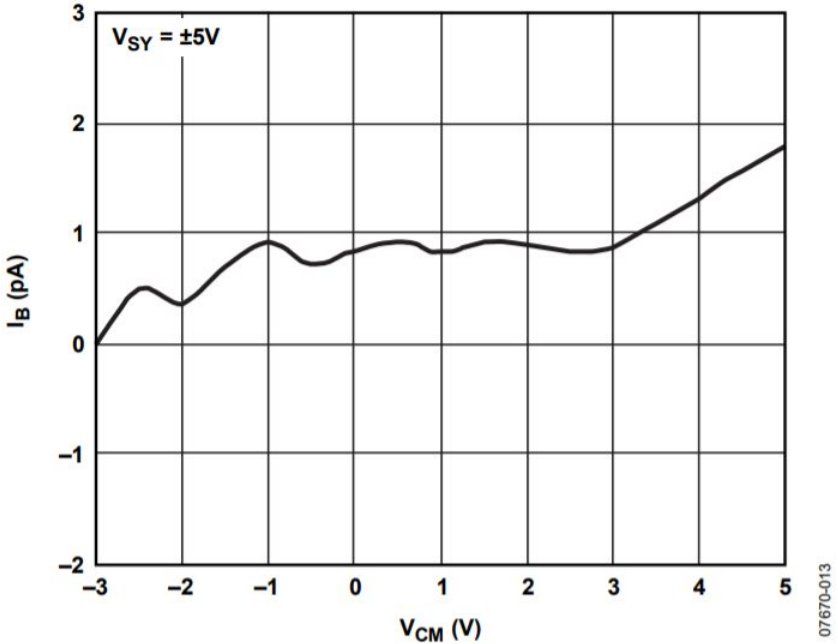
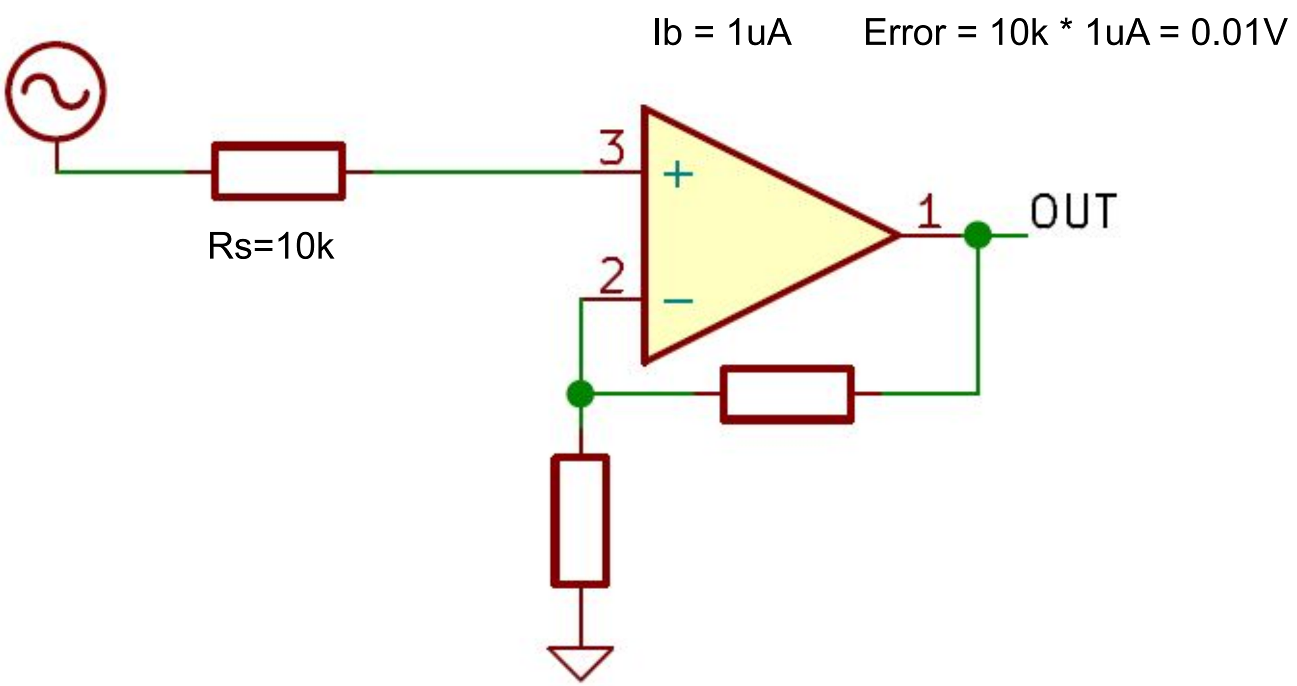


