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Fundamentals of Operational Amplifiers

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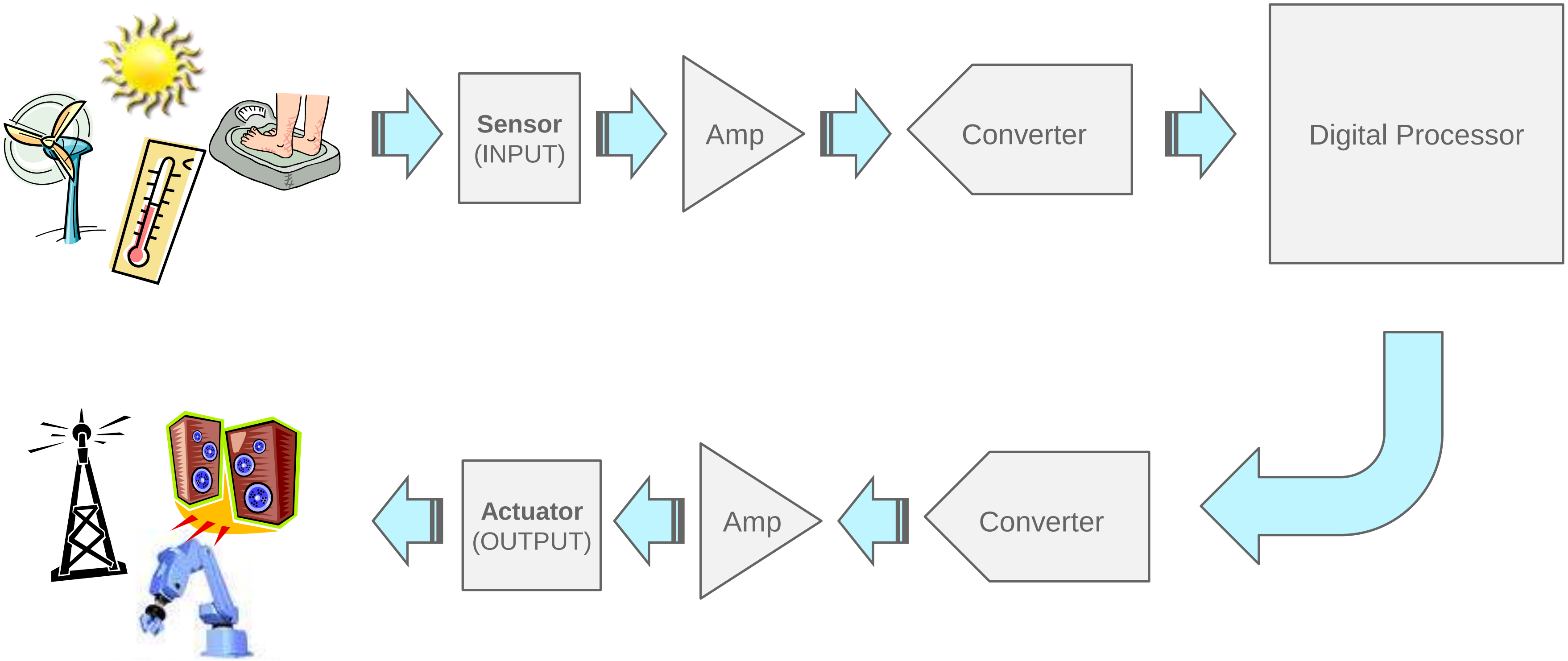
Director of Technical Marketing

05/19/2016

Analog to Electronic Signal Processing



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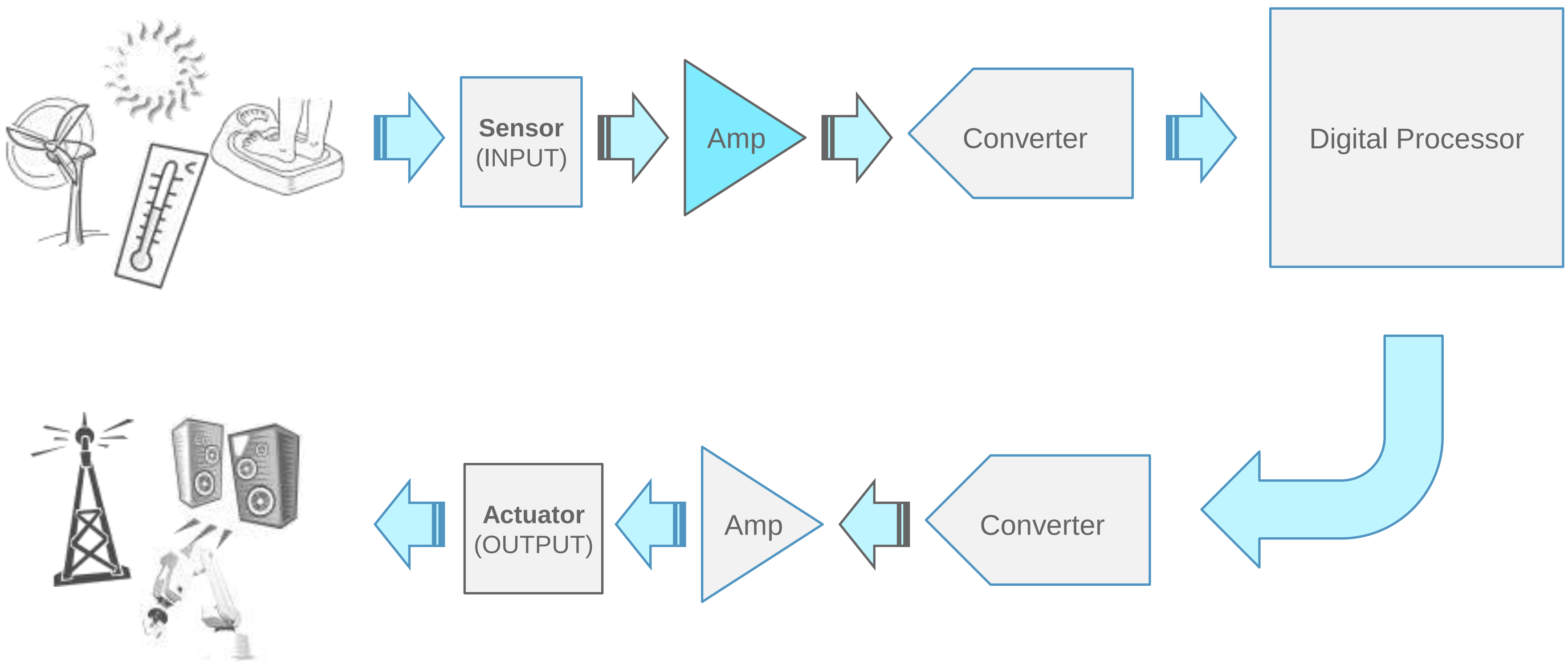
Analog to Electronic Signal Processing



Amplifiers and Operational Amplifiers

- Amplifiers
  - Make a low-level, high-source impedance signal into a high-level, low-source impedance signal
  - Op amps, power amps, RF amps, instrumentation amps, etc.
  - Most complex amplifiers built up from combinations of op amps
- Operational amplifiers
  - Three-terminal device (plus power supplies)
  - Amplify a small signal at the input terminals to a very, very large one at the output terminal

Operational Amplifiers

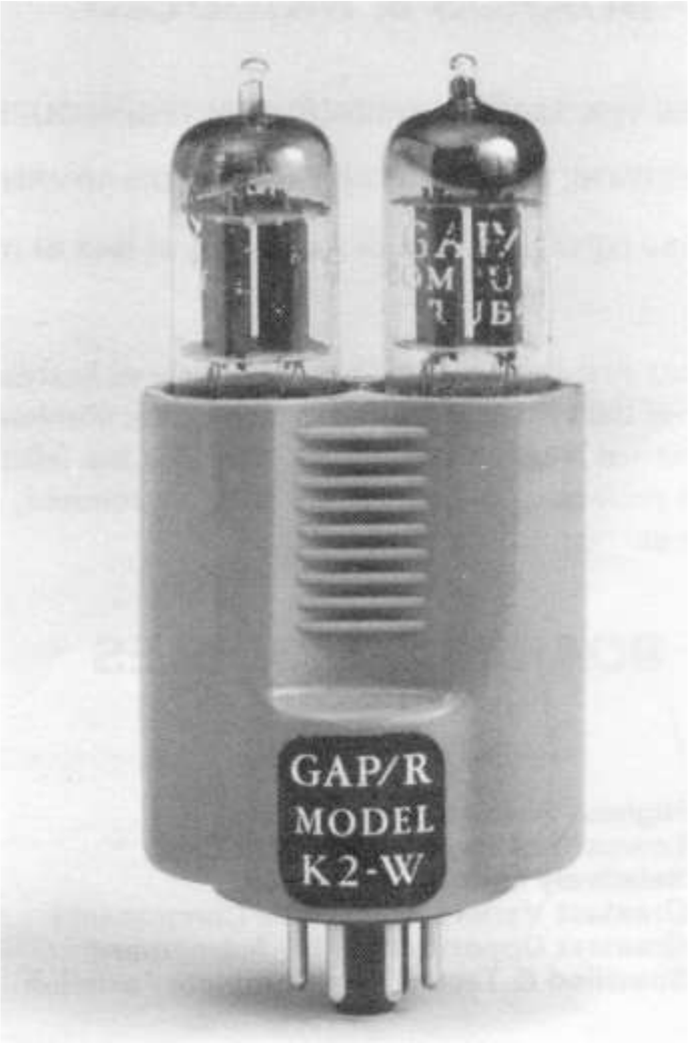
Operational

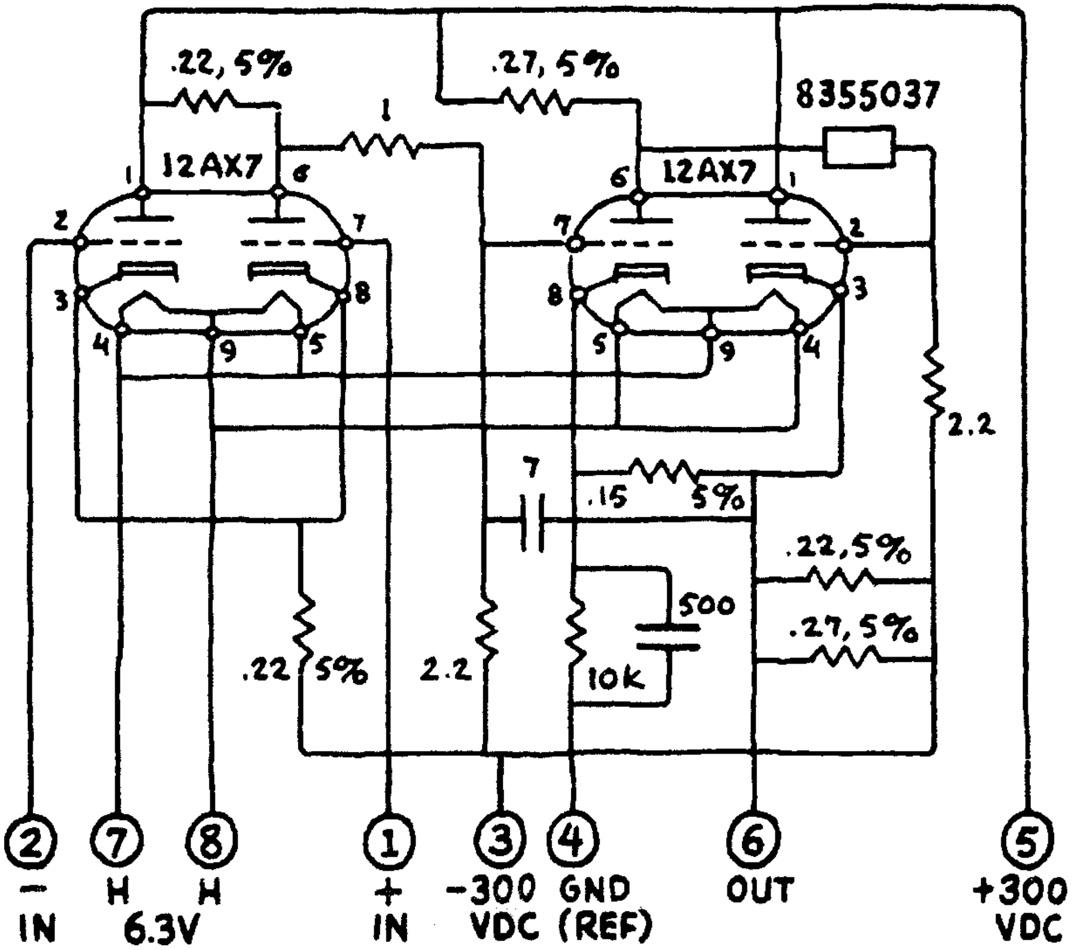
- Op amps can be configured with feedback networks in multiple ways to perform 'operations' on input signals
- 'Operations' include positive or negative gain, filtering, nonlinear transfer functions, comparison, summation, subtraction, reference buffering, differential amplification, integration, differentiation, etc.

Applications

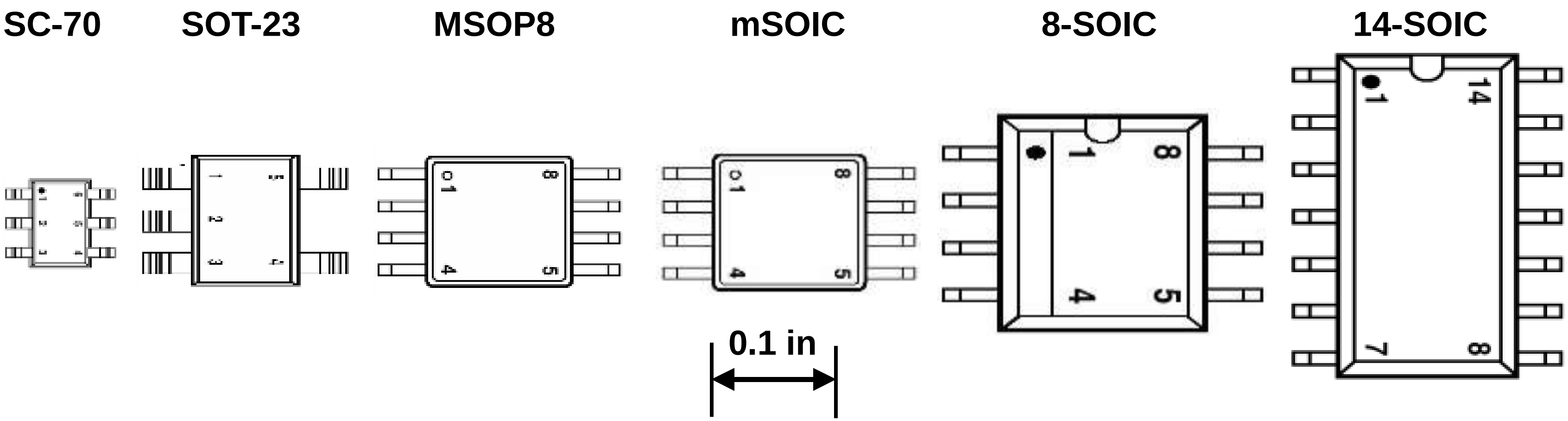
- Fundamental building block for analog design
- Sensor input amplifier
- Simple and complex filters – anti-aliasing
- ADC driver

Original vacuum-tube op-amp from Philbrick Research in 1953 – it used +/- 300V supplies

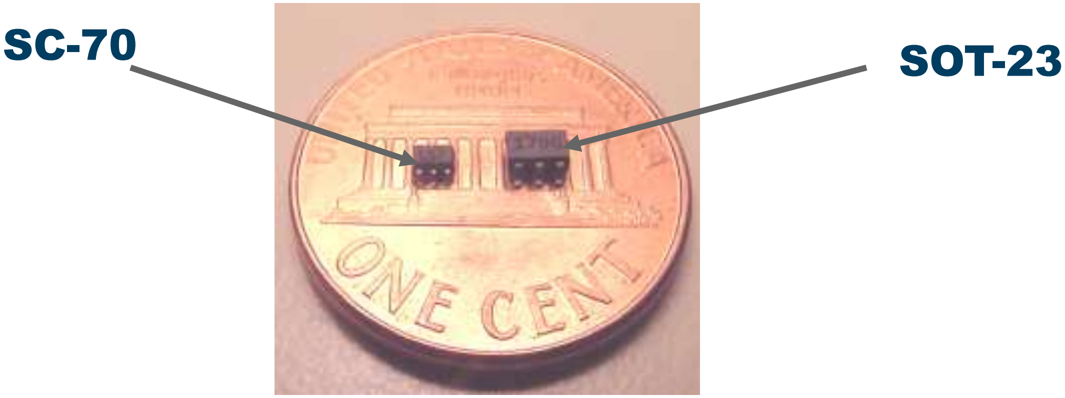




The Relative Scale of Some Modern IC Op Amp Packages



(ALL PACKAGES ABOVE TO SAME SCALE)



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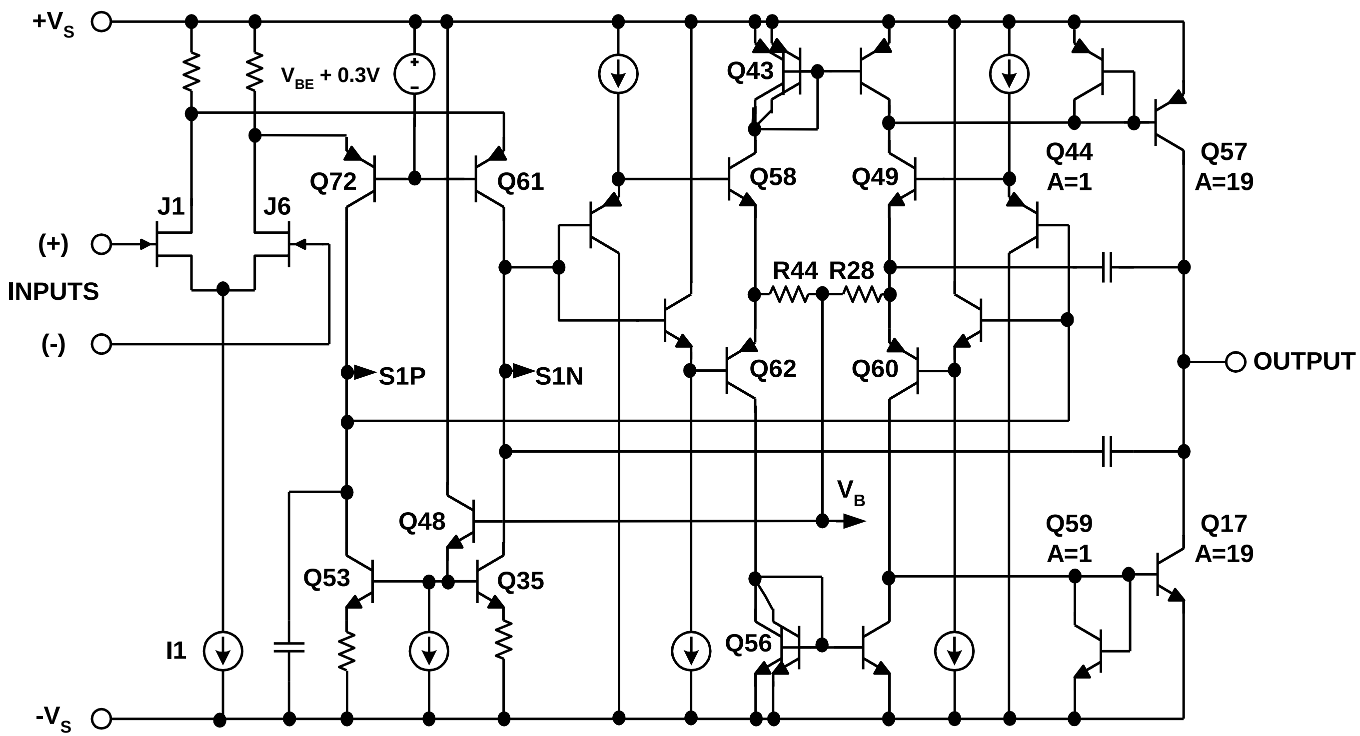
AD823 JFET Input Op Amp Simplified Schematic



