Amplifiers

Operational Amplifier

Instrumentation Amplifier

Analog Computation

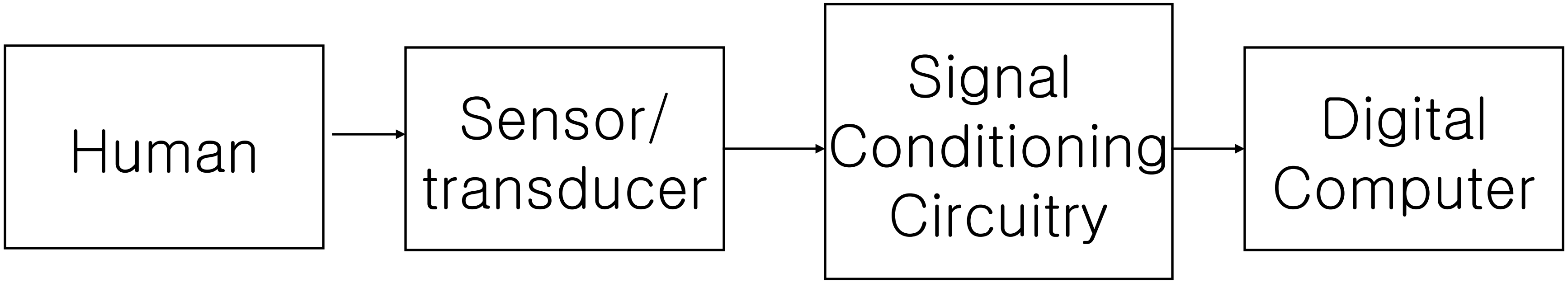
Active Filter

Grounding

Isolation

Function of Amplifiers

- Amplifiers provides
  - GAIN
  - Filtering, Signal processing, Correction for Nonlinearities



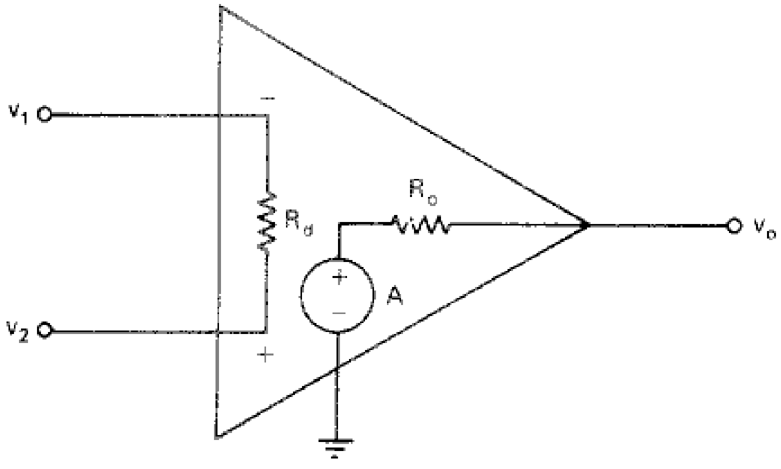
Human

Sensor/ transducer

Signal Conditioning Circuitry

Digital Computer

Ideal Amps

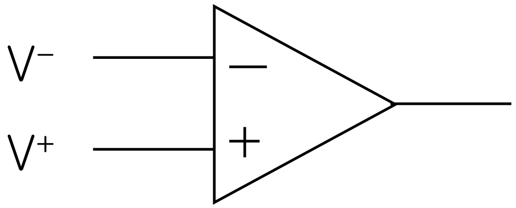


- Assumptions
  - Open loop Gain = Infinity
  - Input Impedance Rd = Infinity
  - Output Impedance Ro = 0
  - Bandwidth = Infinity
    - Infinite Frequency Response
  - v_o=0 when $v_1 = v_2$
    - No Offset Voltage

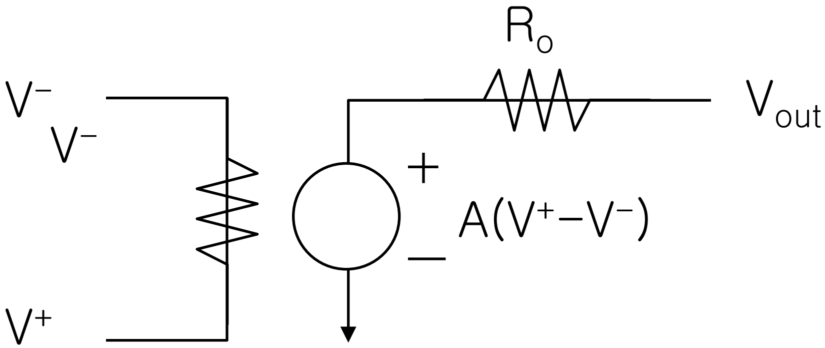
OP Amplifier Properties

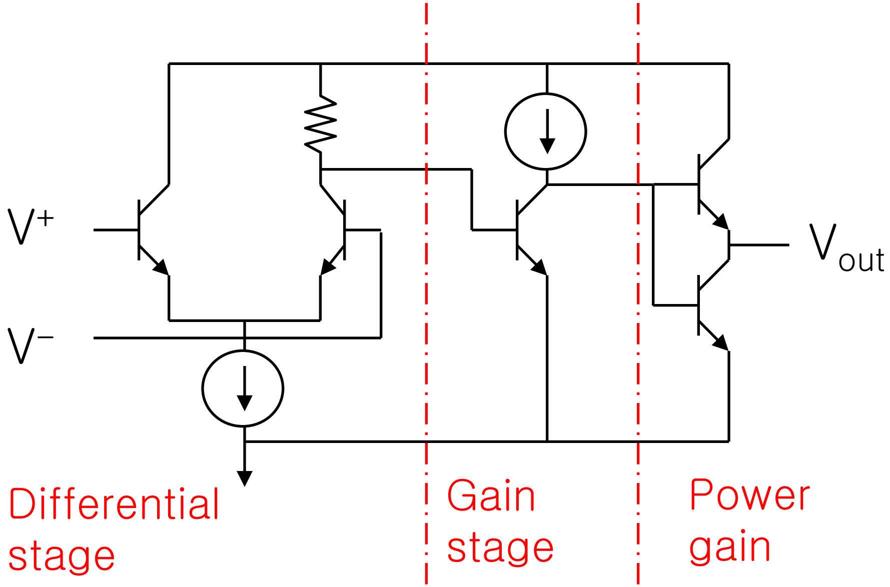
Ideal Op. Amp.	ideally	means
gain(open-loop)	∞	$\geq 10^4$
open-loop BW	∞	Dominant Pole at 10Hz
CMRR	∞	≥ 70dB
Ri	∞	≥ 10MΩ
Ro	0	< 500Ω
I B	0	< 0.5μA
Vos	0	< 10mV
Ios	0	< 0.2μA

How do we achieve these properties?



$V_{out} = A(V^+ - V^-)$





741인 경우

(Stage 1) R=1.6MΩ
Gain=1200

(Stage 2) V_{tg} gain=220

(Stage 3) Ro=60Ω
V_{tg} gain=1

Overall Gain=108dB

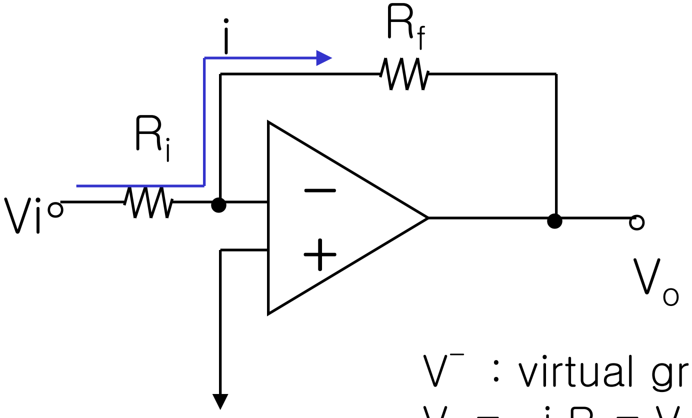
Two rules of Ideal OP Amps

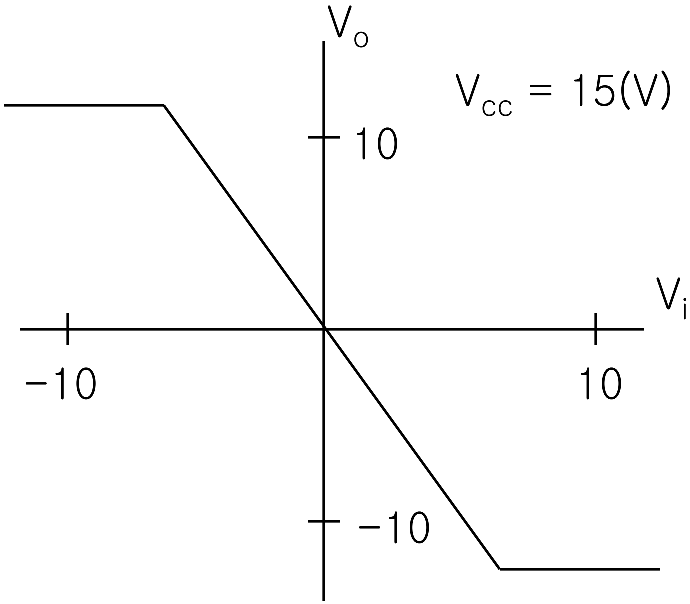
- Note
  - $v_0 = A(v_2 - v_1)$
    - For finite v_0 and $A = \infty$ (Typically 100,000)
      - $v_2 - v_1$ should be 0 $\Rightarrow v_2 = v_1$
    - Since $v_2 = v_1$ and input impedance is ∞,
      - There should be no currents flowing into the input terminals
- Rule 1
  - When the OP Amp is in linear range the two inputs are at the same voltage (Virtual Ground)
- Rule 2
  - No Current flows into either terminal of the OP Amp

Basic OP Amp Circuit Blocks

- Inverting Amplifier
- Noninverting Amplifier
- Unity-Gain Amplifier
- Differential Amplifier
- Instrumental Amplifier
- The ECG(Electrocardiogram) Amplifier

Inverting Amp.