Figure 13. Input Bias Current vs. Common-Mode Voltage

Input Bias Current Problem #1 - Source Impedance



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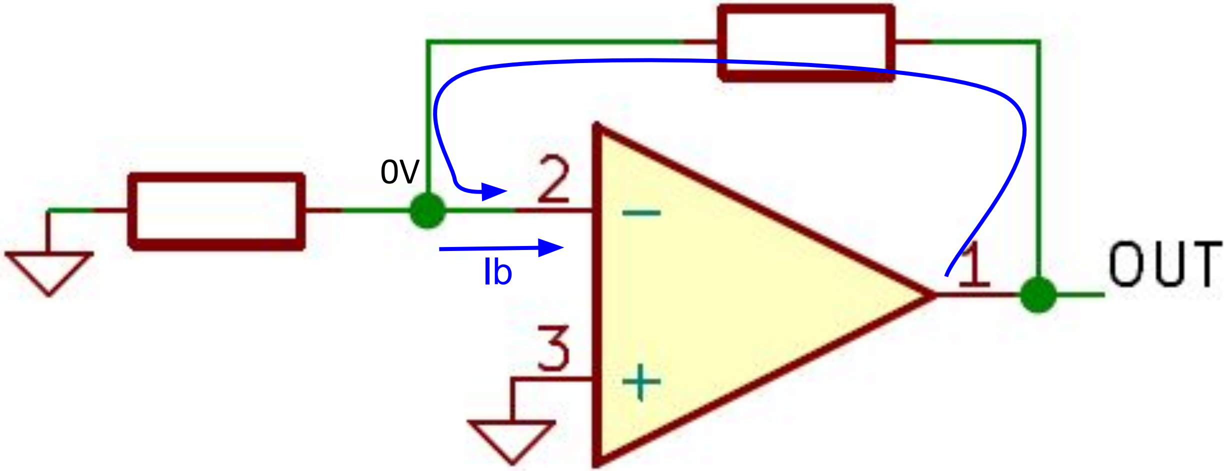
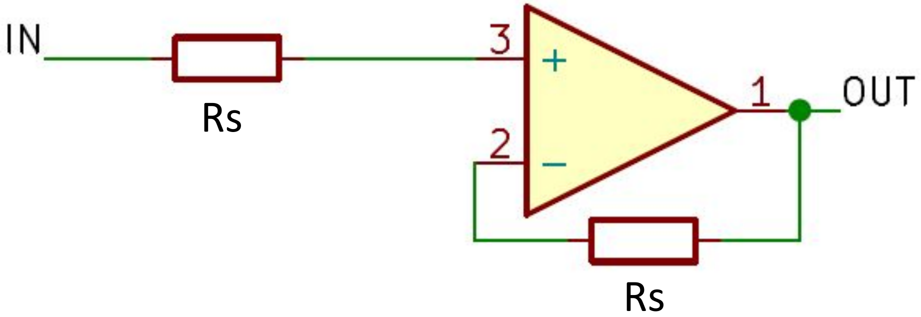
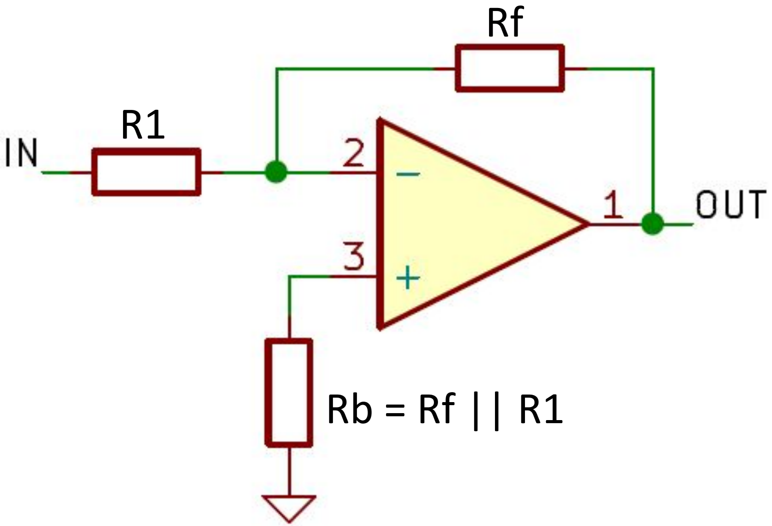
Input Bias Current Problem #2 - Gain Network



Some solutions





Input offset voltage is another hidden gotcha

Table 2.

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
INPUT CHARACTERISTICS						
Offset Voltage	V_{OS}					
B Grade (ADA4062-2, 8-Lead SOIC Only)				0.5	1.5	mV
		$-40°C \le T_A \le +125°C$			3	mV
A Grade				0.75	2.5	mV
		$-40°C \le T_A \le +125°C$			5	mV
Offset Voltage Drift	$\Delta V_{OS}/\Delta T$	$-40°C \le T_A \le +125°C$		5		μV/°C

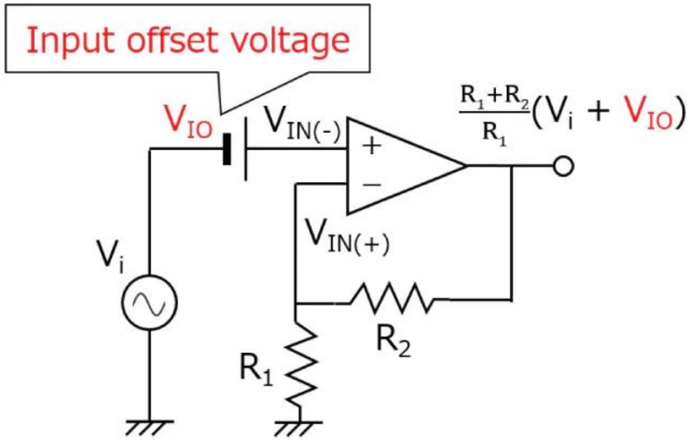


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Image: Toshiba Semiconductor