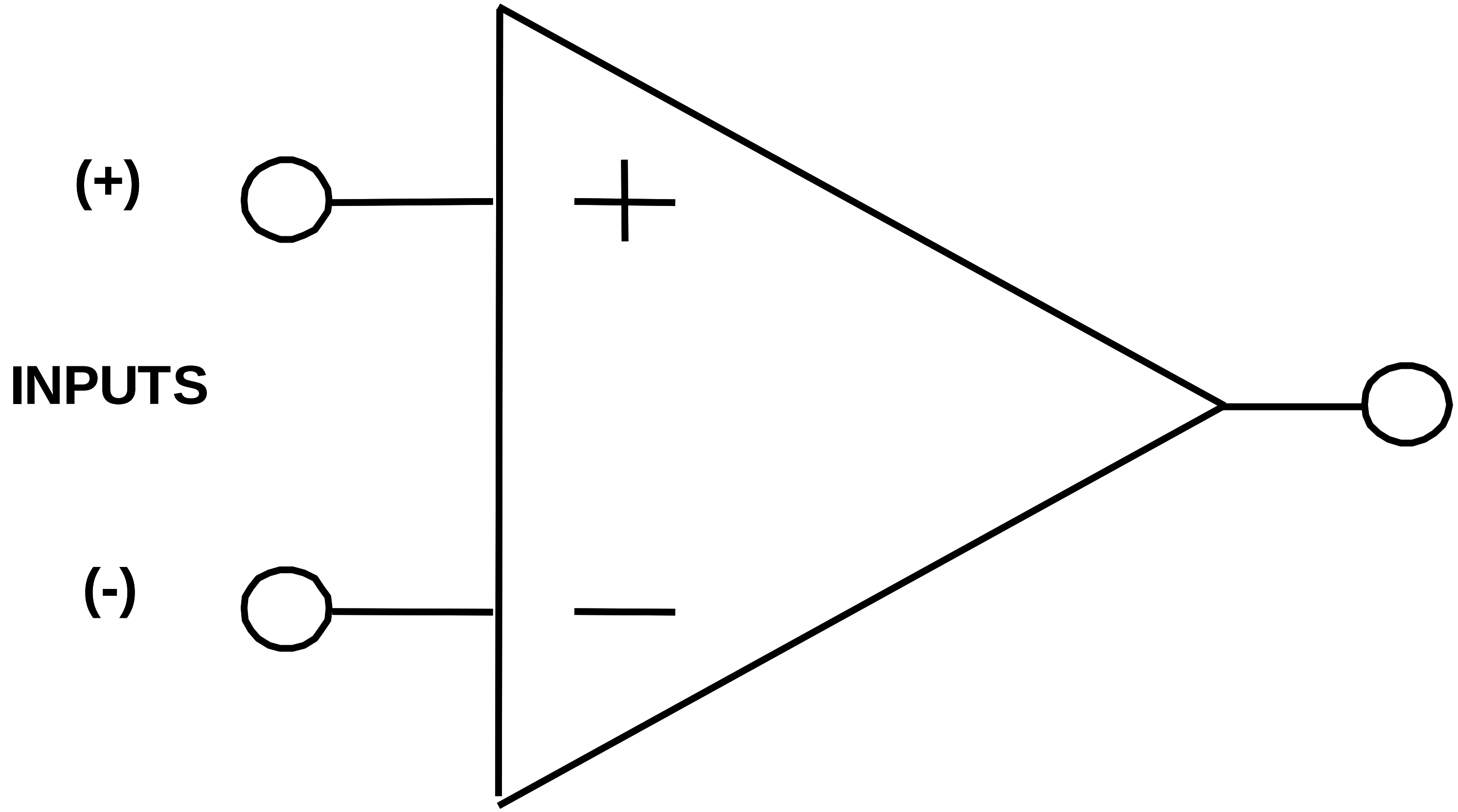
BIAS CURRENT = 25pA MAX @ +25°C

INPUT OFFSET VOLTAGE = 0.8mV MAX @ +25°C

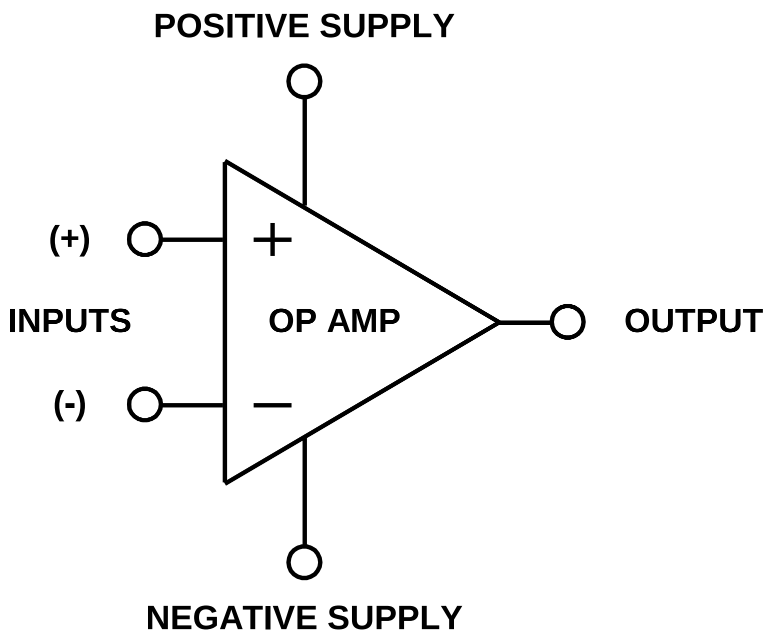
INPUT VOLTAGE NOISE = 15nV/√Hz

INPUT CURRENT NOISE = 1fA/√Hz

Standard Op Amp Symbol



The Ideal Op Amp and its Attributes



IDEAL OP AMP ATTRIBUTES:

- Infinite Differential Gain
- Zero Common Mode Gain
- Zero Offset Voltage
- Zero Bias Current

OP AMP INPUTS:

- High Input Impedance
- Low Bias Current
- Respond to Differential Mode Voltages
- Ignore Common Mode Voltages

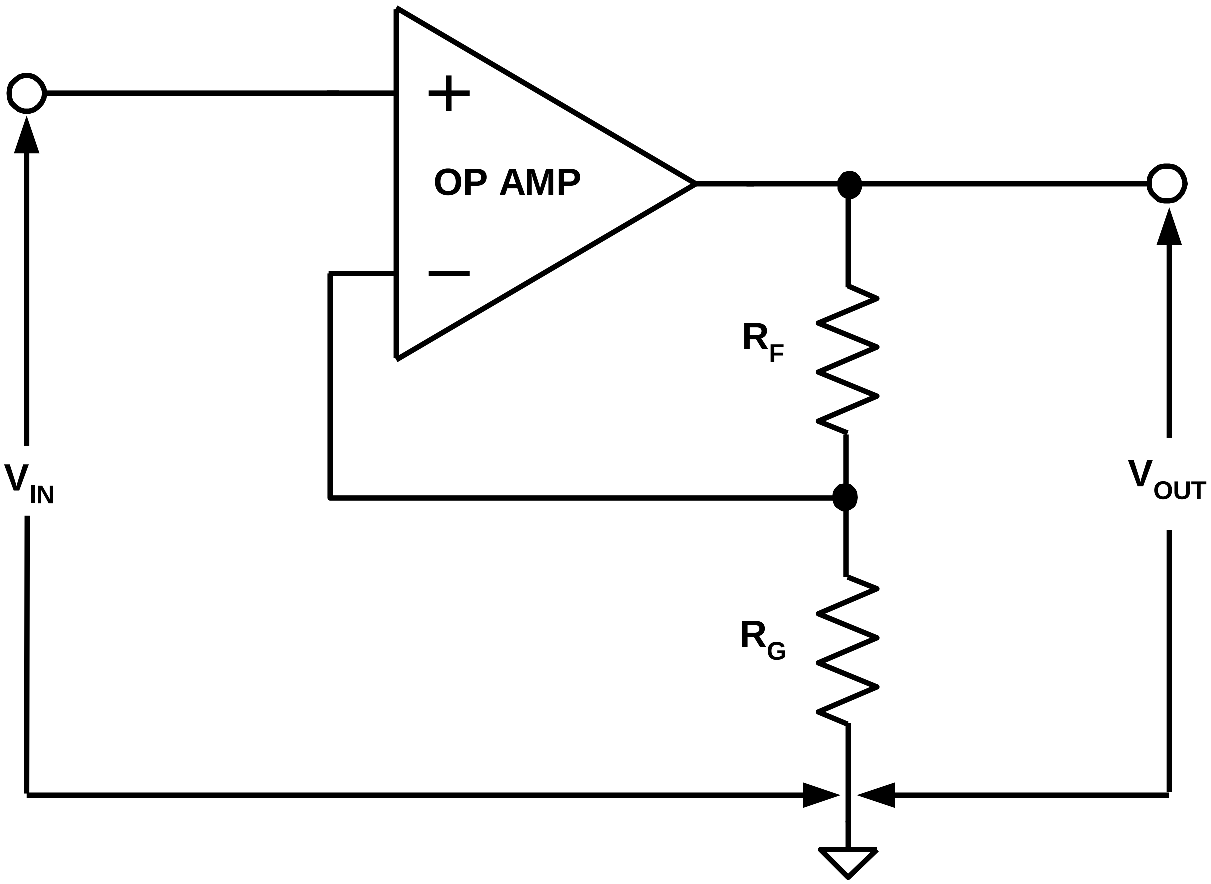
OP AMP OUTPUT:

- Low Source Impedance

Operational Amplifier Circuit Design

- Use of negative feedback
  - The output signal, or a controlled portion of it, is fed back to the negative (-) input terminal
  - The op amp will adjust the output signal until the input difference goes to zero
- Example of high-gain
  - Assume op amp gain of 10^6 (one million)
  - Apply signal of one volt to positive input
  - Feedback directly from output to negative input
  - Output will go to one volt (minus one microvolt)
  - Difference at input will be one microvolt

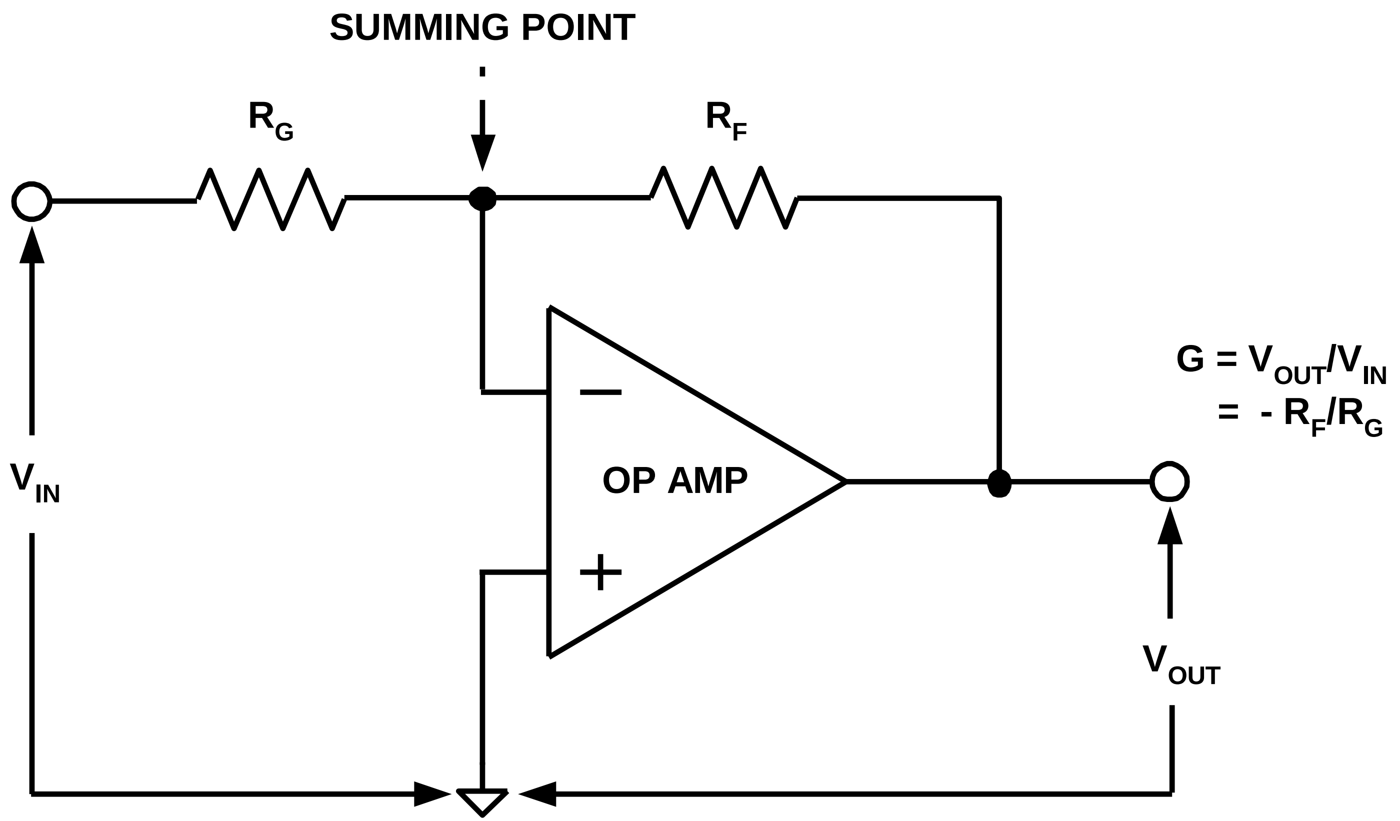
Non-inverting Mode Op Amp Stage



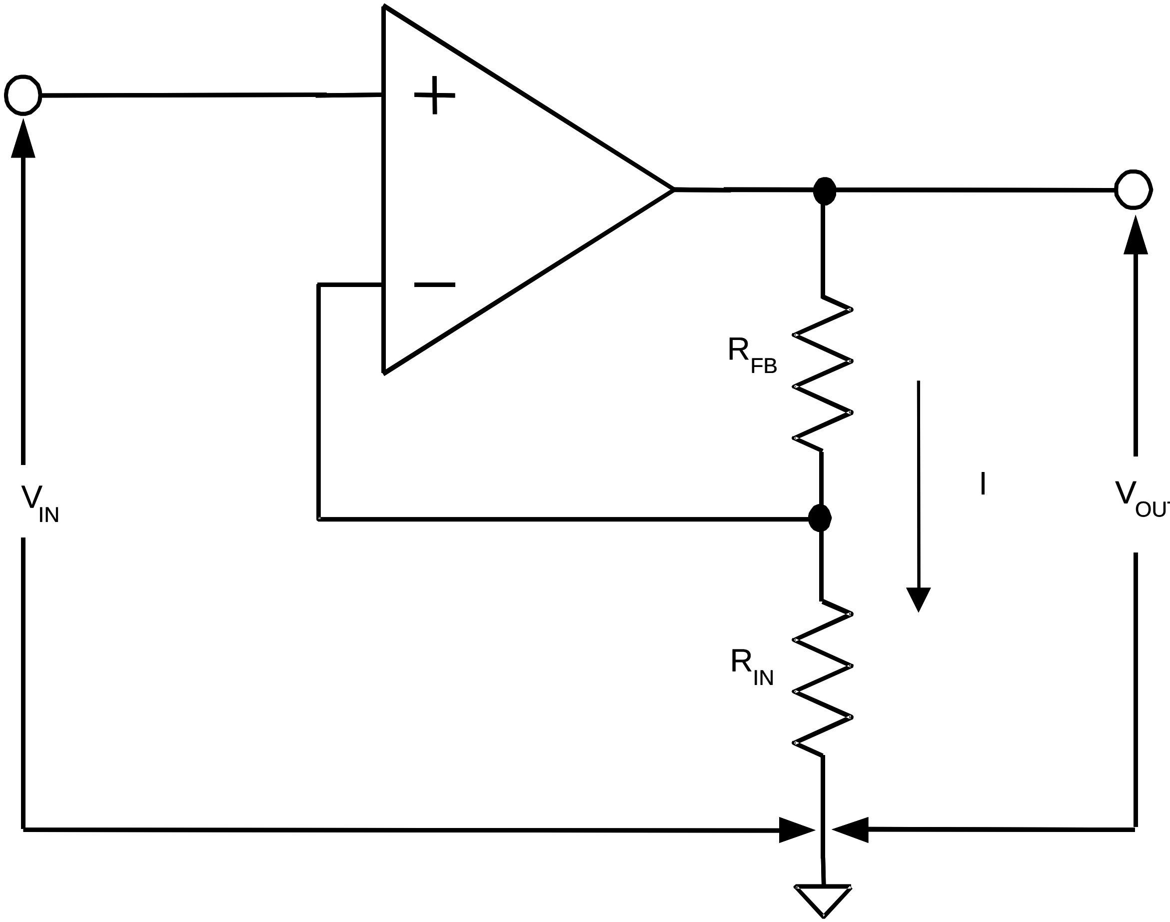
$G = V_{OUT}/V_{IN}$

$= 1 + (R_F/R_G)$

Inverting Mode Op Amp Stage



Non-Inverting Amplifier Gain

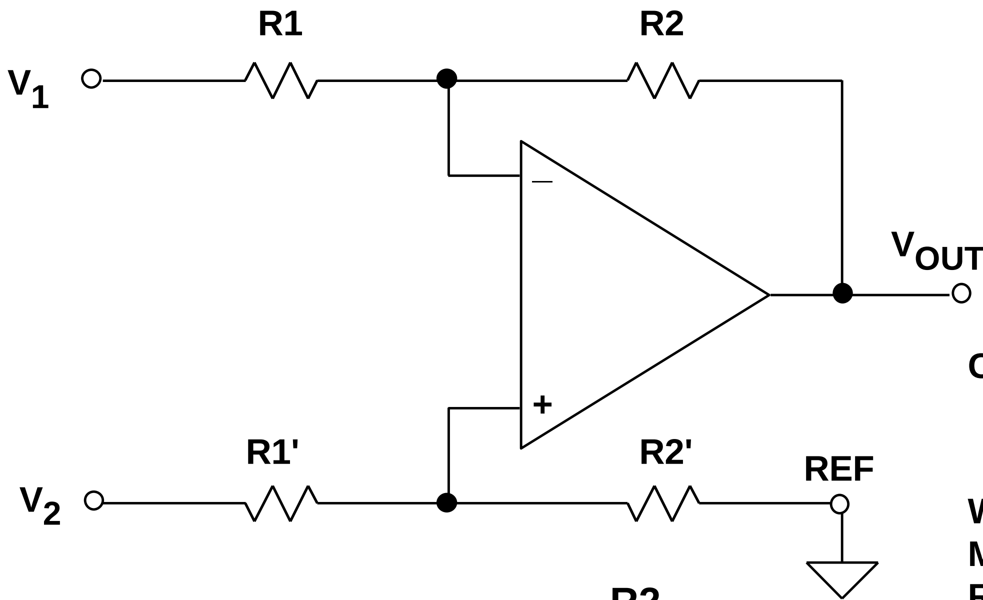


$$G = \frac{V_{OUT}}{V_{IN}}$$

$$= 1 + \frac{R_{FB}}{R_{IN}}$$

Op Amp Subtractor or Difference Amplifier

This configuration has signals driving both input pins



$$CMR = 20\log_{10}\left[\frac{1+\frac{R2}{R1}}{Kr}\right]$$

Where Kr = Total Fractional Mismatch of R1/ R2 TO R1'/R2'

