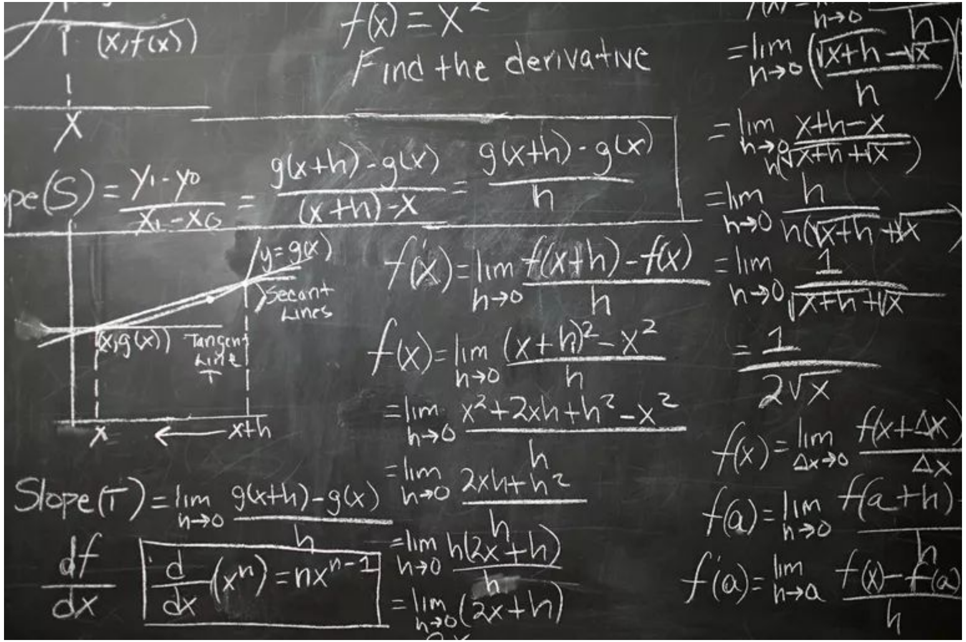



# Operational Amplifiers

John R. Leeman

GEARS 2022



Image: ThoughtCo

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

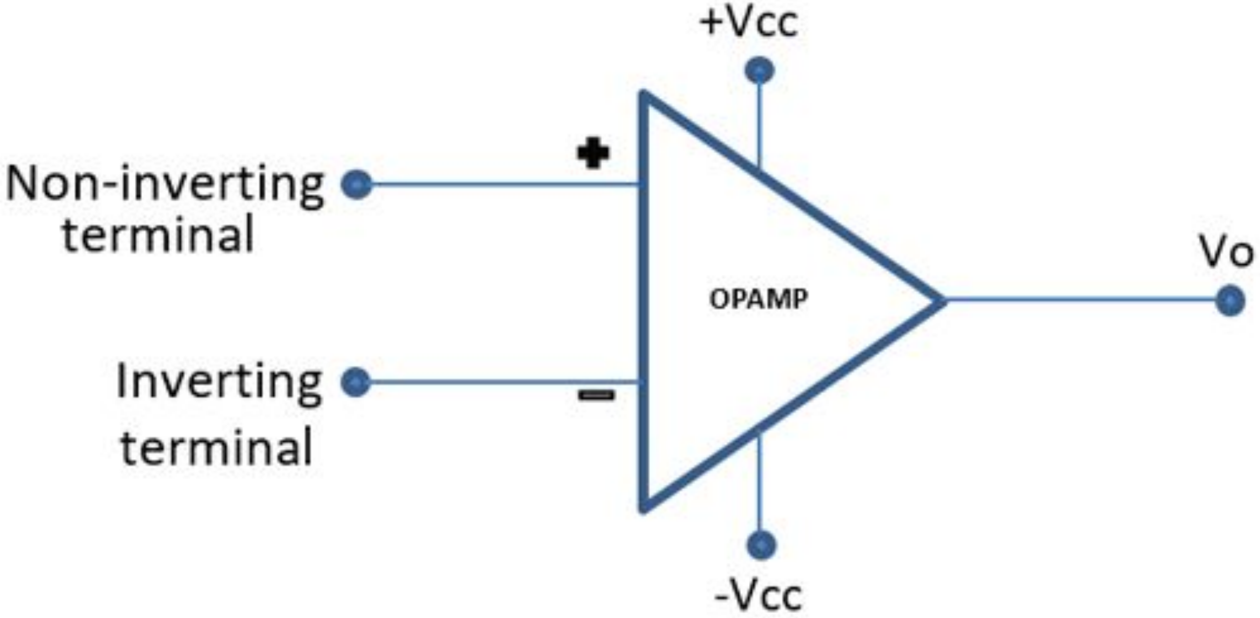





Image: Circuit Digest

# 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

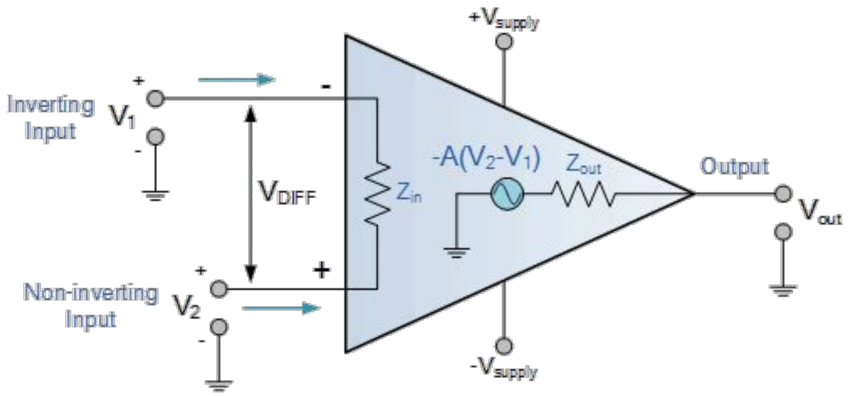





Image: Electronics Tutorials

# The most straightforward circuit is a comparator

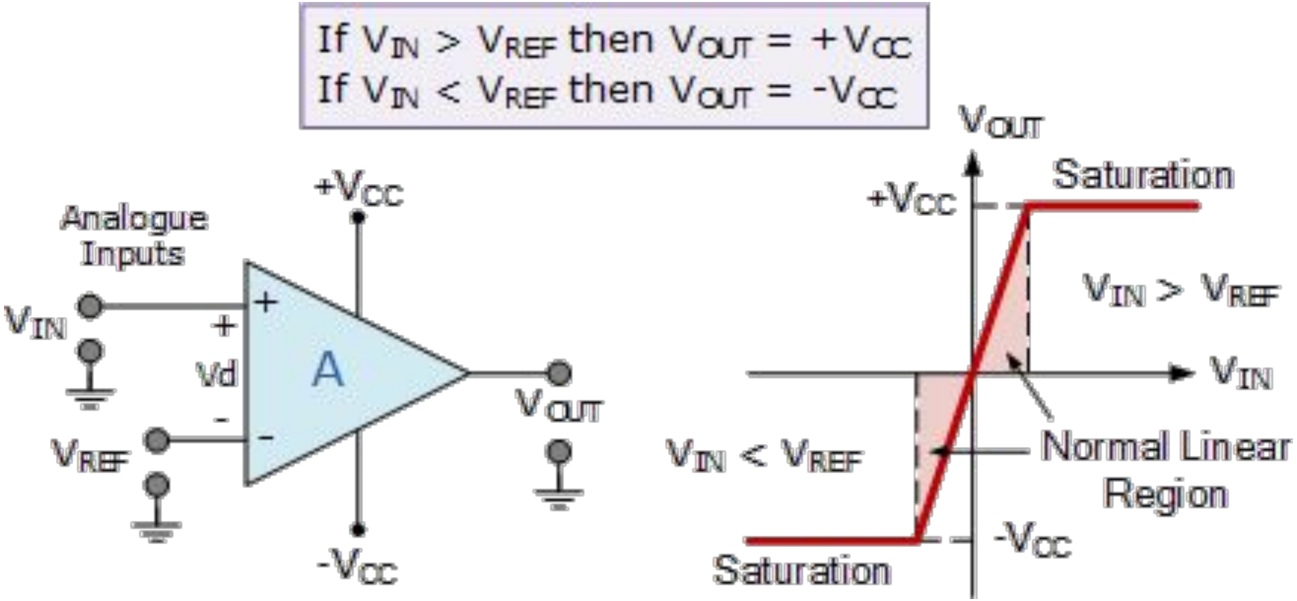





Image: Electronics Tutorials