Vios can be compensated for with null terminals on some amplifiers

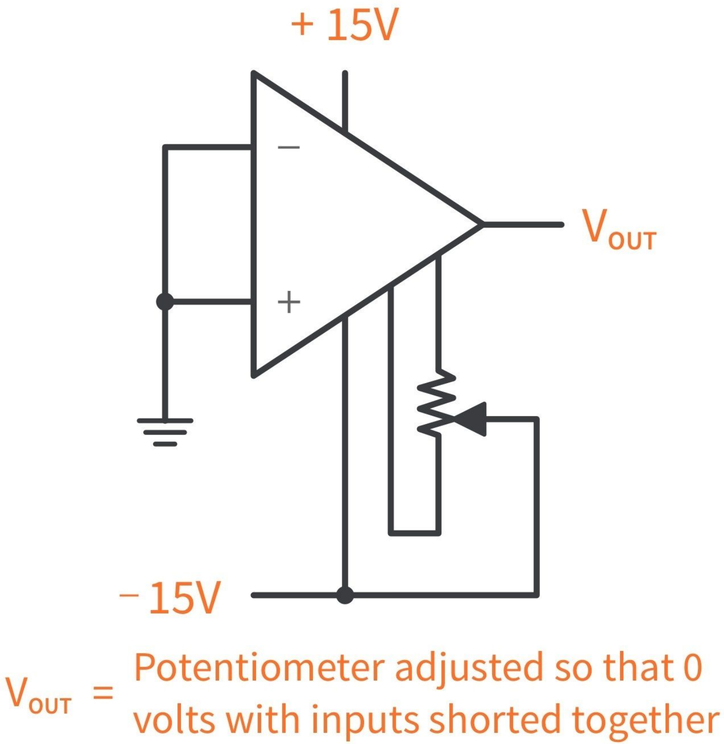

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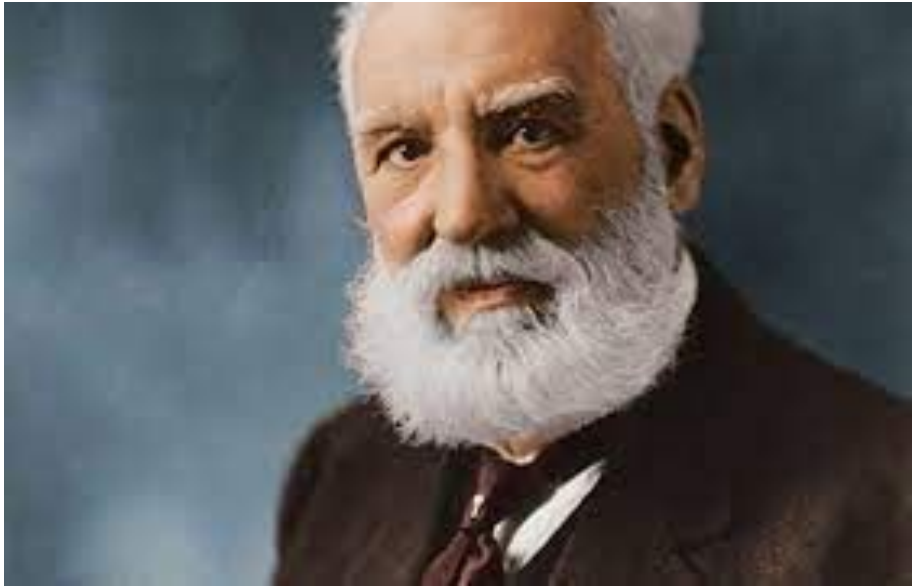
Image: Circuit Bread

A quick aside to talk about decibels (dBs) as the engineer thinks



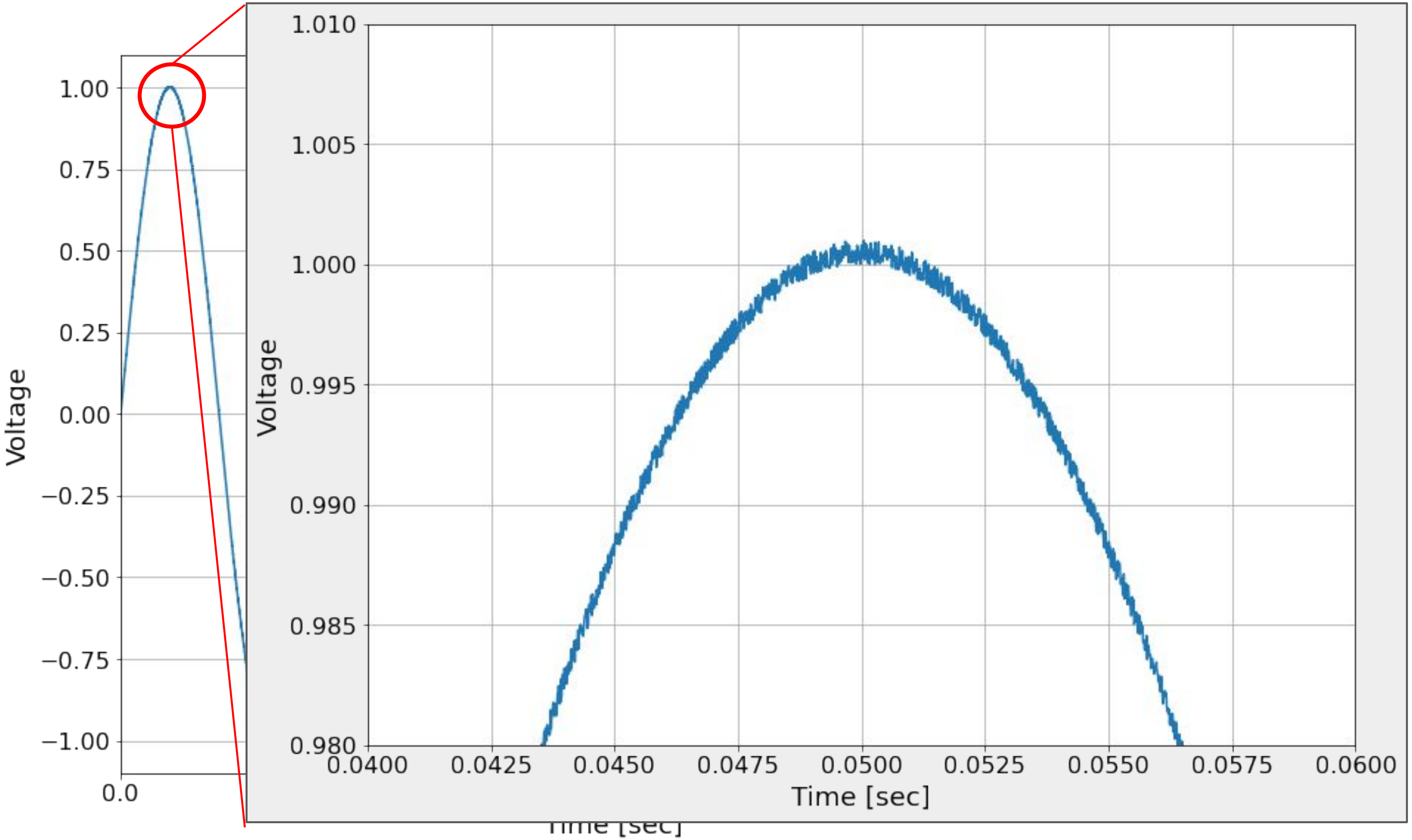
$$dB = 10\log_{10}\frac{P_1}{P_2}$$

$$dB = 20\log_{10}\frac{V_1}{V_2}$$

Why? It actually makes the math easier to do!