- $V_{OUT} = (V_2 - V_1)\frac{R2}{R1}$
- $\frac{R2}{R1} = \frac{R2'}{R1'}$ CRITICAL FOR HIGH CMR
- EXTREMELY SENSITIVE TO SOURCE IMPEDANCE IMBALANCE
- 0.1% TOTAL MISMATCH YIELDS $\approx$ 66dB CMR FOR R1 = R2

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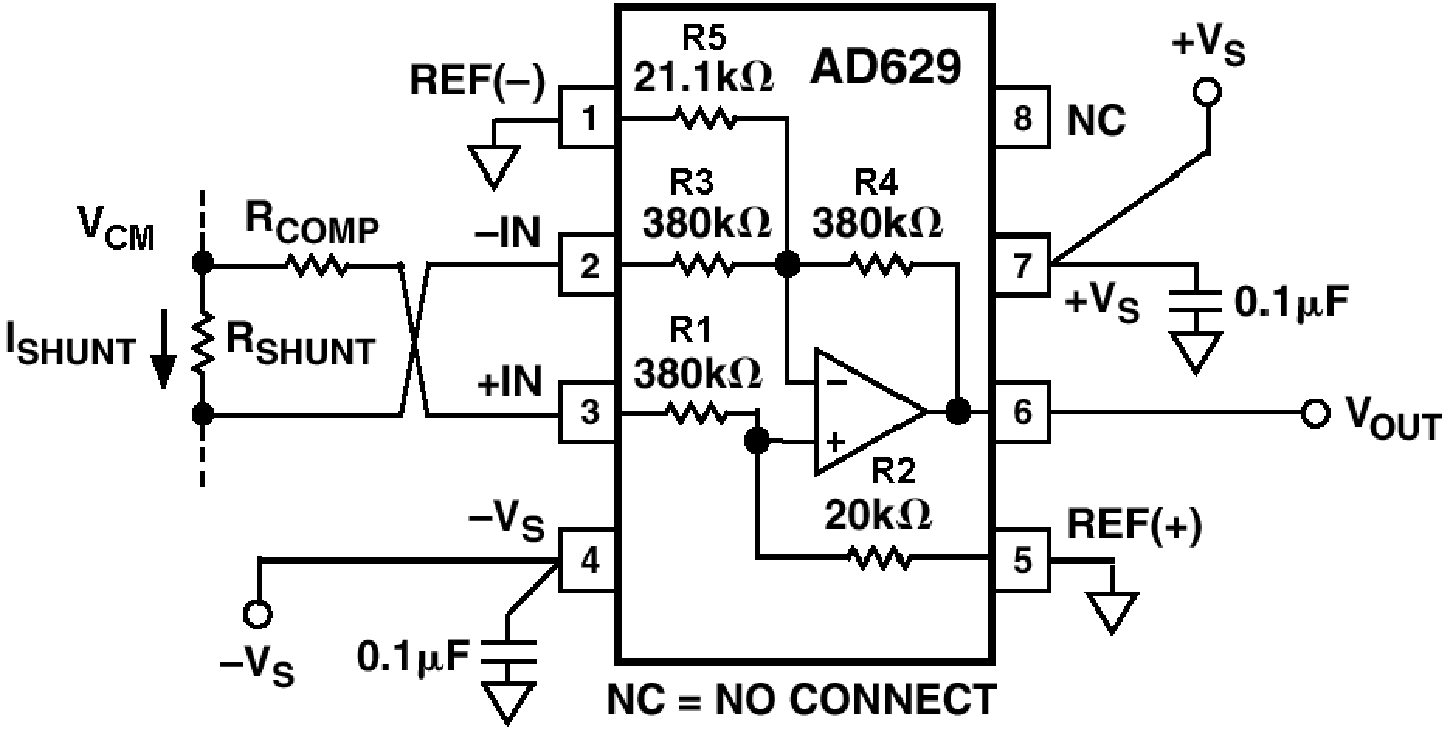
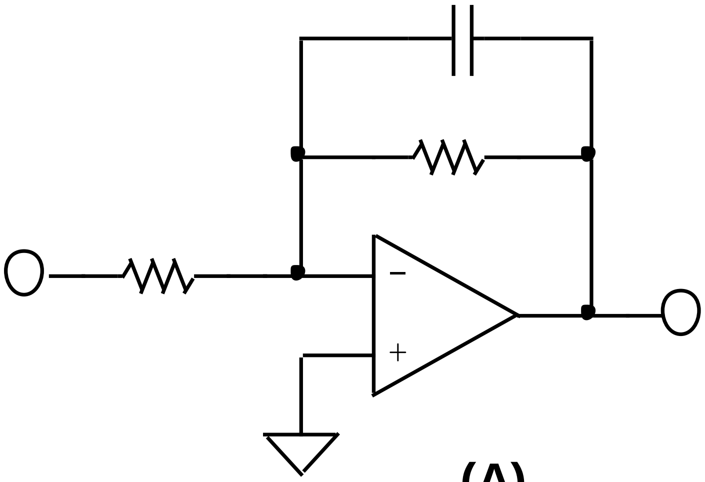
High Common-Mode Current Sensing Using the AD629 Difference Amplifier

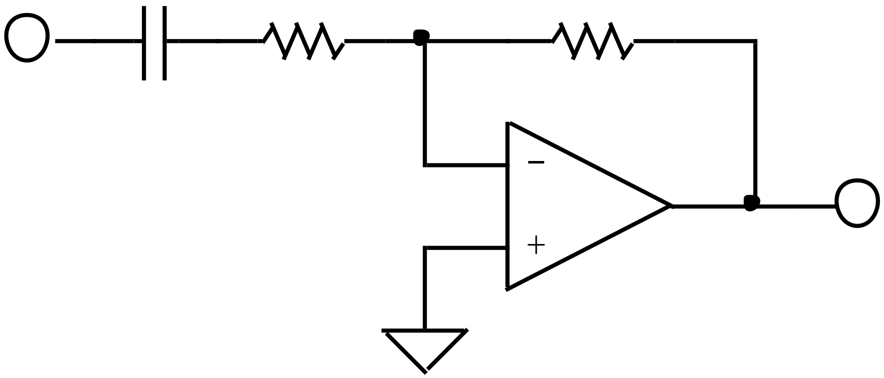


$V_{CM} = \pm 270V$ for $V_S = \pm 15V$

Single Pole Op Amp Active Filters



(A)
LOWPASS

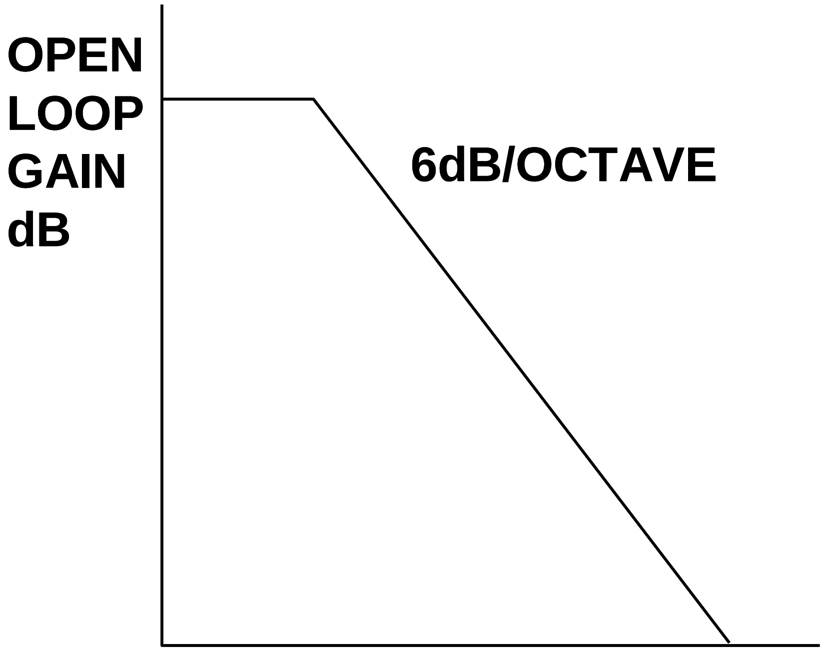


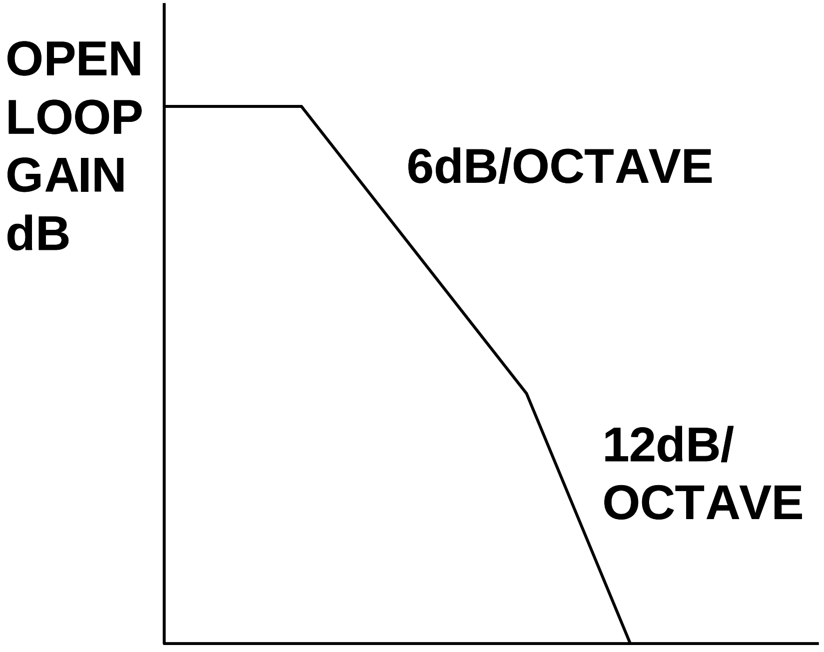
(B)
HIGHPASS

Key Op Amp Performance Features

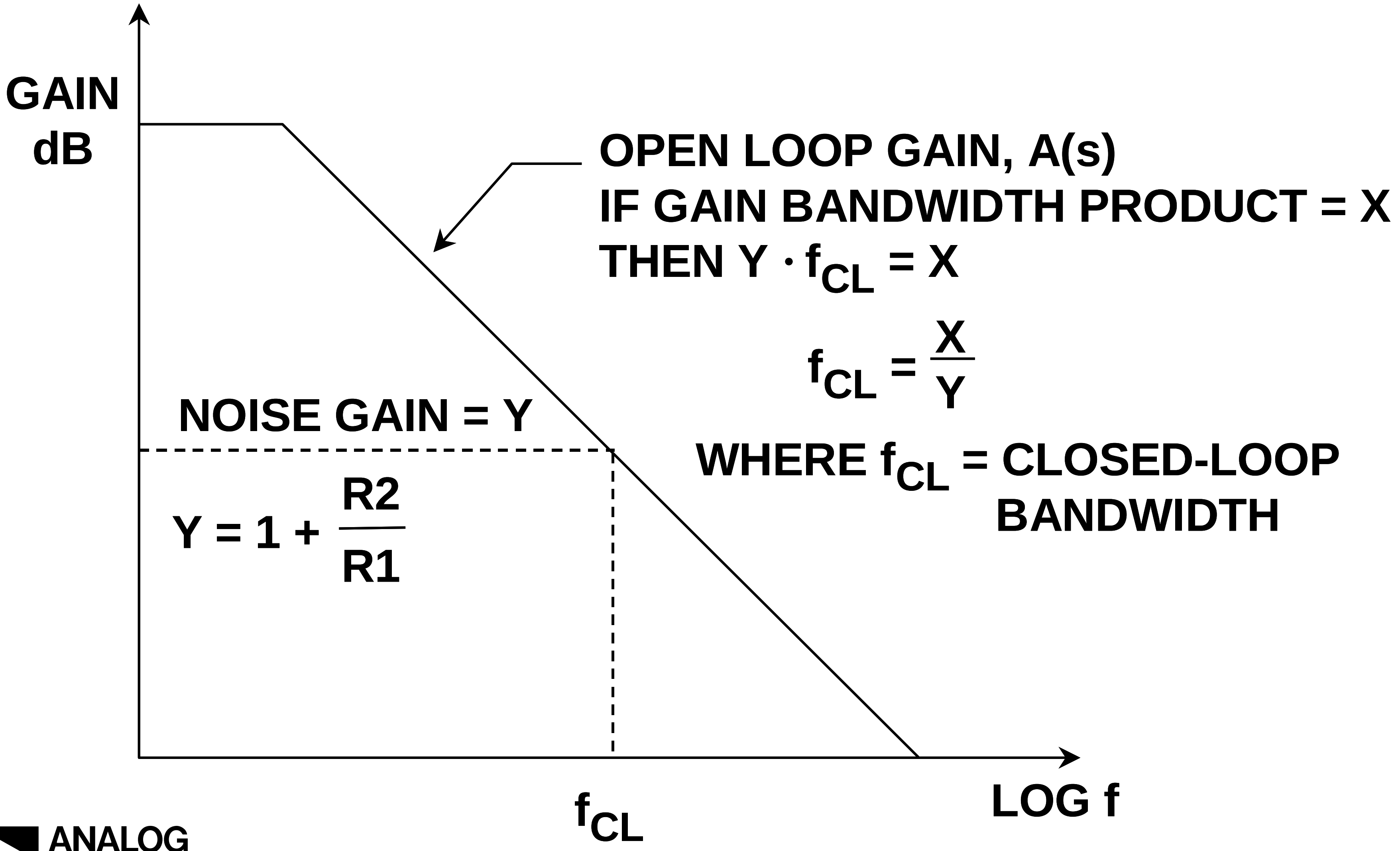
- Bandwidth and slew rate
  - The speed of the op amp
  - Bandwidth is the highest operating frequency of the op amp
  - Slew rate is the maximum rate of change of the output
  - Determined by the frequency of the signal and the gain needed
- Offset voltage and current
  - The errors of the op amp
  - Determines measurement accuracy
- Noise
  - Op amp noise limits how small a signal can be amplified with good fidelity

Open Loop Gain (Bode Plot)

