


Wrocław University of Science and Technology

Measurement circuits and systems

instrumentation and differential amplifiers



---

---

---

---

---

---

---

---

References

C. Kitchin, L. Counts,  
A Designer's Guide To Instrumentation Amplifiers,  
Analog Devices, 3rd edition, 2006

<https://www.analog.com/en/education/education-library/dh-designers-guide-to-instrumentation-amps.html>

---

---

---

---

---

---

---

---

outline:

1. Introduction: understanding IN-AMP
2. IN-AMP inside
3. monolithic in-amps review
  - auto-zeroing amps
4. monolithic dif-amps review
5. application tips
6. application circuits
7. summary

---

---

---

---

---

---

---

---

**instrumentation amplifier (in-amp)**

1. Not all amplifiers used in instrumentation applications are instrumentation amplifiers,
2. and by no means are all in-amps used only in instrumentation applications.

In-amps are used in many applications, from motor control to data acquisition to automotive. The intent of this guide is to explain the fundamentals of what an instrumentation amplifier is, how it operates, and how and where to use it. In addition, several different categories of instrumentation amplifiers are addressed in this guide.

---

---

---

---

---

---

---

---

**in-amps vs. op-amps:  
what are the differences?**

IN-AMP	OP-AMP
Internal closed-loop gain	closed-loop gain is determined by external resistors
Gain adjuster resistor(s) is not connected with any input	Loop resistors affect input impedance (can change the input resistance)

---

---

---

---

---

---

---

---

**Op-amps features**

$R_{IN} = R1$  (-1k $\Omega$  TO 1M $\Omega$ )  
 GAIN =  $R2/R1$

$R_{IN} = R+ (10^6\Omega$  TO  $10^{12}\Omega)$   
 GAIN =  $1 + (R2/R1)$

A MODEL SHOWING THE INPUT RESISTANCE OF A TYPICAL OP AMP OPERATING AS AN INVERTING AMPLIFIER—AS SEEN BY THE INPUT SOURCE

A MODEL SHOWING THE INPUT RESISTANCE OF A TYPICAL OP AMP IN THE OPEN-LOOP CONDITION  
 $(R-) = (R+) = 10^6\Omega$  TO  $10^{15}\Omega$

OP AMP INPUT CHARACTERISTICS

---

---

---

---

---

---

---

---



In-amp applications

- Data Acquisition
- Medical Instrumentation (EEG, EEC)
- Monitor and Control Electronics (current, voltage monitoring)
- Power Control Applications
- Audio Applications (very high CMRR vs.frequency)
- High Speed Signal Conditioning (including video signals) ??

---

---

---

---

---

---

---

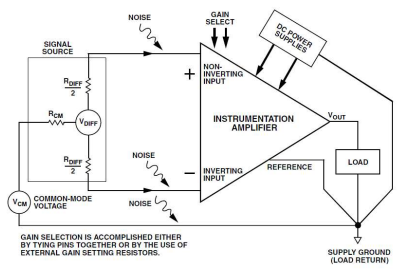
---

---

---

common mode and differential signals

$$V_{out} = G V_{DIFF} + \frac{G}{CMRR} (V_{CM})$$




---

---

---

---

---

---

---

---

---

---

in-amp properties

- High AC (and DC) Common-Mode Rejection
- Low Offset Voltage and Offset Voltage Drift (1 uV/deg to 10uV/deg)
- **A Matched, High Input Impedance**
- Low Input Bias and Offset Current Errors (pA)
- Low Noise -10 nV/√Hz @ 1 kHz (gain > 100)
- Low Nonlinearity (0.01% or better)
- Simple Gain Selection
- Adequate Bandwidth (up to 5MHz)
- Differential to Single-Ended Conversion
- Rail-to-Rail Input and Output Swing (often)
- Power vs. Bandwidth, Slew Rate, and Noise (disadvantage – power desipation)

---

---

---

---

---

---

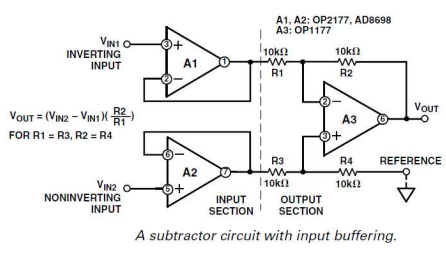
---

---

---

---

### INSIDE AN INSTRUMENTATION AMPLIFIER




---

---

---

---

---

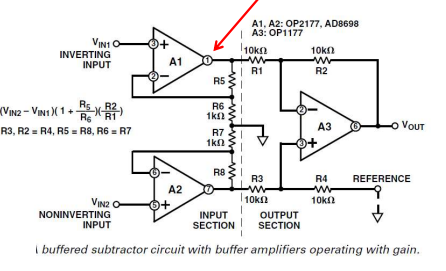
---

---

---

### in-amp inside cont.

$$V_{o1} = \frac{V_{in1} + V_{in2}}{2} \frac{R_5}{R_6} = V_{CM} \frac{R_5}{R_6}$$