Image: Biography.com

On a scope we are limited in range by the linear scale



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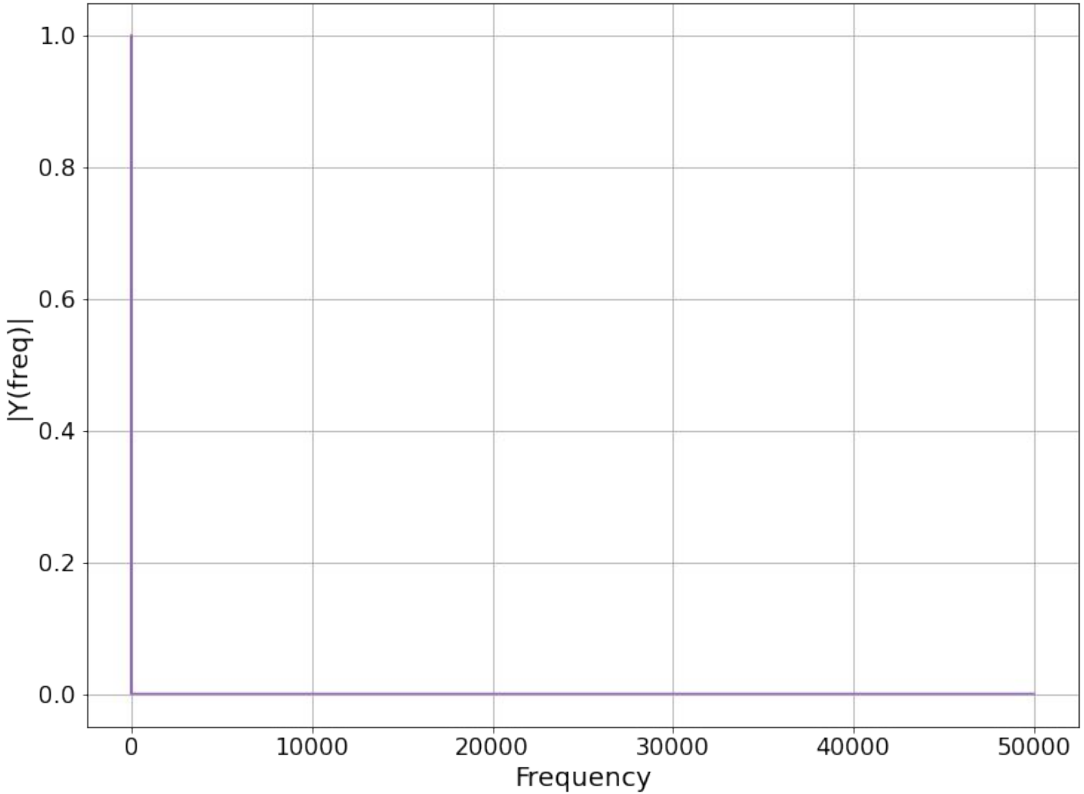
The frequency domain is not any better



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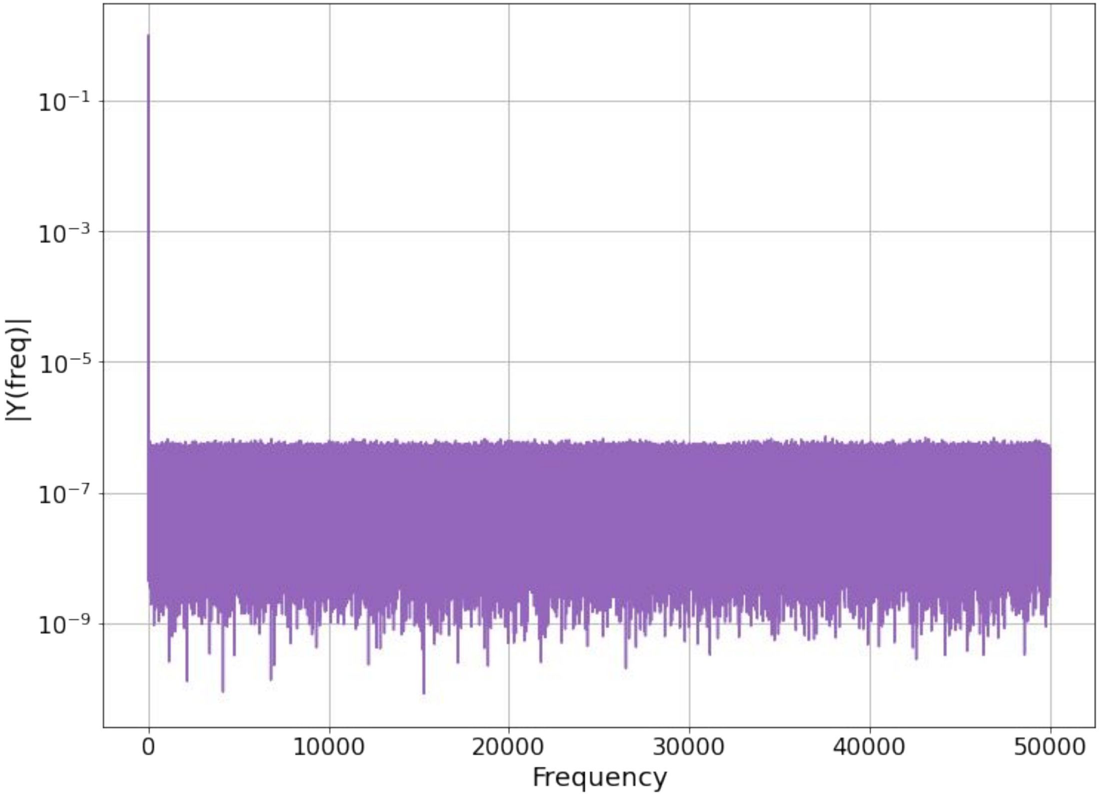
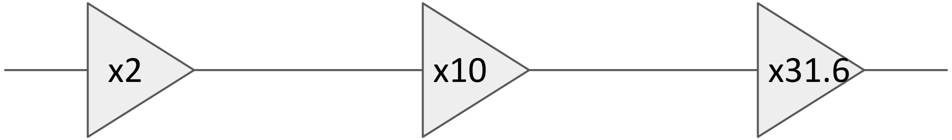
But with log scaling we can see details over a much larger range