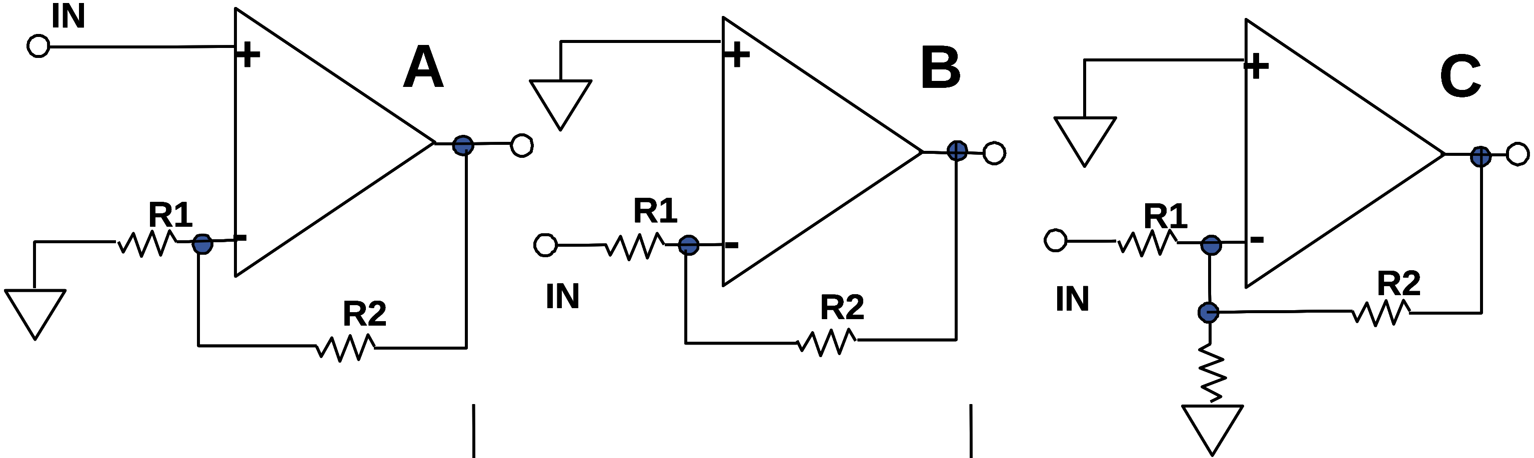




Gain-Bandwidth Product



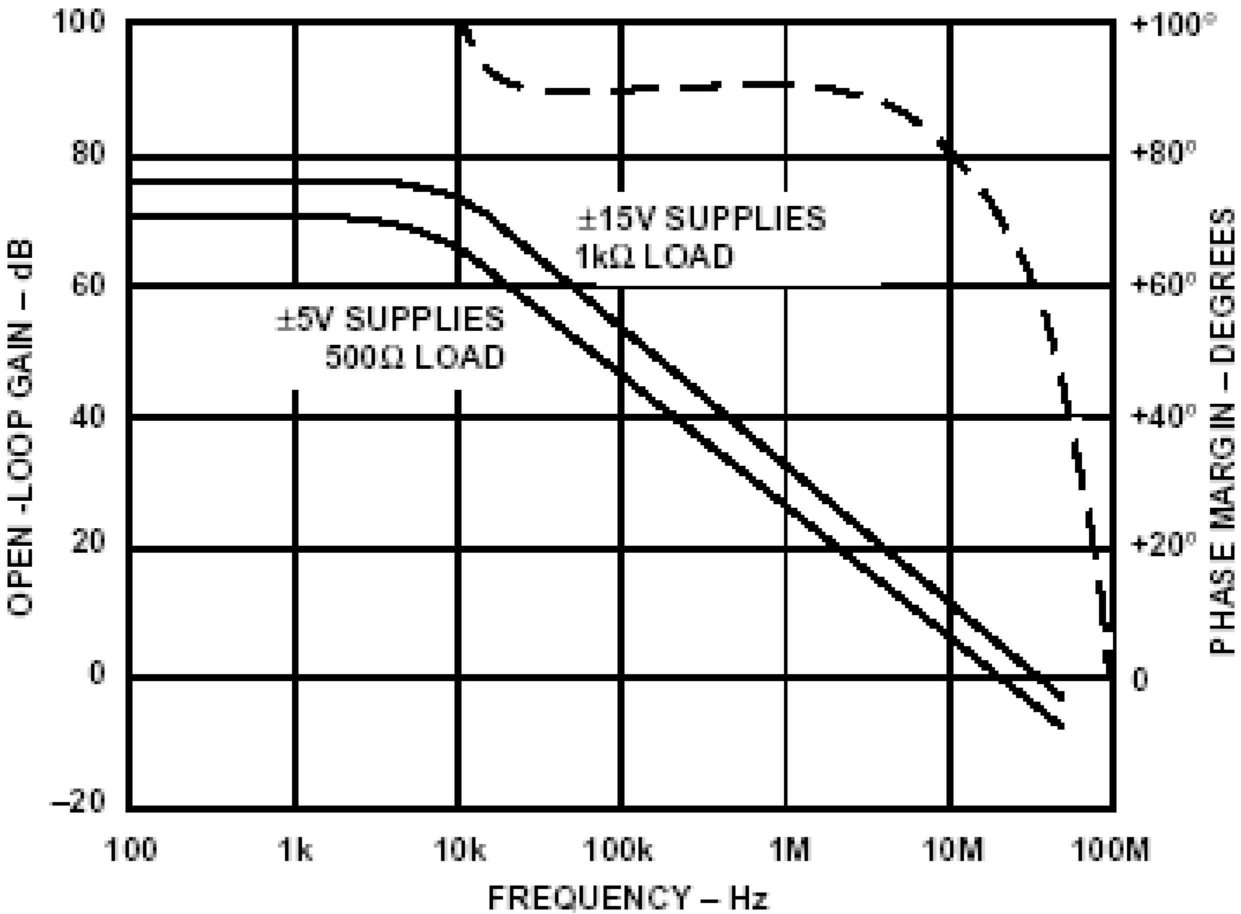
Noise Gain



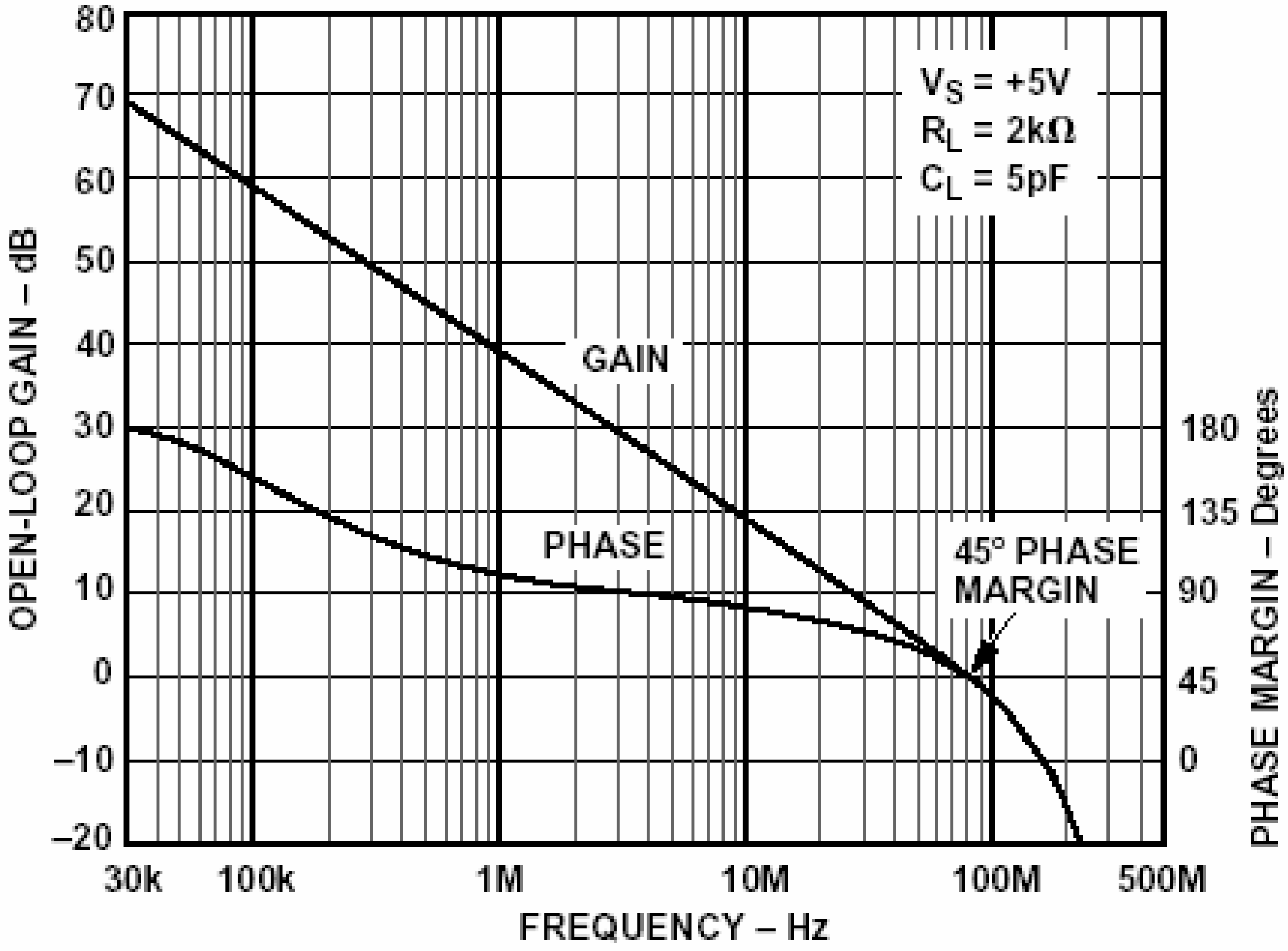
A	B	C
Signal Gain = 1 + R2/R1	Signal Gain =- R2/R1	Signal Gain =- R2/R1
Noise Gain = 1 + R2/R1	Noise Gain = 1 + R2/R1	Noise Gain = $1 + \frac{R2}{R1 \parallel R3}$

- Voltage Noise and Offset Voltage of the op amp are reflected to the output by the Noise Gain.
- Noise Gain, not Signal Gain, is relevant in assessing stability.
- Circuit C has unchanged Signal Gain, but higher Noise Gain, thus better stability, worse noise, and higher output offset voltage.

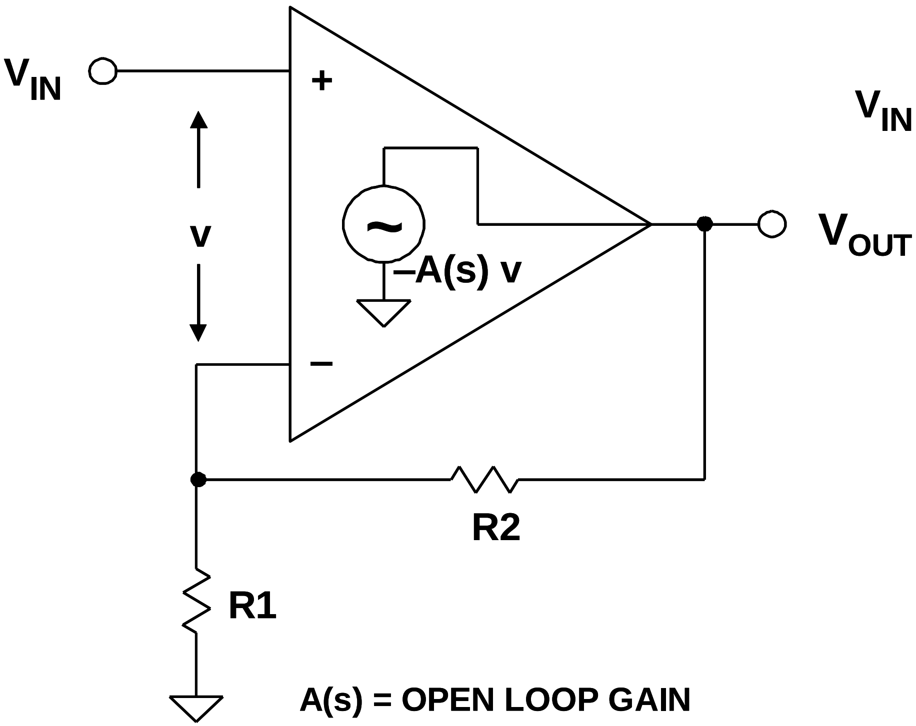
AD847 Open Loop Gain



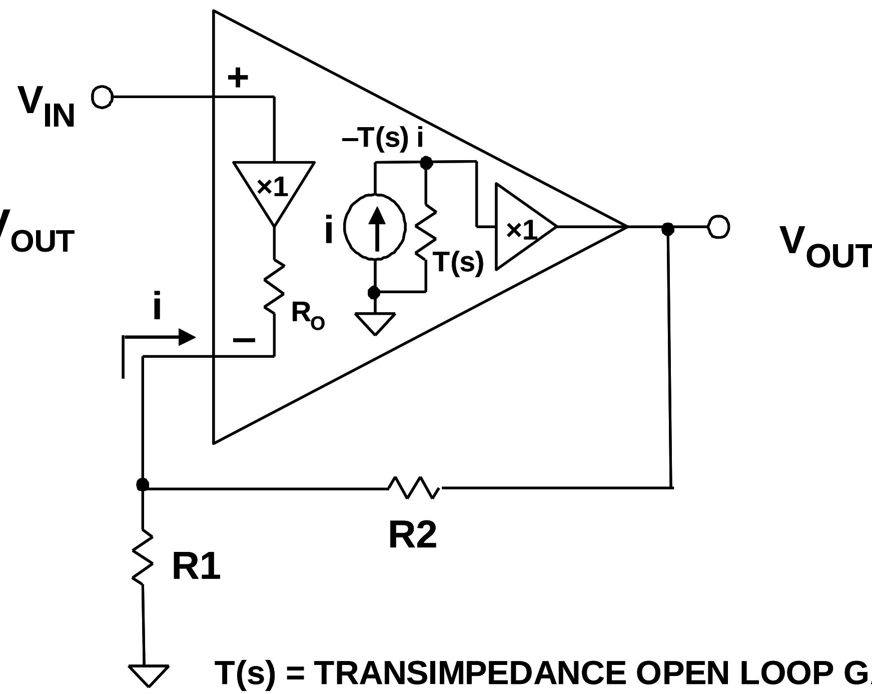
AD8051 Phase Margin



VFB and CFB Amplifiers

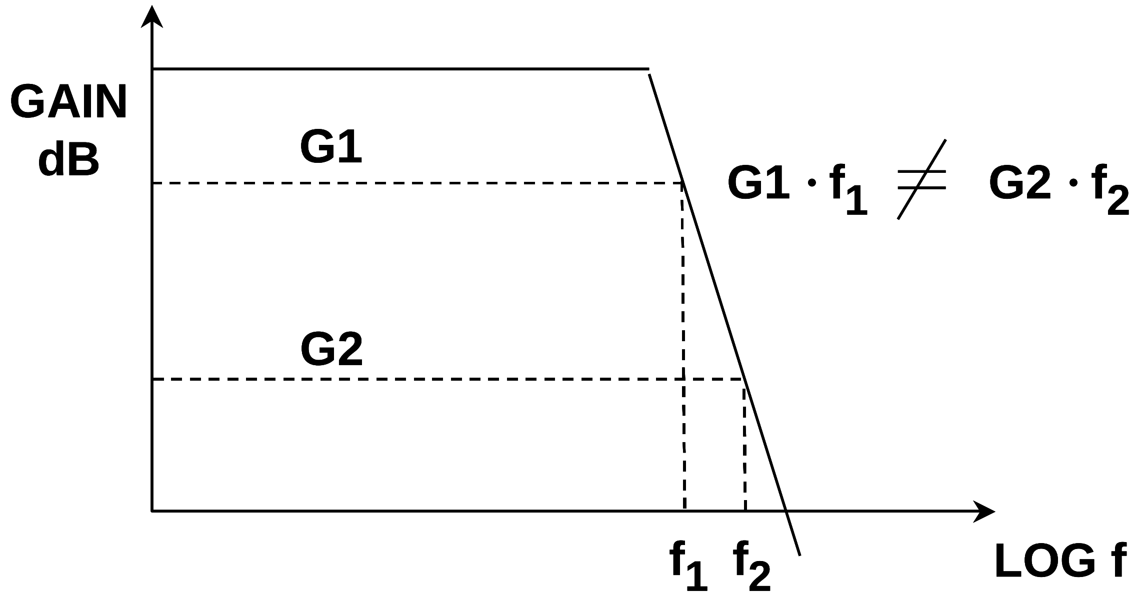


A(s) = OPEN LOOP GAIN
V_{OUT} = A(s)*v



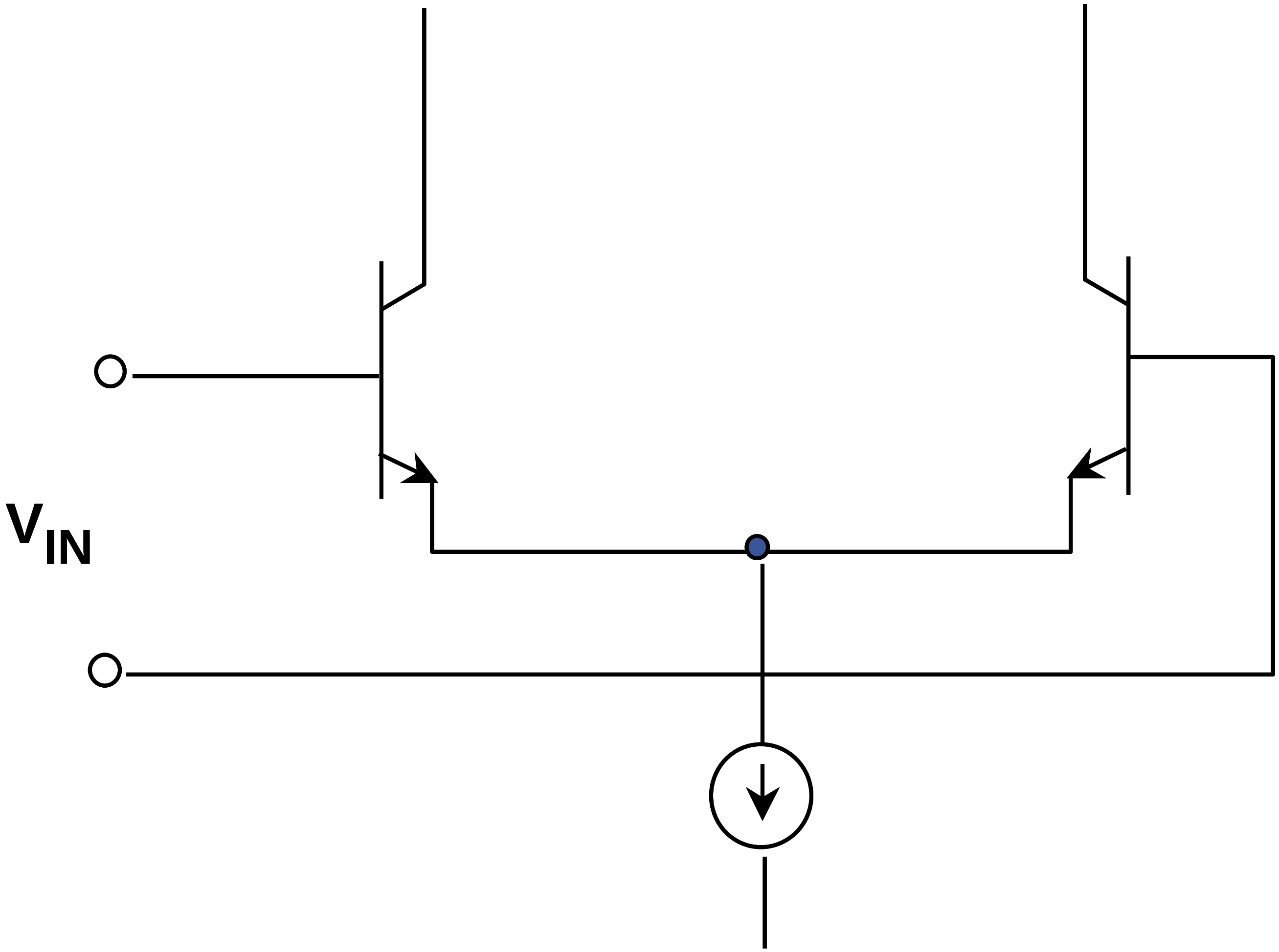
T(s) = TRANSIMPEDANCE OPEN LOOP GAIN
V_{OUT} = -T(s)*i

Current Feedback Amplifier Frequency Response

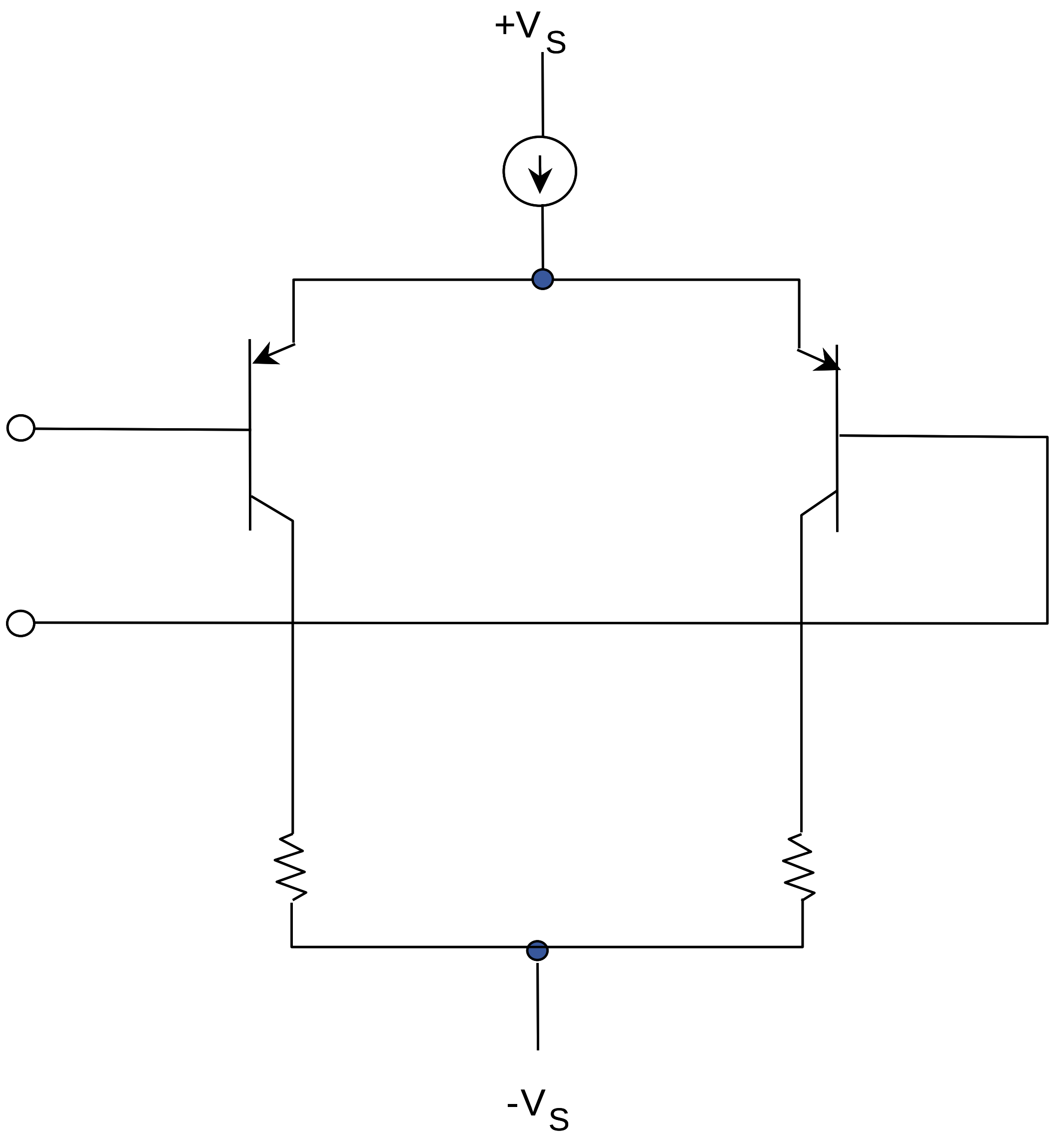


- Feedback resistor fixed for optimum performance. Larger values reduce bandwidth, smaller values may cause instability.
- For fixed feedback resistor, changing gain has little effect on bandwidth.
- Current feedback op amps do not have a fixed gain-bandwidth product.