---

---

---

---

---

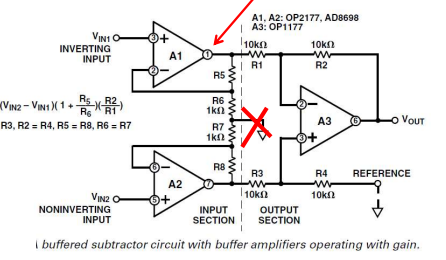
---

---

---

### in-amp inside cont.

$$V_{o1} = \frac{V_{in1} + V_{in2}}{2} \frac{R_5}{R_6} = V_{CM} \frac{R_5}{R_6}$$




---

---

---

---

---

---

---

---





In-amp example

$$G = \frac{49.4 \cdot 10^3}{R_G + 1}$$


---

---

---

---

---

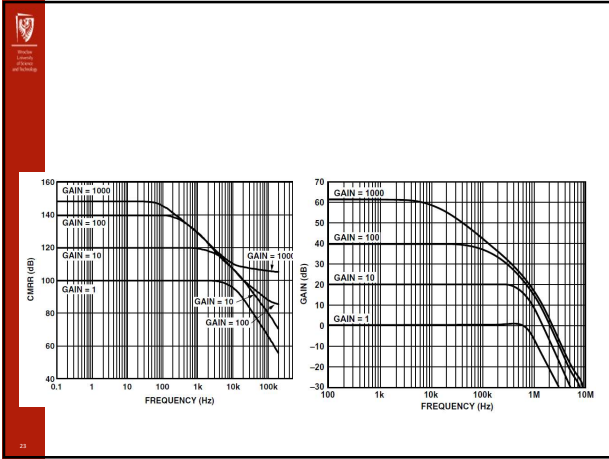
---

---

---

---

---




---

---

---

---

---

---

---

---

---

---

### Auto-Zeroing Instrumentation Amplifiers (AD8230)

The differential component of the input signal is stored on sampling capacitors,  $C_{SAMPLE}$ . The gain amp conditions the signal stored on the hold capacitors,  $C_{HOLD}$ . Gain is set with the  $R_G$  and  $R_F$  resistors.

The differential signal is transferred to the hold capacitors, refreshing the value stored on  $C_{HOLD}$ . The gain amp continues to condition the signal stored on the hold capacitors,  $C_{HOLD}$ .