Let's consider a chain of amplifiers and we want to know the total amount of gain applied to an input signal



In Gain: 2 * 10 * 31.6 = 632

In dB: 6dB + 20dB + 30dB = 56 dB

Learn the dB "pocket numbers" to make your life easier

Magnitudes

-3dB	0.707
-6dB	0.5
-20dB	0.1

"Half Power" →

Power/Intensity

-3dB	0.5
-10dB	0.1

There are many industry "standard" dB ratings

dBm	1 milliwatt
dBu	1 microwatt
dBV	1 Volt
dbmV	1 millivolt
dbmA	1 milliamp

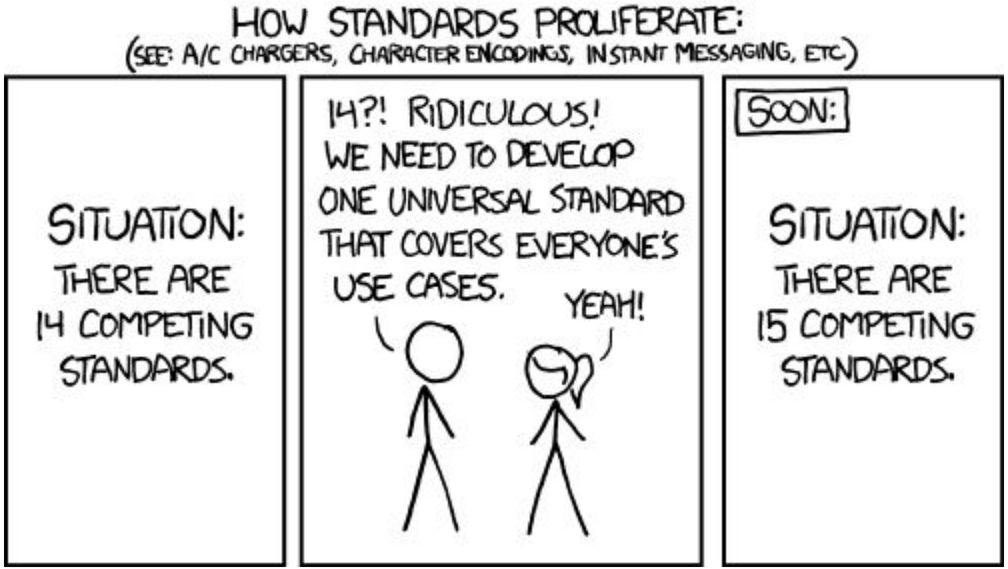


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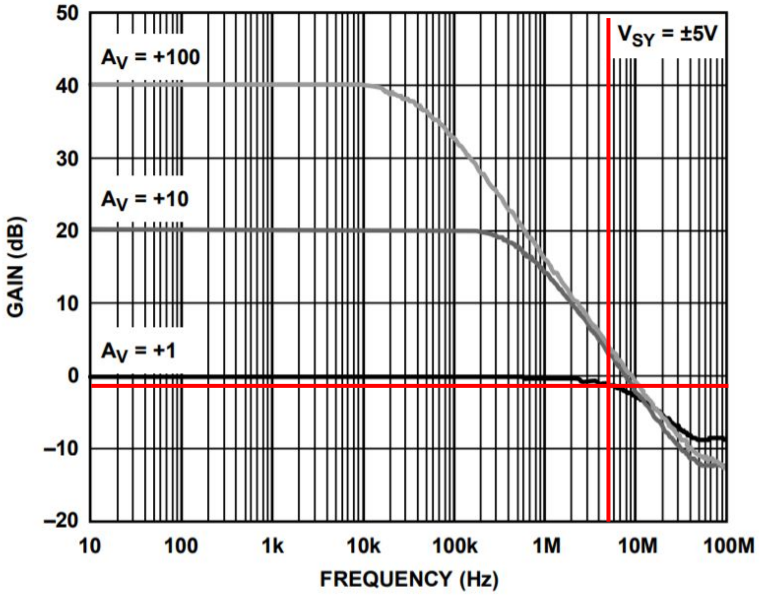
Image: XKCD

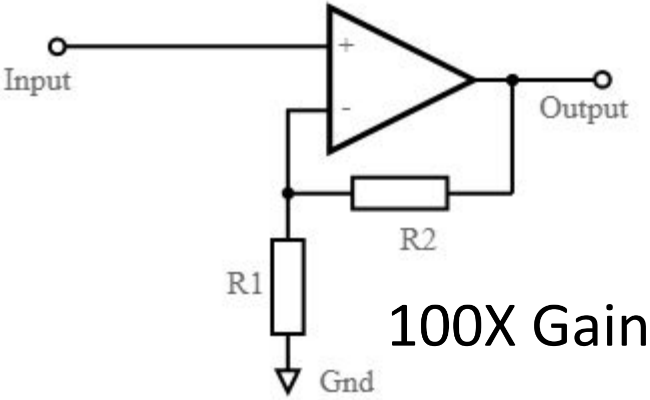
Gain Bandwidth Product (GBWP) is one of the most important considerations