# Two comparators can make a window comparator

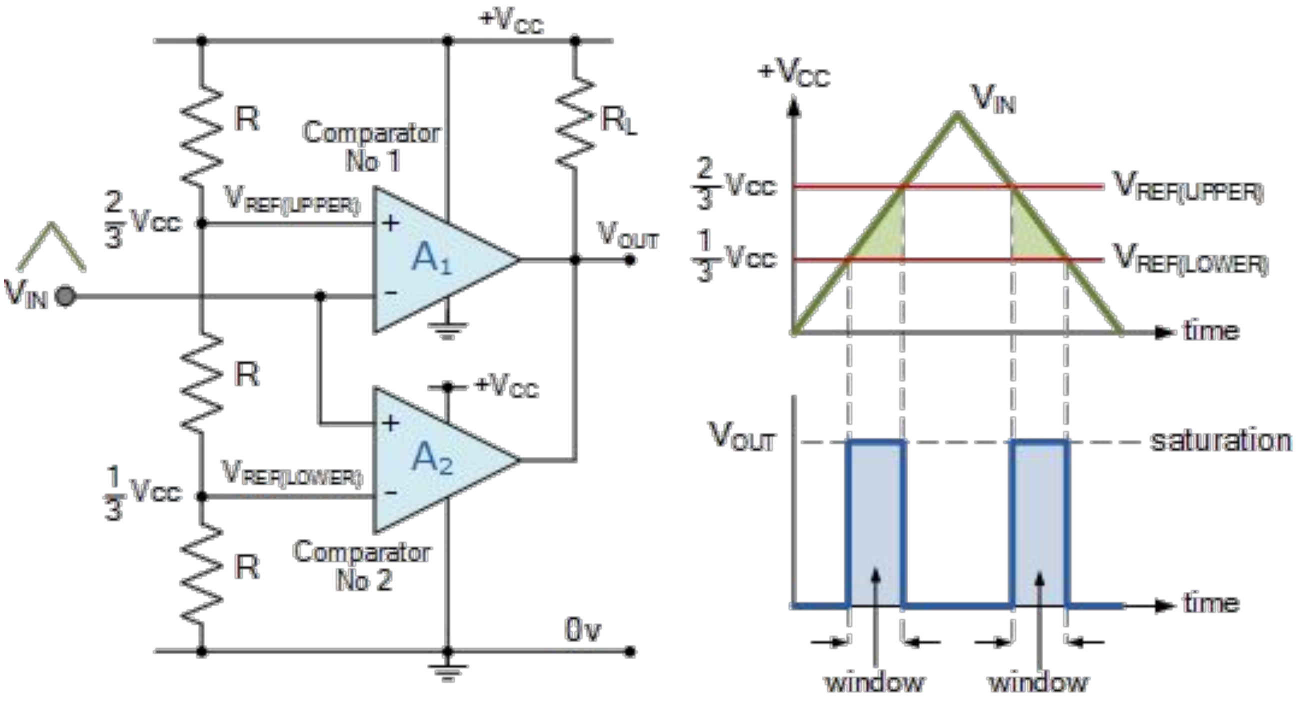



Image: Electronics Tutorials

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

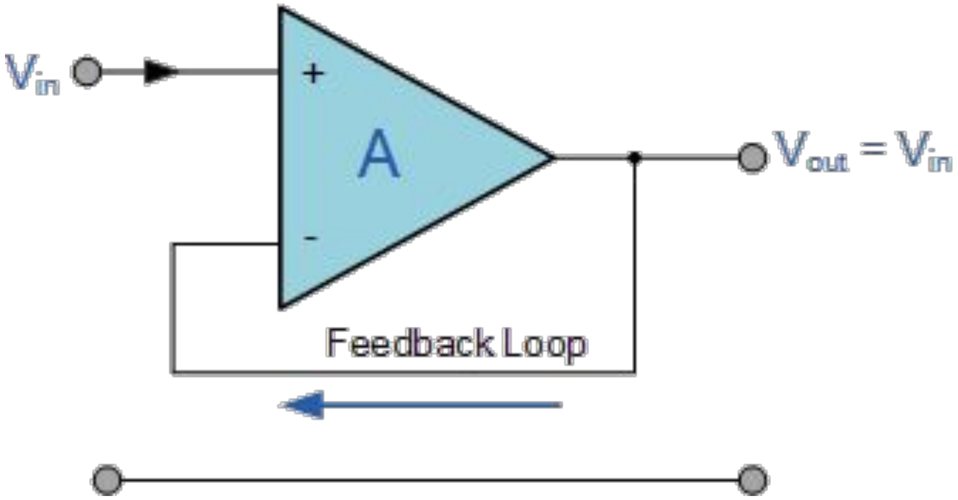



Image: Electronics Tutorials

# Inverting amplifiers have a simple gain formula, but some caveats

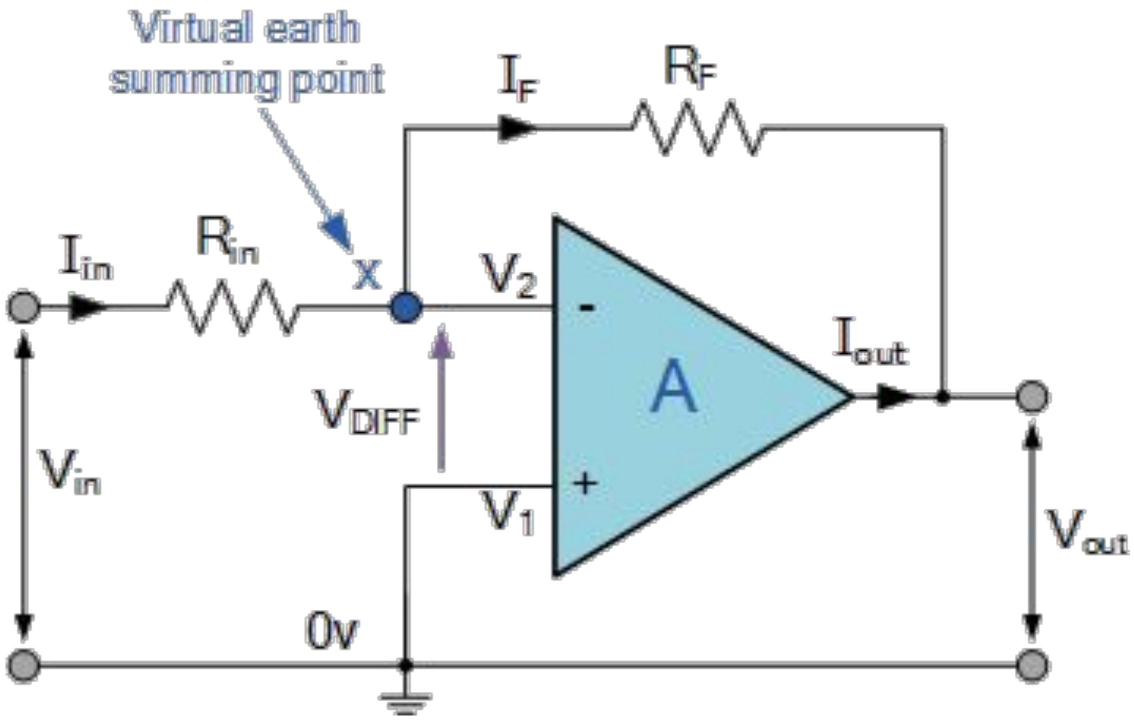



Image: Electronics Tutorials

# Non-inverting amplifiers are modified voltage followers

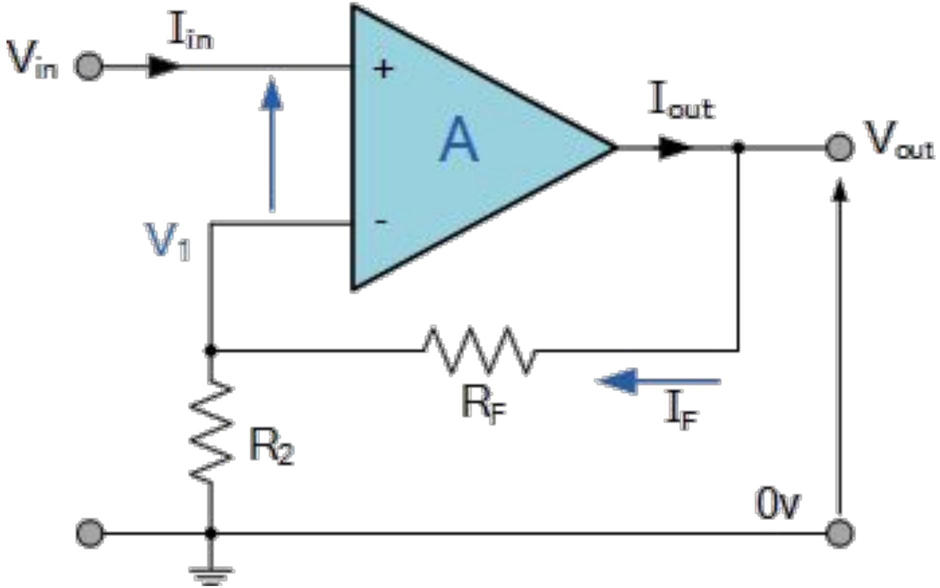
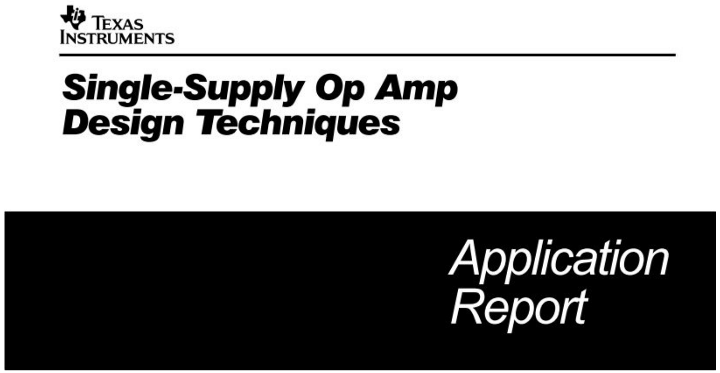
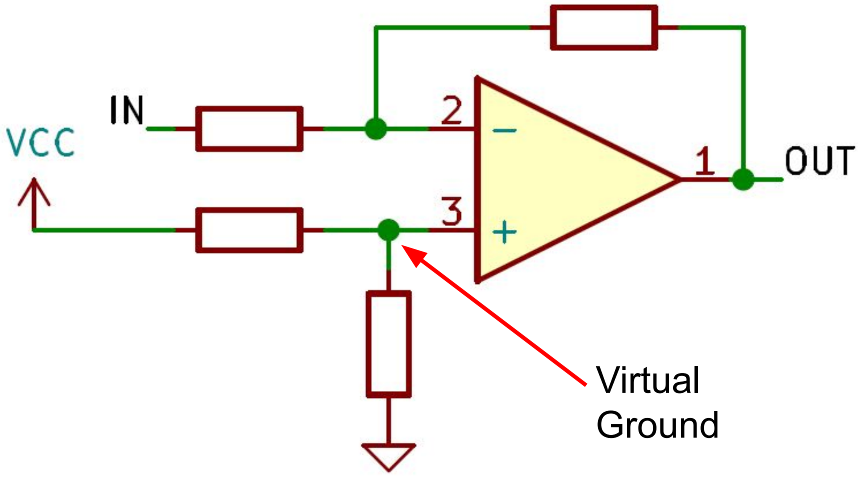