---

---

---

---

---

---

---

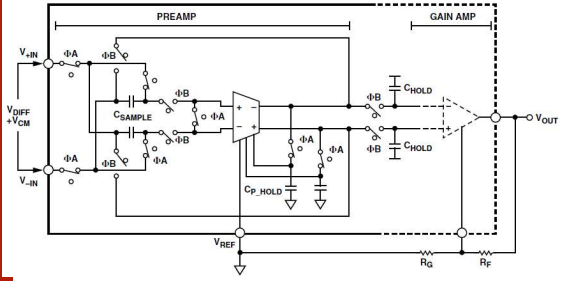
---

---

---



### Auto-Zeroing In-Amps preamplifier phase A



---

---

---

---

---

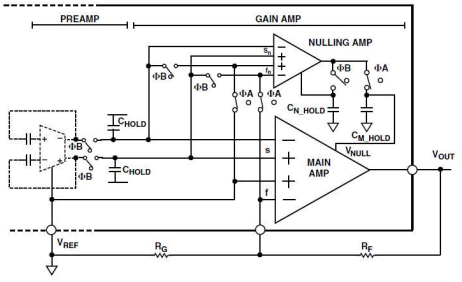
---

---

---



### Auto-Zeroing In-Amps gain amplifier phase A



---

---

---

---

---

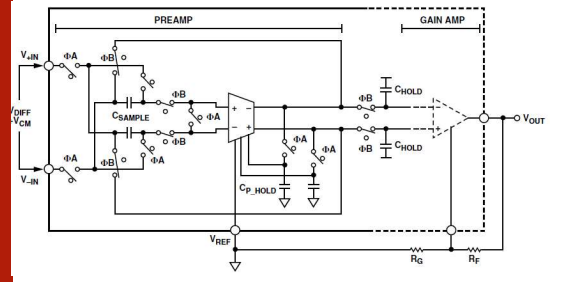
---

---

---



### Auto-Zeroing In-Amps preamplifier phase B



---

---

---

---

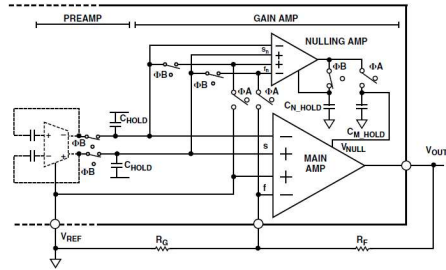
---

---

---

---

### Auto-Zeroing In-Amps gain amplifier phase B




---

---

---

---

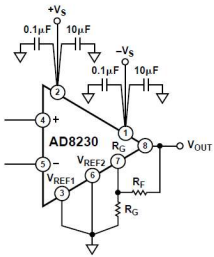
---

---

---

---

### Gain setting



$$G = 2 \left( 1 + \frac{R_F}{R_G} \right)$$

---

---

---

---

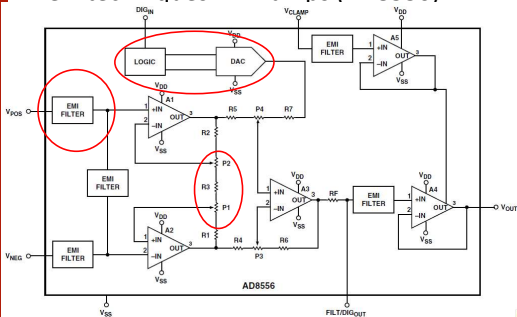
---

---

---

---

### new techniques in in-amps (AD8556)




---

---

---

---

---

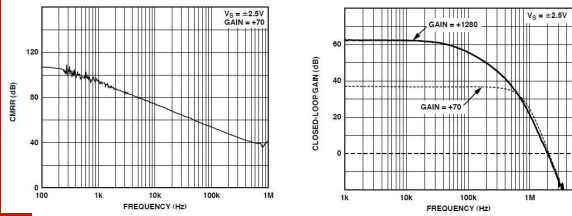
---

---

---



### AD8555




---

---

---

---

---

---

---

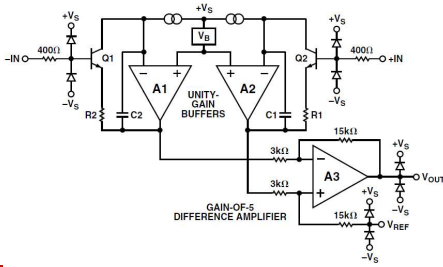
---

---

---



### Fixed Gain (Low Drift) In-Amps: AD8225




---

---

---

---

---

---

---

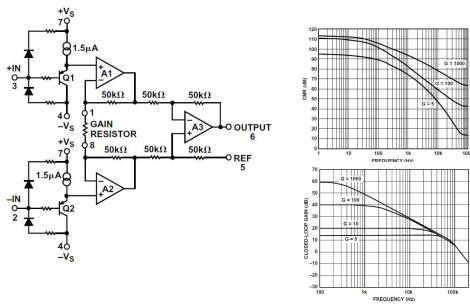
---

---

---



### Monolithic In-Amps Optimized for Single-Supply Operation: AD627




---

---

---

---

---

---

---

---

---

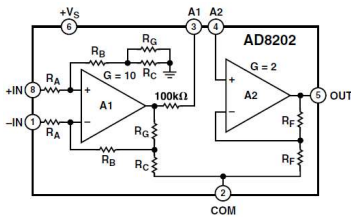
---

## MONOLITHIC DIFFERENCE AMPLIFIERS

Table 4-1. Latest Generation of Analog Devices Difference Amps Summarized<sup>1</sup>

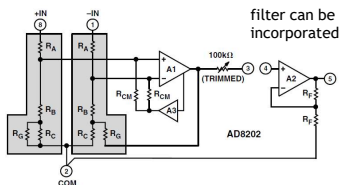
Product	Features	Power Supply Current Typ	-3 dB BW Typ (G = 10)	CMR G = 10 (dB) Min	Input Offset Voltage Max	V <sub>os</sub> Drift (μV/°C) Max	RTI Noise <sup>2</sup> (nV/√Hz) (G = 10)
AD8202	S.S., 28 V CMV, G = 20	250 μA	50 kHz	80 <sup>3,4,5</sup>	1 mV <sup>6</sup>	10	300 typ <sup>3</sup>
AD8203	S.S., 28 V CMV, G = 14	250 μA	60 kHz <sup>2</sup>	80 <sup>5,7</sup>	1 mV <sup>6</sup>	10	300 typ <sup>7</sup>
AD8205	S.S., 65 V CMV, G = 50	1 mA	50 kHz <sup>2</sup>	80 <sup>6,5,6</sup>	2 mV <sup>6</sup>	15 typ	500 typ <sup>8</sup>
AD8206	S.S., 65 V CMV, G = 20	1 mA	100 kHz <sup>2</sup>	76 <sup>6,9</sup>	2 mV <sup>6</sup>	15 typ	500 typ <sup>9</sup>
AD8210	S.S., current shunt monitor	500 μA	500 kHz <sup>2</sup>	100 <sup>3,5</sup>	1 mV <sup>6</sup>	5 typ	80 typ <sup>3</sup>
AD8212	Adjustable gain; CMV up to 500 V <sup>10</sup>	200 μA	500 kHz	90	1 mV	10	100 typ
AD8213	Dual channel	1.3 mA <sup>11</sup>	500 kHz	100	1 mV	10	70 typ
AD8130	270 MHz receiver	12 mA	270 MHz	83 <sup>12,13</sup>	1.8 mV	3.5 mV	12.5 typ <sup>12,14</sup>
AD628	High CMV	1.6 mA	600 kHz <sup>15</sup>	75 <sup>15</sup>	1.5 mV	4	300 typ <sup>15</sup>
AD629	High CMV, G = 1	0.9 mA	500 kHz	77 <sup>12</sup>	1 mV	6	550 typ <sup>12</sup>
AD626	High CMV	1.5 mA	100 kHz	55 <sup>16</sup>	500 μV	1	250 typ
AMP03	High BW, G = 1	3.5 mA	3 MHz	85 <sup>12</sup>	400 μV	NS	750 typ <sup>12</sup>

### monolithic dif-amp, an example



### monolithic dif-amp, an example

bridge (subtractor) circuit



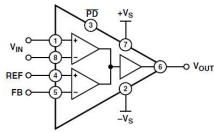
preamp gain = 10

Amplifier A3 detects the common-mode signal applied to A1 and adjusts the voltage on the matched RCM resistors to reduce the common-mode voltage range at the A1 inputs.