DYNAMIC PERFORMANCE				
Slew Rate	SR	R_L = 10 kΩ, C_L = 100 pF, A_V = 1	3.3	V/μs
Settling Time	t_S	To 0.1%, V_{IN} = 10 V step, C_L = 100 pF, R_L = 10 kΩ, A_V = 1	3.5	μs
Gain Bandwidth Product	GBP	R_L = 10 kΩ, A_V = 1	1.4	MHz
Phase Margin	Φ_M	R_L = 10 kΩ, A_V = 1		
Channel Separation (ADA4062-2 Only)	CS	f = 1 kHz		
Channel Separation (ADA4062-4 Only)	CS	f = 1 kHz		

$$\text{Bandwidth} = \frac{\text{GBWP}}{\text{Gain}}$$



Let’s consider the non-inverting amplifier case



100X Gain

Bandwidth = 10kHz

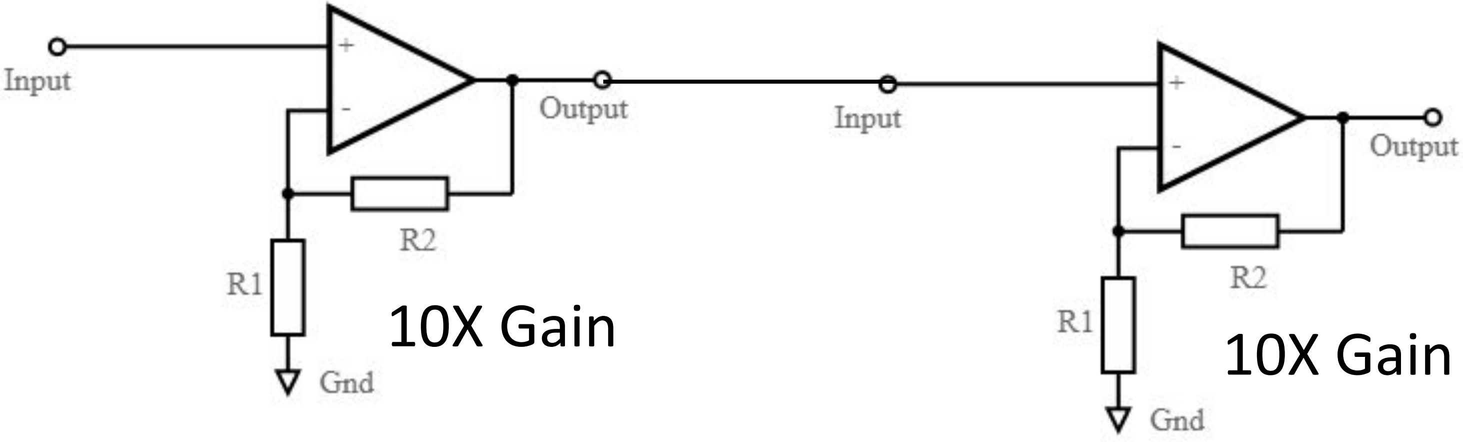
GBWP = 1MHz

Image: Electronics Notes

Cascading amplifiers can greatly improve the amplifier bandwidth

$$\text{Bandwidth}_{\text{total}} = \text{Bandwidth}\sqrt{2^{\frac{1}{N}} - 1}$$

Bandwidth = 64.36kHz



10X Gain

10X Gain

GBWP = 1MHz

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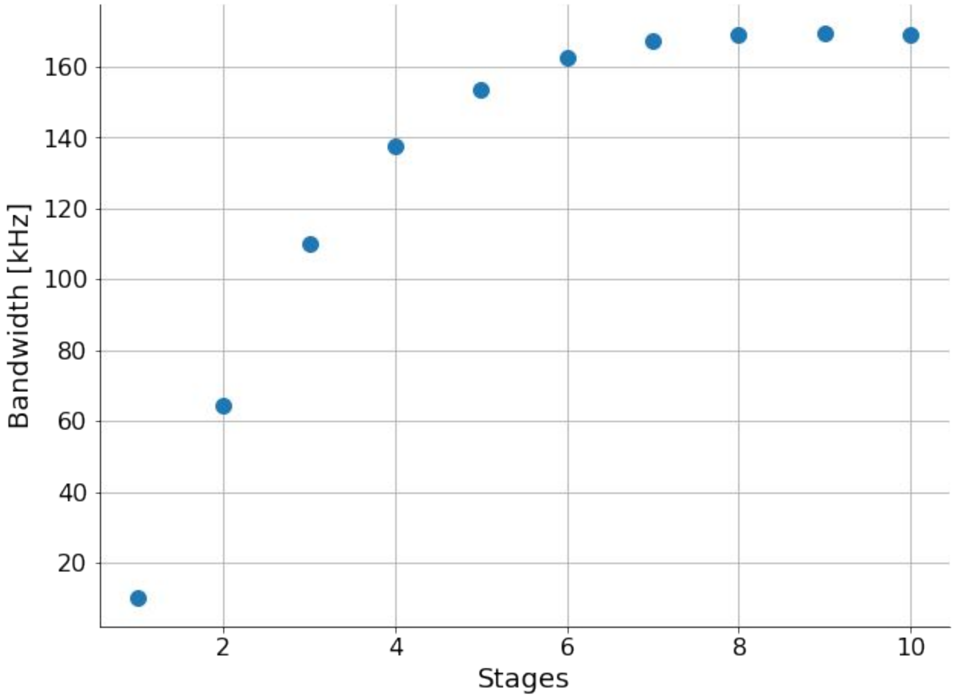
Image: Electronics Notes

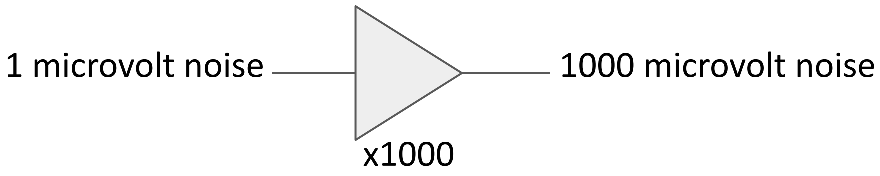
There are decreasing returns with increasing stages