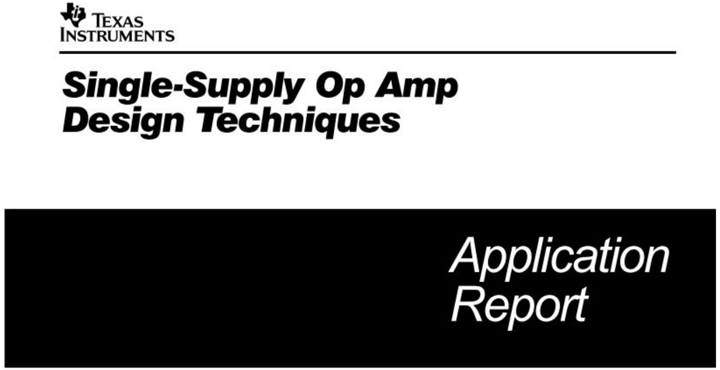

Image: Electronics Tutorials

# Amplifiers don’t have to operate from a bipolar supply



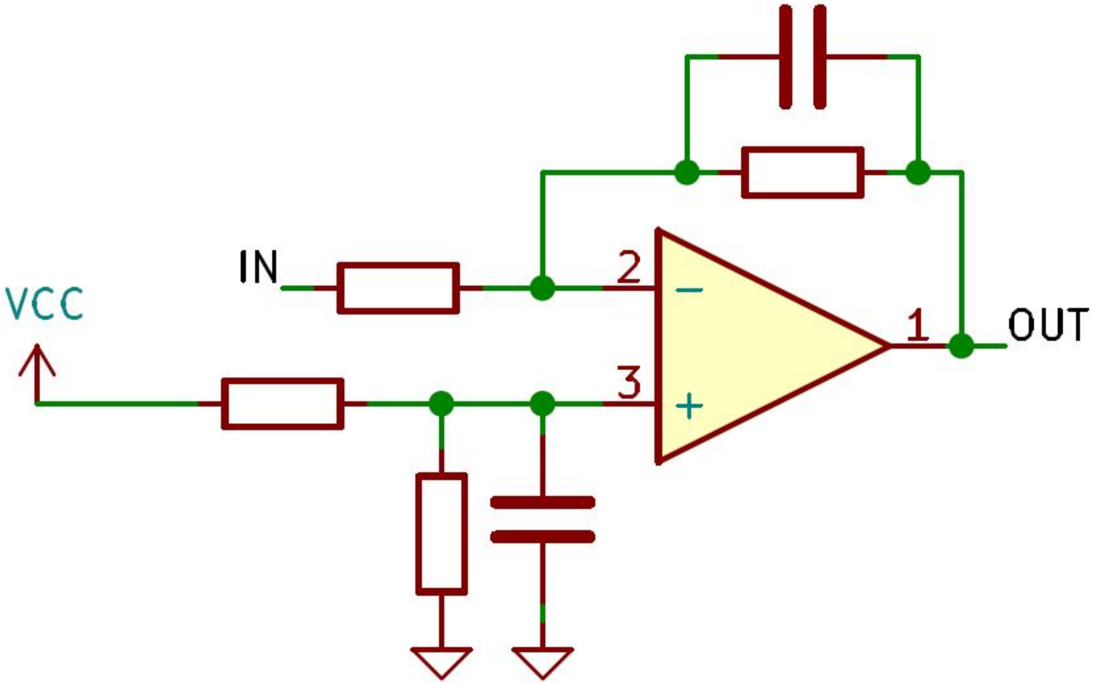



# Amplifiers don’t have to operate from a bipolar supply

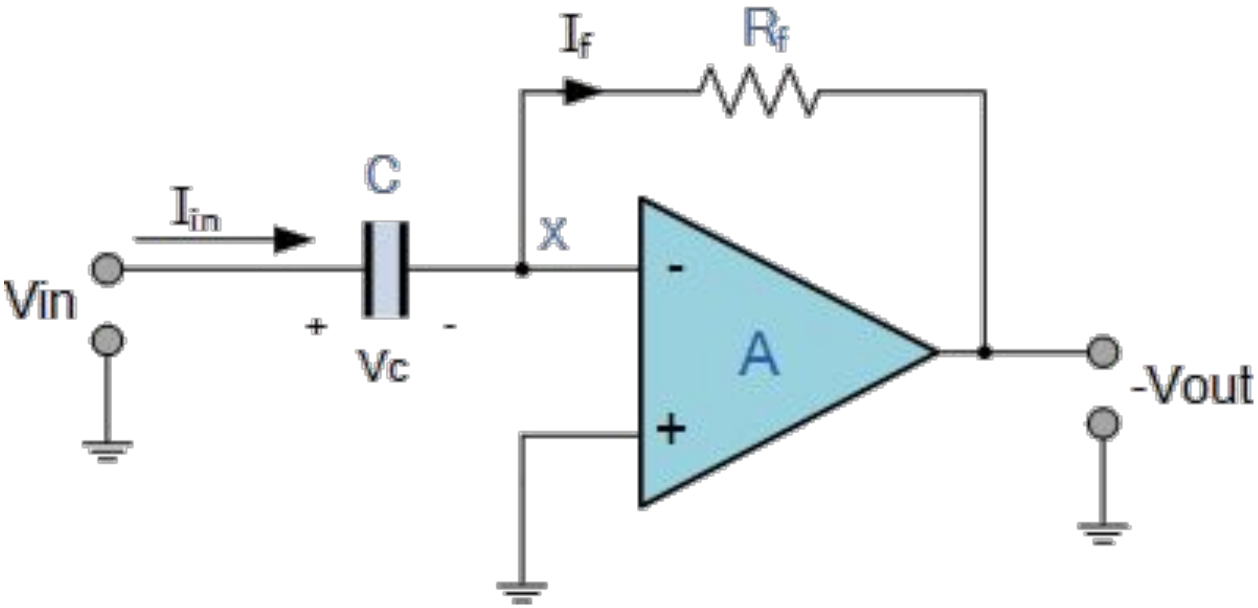

Texas Instruments

Single-Supply Op Amp Design Techniques

Application Report



# Differentiators output the rate of change of the input

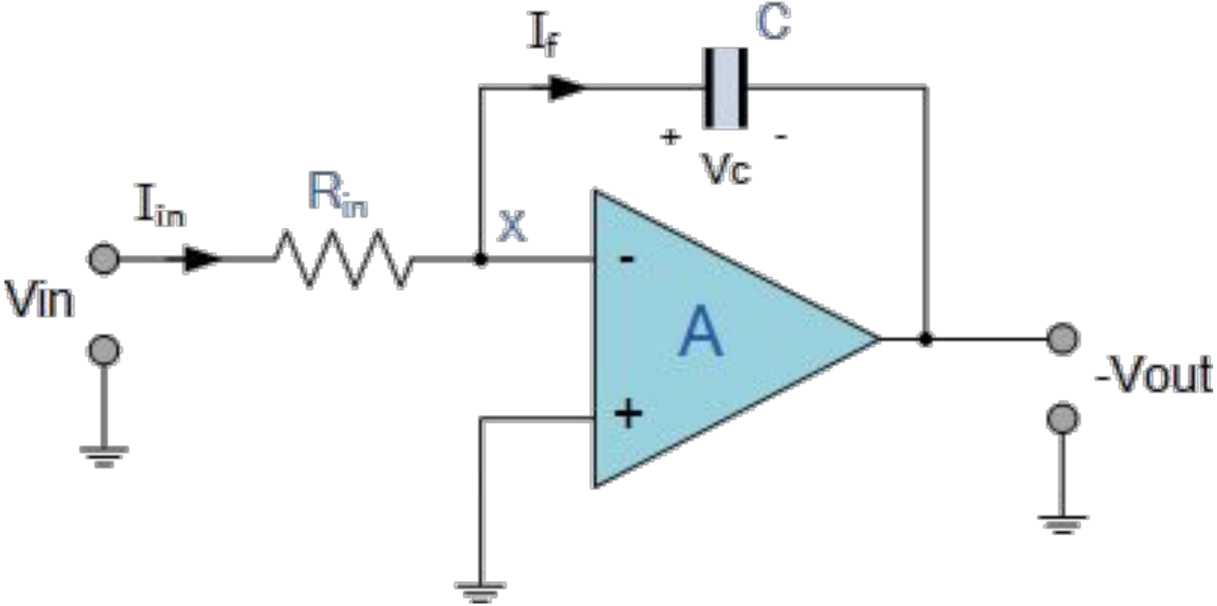



$$V_{OUT} = -R_F C \frac{dV_{IN}}{dt}$$



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

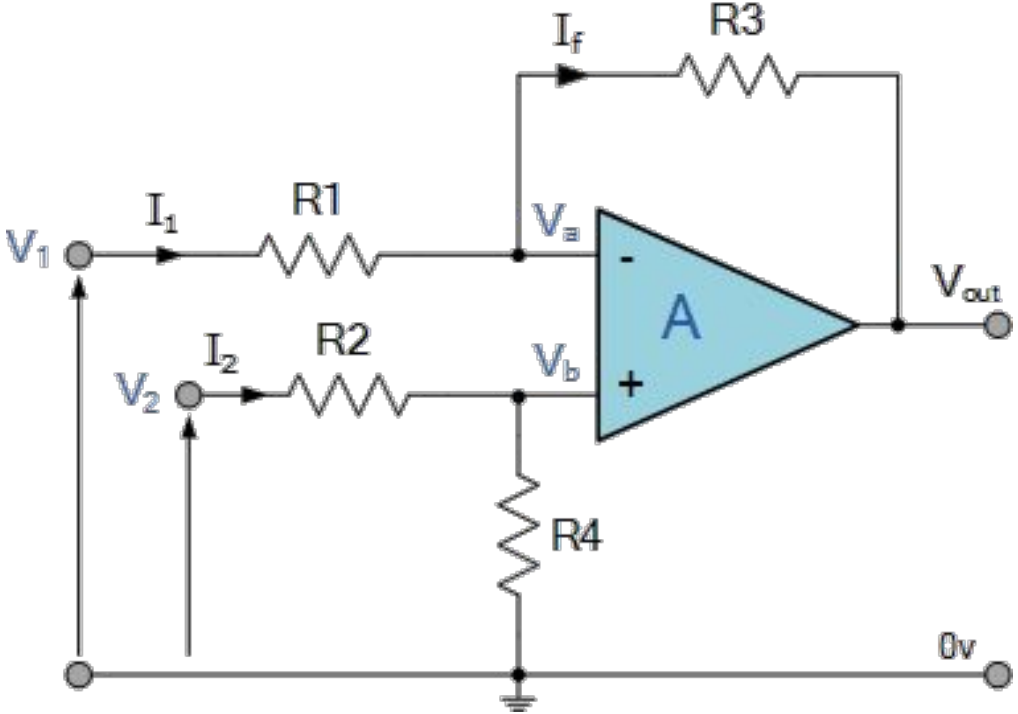
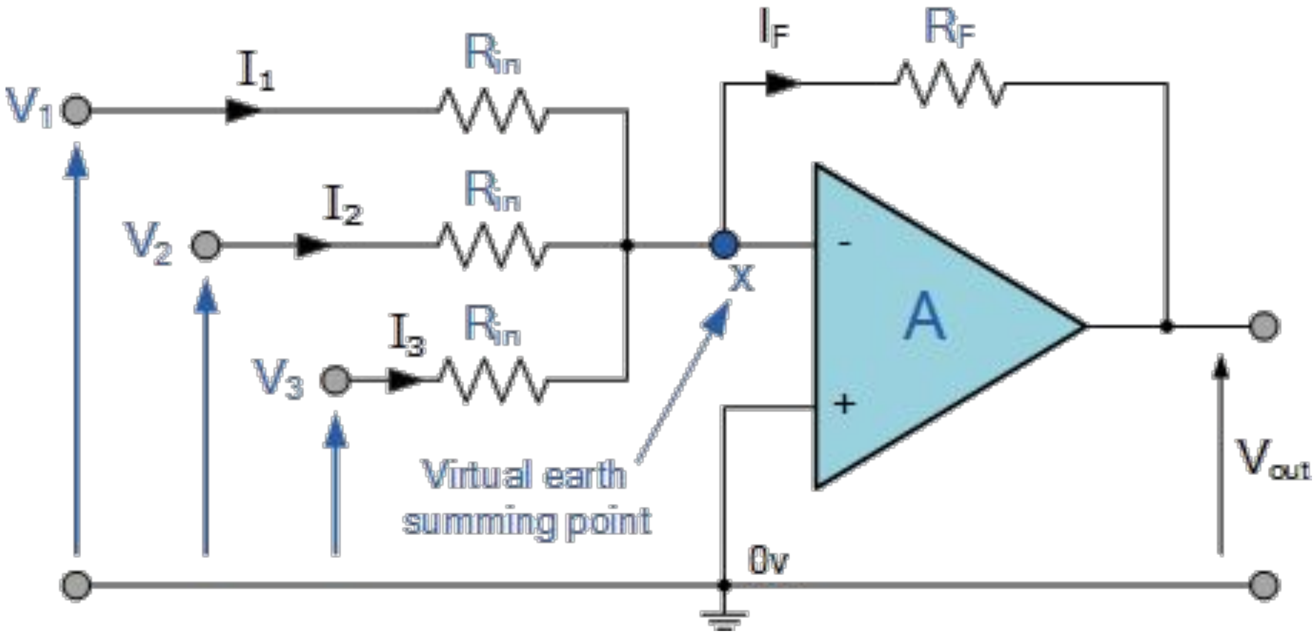





Image: Electronics Tutorials

# Summing amplifiers can be handy as well




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