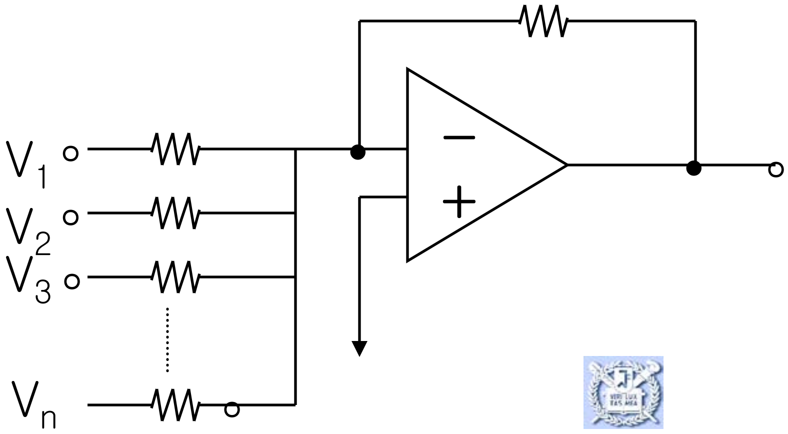


V^- : virtual ground

$V_o = -\ i\ R_f = V_i(R_f / R_i)$

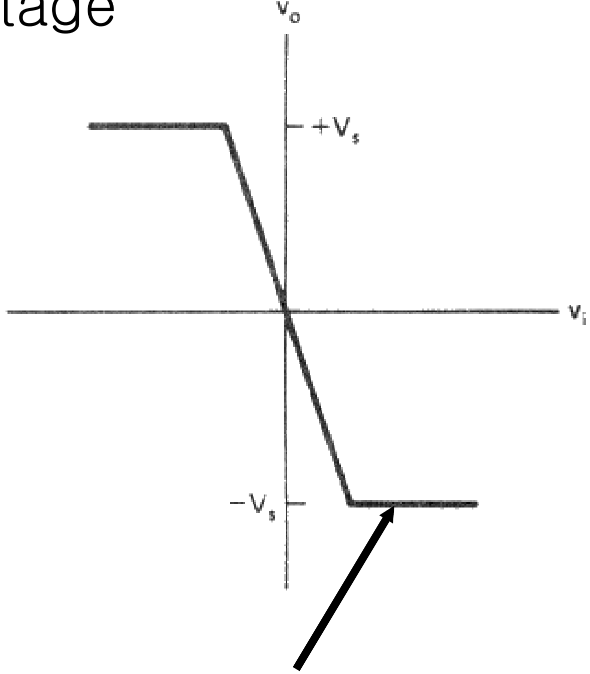
$A_v = -\ (R_f / R_i)$

- Summing



Inverting Amplifier (Cont.)

- Linear Range
  - By Power Supply Voltage

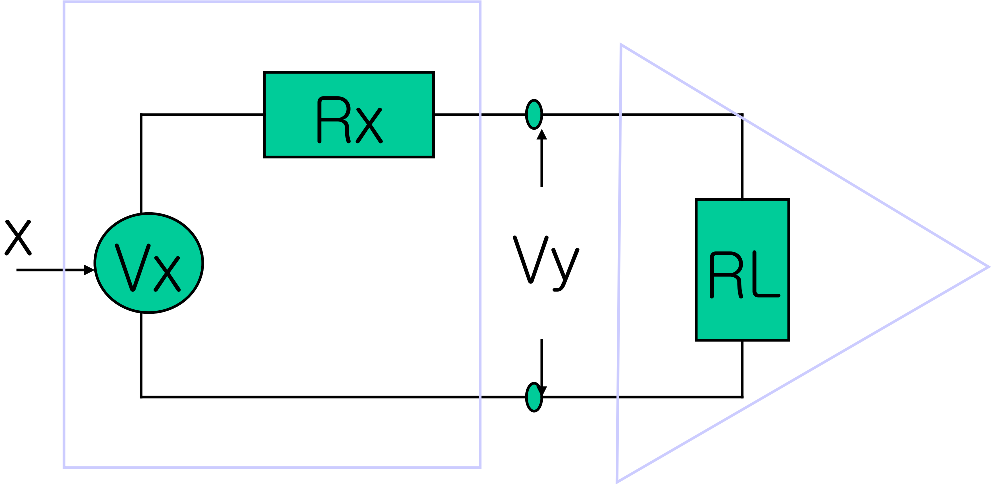


Saturation

- Input Impedance
  - Low (Ri)
  - Increasing Ri → Decreasing Gain
    - Increasing Gain by increasing Rf
      - But there is practical limit

Why High Input Impedance ?

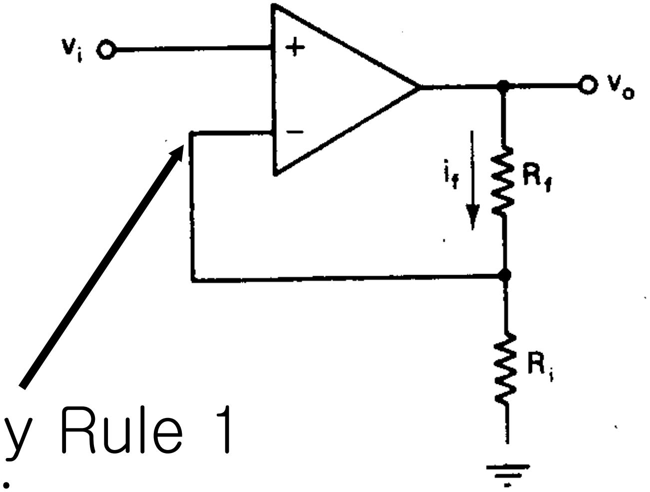
- Concept of Loading
  - To avoid the effect of output value
  - Only depends on the amplitude of sensor output, not on the frequency or digital output



- Open Loop Output
  - Vx
- Voltage Drop by Load
  - $V_y = V_x - V_x \times R_x / (R_L + R_x)$
- Let RL >> Rx
  - $V_y = V_x$
  - We can eliminate the effect of amplifier or detector.

Noninverting Amplifiers

- Noninverting Amp
  - Gain = (Rf + Ri) / Rf

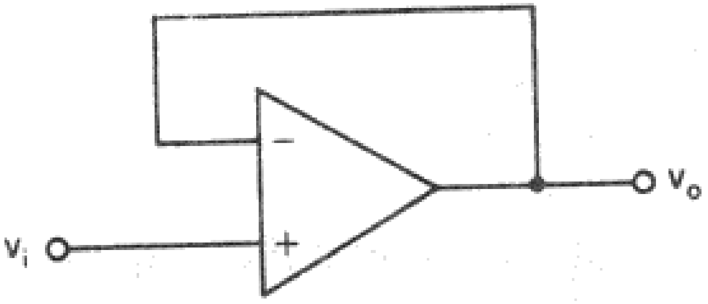


By Rule 1
Vi

- By Rule 2
  - Vo = If × (Rf + Ri)
  - Vi = If × Ri
  - Vo = Vi × (Rf + Ri)/Ri
- Gain: Vo/Vi = 1 + Rf / Ri
- Gain ≥ 1, Always
- Input Impedance
  - Very Large (Infinite)

Unity-Gain Amplifier

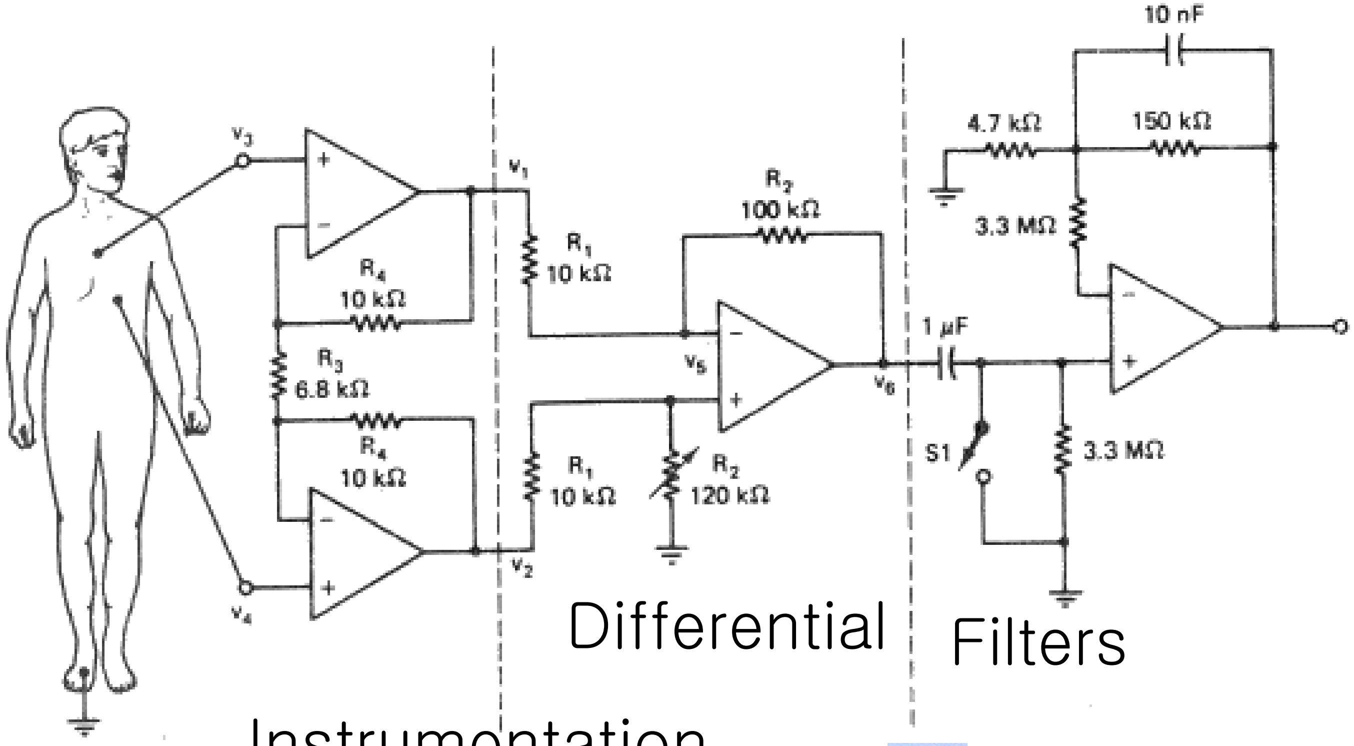
- Homework #2-1
  - Verify that the Gain of Unity-Gain Amp is 1