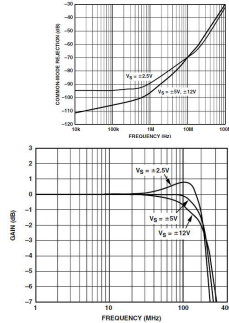




### High Frequency Diff- Receiver/Amplifiers



- 3 dB bandwidth of 270MHz,
- 80dB CMR at 2MHz, and a 70 dB CMR at 10 MHz
- active feedback !!! - feedback do not affect the inputs




---

---

---

---

---

---

---

---

---

---



Making use of an in-amps

- Application assumption:**
- Dual-Supply Operation or Single-Supply Operation
  - Need for True R-R Devices
  - CMRR
  - offset
  - offset drift
  - noise
  - gain

---

---

---

---

---

---

---

---

---

---



Application tips

- power supply bypassing, decoupling, and stability issues
- input ground return
- center polarization of input and output (especially case of single supply)
- properly driving an in-amp's reference input
- input protection from esd and dc overload

---

---

---

---

---

---

---

---

---

---

**Application tips**  
power supply bypassing, decoupling, and stability issues

GND and REFERENCE

capacitors that cover wide frequency range

---

---

---

---

---

---

---

---

**Application tips**  
input ground return

$V_{OS} = (I_{B1} \times R_1) - (I_{B2} \times R_2)$

---

---

---

---

---

---

---

---

**Application tips**  
center polarization of input and output

$C_1 R_1 = C_2 R_2$   
for CMR (h.f.)

$I_{B1} R_1 - I_{B2} R_2 = \Delta U_{off}$

---

---

---

---

---

---

---

---

monolithic, unity-gain, 3 MHz dif-amp  
 basic analog building block for differential amplifier and instrumentation applications

Analog Device advertisement materials

---

---

---

---

---

---

---

---

---

---

Application tips  
 properly driving an in-amp's reference input

EXTERNAL VOLTAGE DIVIDER  
 R1 - EXTERNAL REFERENCE VOLTAGE  
 R2

OP AMP BUFFER

EXTERNAL VOLTAGE DIVIDER

---

---

---

---

---

---

---

---

---

---

Application tips  
 input protection from ESD and dc overload

6mA MAX INPUT CURRENT

internal protection

additional external protection with Schottky diodes

---

---

---

---

---

---

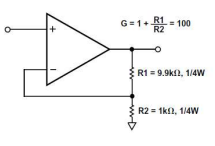
---

---

---

---

Application tips  
gain drift



Different power dissipation in R1 and R2 can cause gain drift even when temperature coefficients of both resistors are equal

---

---

---

---

---

---

---

---

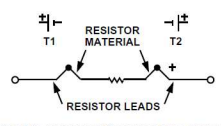
---

---

---

---

Application tips  
gain and offset drift



Error (voltage offset) is due to temperature difference of resistor (or any other component) terminals.

- TYPICAL RESISTOR THERMOCOUPLE EMFs
- CARBON COMPOSITION 400µV/°C
  - METAL FILM 20µV/°C
  - EVENOHM OR MANGANIN 2µV/°C
  - WIRE-WOUND 2µV/°C
  - RCD COMPONENTS HP-SERIES 0.05µV/°C

---

---

---

---

---

---

---

---

---

---

---

---

Application tips  
RTI vs. RTO errors

**Total Error, RTI = Input Error + (Output Error/Gain)**  
**Total Error, RTO = (Gain \* Input Error) + Output Error**

VOLTAGE OFFSET	(Total RTI Error = $V_{OSI} + V_{OSO}/G$ )		
Input Offset, $V_{OSI}$	$V_S = \pm 5 \text{ V to } \pm 15 \text{ V}$	30	125
Over Temperature	$V_S = \pm 5 \text{ V to } \pm 15 \text{ V}$		185
Average TC	$V_S = \pm 5 \text{ V to } \pm 15 \text{ V}$	0.3	1.0
Output Offset, $V_{OSO}$	$V_S = \pm 15 \text{ V}$	400	1000
	$V_S = \pm 5 \text{ V}$		1500
Over Temperature	$V_S = \pm 5 \text{ V to } \pm 15 \text{ V}$		2000
Average TC	$V_S = \pm 5 \text{ V to } \pm 15 \text{ V}$	5.0	15
Offset Referred to the			

Total Offset Error RTI =  $V_{OSI} + (V_{OSO}/G) = 30\mu\text{V} + (400\mu\text{V}/10) = 30\mu\text{V} + 40\mu\text{V} = 70\mu\text{V}$   
 Total Offset Error RTO =  $(G * V_{OSI}) + V_{OSO} = (10 * 30\mu\text{V}) + 400\mu\text{V} = 700\mu\text{V}$