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!



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 | $R_S \leq 10$ kΩ | $T_A = 25°C$ | | 1 | 5 | mV |
| | | $T_{AMIN} \leq T_A \leq T_{AMAX}$ | | | 6 | mV |
| Input offset voltage adjustment range | $T_A = 25°C$, $V_S = \pm20$ V | | | ±15 | | mV |
| Input offset current | $T_A = 25°C$ | | | 20 | 200 | nA |
| | $T_{AMIN} \leq T_A \leq T_{AMAX}$ | | | 85 | 500 | |
| 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

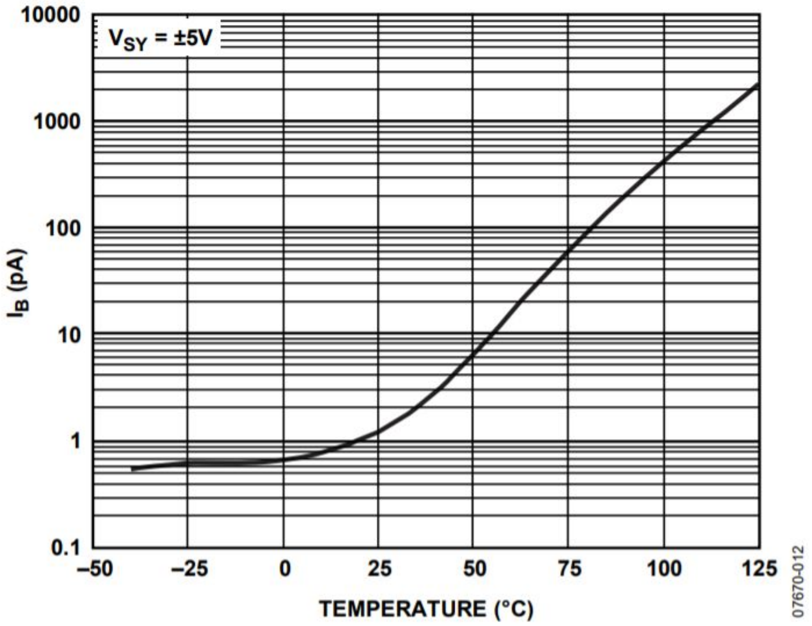



*Figure 12. Input Bias Current vs. Temperature*

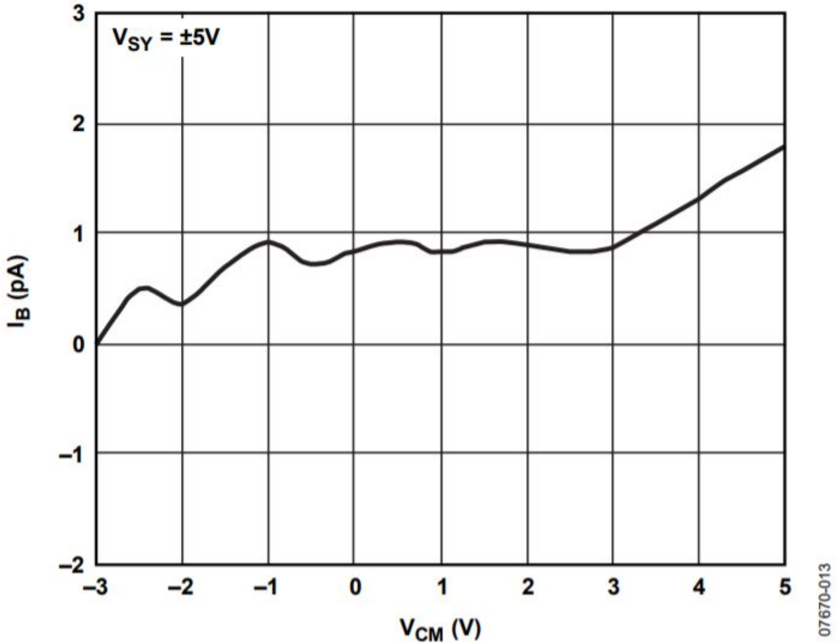



*Figure 13. Input Bias Current vs. Common-Mode Voltage*

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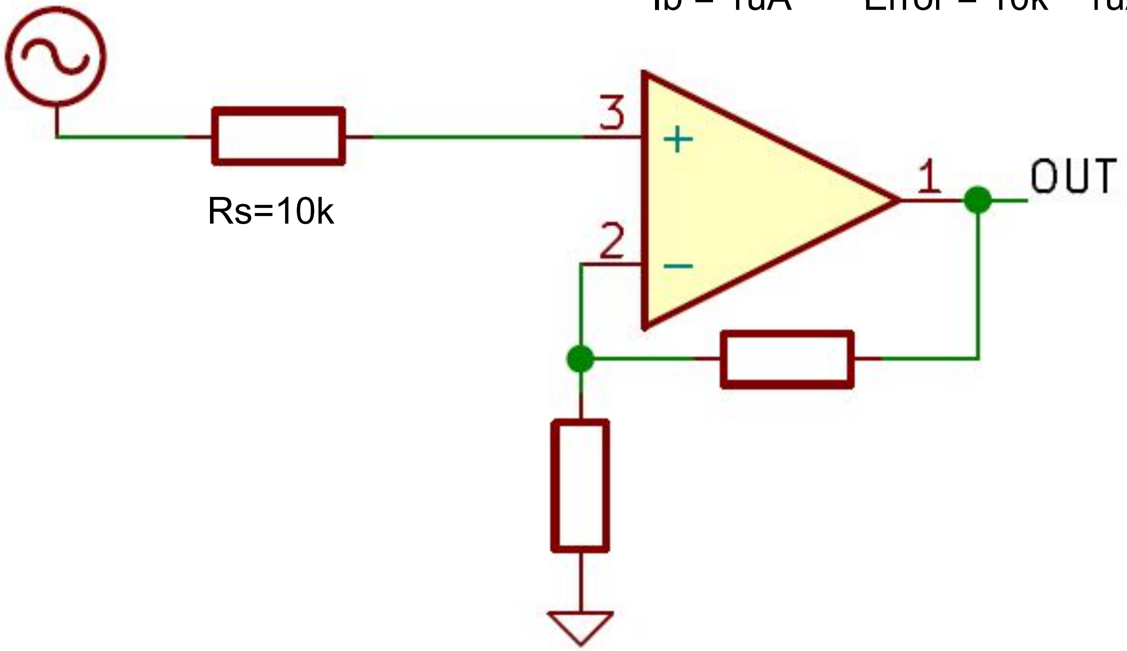
# Input Bias Current Problem #1 - Source Impedance