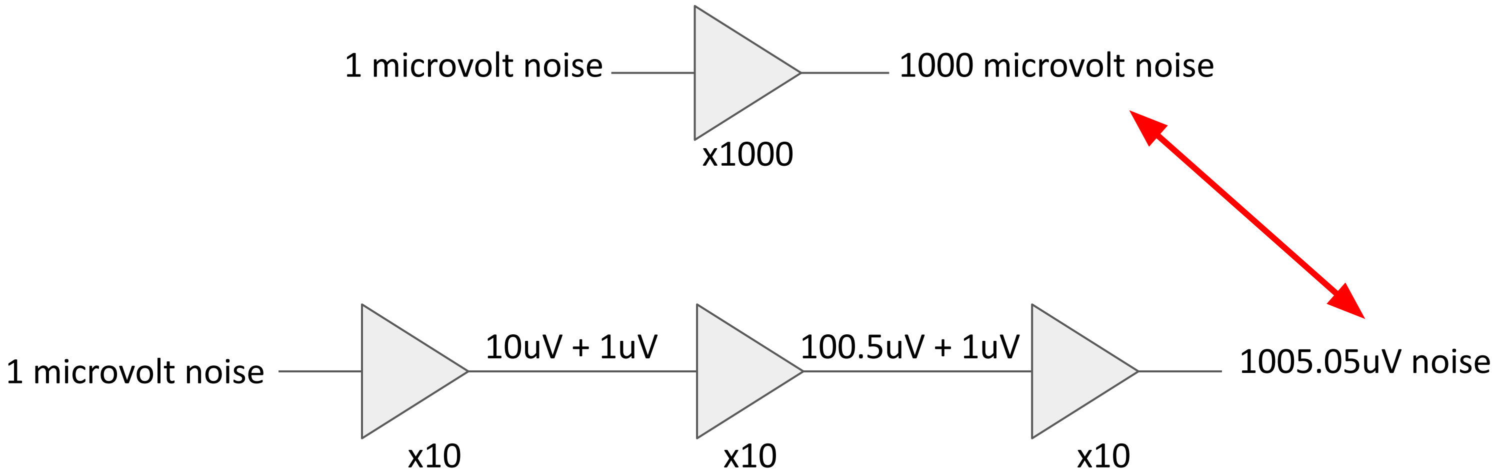
Stages	Stage Gain	BW [kHz]
1	100	10
2	10	64.36
3	4.64	109.83
4	3.16	137.55
5	2.51	153.52
6	2.15	162.43
7	1.93	167.10
8	1.78	169.18
9	1.67	169.62
10	1.58	169.04

$$\text{Bandwidth}_{\text{total}} = \text{Bandwidth}\sqrt{2^{\frac{1}{N}} - 1}$$

So just how bad is the noise amplification from op amp input noise?



So just how bad is the noise amplification from op amp input noise?



$$\text{Noise}_{\text{total}} = \sqrt{N_1^2 + N_2^2 + ... + N_n^2}$$

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Don't forget about ensuring a path for input bias currents

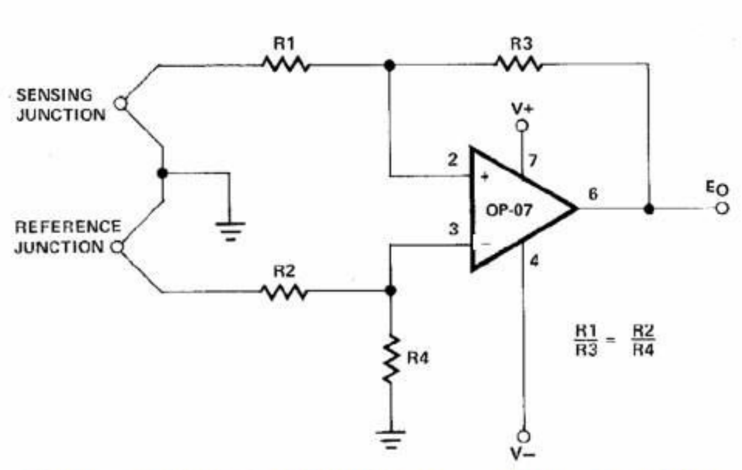
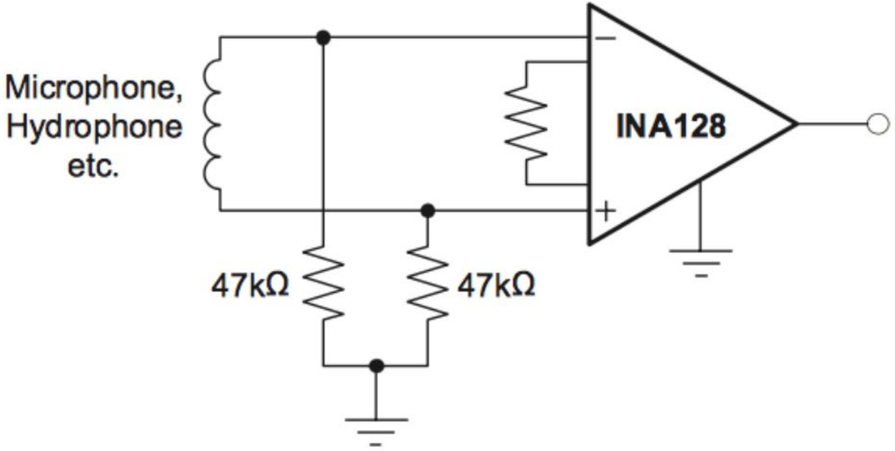