---

---

---

---

---

---

---

---

---

---

---

---

**Application tips - Noise Errors**

$$F = \frac{(130)^2 + (200)^2 + (100)^2 + (41)^2 + (126)^2}{(130)^2} = \frac{(130)^2 + (260)^2}{(130)^2} = 1 + 4 = 5 = 7dB$$

---

---

---

---

---

---

---

---

---

---

**LTC6241 low noise amplifier**

SHOCK SENSOR  
 MURATA-ERIE  
 PKSS-00LD  
 770pF

BIAS RESISTOR  
 VISHAY-TECHNO  
 CRHV2S12AF1007G  
 (OR EQUIVALENT)

$V_{OUT} = 110mV_{ig}$   
 $V_S = \pm 1.4V \text{ to } \pm 5.5V$   
 $BW = 0.2Hz \text{ to } 10KHz$

Linear Technology advertisement materials

---

---

---

---

---

---

---

---

---

---

**LTC6241 twice better SNR (neglecting source noise)**

Linear Technology advertisement materials

---

---

---

---

---

---

---

---

---

---

**Application tips**  
Practical RFI Filters

$$B_{DF} = \frac{1}{2\pi R(2C_2 + C_1)}$$

$$B_{CM} = \frac{1}{2\pi R_1 C_1}$$

*Figure 5-25. Capacitor C2 shunts C1a/C1b and very effectively reduces ac CMR errors due to component mismatching.*

---

---

---

---

---

---

---

---

---

---

**Application tips**  
Practical RFI Filters

**Selecting RFI Input Filter Component Values Using a Cookbook Approach**  
The general rules of designing of RC input filter.

1. the two series resistors
  - typical values between 2 kΩ and 10 k Ω; check if input circuit can drive these impedance,
  - these resistors should not contribute more noise than that of the in-amp itself.
2. value for capacitor C2
  - C2 sets the filter's differential (signal) bandwidth; best to set this as low as possible without attenuating the input signal; a differential bandwidth of 10 times the highest signal frequency is usually adequate.
3. select values for capacitors C1a and C1b; which set the common-mode bandwidth;
  - for decent ac CMR, these should be 10% the value of C2 or less,
  - The common-mode bandwidth should always be less than 10% of the in-amp's bandwidth at unity gain.

---

---

---

---

---

---

---

---

---

---

**EMI protection result**

ANALOG DEVICES

AD8556

AD8556 (ENHANCED PART FOR EMI)

NON-EMI PROTECTED SOLUTION

DEVIATION FROM DC OUTPUT (mV)

FREQUENCY (MHz)

Analog Device advertisement materials

---

---

---

---

---

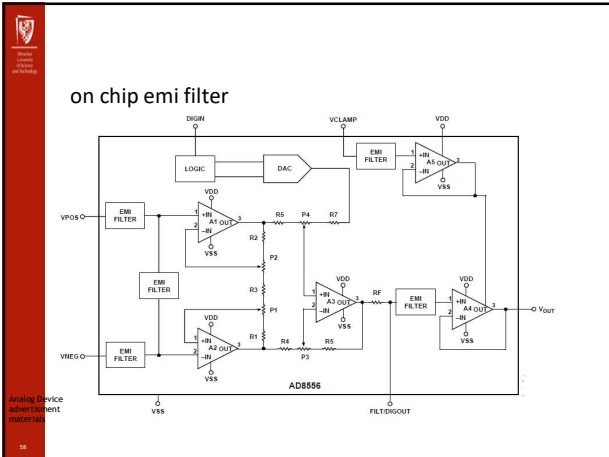
---

---

---

---

---




---

---

---

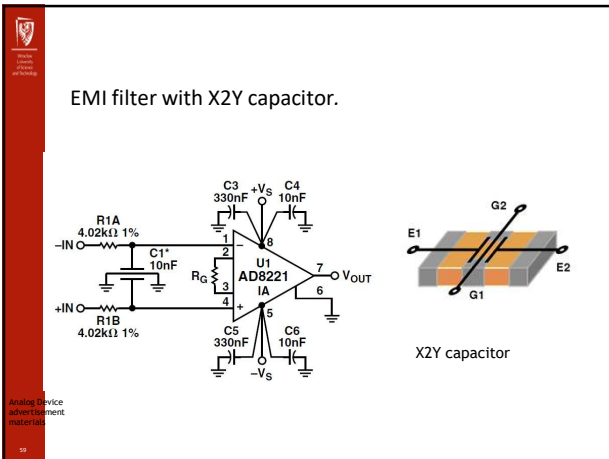
---

---

---

---

---




---

---

---

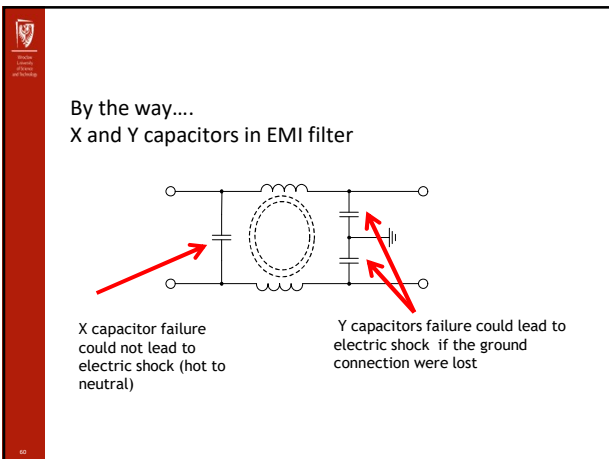
---

---

---

---

---




---

---

---


---

---


---

---

---




Class X Capacitor (Line - to -Line)