- Vo = Vi
- Applications
  - Buffer amplifier
    - Isolate one circuit from the loading effects of a following stage
  - Impedance converter
    - Data conversion System (ADC or DAC) where constant impedance or high impedance is required

Differential Amplifiers

- Can reject 60Hz interference
- Example Use of Diff. Amp. In ECG amplifier



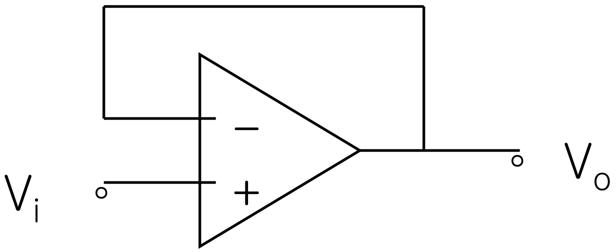
Differential

Filters

Instrumentation

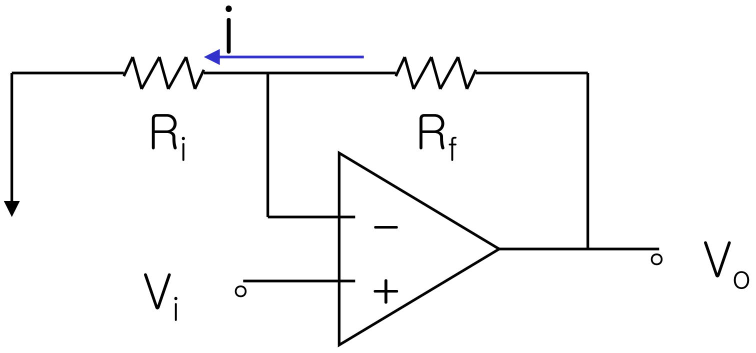
Non Inverting Amp.

- Follower



Buffer, Impedance Converter

- Non-inverting Amp.



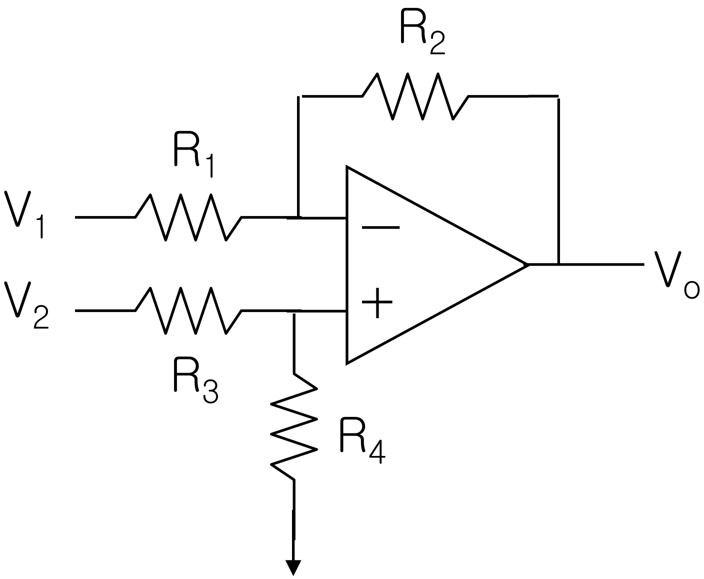
$$V_o = i \cdot (R_i + R_f)$$
$$V_i = i \cdot R_i$$
$$\rightarrow \quad A_v = \frac{R_i + R_f}{R_i}$$

Instrumentation Amp- Differential Amp.

- High gain DC coupled differential amp with single ended output.

  High Z_{in}, CMRR

  Used to Amplify small differential signals from transducer where there may be a large common signal.



$$V^{+} = V_2 \cdot \frac{R_4}{R_3 + R_4}, \quad V^{-} = (V_o - V_1)\frac{R_1}{R_1 + R_2} + V_1$$

From $V^{+}=V^{-}$

$$V_o = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)V_2 - \frac{R_2}{R_1}V_1$$

$$if \quad \frac{R_3}{R_4} = \frac{R_1}{R_2} \quad \rightarrow \quad V_o = \frac{R_2}{R_1}(V_2 - V_1), \quad G_d = \frac{R_2}{R_1}$$

Common mode $V_1=V_2$ → $V_o=0$ → $G_c=0$

CMRR= G_d / G_c

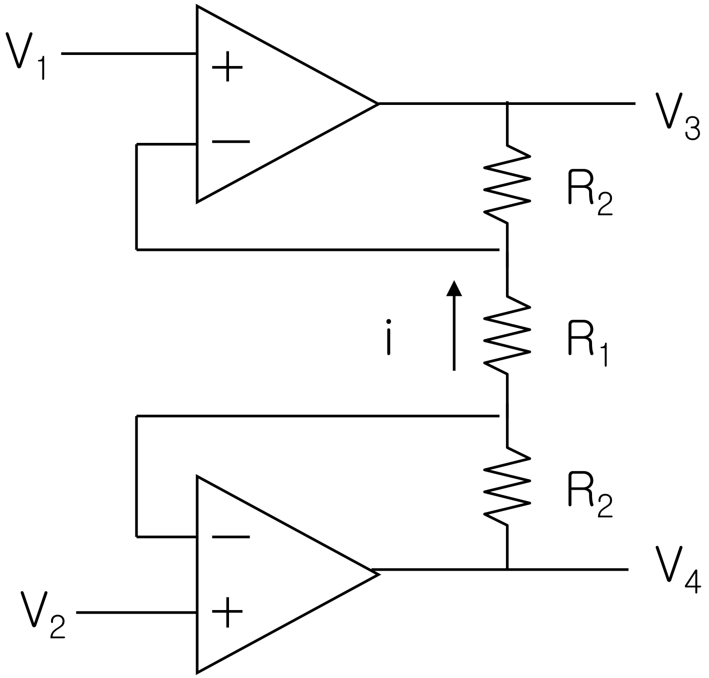
Differential Amplifiers (Cont.)

- CMRR (Common Mode Rejection Ratio)
  - Measure of the ability to reject CMV
  - CMRR = DG / CMG
    - The Higher CMRR, the better quality
    - Typically, 100 ~ 10,000
    - 60Hz noise common to V1 and V2 can be rejected

Instrumentation Amplifiers

- The One OP Amp Differential Amplifier is not desirable.
  - Input Impedance is not so High
    - Good for Low impedance source
      - Strain gage Bridge
    - Bad for High impedance source
- Thus An Instrumentation Amplifier consists of
  - Differential Amp with High Input Impedance and Low Output Impedance
  - Two Noninvering Amp + One Differential Amp

For High Input Impedance



If $V_1=V_2$ (CMG)
→ $i=0$
→ $V_1=V_2=V_3=V_4$
→ G_c (CMG) $=0$

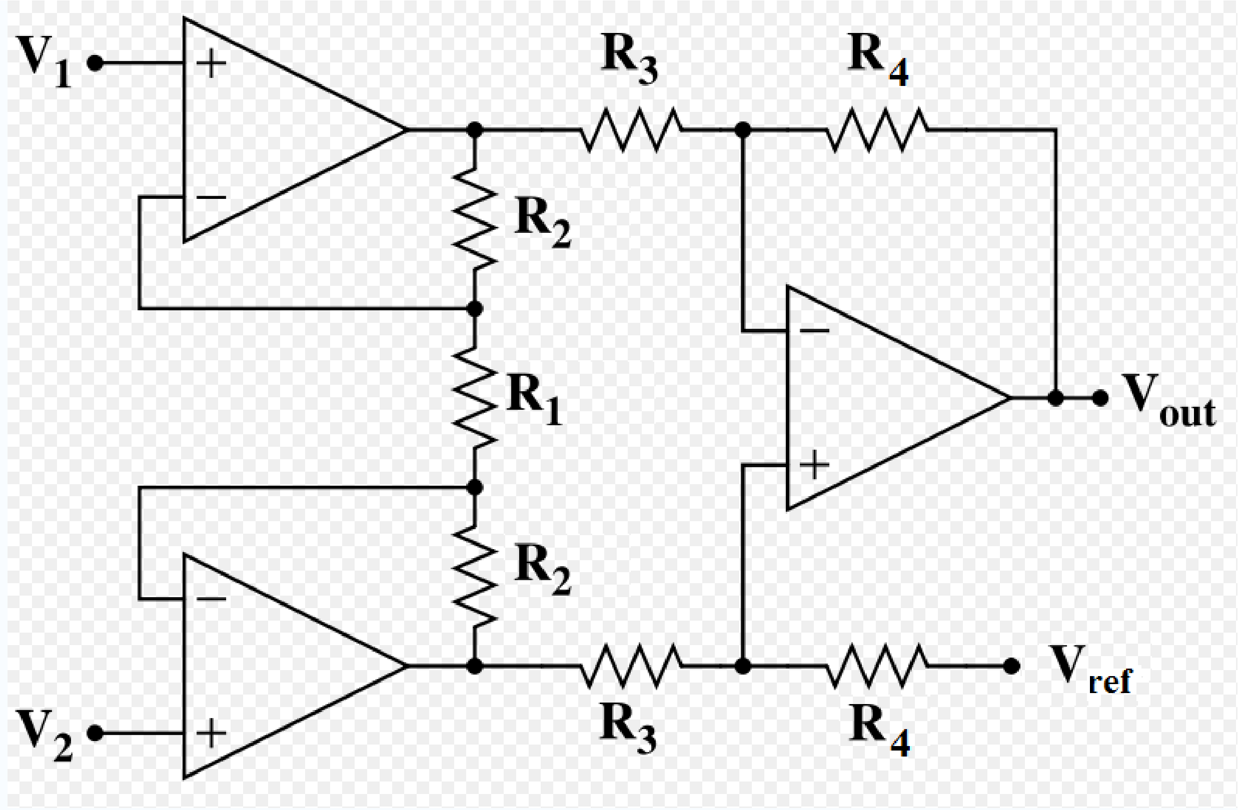
If $V_1 \neq V_2$ (DMG)
→ $i=(V_2-V_1)/R_1$

$$\frac{V_4-V_3}{V_2-V_1}=\frac{R_1+2R_2}{R_1}=1+2\cdot\frac{R_2}{R_1}$$

Complete Design of Instrumentation Amp.