Figure 8. High-Stability Thermocouple Amplifier



Images: Texas Instruments

Instrumentation amplifiers are precision differential amplifiers

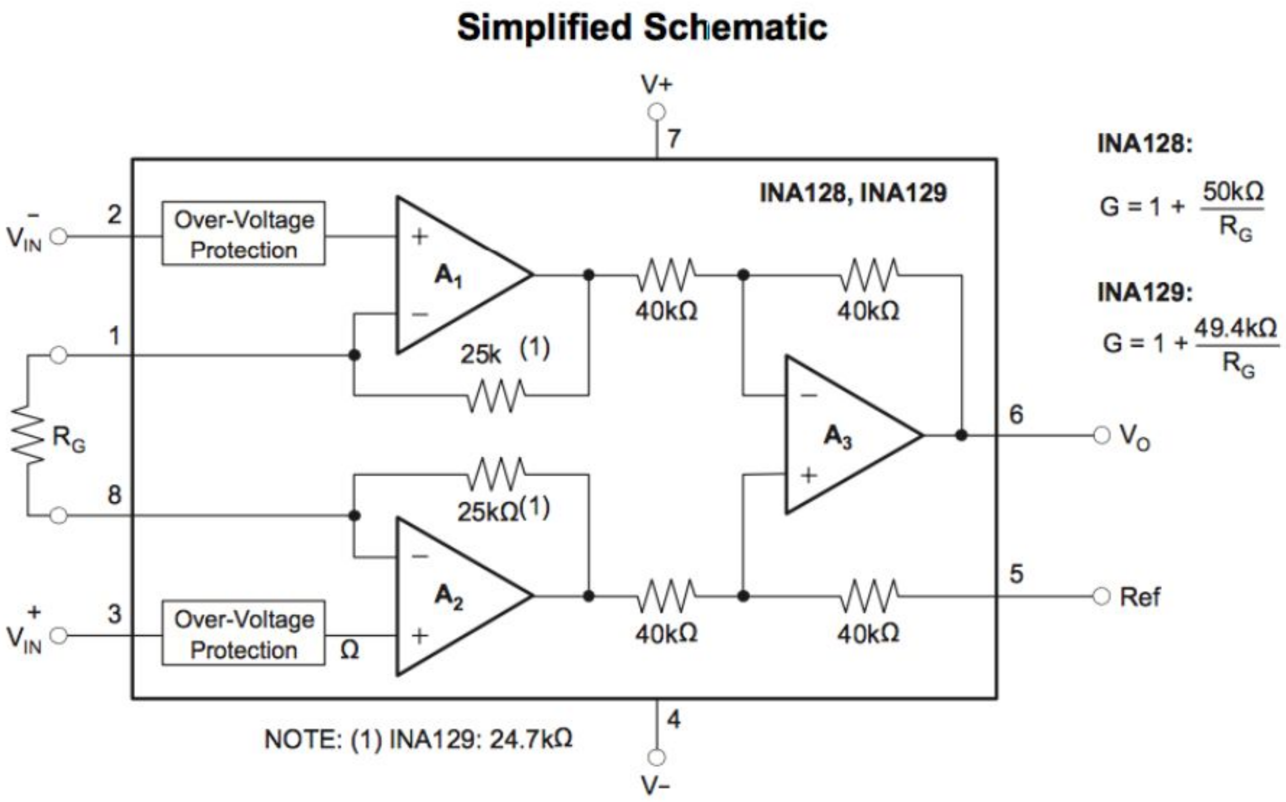


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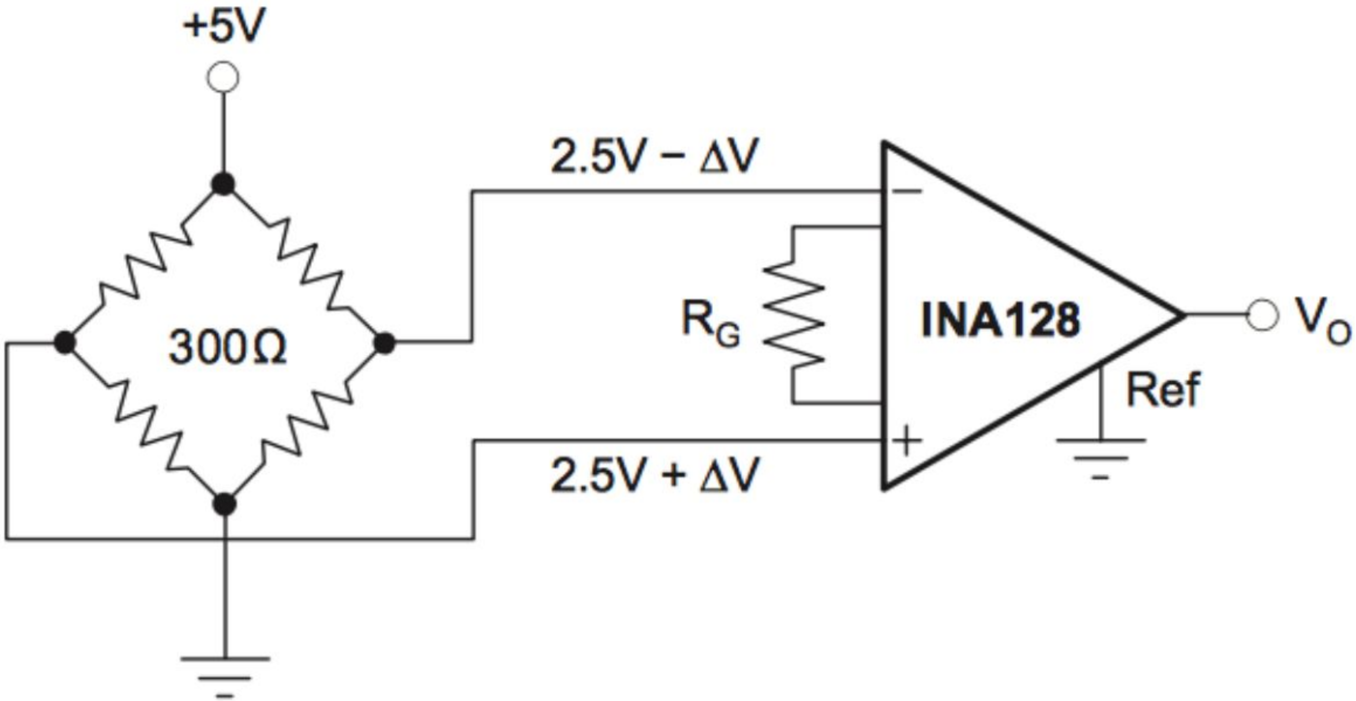
Image: Texas Instruments

IA's are perfect for bridge circuits/transducers



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