Failure could result in fire

Class Y Capacitor (Line - to -Ground)



Failure could result electric shock

---

---

---


---

---

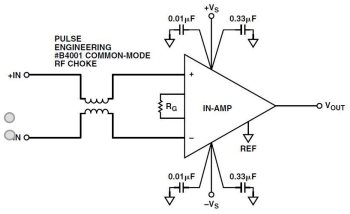
---

---

---



Common mode chock as emi filter




---

---

---


---

---

---

---

---



**USING LOW-PASS FILTERING TO IMPROVE SIGNAL-TO-NOISE RATIO**

To extract data from a noisy measurement, low-pass filtering can be used to greatly improve the signal-to-noise ratio of the measurement by removing all signals that are not within the signal bandwidth. In some cases, band-pass filtering (reducing response both below and above the signal frequency) can be employed for an even greater improvement in measurement resolution

---

---

---

---

---

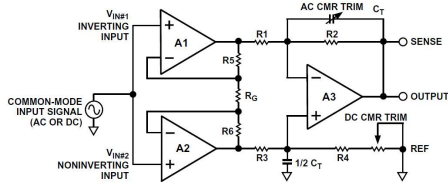
---

---

---



### External CMRR trimming



TIP: discrete design of an In-amp has usually better performance (bandwidth and CMRR)

---

---

---

---

---

---

---

---

---

---



### IN-AMP AND DIFF AMP APPLICATIONS CIRCUITS

---

---

---

---

---

---

---

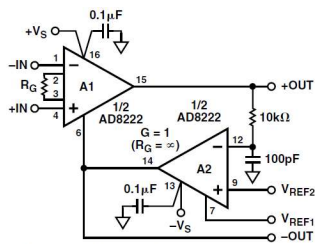
---

---

---



### A True Differential Output In-Amp Circuit



$$V_{OCM} = \frac{V_{ref1} + V_{ref2}}{2}$$

TIP: this is very useful with AD converter -  $V_{ref2}$  can be connected with  $V_{ref}$  of ADC and  $V_{ref1}$  with ADC ground so 0V of input is  $\frac{1}{2}$  value of ADC

---

---

---

---

---

---

---

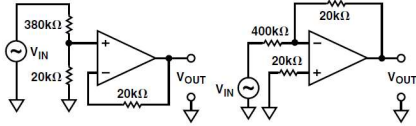
---

---

---



### High voltage measurements



TIP:

1. (on the left) single supply can be used and  $V_{out}$  is positive
2. (on the right) dual supply have to be applied,  $V_{out}$  is negative
3. If  $V_{in}$  are negative tips 1 and 2 have to be exchanged
4. power is dissipated in one resistor - self heating occurs
5. high temp gradient can cause nonlinearities , offset, drift, lower CMRR

27

---

---

---

---

---

---

---

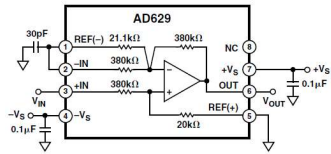
---

---

---



### High voltage measurements improovemet



TIP: one chip - one temperature !