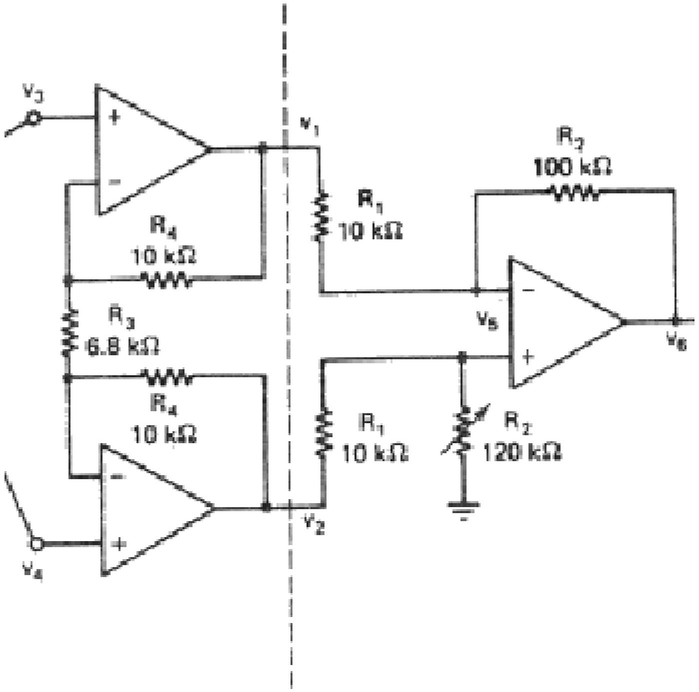
$$V_{out} - V_{ref} = G(v_2 - v_1)$$

$$G = \frac{R_4}{R_3}\left(1 + 2\frac{R_2}{R_1}\right)$$



Instrumentation Amplifiers (Cont.)

- Instrumentation Amp = Noninverting Amp + Differential Amp



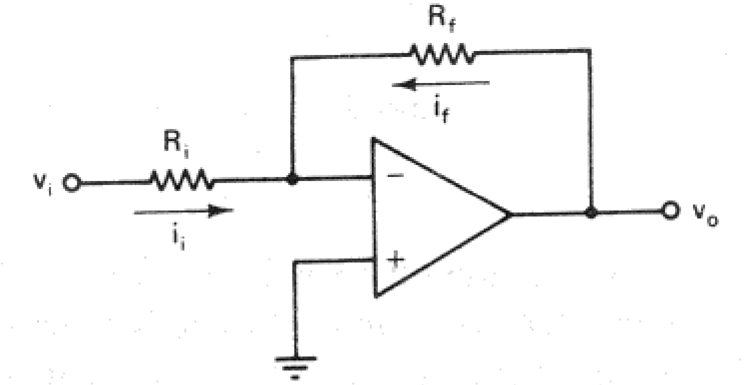
  - DG = (V1−V2) / (V3−V4)
    = (2*R4 + R3) / R3
  - V6 = (V3−V4)*DG*R2 / R1
- First Stage CMRR
  - CMRR = DG/CMG = DG
- Overall CMG = 0
  - High CMRR
- High Input Impedance
- Gain is adjustable by changing R3

Analog Computation

- Digital Signal Processing is preferred
  - Flexibility
  - Easy to Change
  - Elimination of hardware
- Analog Signal Processing
  - Is preferred when DSP consumes too much time

Inverter and Scale Changer

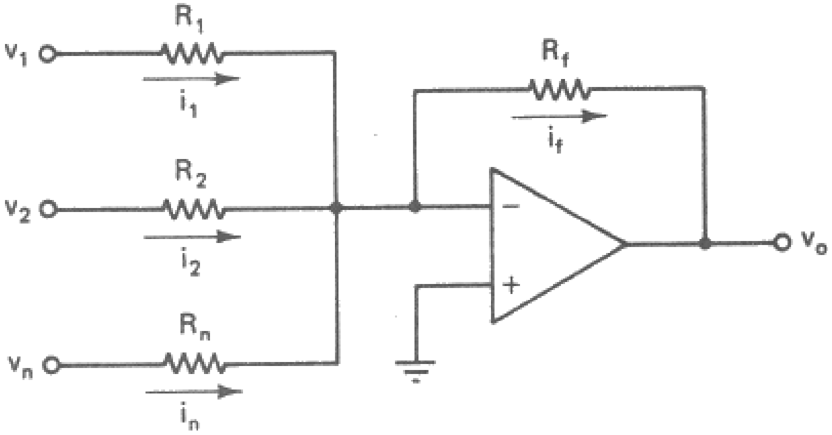
- Inverting Amp with Gain = − Rf / Ri



- Inverter
  - Rf / Ri = 1
- Inverter and Scale Changer
  - Proper choice of Rf / Ri
- Application
  - Use of inverter to scale the output of DAC

Adders (Summing Amplifiers)

- Adder
  - Inverter with Several inputs

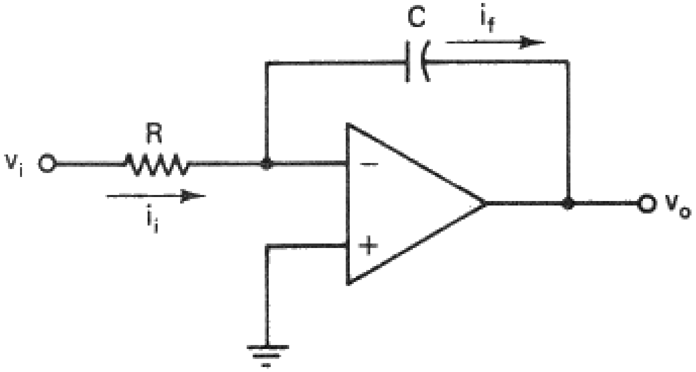


- Vo = −Rf(V1/R1 + V2/R2 +⋯ + Vn/Rn)
  - If = I1 + I2 + In
  - I1 = V1/R1, ⋯
  - Vo = −If * Rf
- Rf determines overall Gain
- Ri determines weighting factor and input impedance

Integrator

- Self homework
  - Show that

$$v_0 = \frac{-1}{RC}\int_0^{t_1} v_i dt + v_{ic}$$

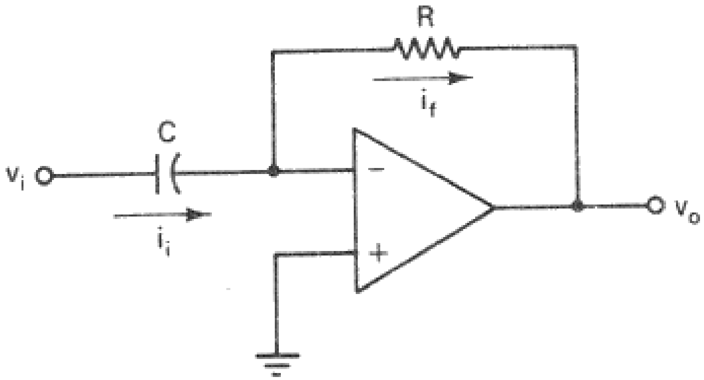


- Drawbacks
  - Vo will reach saturation voltage, if Vi is left connected indefinitely
    - Integrator operates as an open-loop amplifier for DC inputs

Differentiators

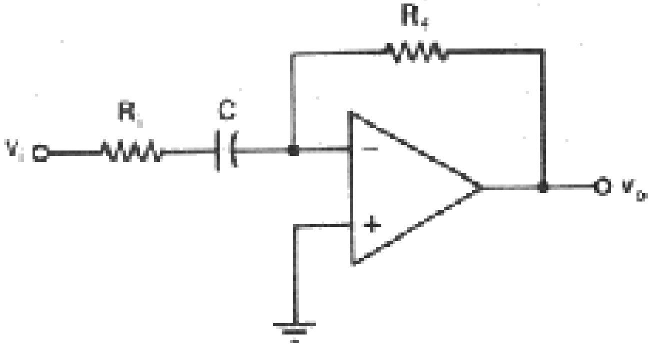
- Self Homework
- Show that

$$v_0 = -RC\frac{dv_i}{dt}$$



- Drawbacks
  - Instability at High frequencies
- Practical Differentiator
  - To Stable

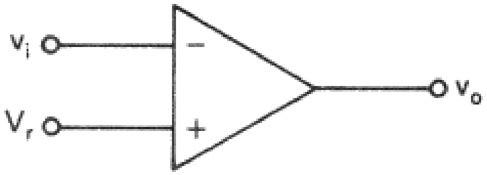
$$R_i = \sqrt{\frac{R}{A_0\omega_0 C}}$$

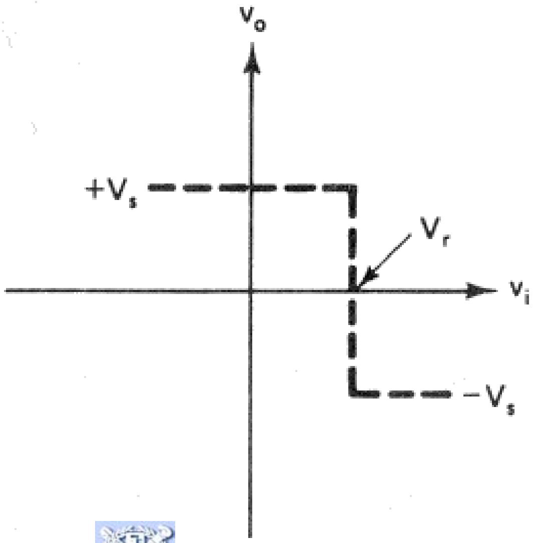


Comparators

- Compare Two Inputs
  - Vi > Vr
    - Vo = −Vs
  - Vi < Vr
    - Vo = Vs

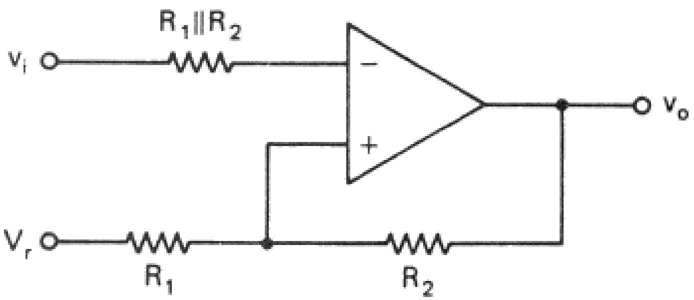
- Drawbacks
  - If Vi = Vr + small noise
    - Rapid fluctuation between ± Vs