Ib = 1uA    Error = 10k * 1uA = 0.01V

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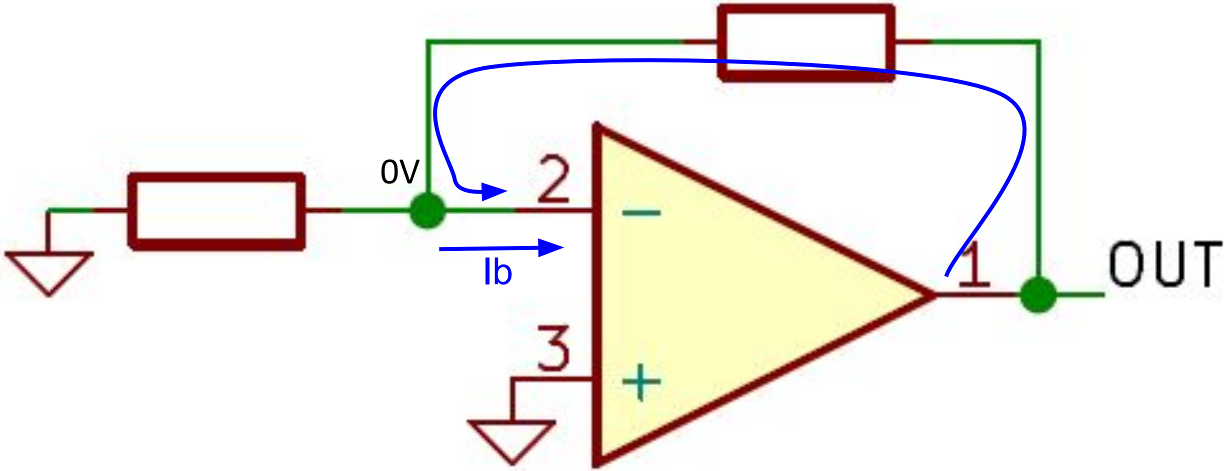
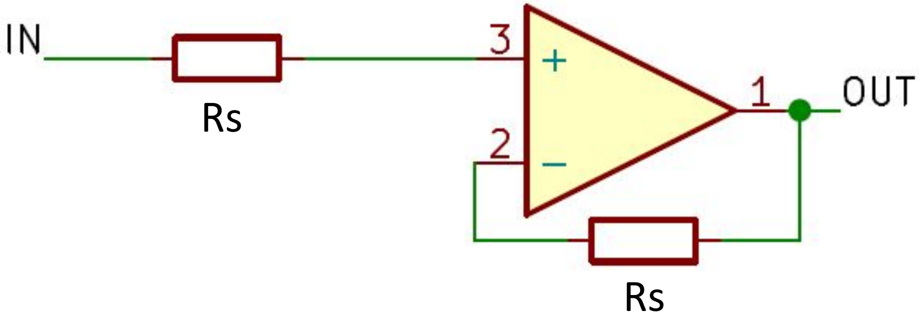
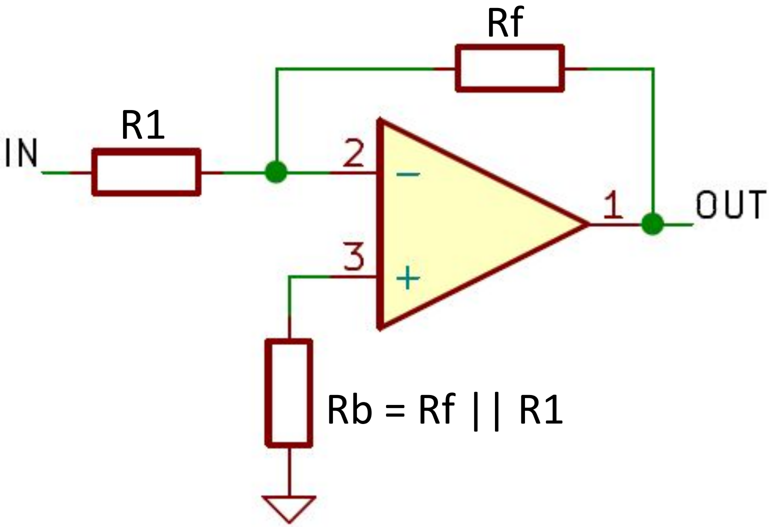
# Input Bias Current Problem #2 - Gain Network



# 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 |

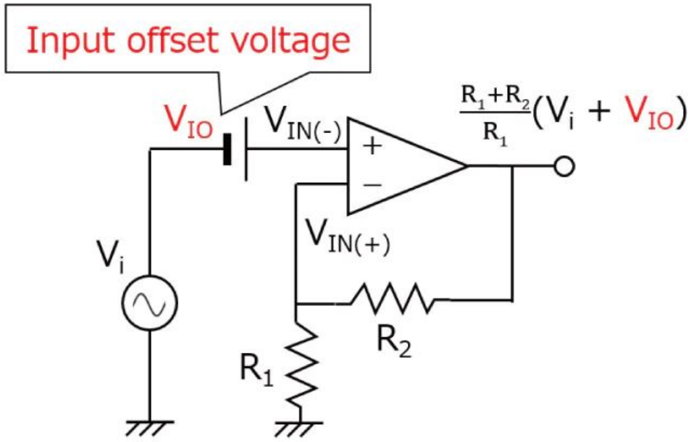



Image: Toshiba Semiconductor

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# Vios can be compensated for with null terminals on some amplifiers

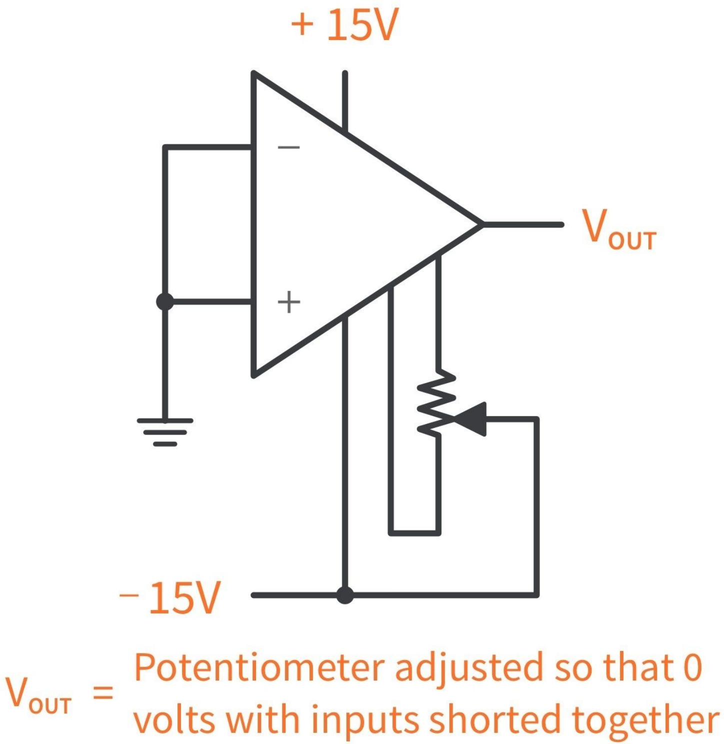
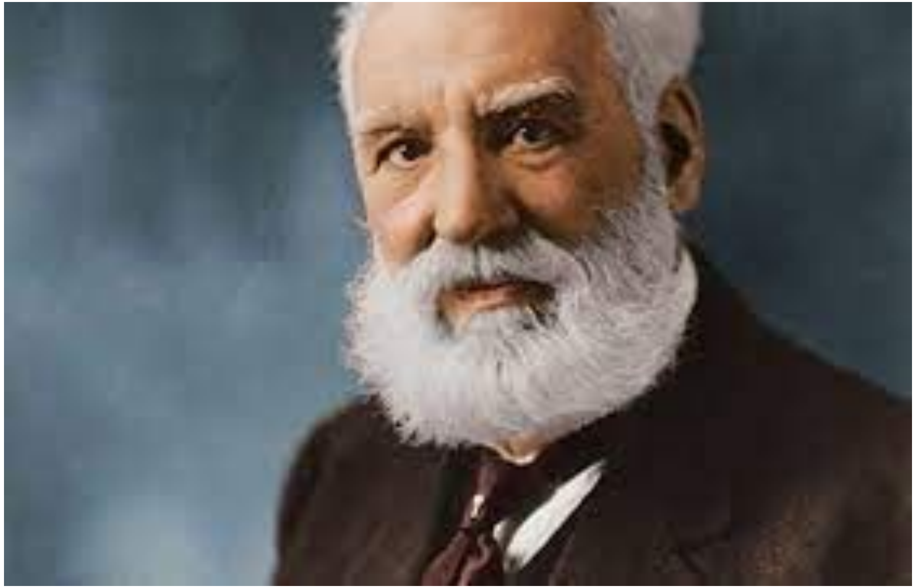





Image: Circuit Bread

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



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

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

Why? It actually makes the math easier to do!