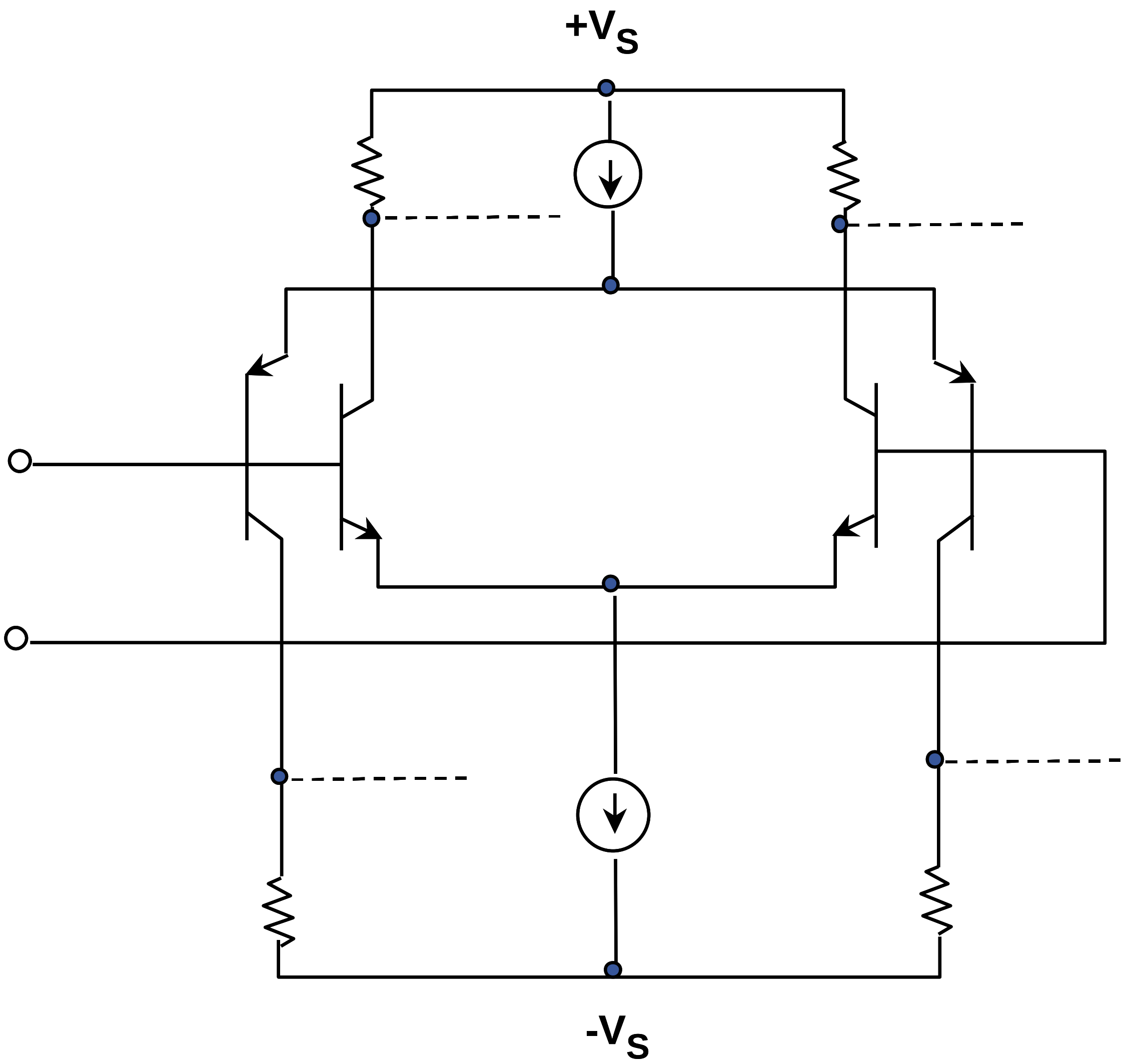
Standard Input Stage (Differential Pair)



PNP Input Stage



Compound Input Stage



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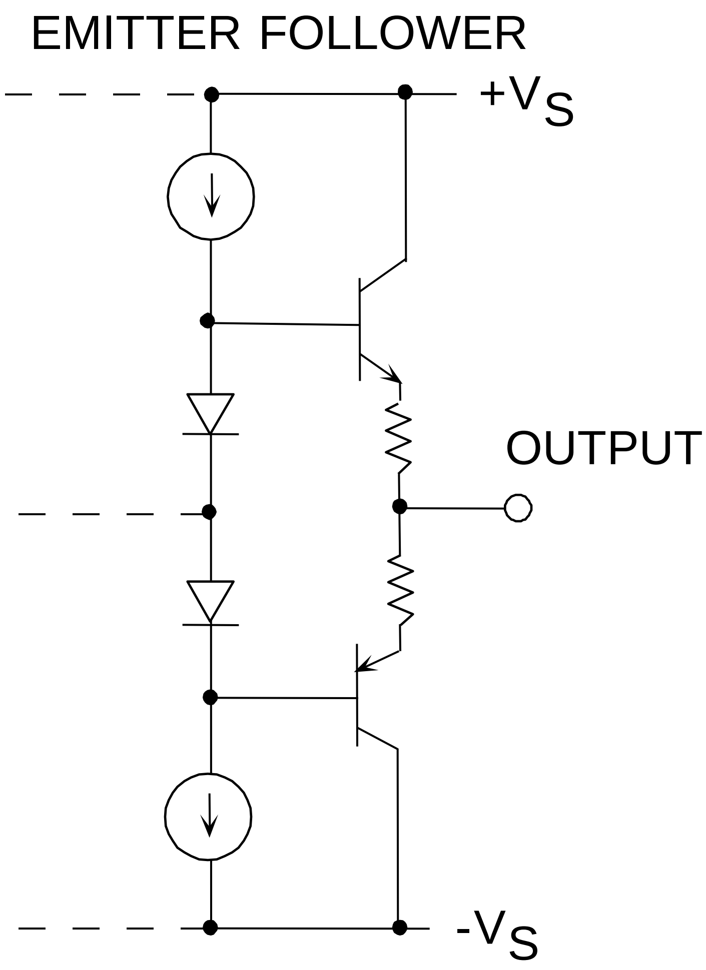
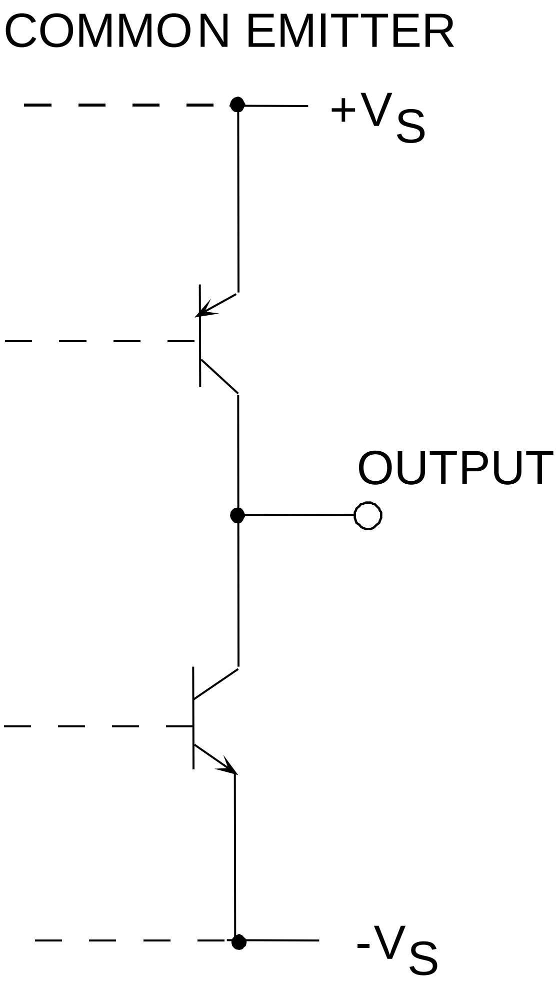
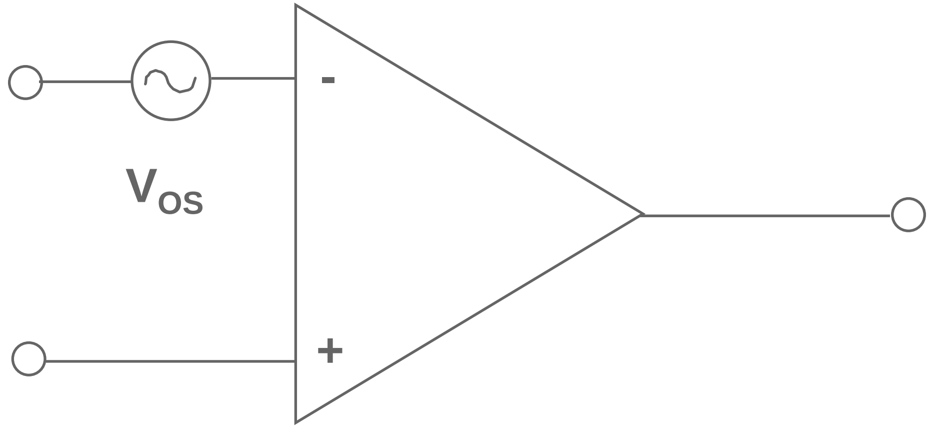
Output Stages. Emitter Follower for Standard Configuration and Common Emitter for "Rail-to-Rail" Configuration



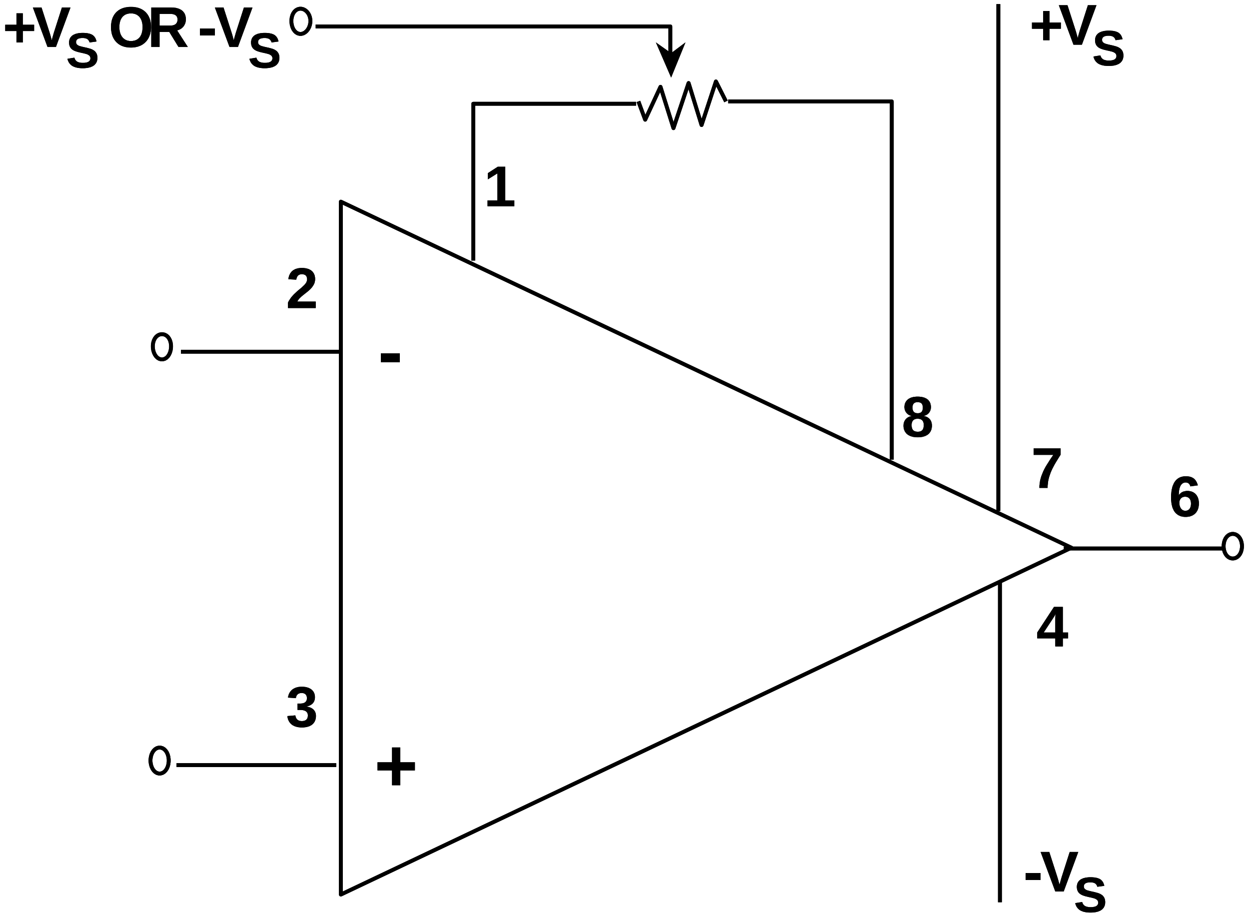


Input Offset Voltage



- Offset Voltage: The differential voltage which must be applied to the input of an op amp to produce zero output.
- Ranges:
  - Zero-Drift Chopper Stabilized Op Amps: <1µV
  - General Purpose Precision Op Amps: 50-500µV
  - Best Bipolar Op Amps: 10-25µV
  - Best FET Op Amps: 100-1,000µV
  - High Speed Op Amps: 100-2,000µV
  - Untrimmed CMOS Op Amps: 5,000-50,000µV
  - DigiTrim™ CMOS Op Amps: <1,000µV

Offset Adjustment Pins



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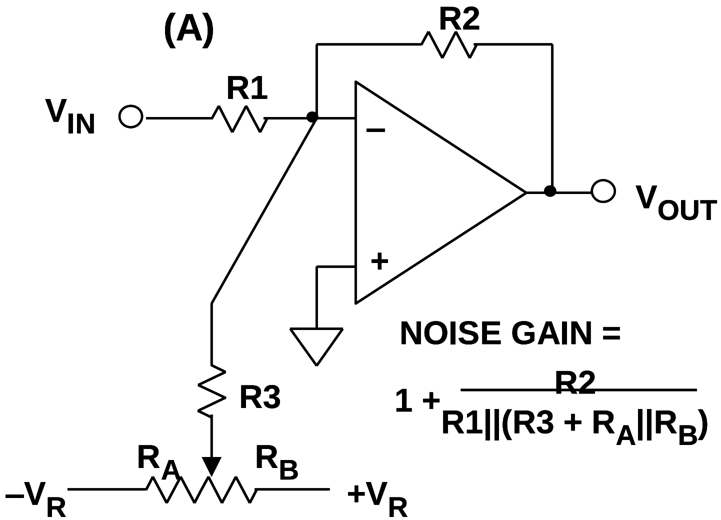
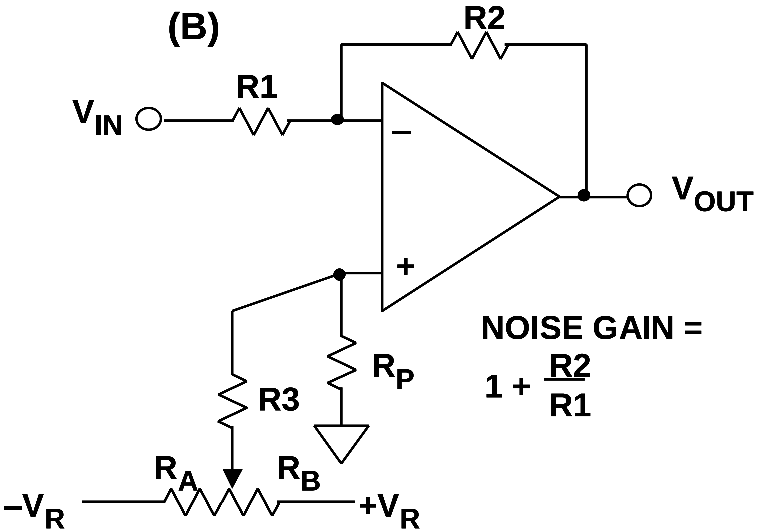
External Offset Adjustment



NOISE GAIN =

$$1 + \frac{R2}{R1||(R3 + R_A||R_B)}$$



NOISE GAIN =

$$1 + \frac{R2}{R1}$$

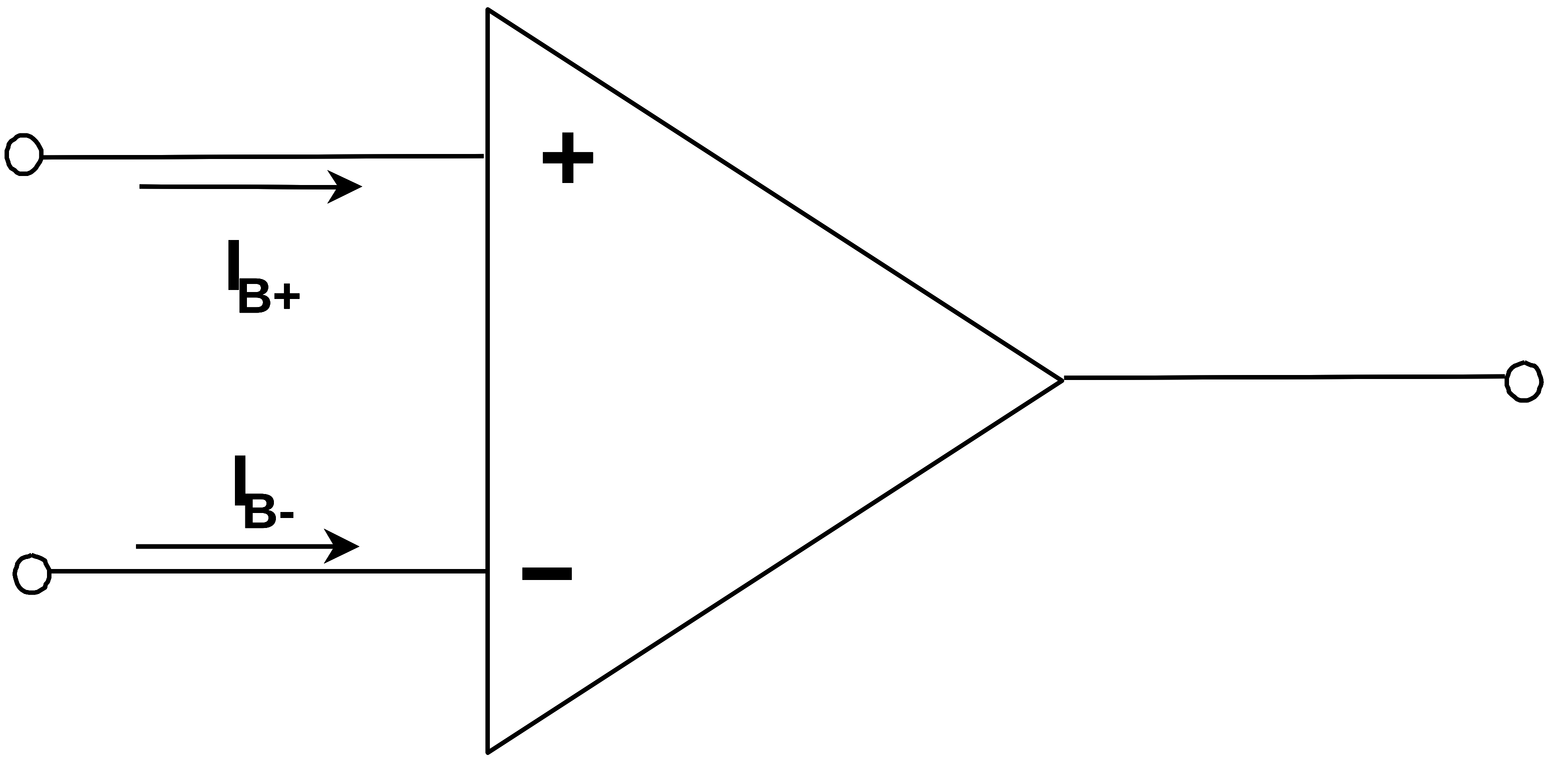
$$V_{OUT} = -\frac{R2}{R1} V_{IN} \underbrace{\pm \frac{R2}{R3} V_R}_{\text{MAX OFFSET}}$$

$$V_{OUT} = -\frac{R2}{R1} V_{IN} \underbrace{\pm \left[1 + \frac{R2}{R1}\right] \left[\frac{R_P}{R_P + R3}\right] V_R}_{\text{MAX OFFSET}}$$