Comparators with Hysteresis

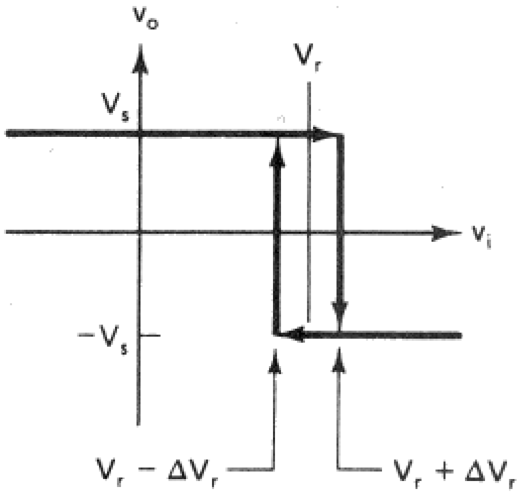
- Positive Feedback
  - Hysteresis loop
  - Can remove the effect of Small Noise
    - Reduce Fluctuation



- Homework
  - Show that

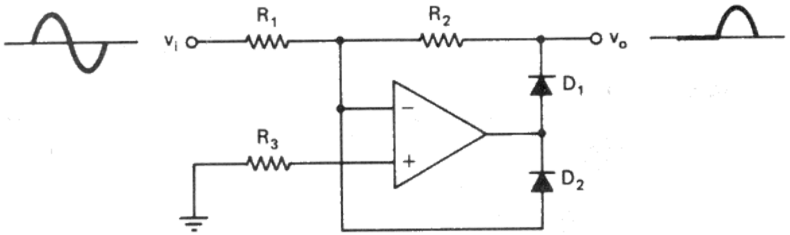
$$V_r+\Delta V_r=V_r+\frac{(V_S-V_r)R_1}{R_1+R_2}$$

$$V_r-\Delta V_r=V_r+\frac{(-V_S-V_r)R_1}{R_1+R_2}$$

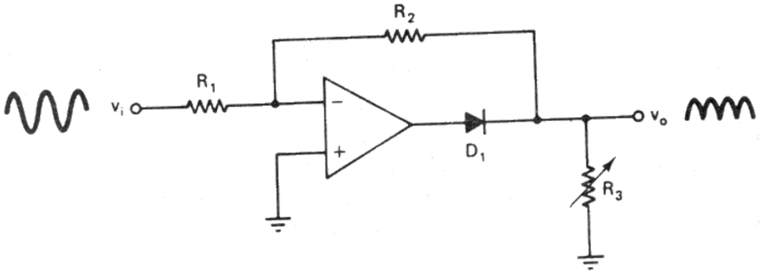


Rectifiers

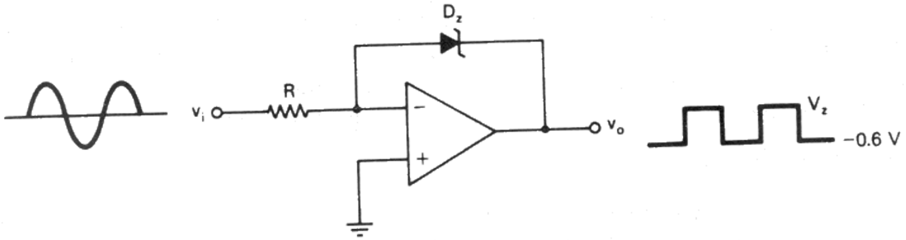
- Precision Half Wave Rectifier



- Precision Full Wave Rectifier



- Limiters



Practical OP Amp Considerations

- Effects of Nonlinear characteristics
  - Compensation
    - Undesirable Oscillation at High frequency
      - Add external Capacitance according to Spec sheet
  - GBW (Gain Bandwidth Product)
    - Gain × Bandwidth = Constant (Typically 1MHz)
      - For Noninverting Amp: Bandwidth = GBW / Gain
  - Input Offset Voltage
    - Practical OP Amp
      - Zero input Does NOT give Zero output
    - Input Offset Voltage
      - Applied input voltage to obtain Zero output
    - Nulling the offset Voltage
      - Adding External Resister according to Spec sheet

OP Amp Considerations (Cont.)

- Input Bias Current
  - Practical OP amp
    - Current flowing into the terminal is NOT Zero
    - To keep the input Tr of OP amp turned on
    - Causes errors proportional to feedback network R
  - To minimize errors
    - feedback R should be low (<10KΩ)
- Slew Rate
  - Maximal rate of change of amplifier output voltage
    - Ex: Slew rate of 741 = 0.5 V / μs
      - » Time to output change from –5V to 5V = 20 μs
  - To Minimize slew rate problem
    - Use OP amp with smaller external compensating C

OP Amp Considerations (Cont.)

- Power Supply
  - Usually ±15V
    - Linear Range ±13V
  - Reducing power supply voltage
    - Results reduced linear range
    - Device does not work < 4V
- Different OP Amps
  - Bipolar Op Amps
    - Good input offset stability
    - Moderate input bias current and Input resistances
  - FET
    - Very Low input bias current and Very High Input resistances
    - Poor Input offset voltage stability

OP Amps on the market

- Common OP amps, Typical Specifications

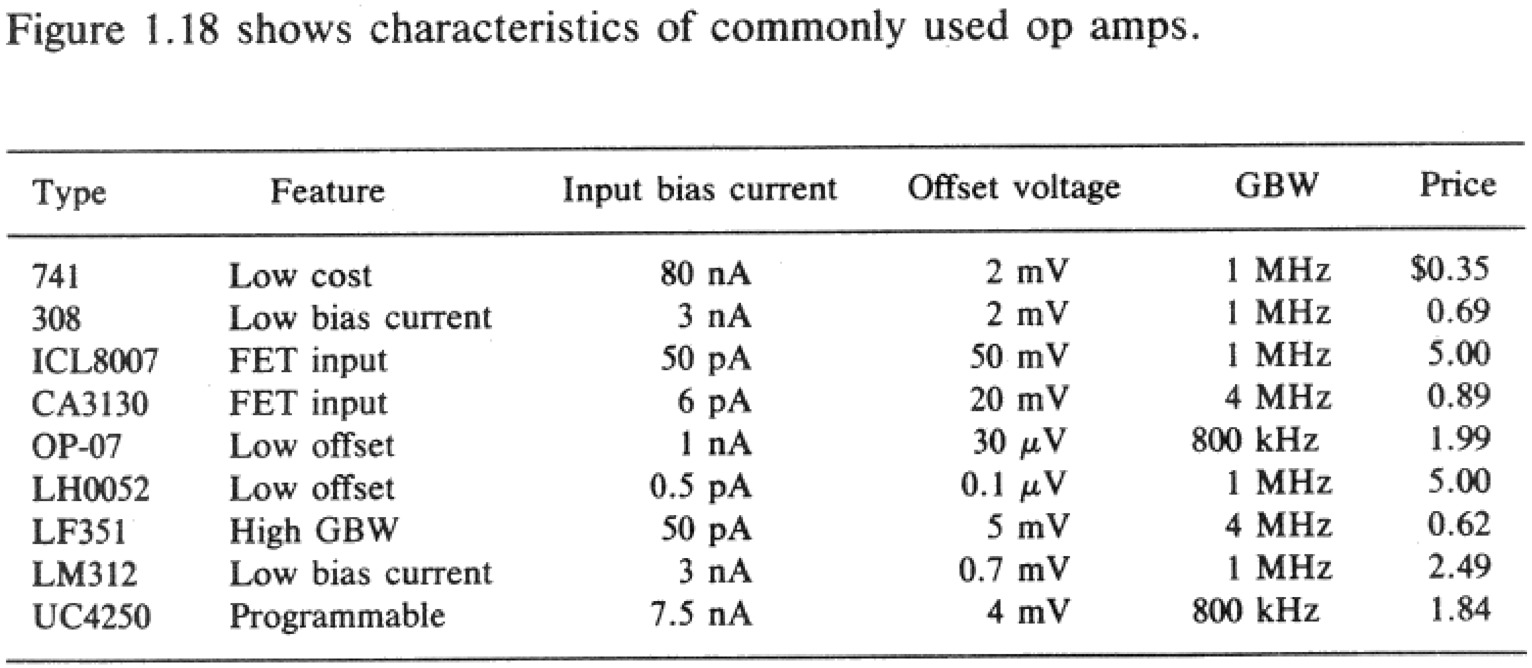


Figure 1.18 shows characteristics of commonly used op amps.

Type	Feature	Input bias current	Offset voltage	GBW	Price
741	Low cost	80 nA	2 mV	1 MHz	$0.35
308	Low bias current	3 nA	2 mV	1 MHz	0.69
ICL8007	FET input	50 pA	50 mV	1 MHz	5.00
CA3130	FET input	6 pA	20 mV	4 MHz	0.89
OP-07	Low offset	1 nA	30 μV	800 kHz	1.99
LH0052	Low offset	0.5 pA	0.1 μV	1 MHz	5.00
LF351	High GBW	50 pA	5 mV	4 MHz	0.62
LM312	Low bias current	3 nA	0.7 mV	1 MHz	2.49
UC4250	Programmable	7.5 nA	4 mV	800 kHz	1.84

Filters

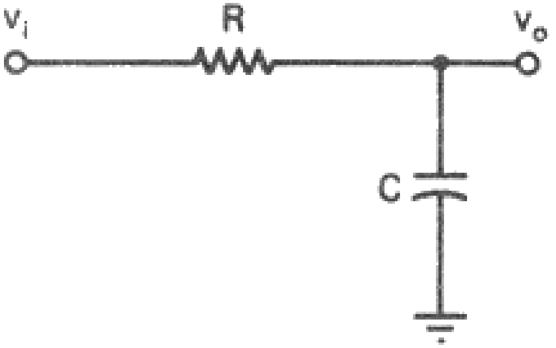
- Passive Circuits
  - Contains only passive elements
    - Registers, Capacitors and Inductors
  - Examples
    - Bridge Circuit
    - Voltage Divider
    - Filters
- Filters
  - Eliminate unwanted signal from the loop
  - Low Pass, High Pass, Band Pass, Notch, …