22

---

---

---

---

---

---

---

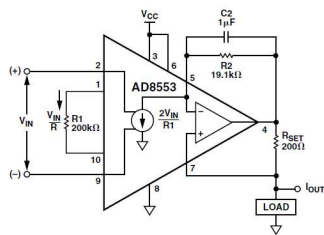
---

---

---



### Precision Current Source



23

---

---

---

---

---

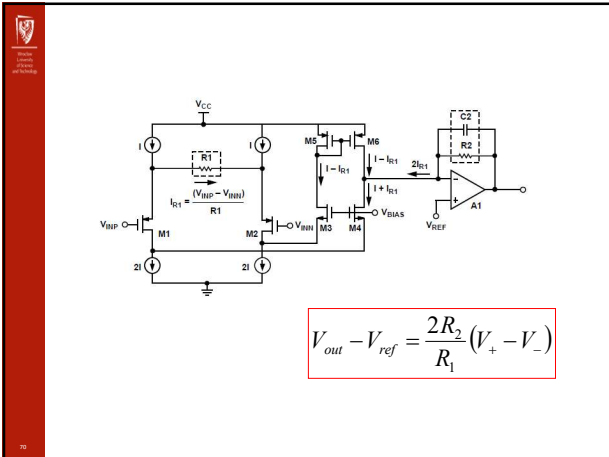
---

---

---

---

---




---

---

---

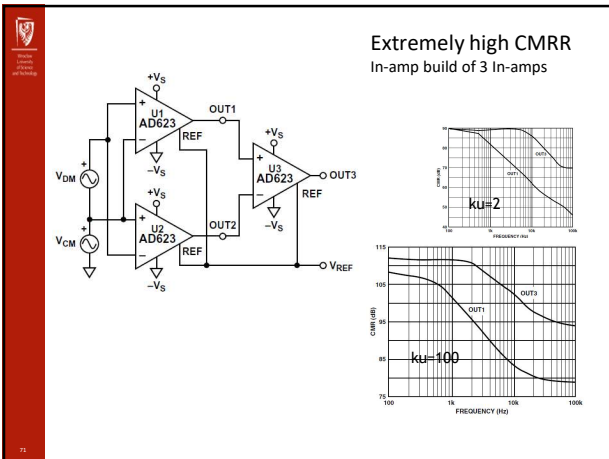
---

---

---

---

---




---

---

---

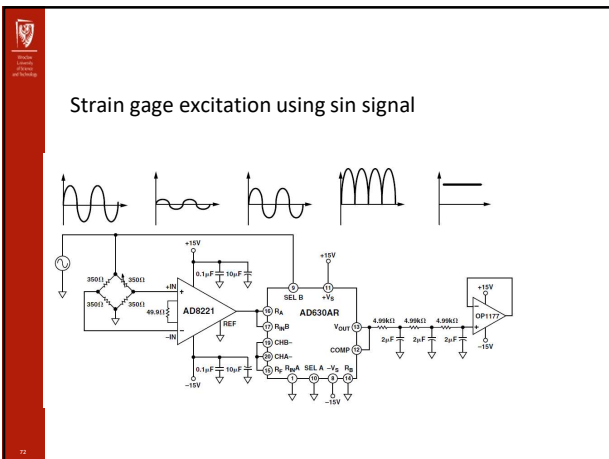
---

---

---

---

---




---

---

---

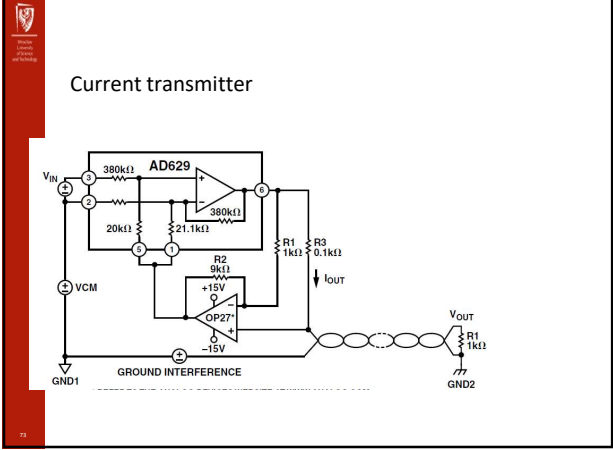
---

---

---

---

---




---

---

---

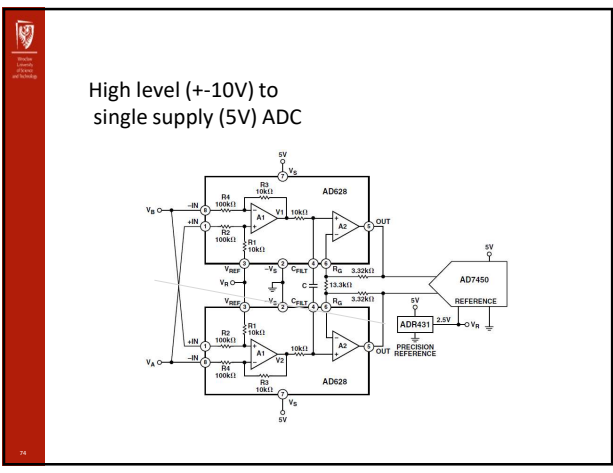
---

---

---

---

---




---

---

---

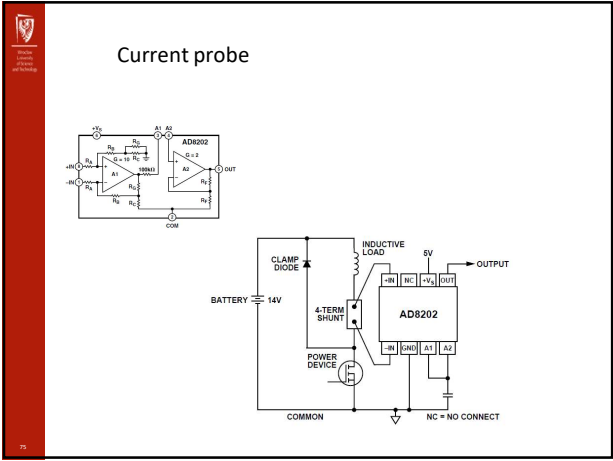
---

---

---

---

---




---

---

---

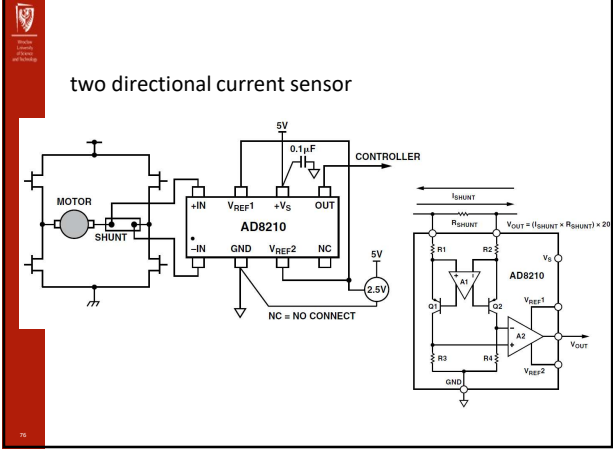
---

---

---

---

---




---

---

---

---

---

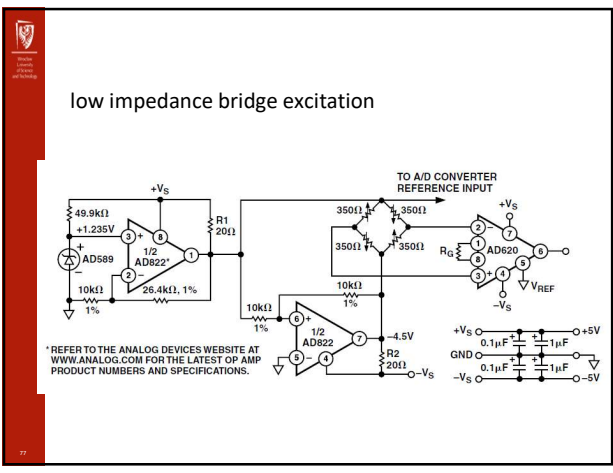
---

---

---

---

---




---

---

---

---

---

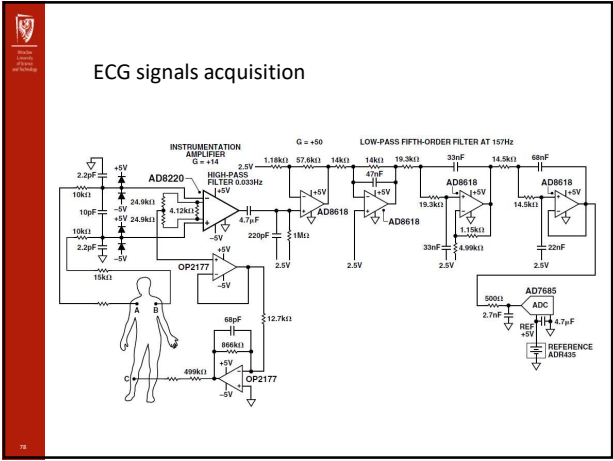
---

---

---

---

---




---

---

---

---

---

---

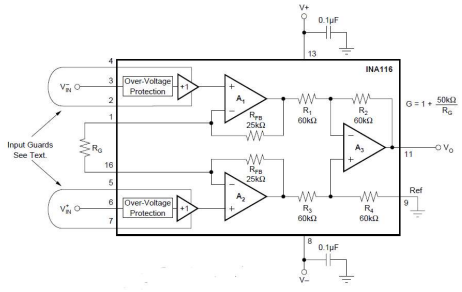
---

---

---

---

Driven Shield Inputs - example




---

---

---

---

---

---