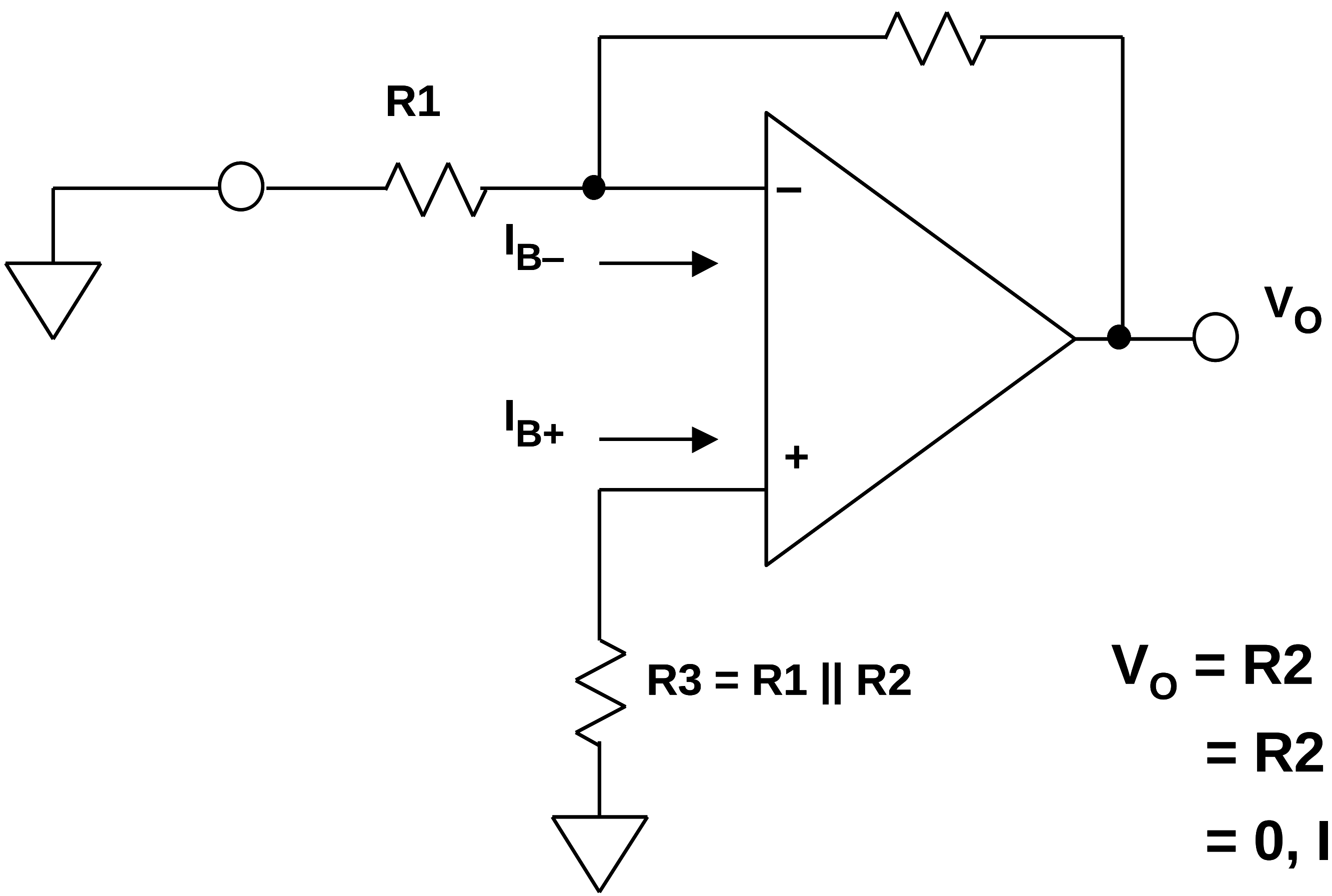
$R_P = R1||R2$ IF $I_{B+} \approx I_{B-}$

$R_P \leq 50\Omega$ IF $I_{B+} \neq I_{B-}$

Input Bias Current



Bias Current Compensation



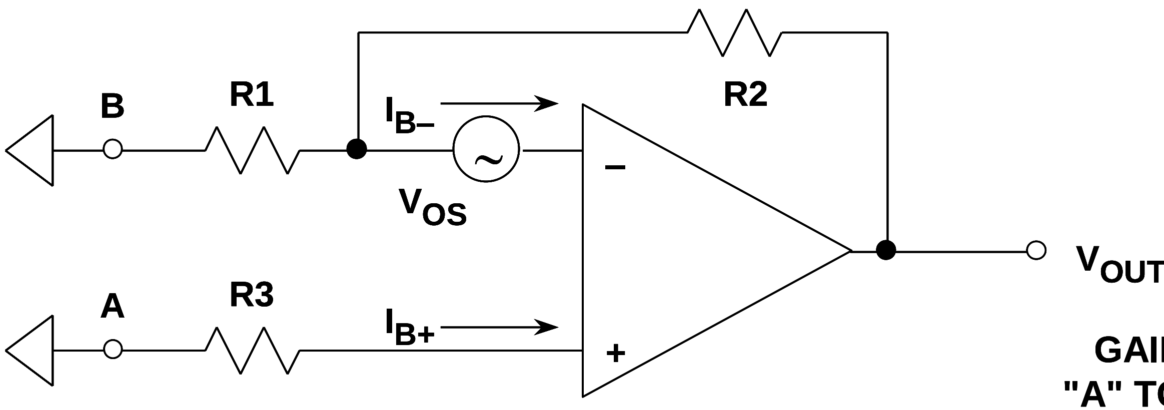
$$V_O = R2\,(I_{B-} - I_{B+})$$
$$= R2\,I_{OS}$$
$$= 0,\ \text{IF}\ I_{B+} = I_{B-}$$

NEGLECTING V_{OS}

Low Bias Current Precision BiFET Op Amps (Electrometer Grade)

PART #	Vos MAX	TC Vos MAX	I_B MAX	P-P Noise	PACKAGE
ADA4530-1	50µV	0.5µV/°C	20fA	4µV p-p	SOIC
ADA4665	1mV	3µV/°C	100fA	3µV p-p	SOIC
AD8603	50µV	1µV/°C	200fA	2.5µV p-p	TSOT
AD8661	30µV	3µV/°C	300fA	2.5µV p-p	LFSCP

Total Offset Voltage Calculations



GAIN FROM "A" TO OUTPUT = NOISE GAIN =

$$NG = 1 + \frac{R2}{R1}$$

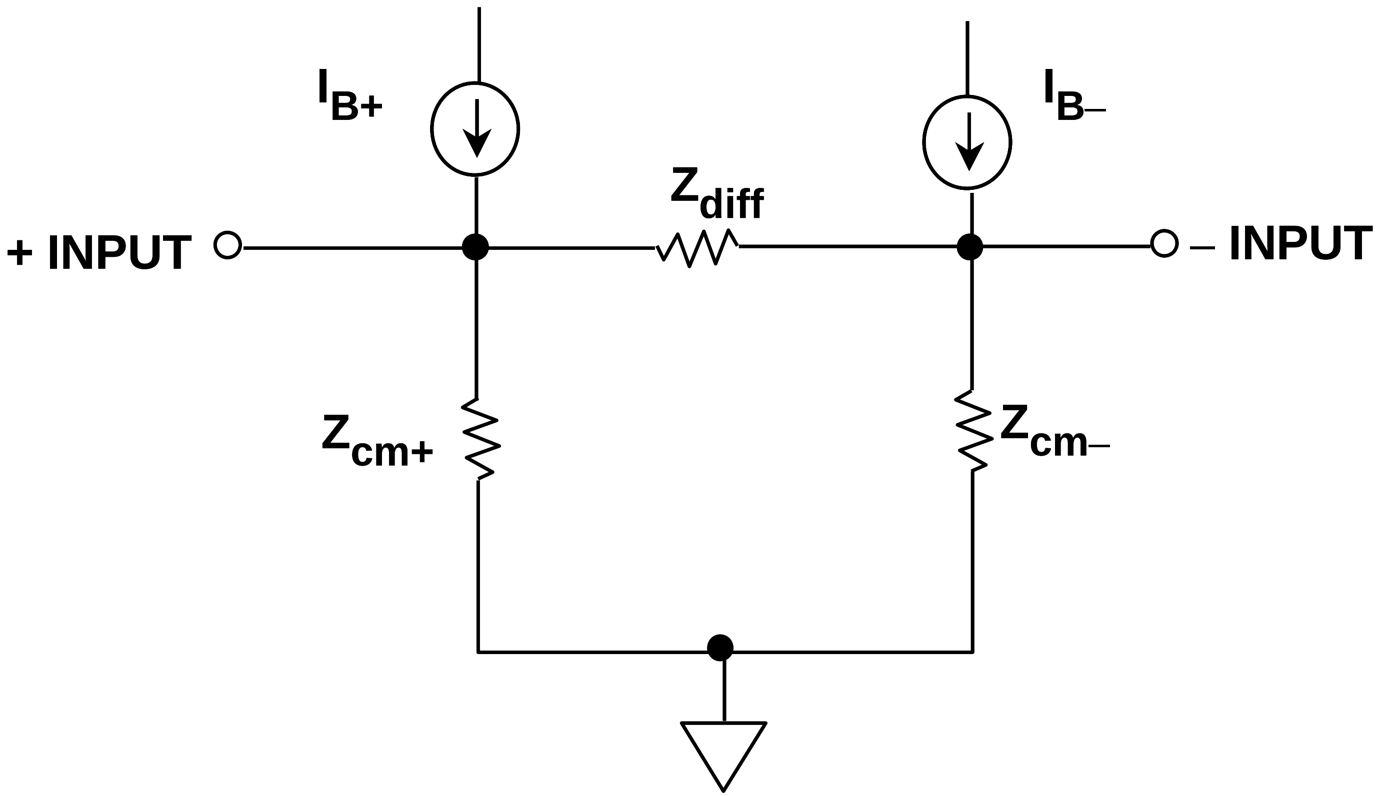
$$\text{GAIN FROM "B" TO OUTPUT} = -\frac{R2}{R1}$$

- $$\text{OFFSET (RTO)} = V_{OS}\left[1 + \frac{R2}{R1}\right] + I_{B+} \cdot R3 \left[1 + \frac{R2}{R1}\right] - I_{B-} \cdot R2$$
- $$\text{OFFSET (RTI)} = V_{OS} + I_{B+} \cdot R3 - I_{B-}\left[\frac{R1 \cdot R2}{R1 + R2}\right]$$

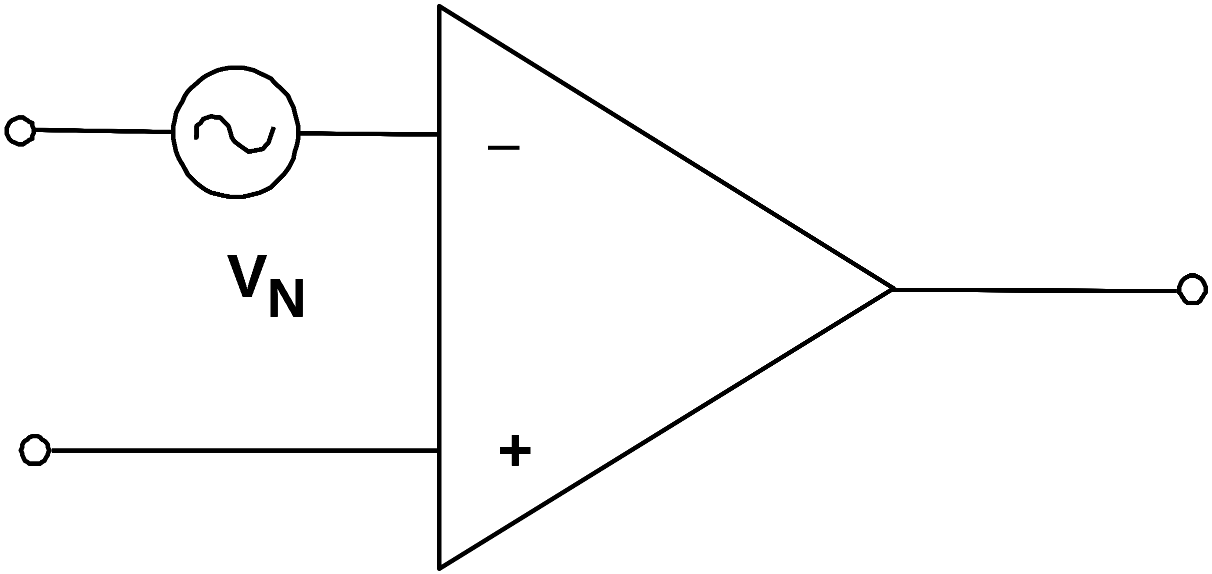
FOR BIAS CURRENT CANCELLATION:

$$\text{OFFSET (RTI)} = V_{OS} \quad \text{IF } I_{B+} = I_{B-} \text{ AND } R3 = \frac{R1 \cdot R2}{R1 + R2}$$

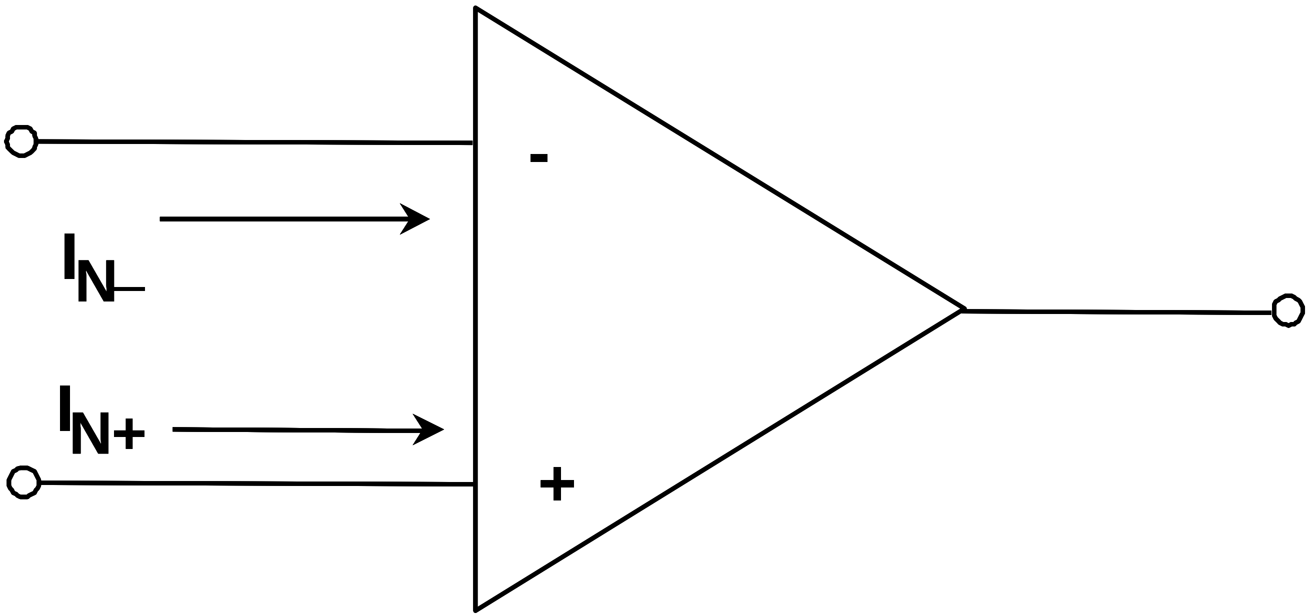
Input Impedance



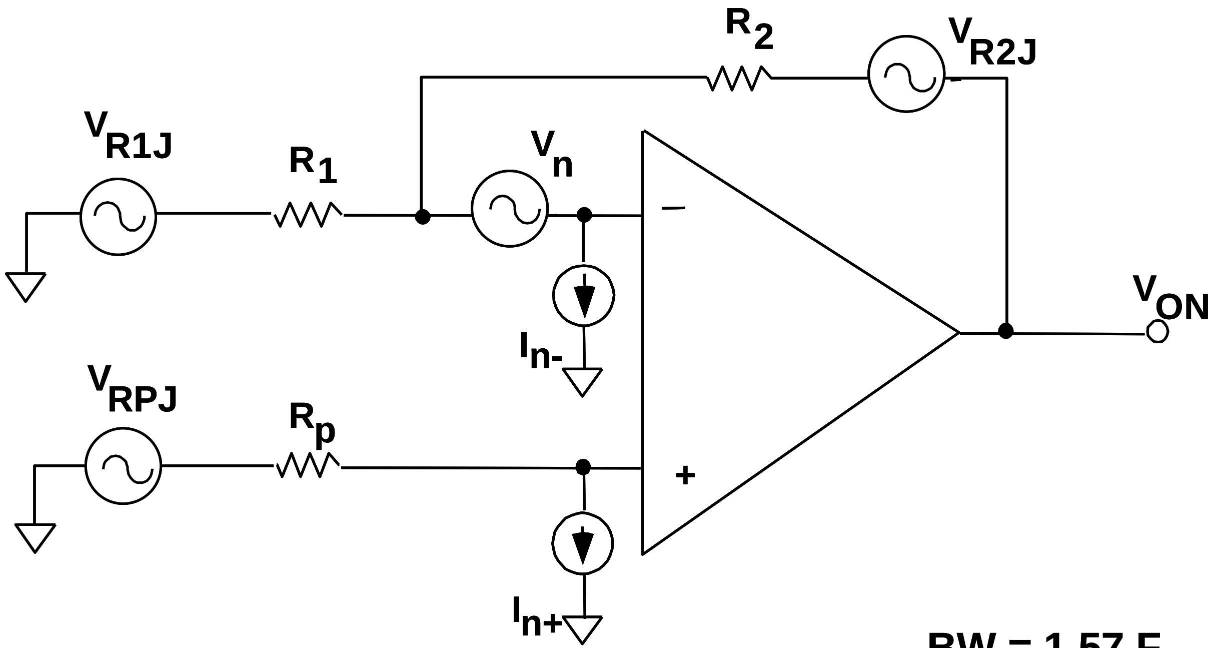
Voltage Noise



Current Noise



Total Noise Calculation



$BW = 1.57\ F_{CL}$

F_{CL} = CLOSED LOOP BANDWIDTH

$$V_{ON} = \sqrt{BW}\ \sqrt{[(In-^{2})R_2^{2}]\ [NG] + [(In+^{2})R_P^{2}]\ [NG] + V_N^{2}\ [NG] + 4kTR_2\ [NG-1] + 4kTR_1\ [NG-1] + 4kTR_P\ [NG]}$$

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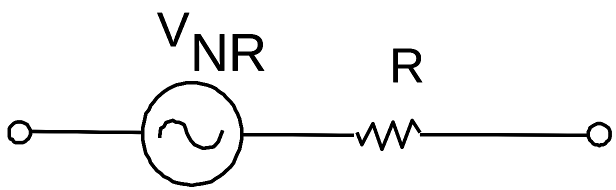
Resistor Noise