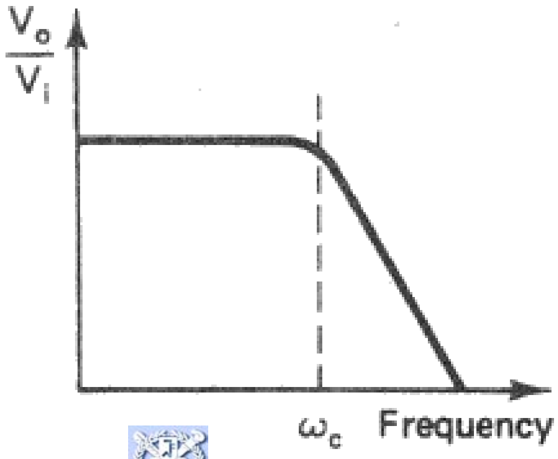
Passive first-order Low pass Filter

- Pass desired Audio signal and reject undesired RF
- Order of Filter
  - Number of C and L
- Show that

$$\frac{V_o}{V_i} = \frac{1}{1 + j\omega\tau}, \quad \tau = RC$$

  - Plot Magnitude and Phase plot (Bode plot)
  - Meaning of ω_C





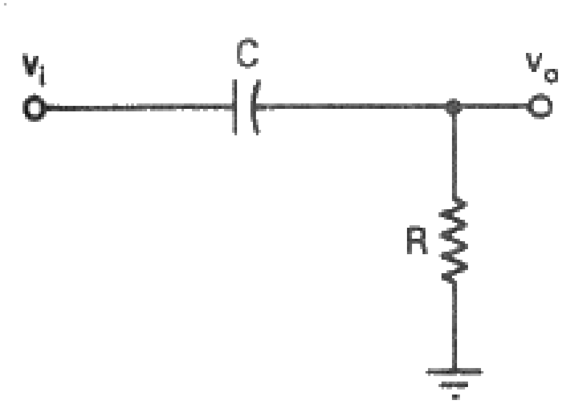
Passive first-order High pass Filter

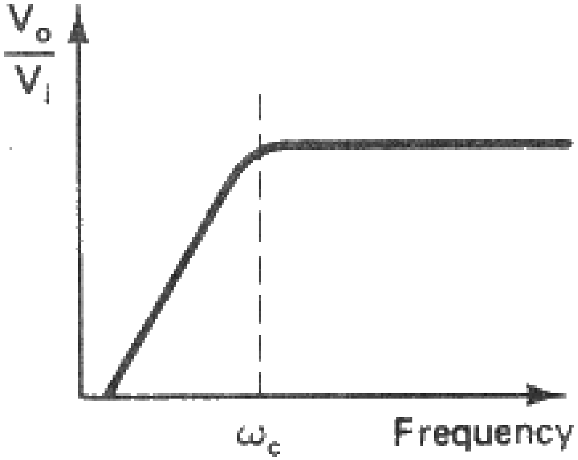
- Pass desired High frequency signal and reject undesired low frequency signal

- Show that

$$\frac{V_o}{V_i}=\frac{j\omega\tau}{1+j\omega\tau}, \quad \tau = RC$$

- Plot Magnitude and Phase plot (Bode plot)
- Meaning of ω_C





Passive second-order Low pass Filter

- To increase the attenuation of transfer function
- Order of Filter
  - ◆ Number of C and L

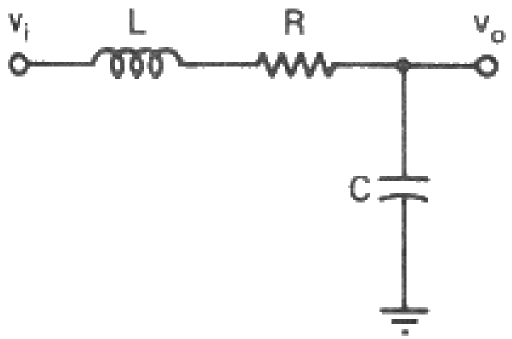
◆ Show that

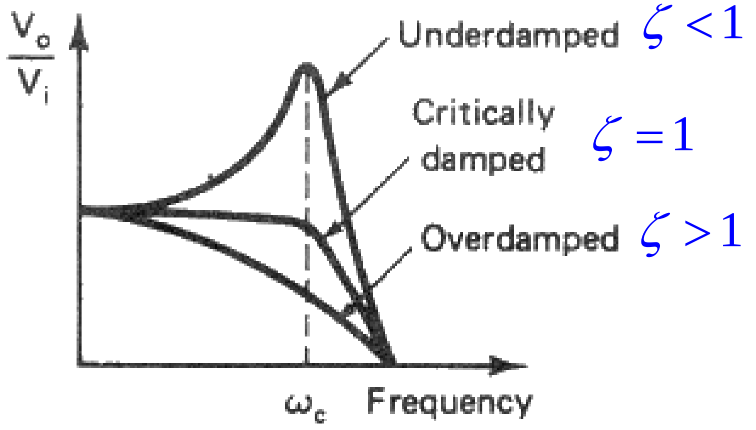
$$\frac{V_o}{V_i} = \frac{1}{(j\omega/\omega_c)^2 + (2\zeta\, j\omega/\omega_c) + 1}$$

$$\omega_c = \sqrt{\frac{1}{LC}}, \zeta = \frac{R}{2}\sqrt{\frac{C}{L}}$$

◆ Meaning of Quality factor

$$Q = \frac{1}{2\zeta} = \frac{\omega_c}{\Delta\omega}, \Delta\omega = 3dB\,BW$$





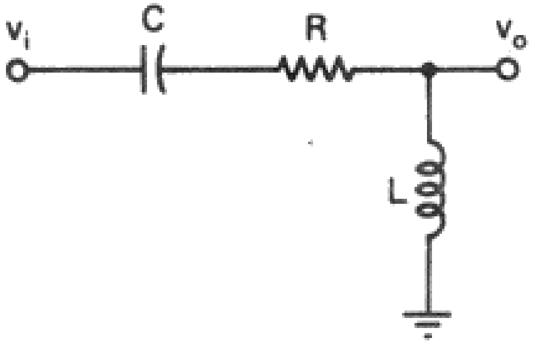
Passive second-order High pass Filter

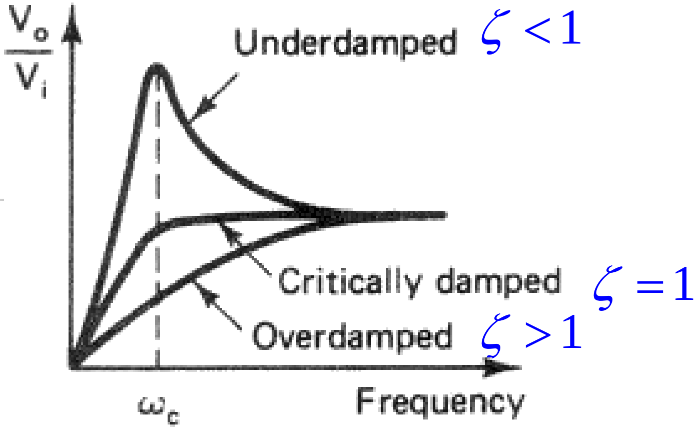
- To increase the attenuation of transfer function
- Order of Filter
  - ◆ Number of C and L

◆ Show that

$$\frac{V_o}{V_i} = \frac{\omega^2}{(j\omega/\omega_c)^2 + (2\zeta\, j\omega/\omega_c) + 1}$$

$$\omega_c = \sqrt{\frac{1}{LC}}, \zeta = \frac{R}{2}\sqrt{\frac{C}{L}}$$

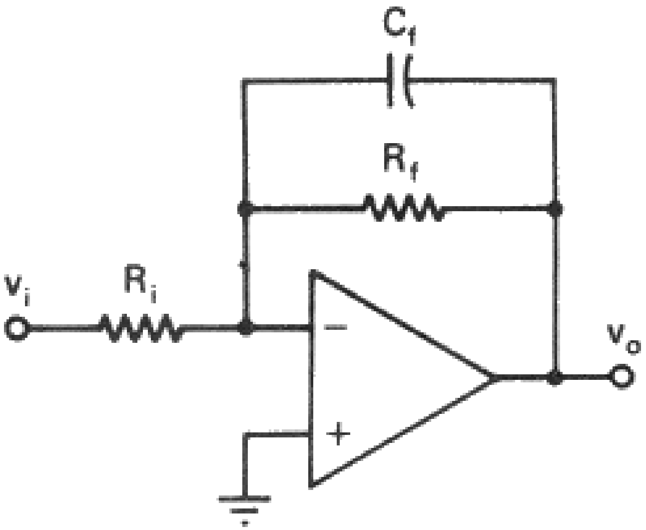


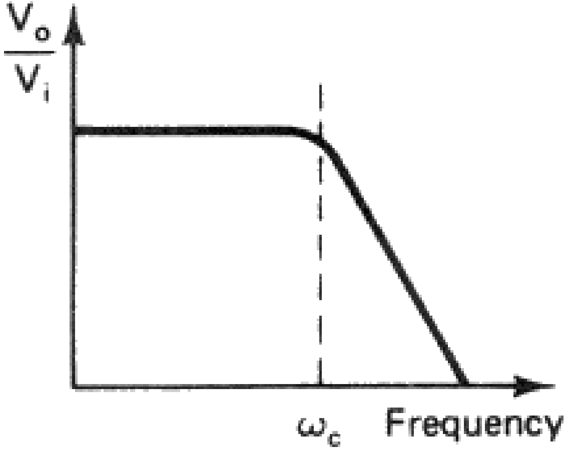


Active First-order Low Pass Filter

- Inverting Amp + Feedback Capacitor

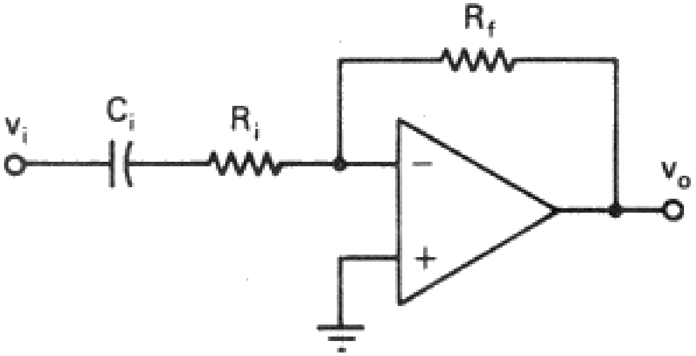
- Identical frequency response with Passive filter
- Very Low Output impedance
  - Negligible Loading Effect