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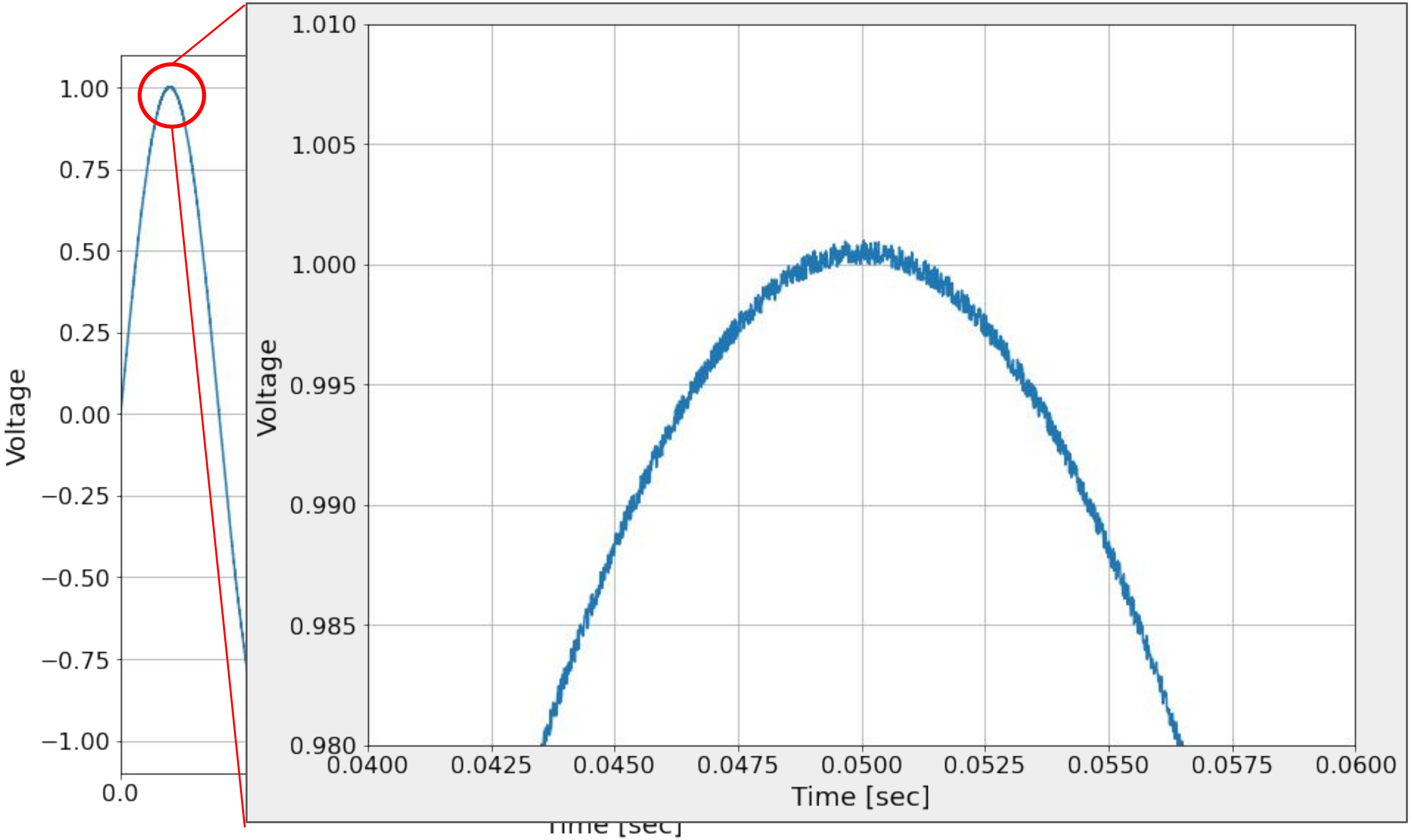
Image: Biography.com

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

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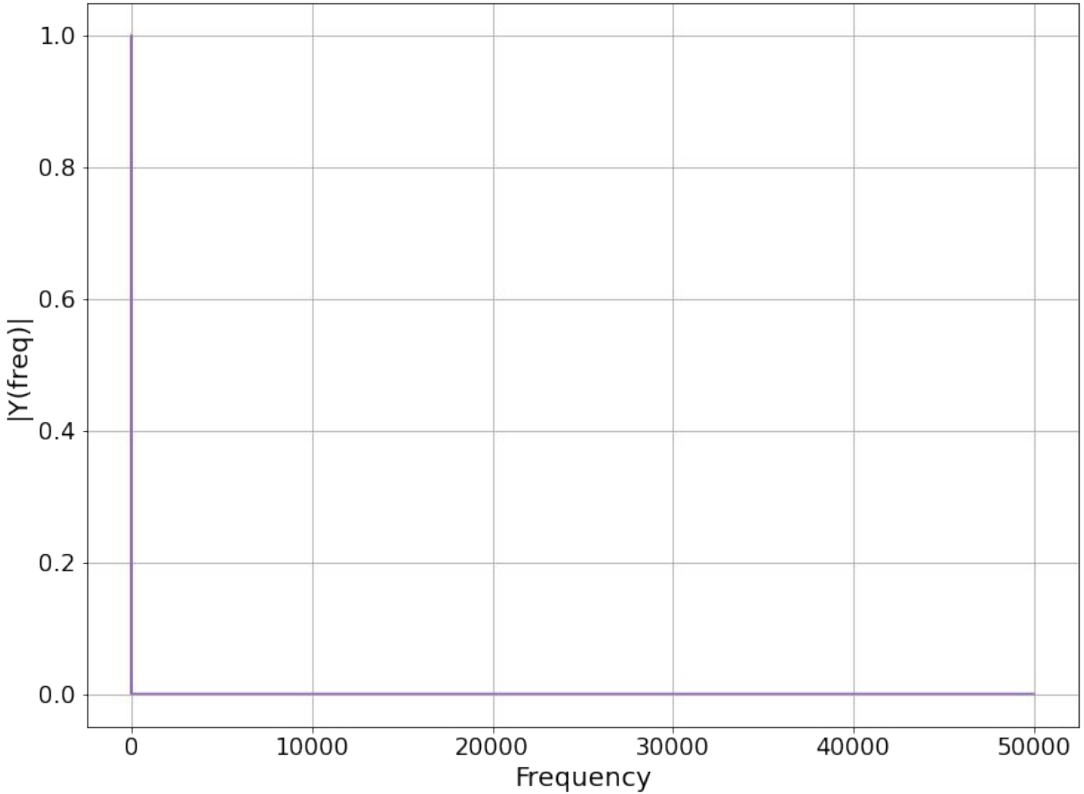
# The frequency domain is not any better

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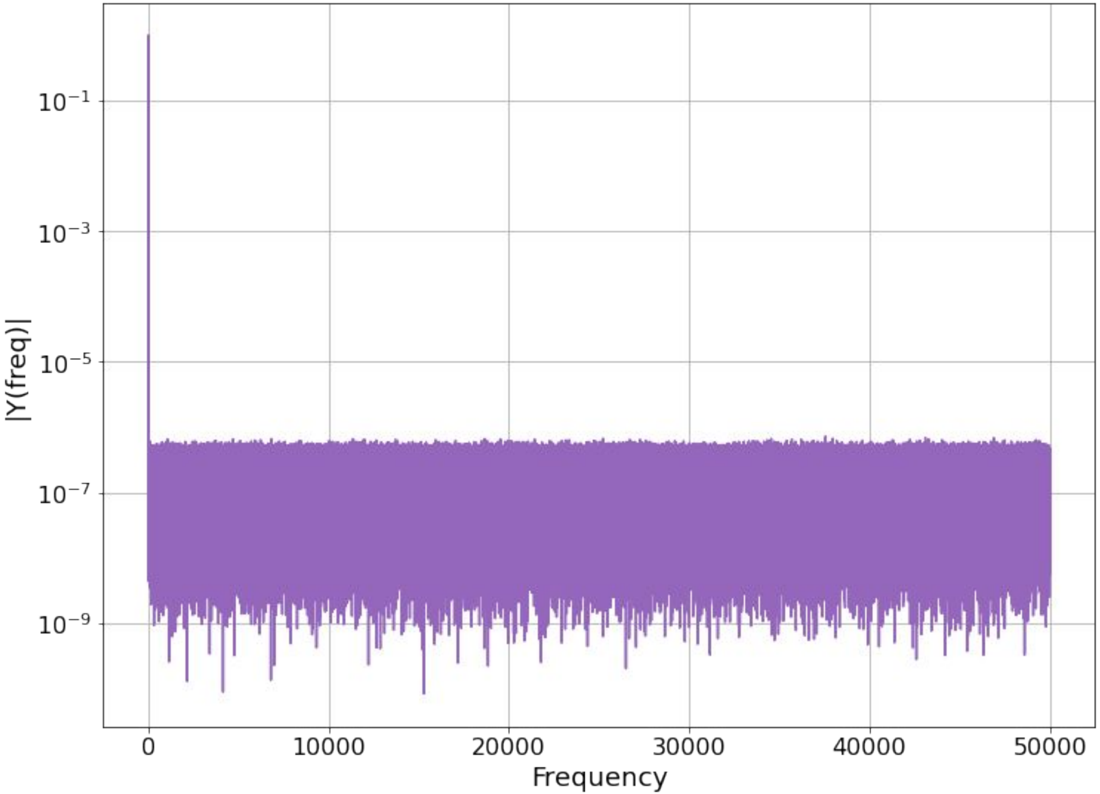
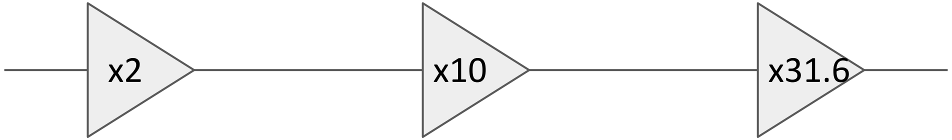
# But with log scaling we can see details over a much larger range