- ALL resistors have a voltage noise of $V_{NR} = \sqrt{(4kTBR)}$
- T = Absolute Temperature = T (°C) + 273.15
- B = Bandwidth (Hz)
- k = Boltzmann's Constant (1.38×10^{-23} J/K)
- A 1000 Ω resistor generates 4 nV / √Hz @ 25°C

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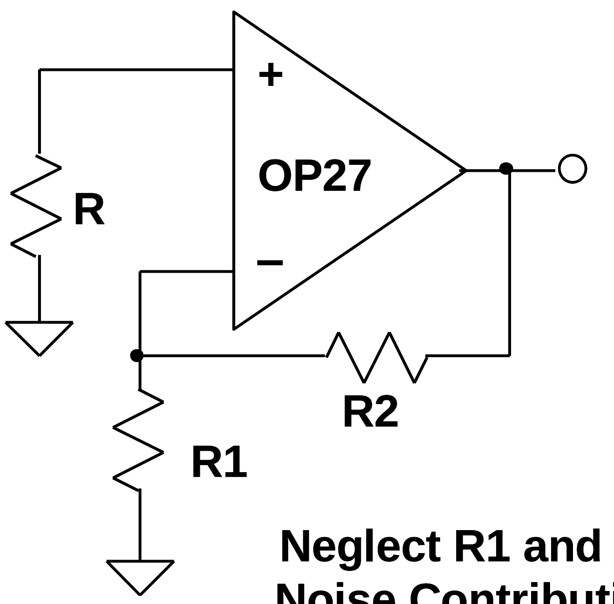
Dominant Noise Source Determined by Input Impedance

EXAMPLE: OP27
Voltage Noise = 3nV / √ Hz
Current Noise = 1pA / √ Hz
T = 25°C



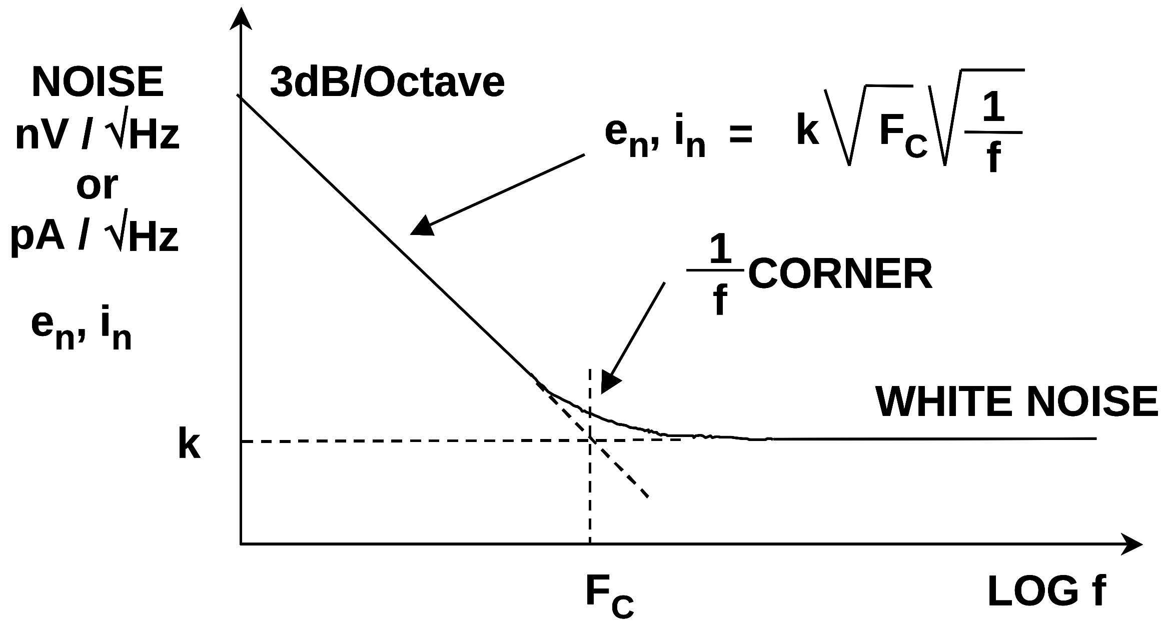
Neglect R1 and R2 Noise Contribution

CONTRIBUTION FROM	VALUES OF R		
	0	3kΩ	300kΩ
AMPLIFIER VOLTAGE NOISE	**3**	3	3
AMPLIFIER CURRENT NOISE FLOWING IN R	0	3	**300**
JOHNSON NOISE OF R	0	**7**	70

RTI NOISE (nV / √ Hz)

Dominant Noise Source is Highlighted

1/f Noise Bandwidth



- 1/f Corner Frequency is a figure of merit for op amp noise performance (the lower the better)
- Typical Ranges: 2Hz to 2kHz
- Voltage Noise and Current Noise do not necessarily have the same 1/f corner frequency

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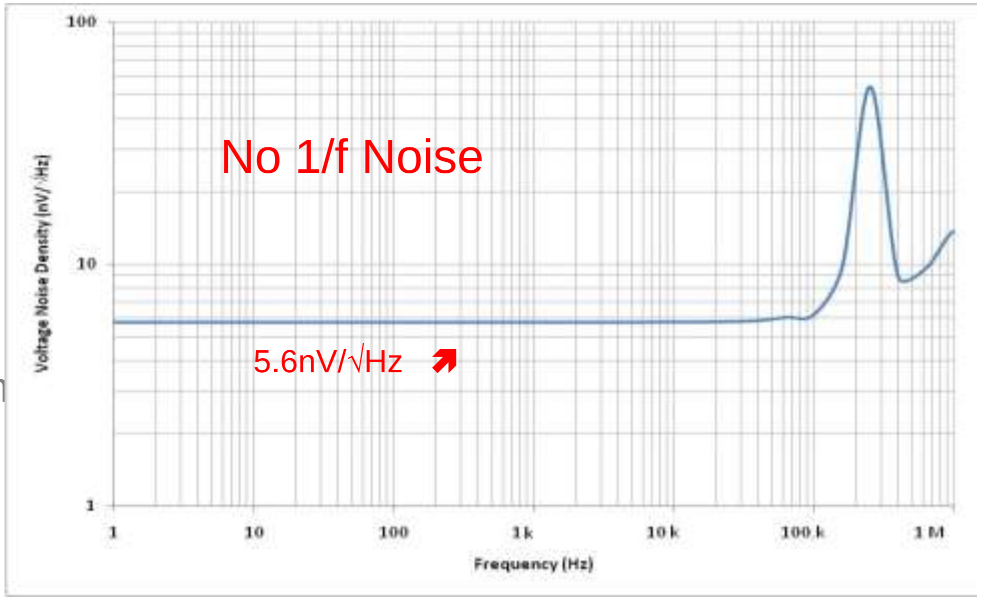
ADA4528-x World’s Most Accurate Op Amp Low Noise Zero-Drift Amplifier

- Key Features
  - Lowest noise zero-drift amp
    - 5.6 nV/√Hz noise floor
    - No 1/f noise
  - High DC accuracy
    - Low offset voltage: 2.5 µV max
    - Low offset voltage drift: 0.015 µV/ºC m
  - Rail-to-rail input/output
  - Operating voltage: 2.2 V to 5.5 V



- Applications
  - Transducer applications
  - Temperature measurements
  - Electronic scales
  - Medical instrumentation
  - Battery-powered instruments

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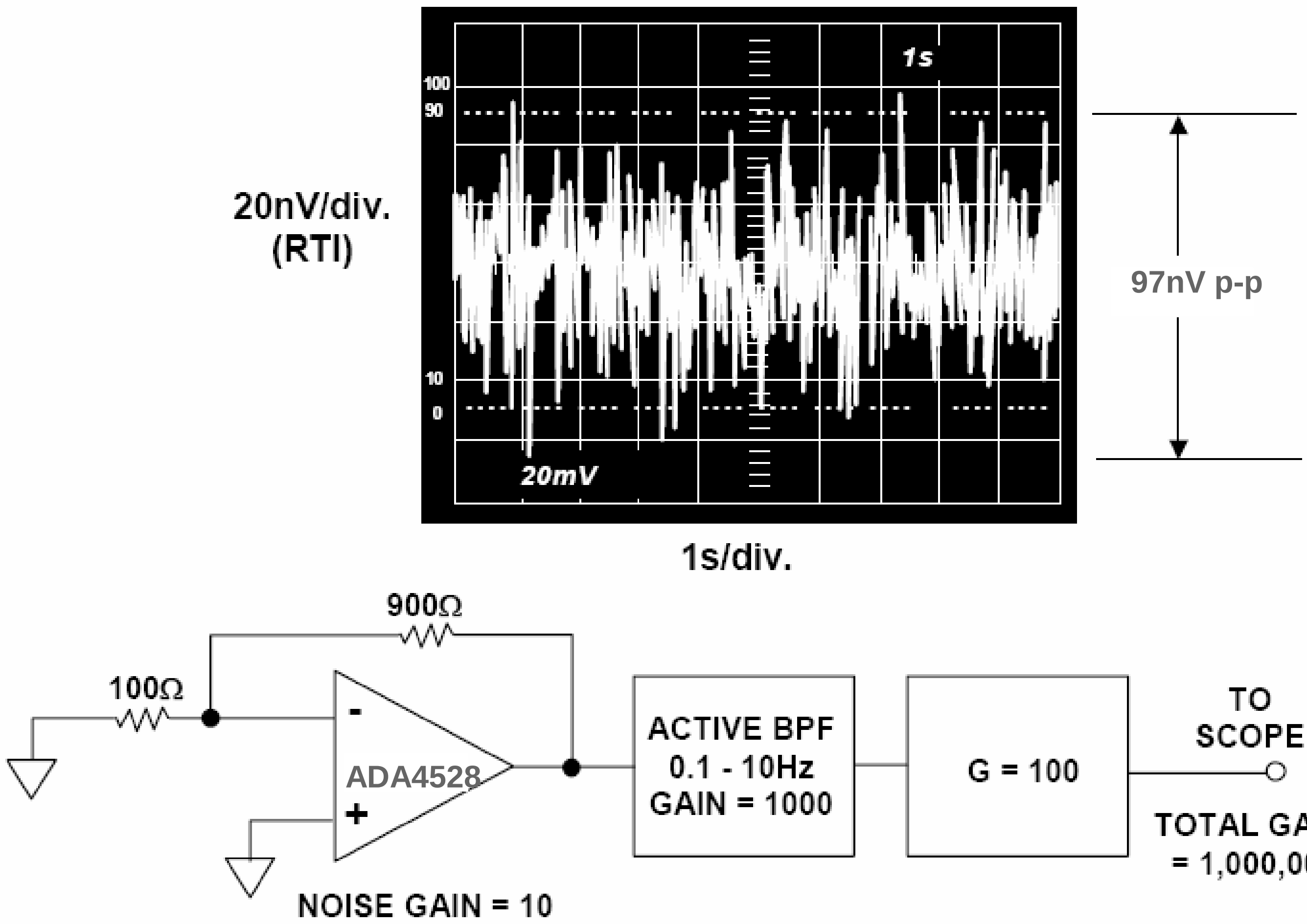
RMS to Peak to Peak Voltage Comparison Chart

Nominal Peak-to-Peak	% of the Time Noise will Exceed Nominal Peak-to-Peak Value
2 × rms	32%
3 × rms	13%
4 × rms	4.6%
5 × rms	1.2%
6 × rms	0.27%
6.6 × rms**	0.10%
7 × rms	0.046%
8 × rms	0.006%

**Most often used conversion factor is 6.6

The Peak-to-Peak Noise in the 0.1 Hz to 10 Hz Bandwidth ADA4528



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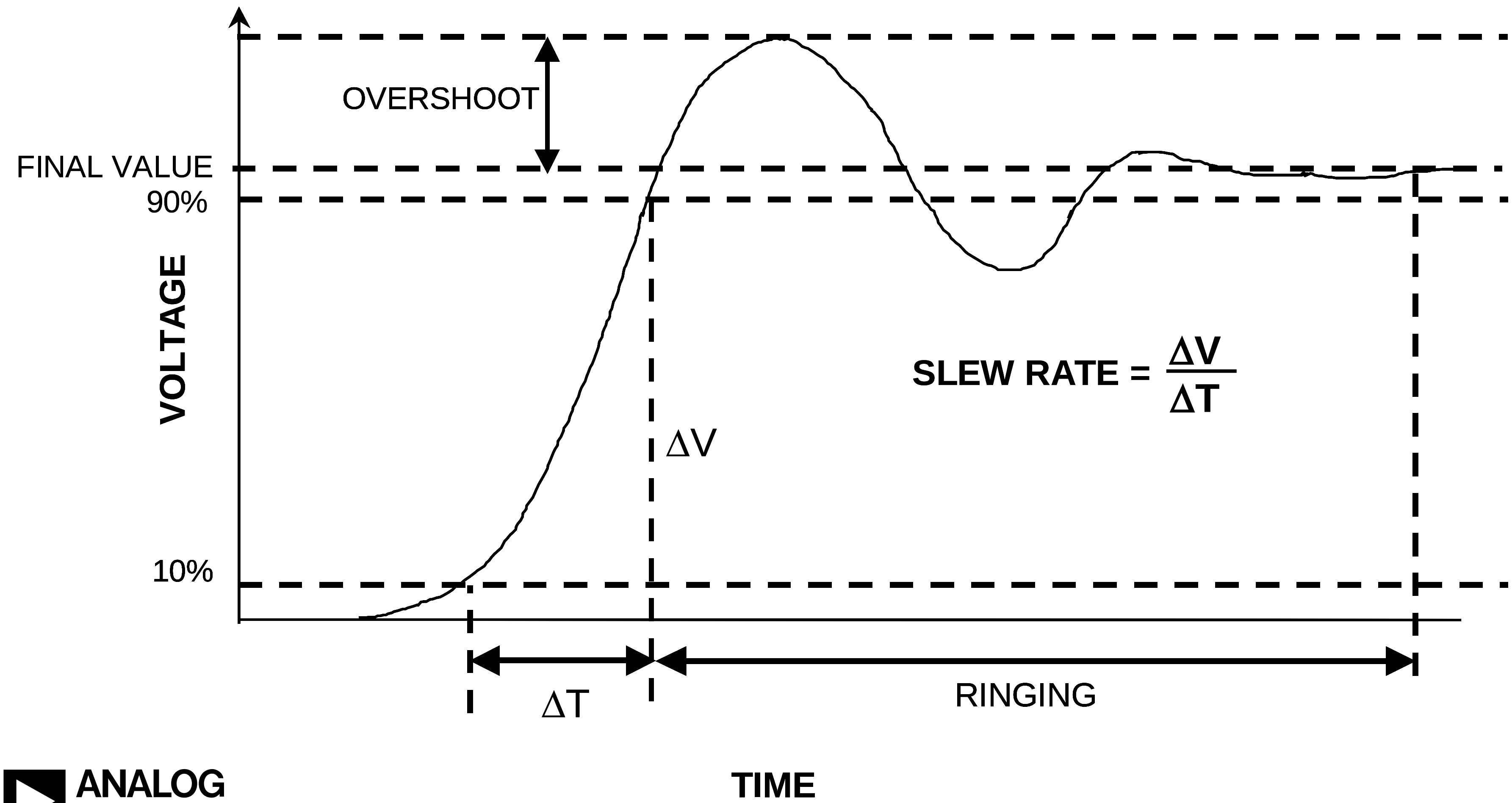
Slew Rate



OVERSHOOT
FINAL VALUE
90%
VOLTAGE
SLEW RATE = $\frac{\Delta V}{\Delta T}$
ΔV
10%
ΔT
RINGING
TIME

Slew Rate and Full Power Bandwidth

Slew Rate = Maximum rate at which the output voltage of an op amp can change

Ranges: A few volts / μs to several thousand volts / μs

For a sinewave, $V_{out} = V_p \sin 2\pi f t$

$$dV/dt = 2\pi f V_p \cos 2\pi f t$$

$$(dV/dt)_{max} = 2\pi f V_p$$

If $2 V_p$ = full output span of op amp, then

$$\text{Slew Rate} = (dV/dt)_{max} = 2\pi * \text{FPBW} * V_p$$

$$\text{FPBW} = \text{Slew Rate} / 2\pi V_p$$

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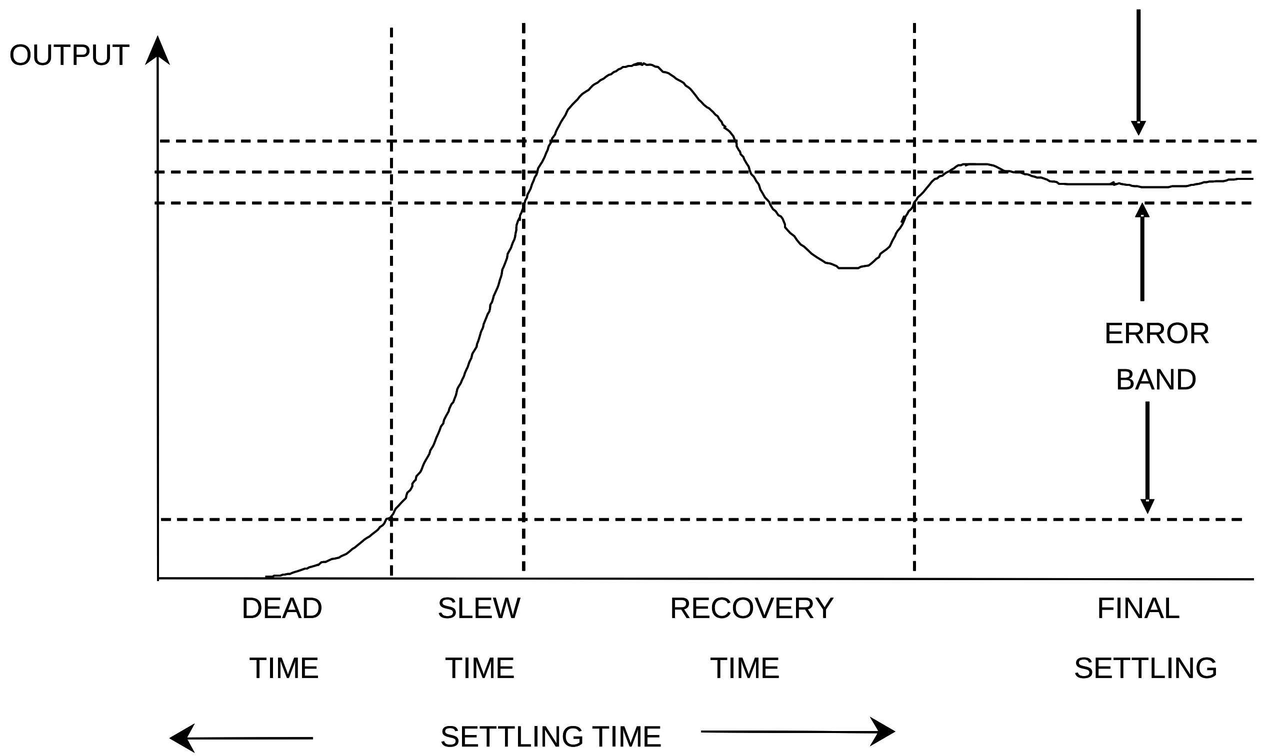
Settling Time



Error band is usually defined to be a percentage of the step 0.1 % 0.05%, 0.01%, etc.

Settling time is non -linear; it may take 30 times as long to settle to 0.01% as to 0.1%.

Manufacturers often choose an error band which makes the op amp look good.