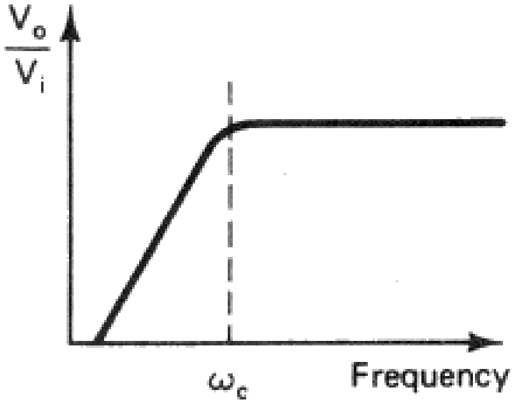




Active First-order High Pass Filter

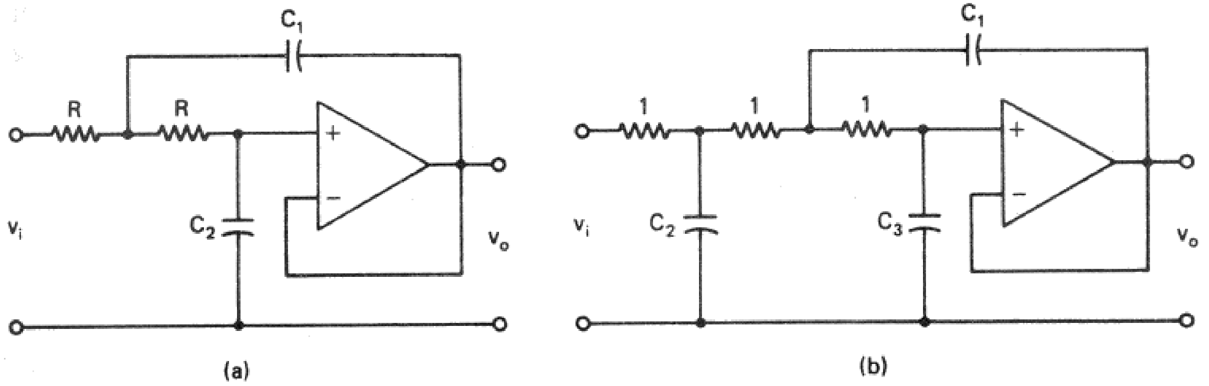
- Inverting Amp + Input Capacitor
- Identical frequency response with Passive filter
- Very Low Output impedance
  - Negligible Loading Effect



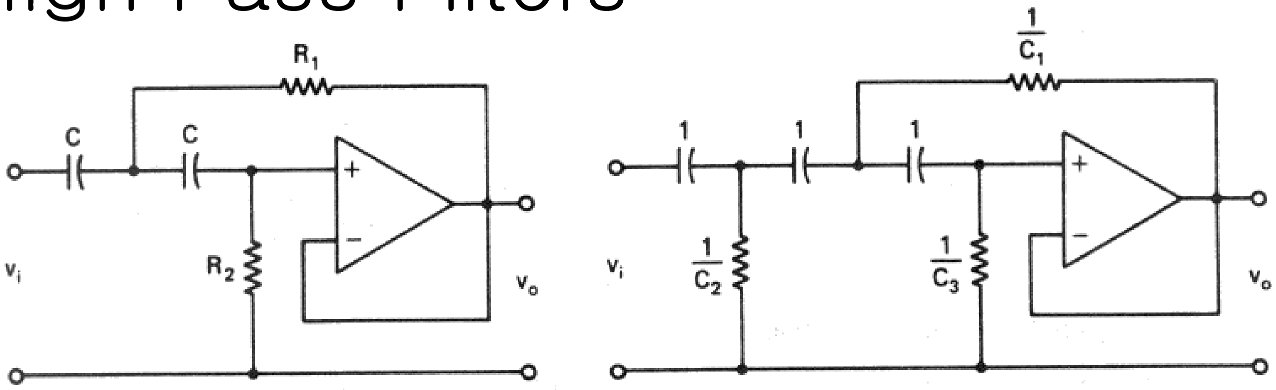


Active High-order Filters

- Low Pass Filters



- High Pass Filters

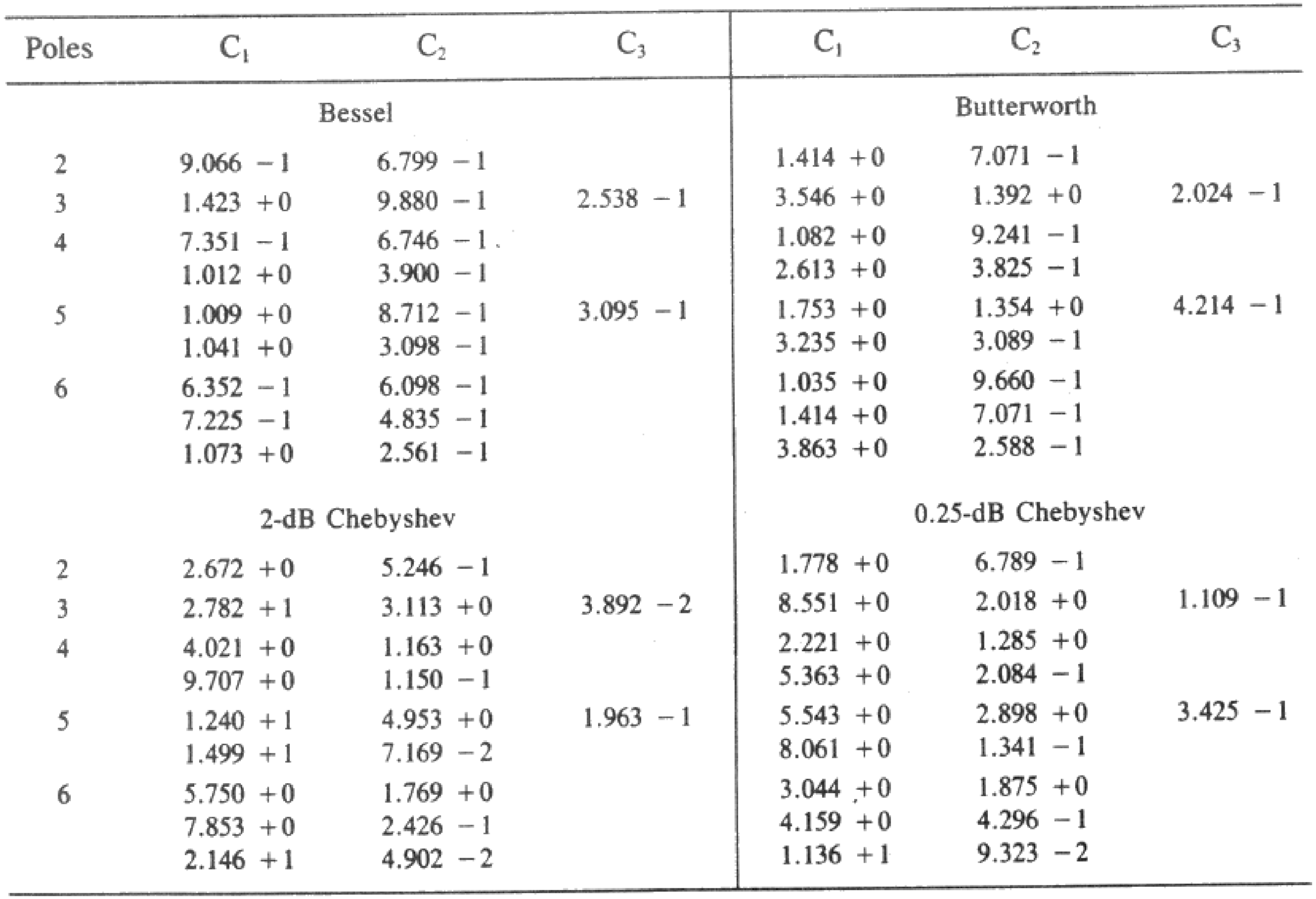


Bandpass and Band-reject Filters

- Butterworth Filters
  - Maximally Flat Magnitude response in pass band
  - High Attenuation Rate
- Chebyshev Filters
  - Maximum Attenuation Rate
  - Ripple in pass band
- Bessel Filters
  - Maximally flat time delay in response to step input
  - Attenuation Rate is very gradual