# 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 |

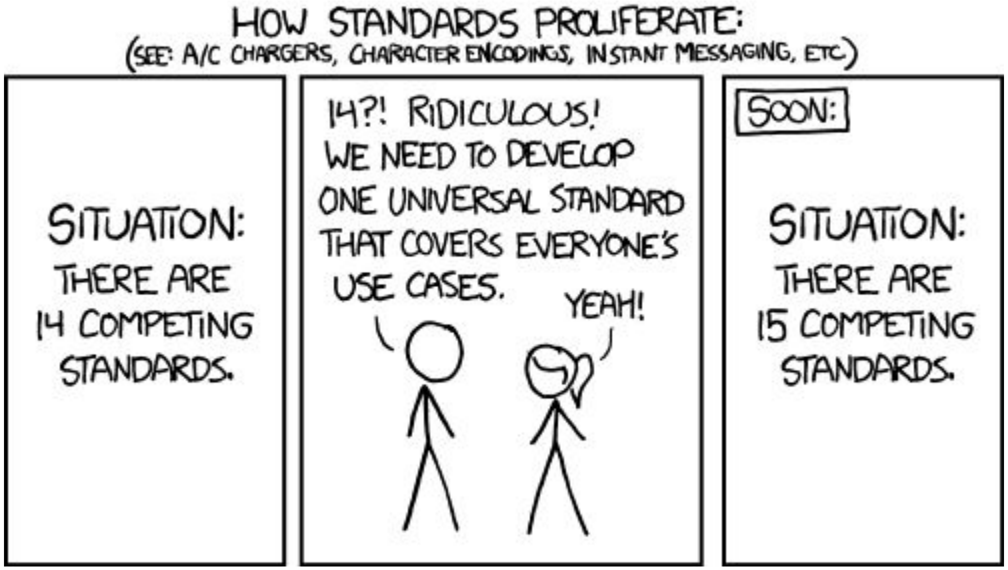



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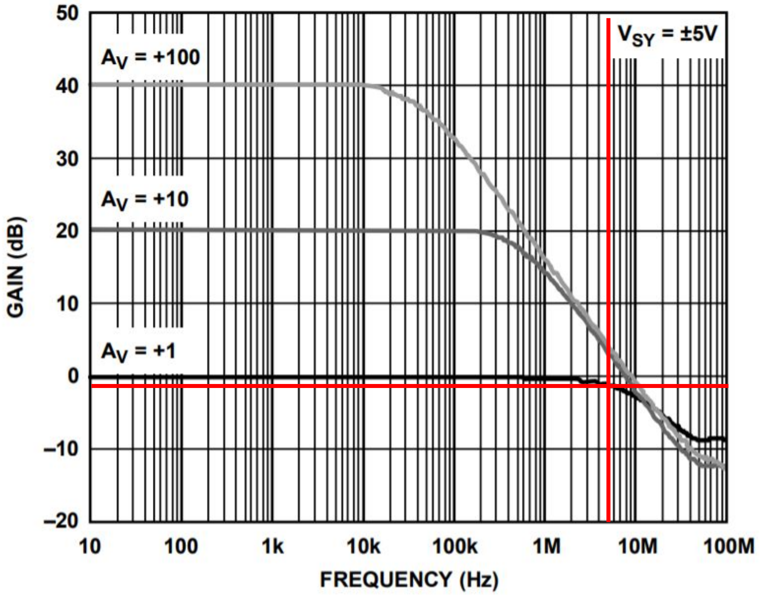
Image: XKCD

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

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

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

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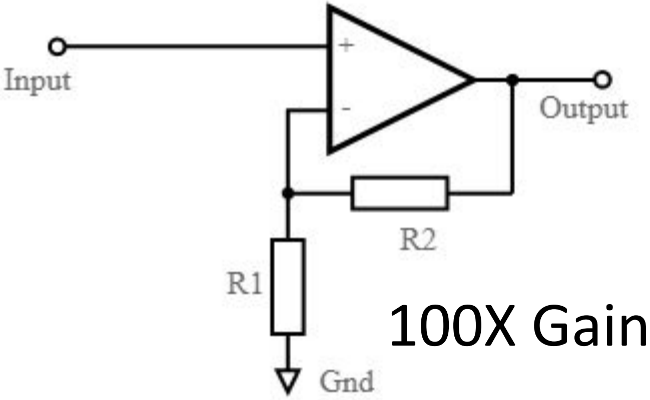
# Let’s consider the non-inverting amplifier case




100X Gain

Bandwidth = 10kHz

GBWP = 1MHz

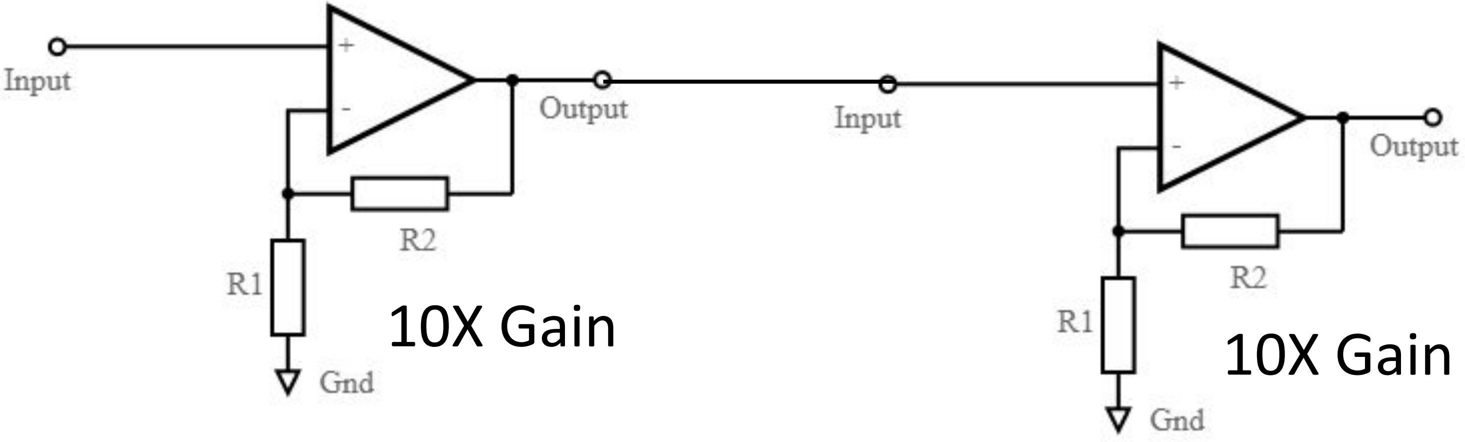


Image: Electronics Notes

# 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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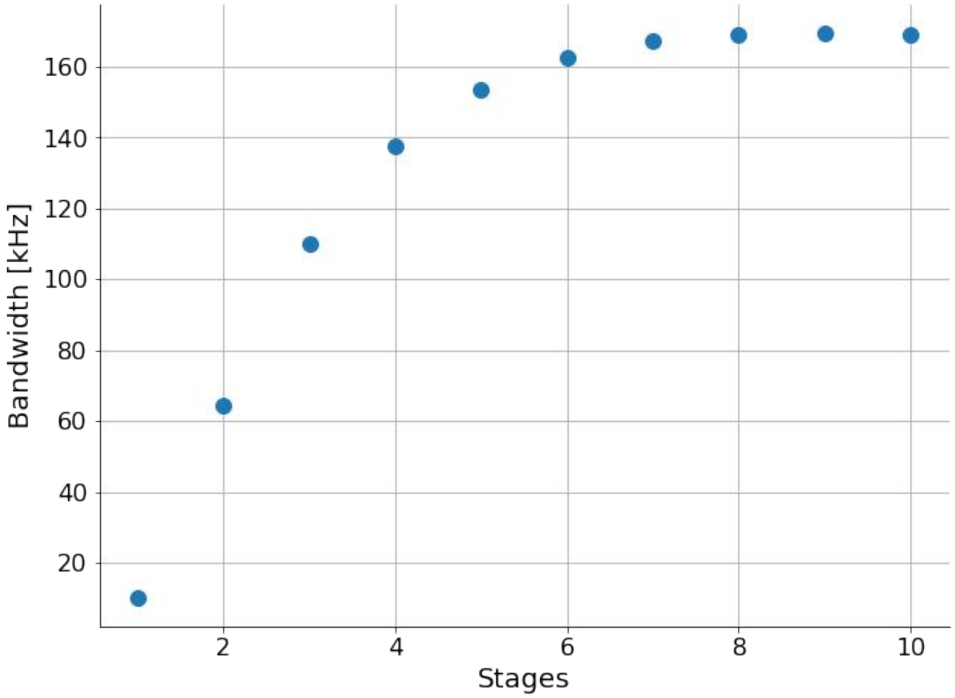
Image: Electronics Notes

# 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 |

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

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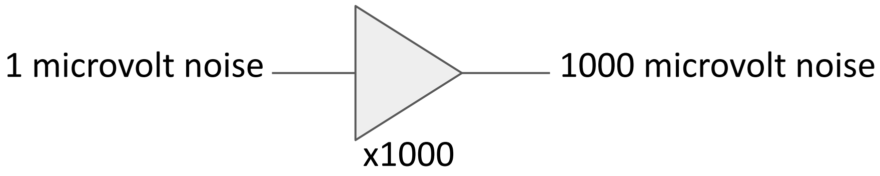
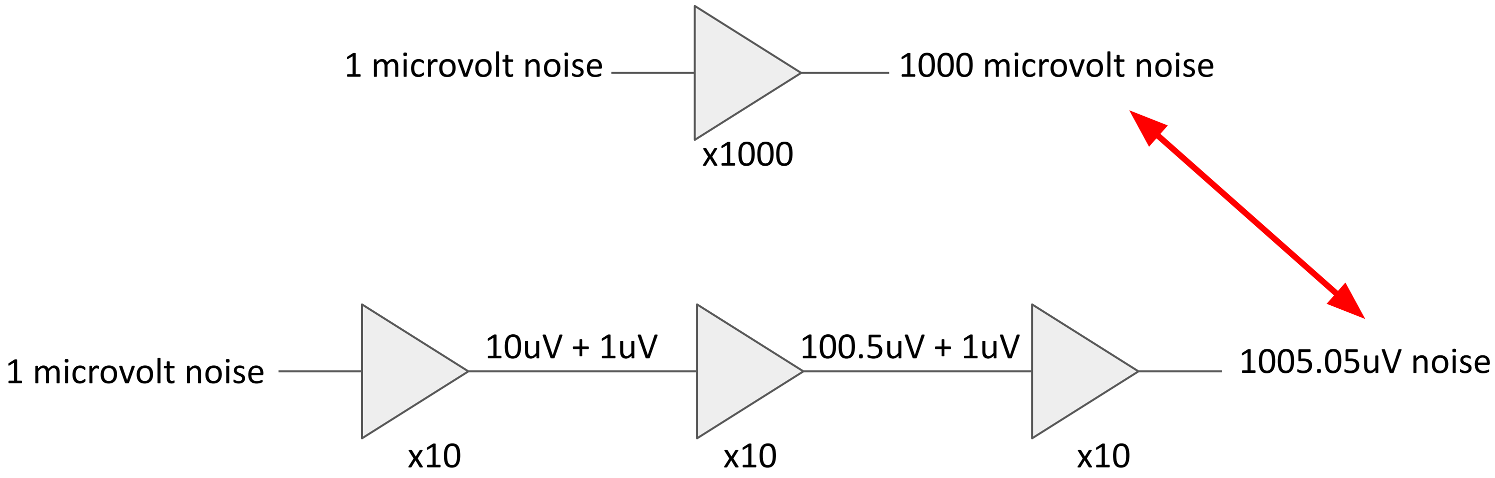
# So just how bad is the noise amplification from op amp input noise?