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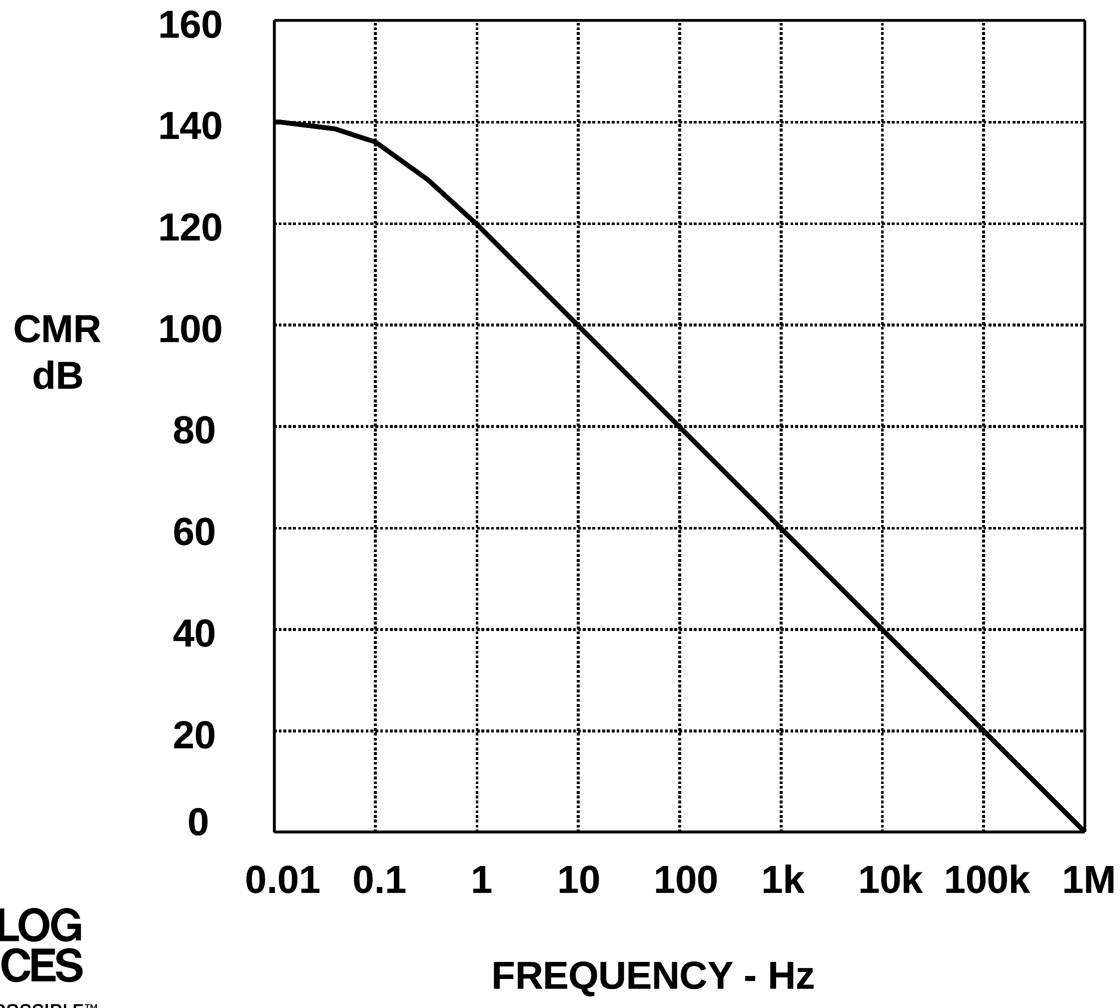
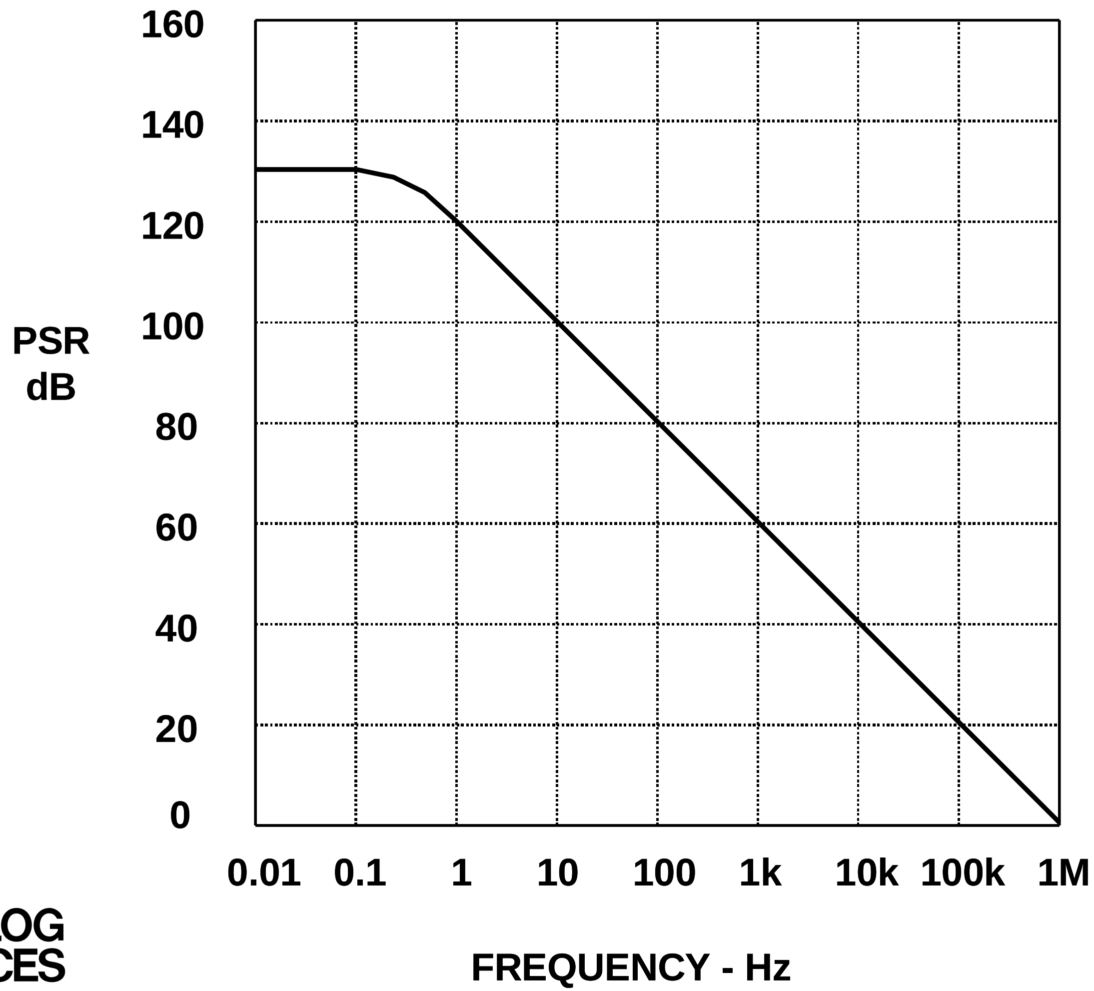
Common Mode Rejection Ratio for the OP177



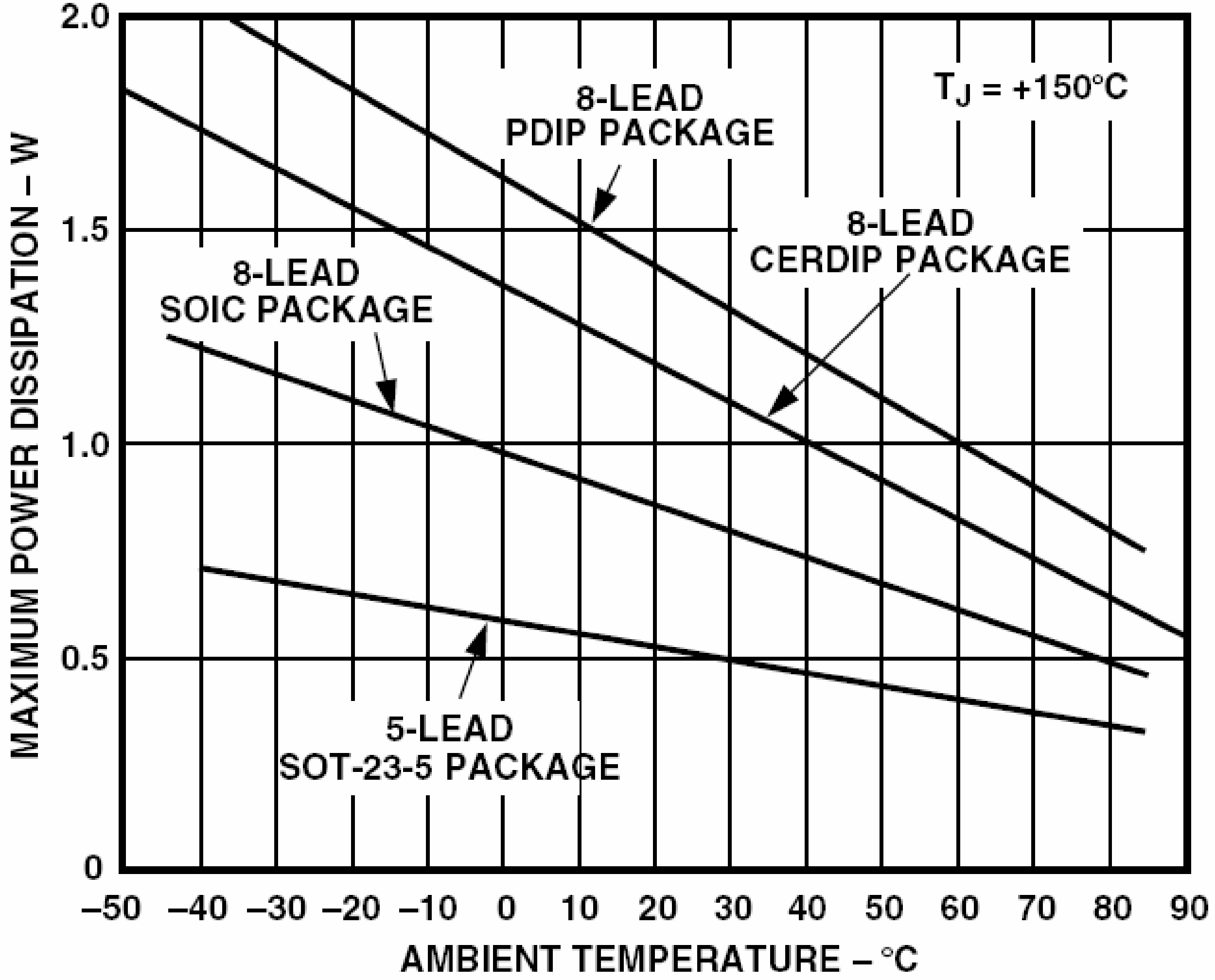
CMR =
$20 \log_{10}$ CMRR

Power Supply Rejection Ratio

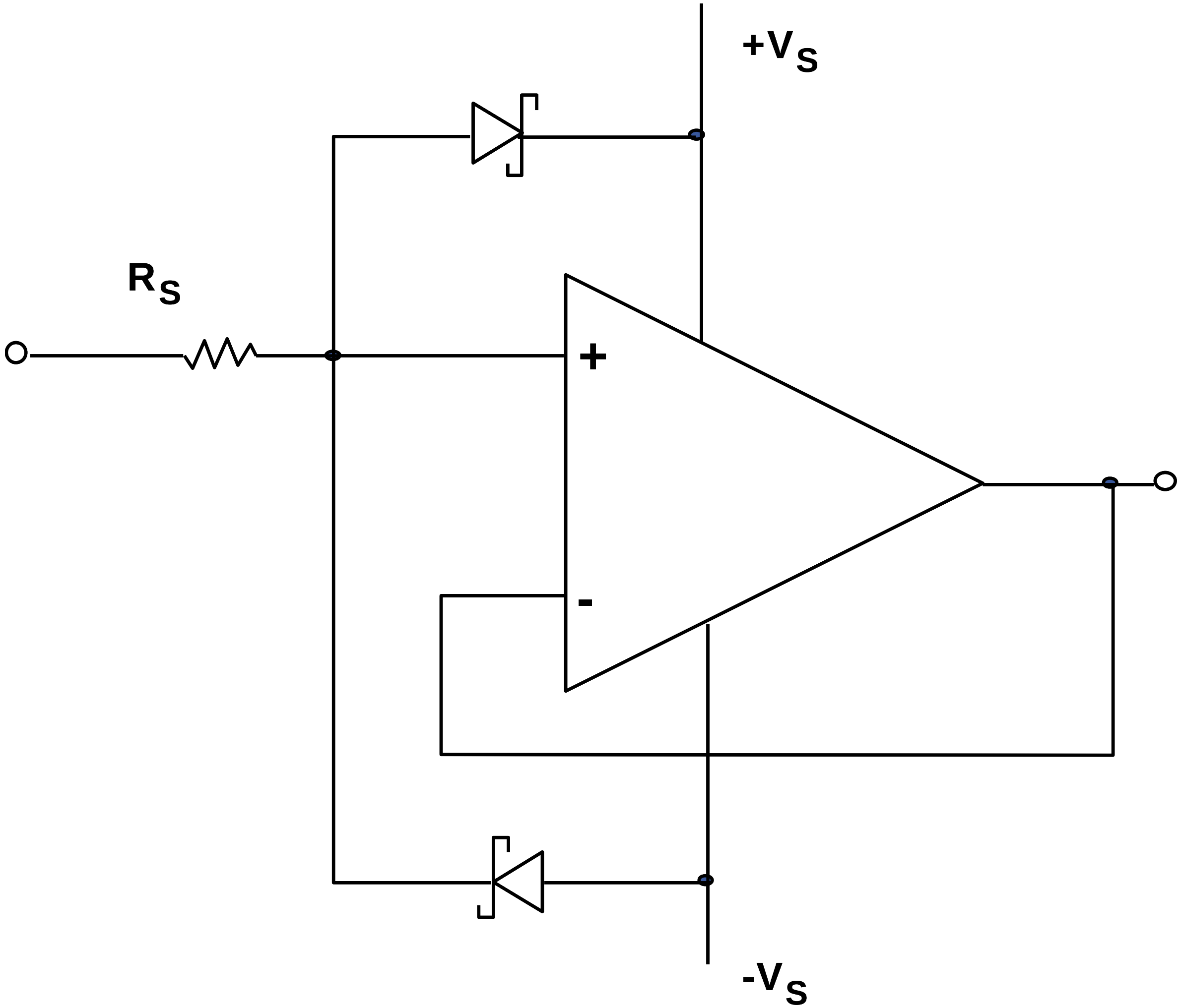


PSR = $20 \log_{10}$ PSRR

Maximum Power Chart (from the AD8001)



Input Protection



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Typical Absolute Maximum Ratings

ABSOLUTE MAXIMUM RATINGS[1]

Supply Voltage	12.6 V
Internal Power Dissipation[2]	
Plastic DIP Package (N)	1.3 W
Small Outline Package (R)	0.9 W
SOT-23-5 Package (RT)	0.5 W
Input Voltage (Common Mode)	$\pm V_S$
Differential Input Voltage	±1.2 V
Output Short Circuit Duration	Observe Power Derating Curves
Storage Temperature Range N, R	–65°C to +125°C
Operating Temperature Range (A Grade)	–40°C to +85°C
Lead Temperature Range (Soldering 10 sec)	+300°C

NOTES

[1]Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

[2]Specification is for device in free air:

8-Lead Plastic DIP Package: θ_{JA} = 90°C/W

8-Lead SOIC Package: θ_{JA} = 155°C/W

8-Lead Cerdip Package: θ_{JA} = 110°C/W

5-Lead SOT-23-5 Package: θ_{JA} = 260°C/W

ANALOG DEVICES

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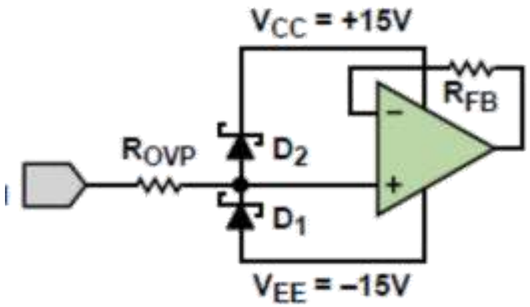
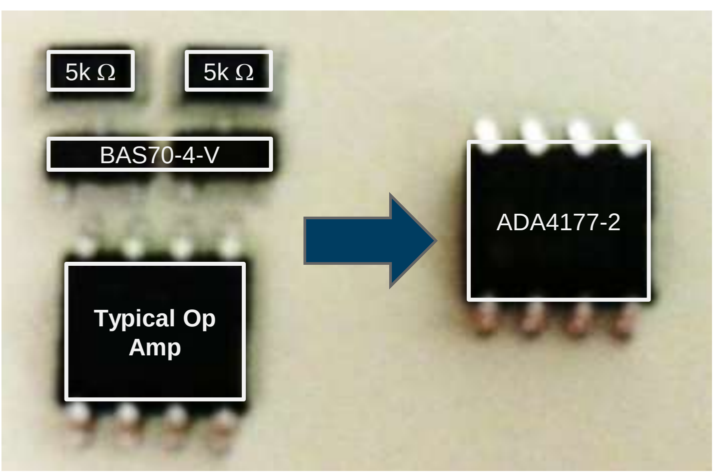
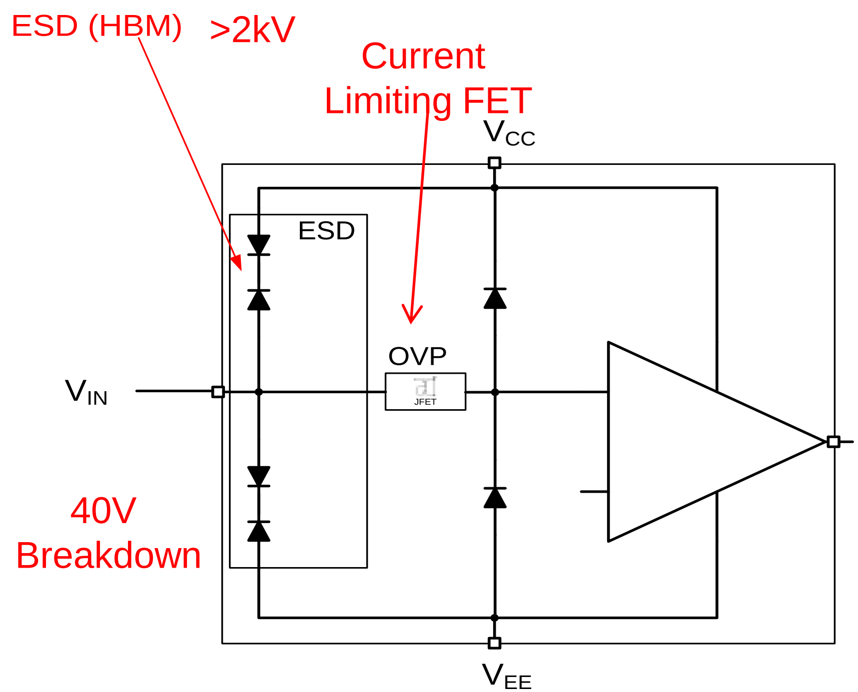
Over-Voltage Protection – Discrete versus Integrated

External Solution





Integrated Solution



Single-Supply Op Amps

- Single Supply Offers:
  - Lower Power
  - Battery Operated Portable Equipment
  - Requires Only One Voltage

- Design Tradeoffs:
  - Reduced Signal Swing Increases Sensitivity to Errors Caused by Offset Voltage, Bias Current, Finite Open-Loop Gain, Noise, etc.
  - Must Usually Share Noisy Digital Supply
  - Rail-to-Rail Input and Output Needed to Increase Signal Swing
  - Precision Less than the best Dual Supply Op Amps but not Required for All Applications
  - Many Op Amps Specified for Single Supply, but do not have Rail-to-Rail Inputs or Outputs

Thank You For Watching!

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