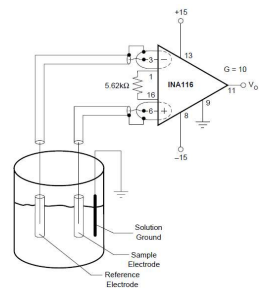
---

---

---

---

pH transducer




---

---

---

---

---

---

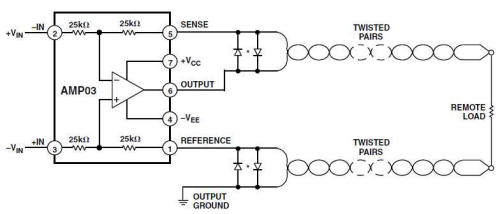
---

---

---

---

remote load driver




---

---

---

---

---

---

---

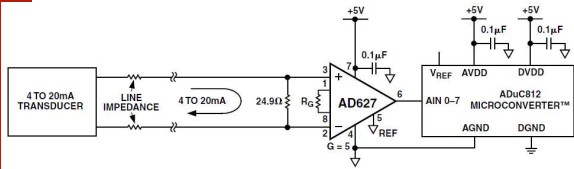
---

---

---



### 4-20mA loop receiver



22

---

---

---

---

---

---

---

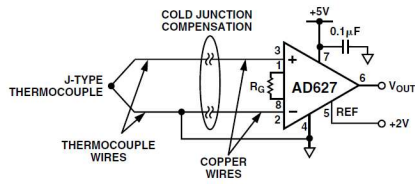
---

---

---



### termocouple transducer



23

---

---

---

---

---

---

---

---

---

---



### summary

1. Properties of an in-amp
2. in-amp vs. op-amp
3. in-amp vs. dif-amp
4. in-amp of 3 vs. 2 op-amp
5. Application tips:
  - EMI filtering
  - input ESD protection
  - DC biasing
  - thermal noise
  - single supply problems
  - CMR trimming

24

---

---

---

---

---

---

---

---

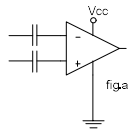
---

---



Test questions examples:

- Draw two basic diagrams of a instrumentation amplifiers ?
- Compare in-amp vs. op-amp
- What wrong with the circuit (in-amp with two capacitor at the input) ? (fig.a)



---

---

---

---

---

---

---

---