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




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

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

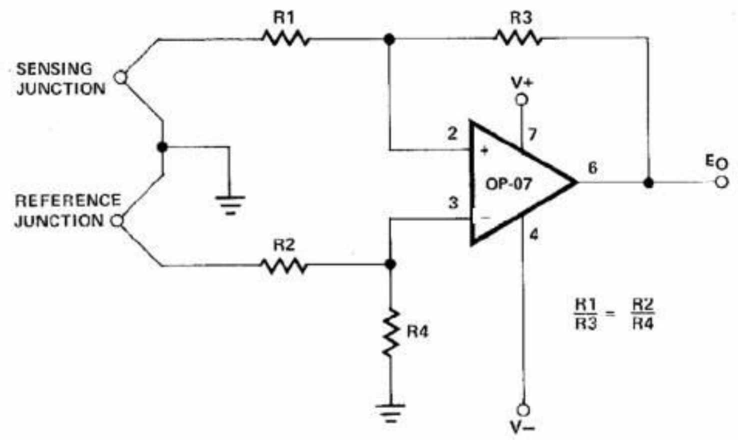
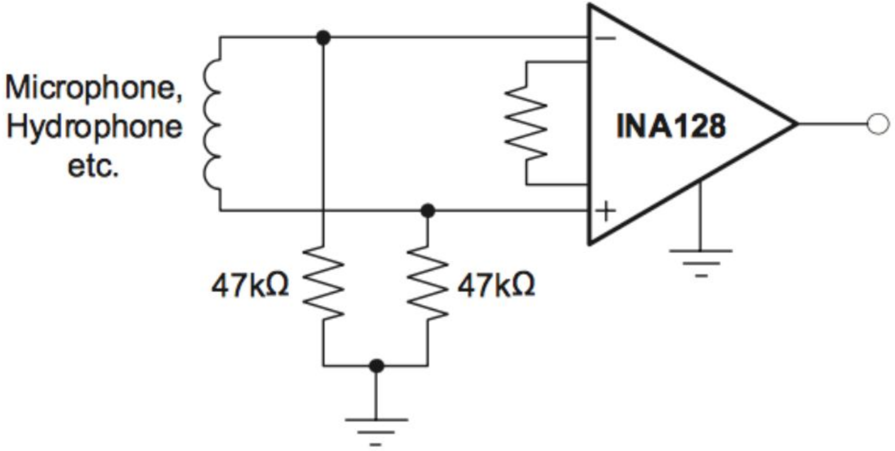



*Figure 8. High-Stability Thermocouple Amplifier*






Images: Texas Instruments

# Instrumentation amplifiers are precision differential amplifiers

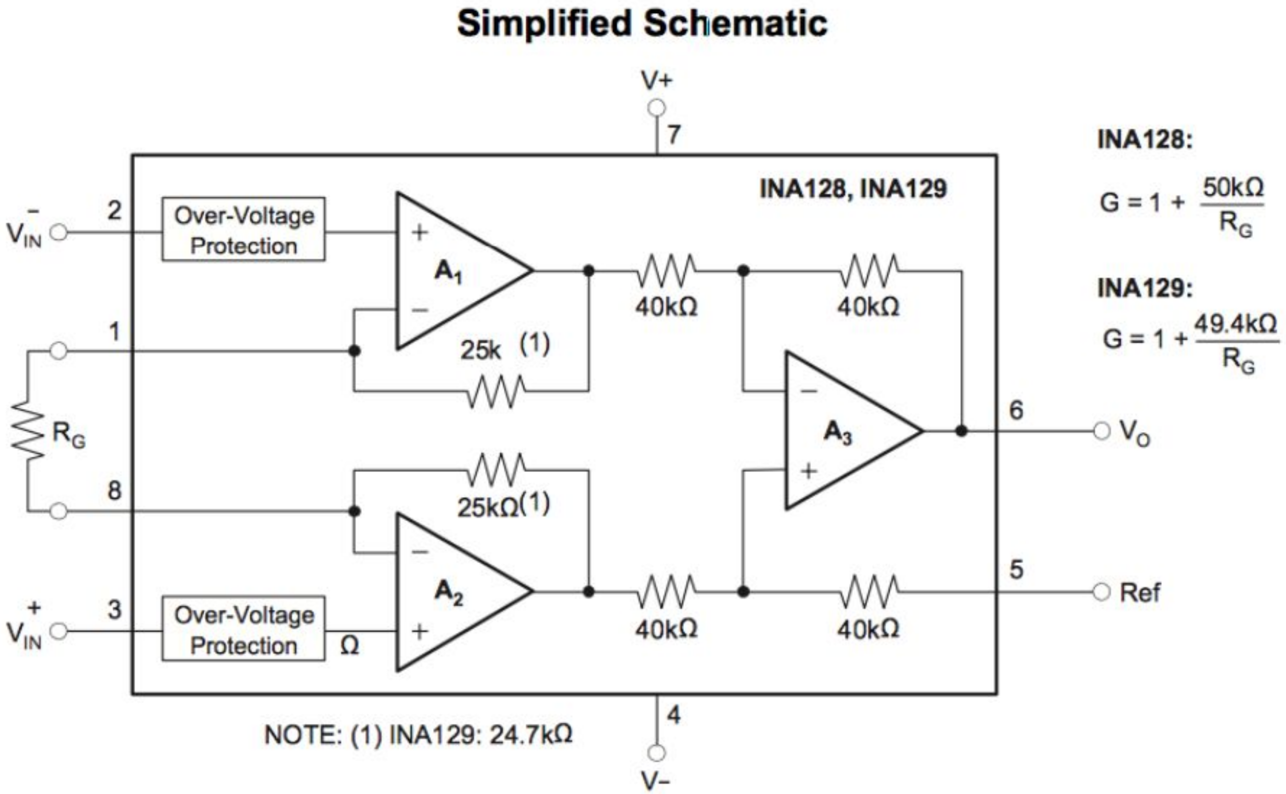



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Image: Texas Instruments

# IA's are perfect for bridge circuits/transducers

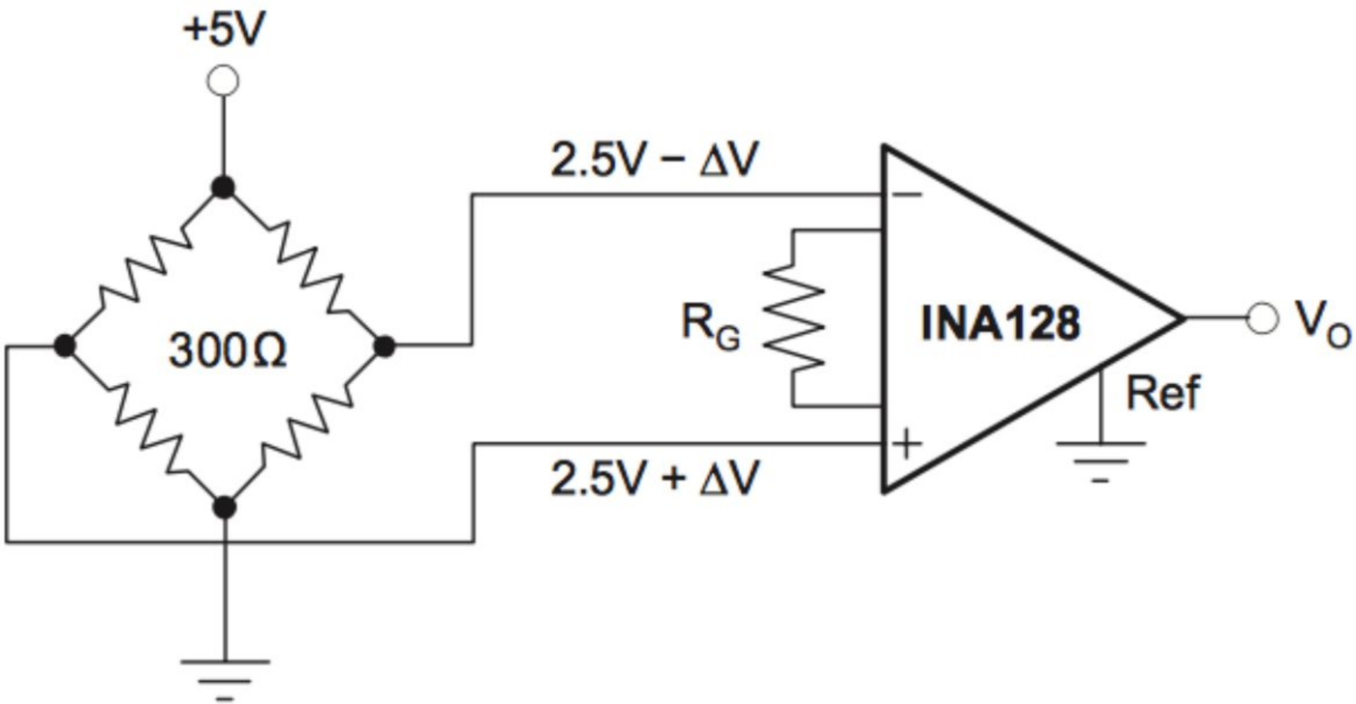


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Image: Texas Instruments