Filter Design Table

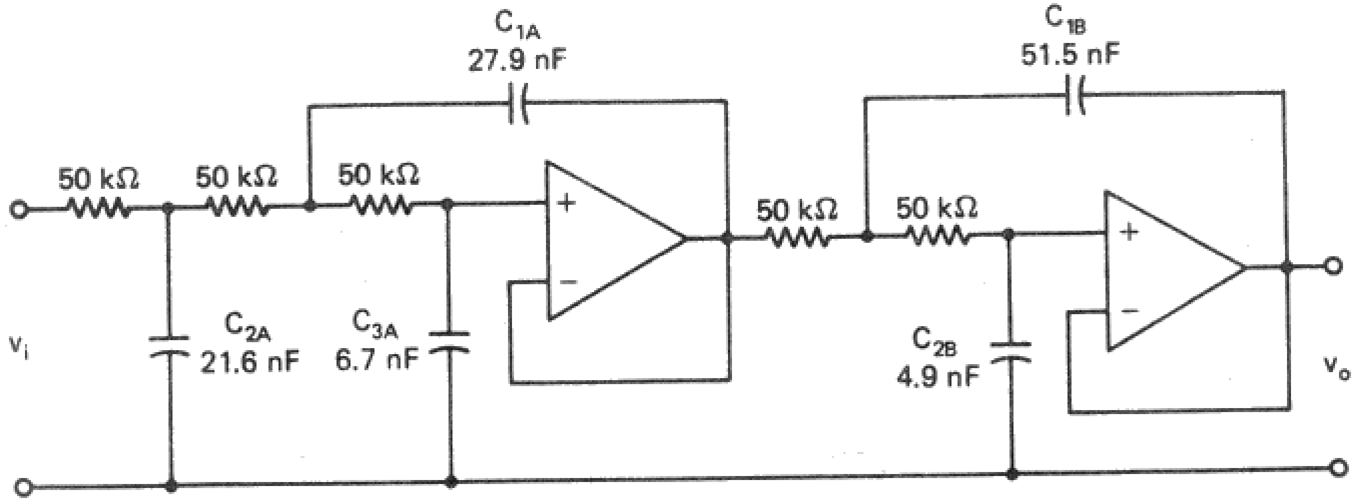
- C when $\omega_0 = R_0 = 1$



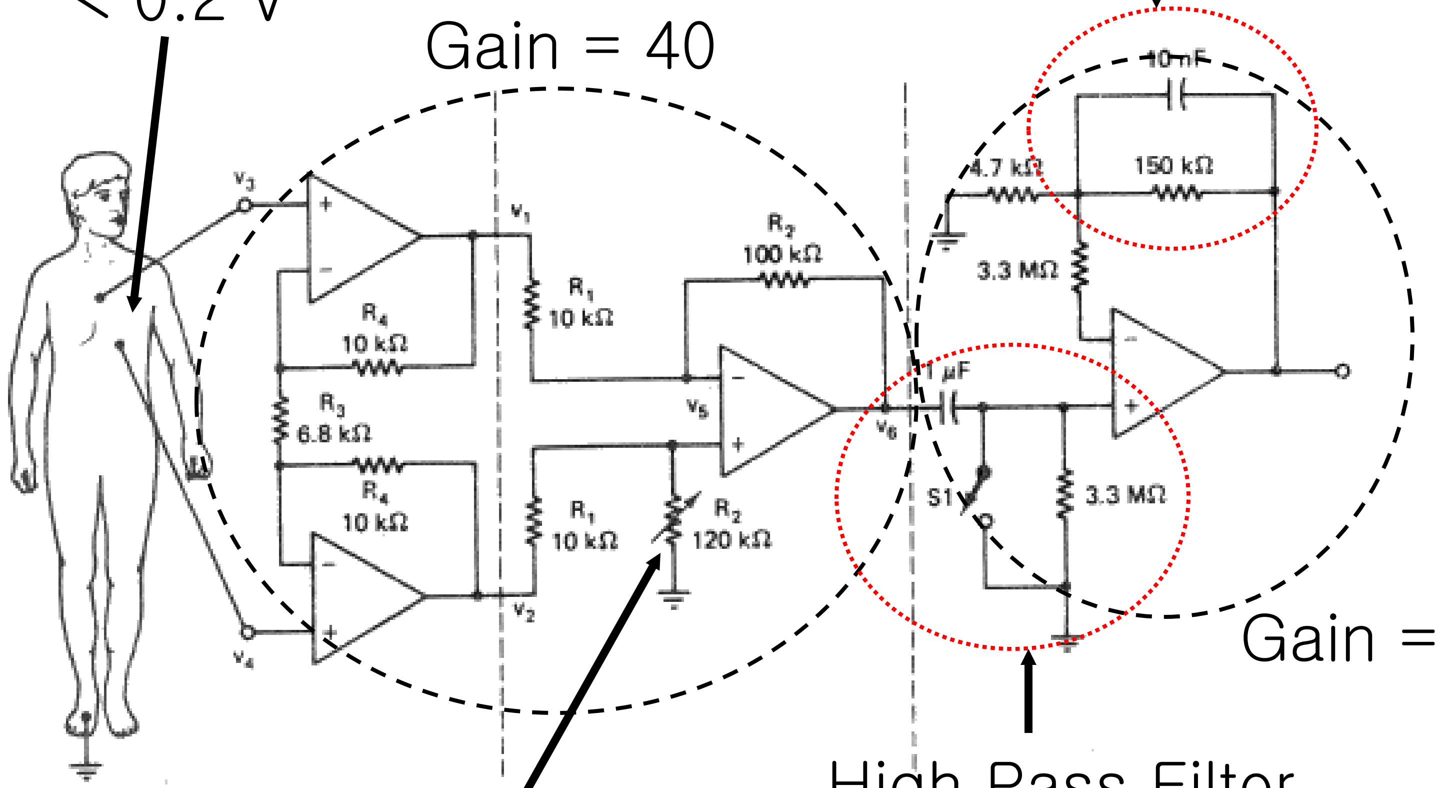
Poles	C_1	C_2	C_3	C_1	C_2	C_3
		Bessel			Butterworth	
2	9.066 −1	6.799 −1		1.414 +0	7.071 −1	
3	1.423 +0	9.880 −1	2.538 −1	3.546 +0	1.392 +0	2.024 −1
4	7.351 −1	6.746 −1		1.082 +0	9.241 −1	
	1.012 +0	3.900 −1		2.613 +0	3.825 −1	
5	1.009 +0	8.712 −1	3.095 −1	1.753 +0	1.354 +0	4.214 −1
	1.041 +0	3.098 −1		3.235 +0	3.089 −1	
6	6.352 −1	6.098 −1		1.035 +0	9.660 −1	
	7.225 −1	4.835 −1		1.414 +0	7.071 −1	
	1.073 +0	2.561 −1		3.863 +0	2.588 −1	
		2-dB Chebyshev			0.25-dB Chebyshev	
2	2.672 +0	5.246 −1		1.778 +0	6.789 −1	
3	2.782 +1	3.113 +0	3.892 −2	8.551 +0	2.018 +0	1.109 −1
4	4.021 +0	1.163 +0		2.221 +0	1.285 +0	
	9.707 +0	1.150 −1		5.363 +0	2.084 −1	
5	1.240 +1	4.953 +0	1.963 −1	5.543 +0	2.898 +0	3.425 −1
	1.499 +1	7.169 −2		8.061 +0	1.341 −1	
6	5.750 +0	1.769 +0		3.044 +0	1.875 +0	
	7.853 +0	2.426 −1		4.159 +0	4.296 −1	
	2.146 +1	4.902 −2		1.136 +1	9.323 −2	

Filter Design Example

- Low pass five-pole Butterworth filter with a corner frequency of 200Hz and input resistance of 50KΩ
  - Economic Solution = 3rd order + 2nd order
  - Desired R and C ?
    - $C_{1A} = (\omega_0 R_0 C_0) / (\omega R)$
      $= 1 \times 1 \times 1.753 / 2\pi \times 200 \times 50K = 27.9$ nF
    - $C_{2A} = 21.6$ nF, $C_{3A} = 6.7$ nF, $C_{1B} = 51.5$ nF, $C_{2B} = 4.9$ nF



The Electrocardiogram Amplifier



Low Pass Filter
< 100Hz

< 0.2 V

Gain = 40

Gain = 32

Maximize CMRR

High Pass Filter
>0.05Hz

Interference

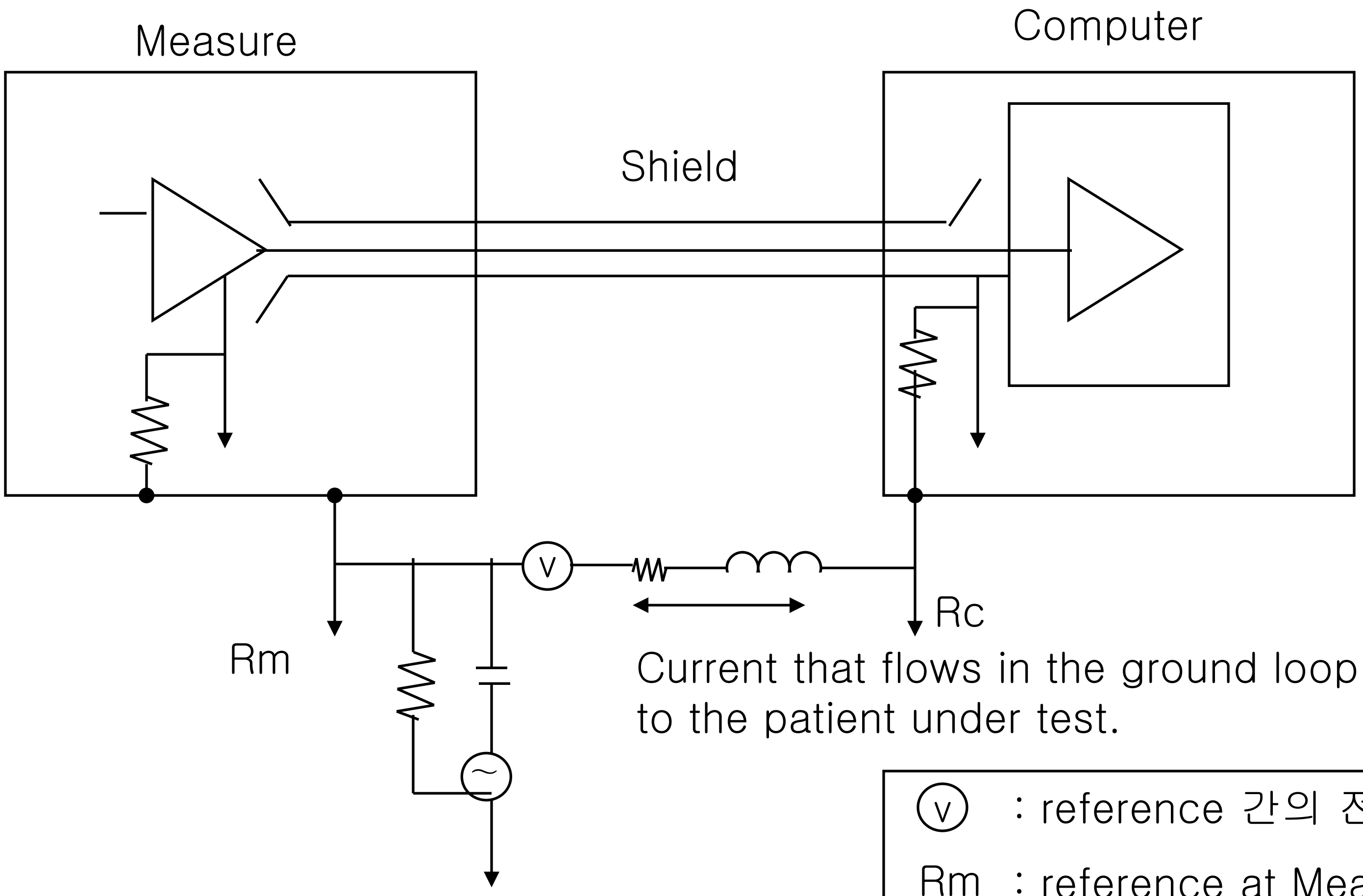
- Noise : random
- Interference : not random, comes from a known source

- Dominant interference : 60Hz
  - Thru. ① AC capacitive coupling
    ② AC inductive coupling
    ③ Ground loops
  - Solutions
    (1) Elimination at the source
      - Use of Instrumentation Amps and Isolation Amps.
      - Star Ground (one true ground)

    (2) (Adaptive) Filtering

Grounding & Instrumentation Amp.

- Ground Loop is a problem.



Current that flows in the ground loop can be fatal to the patient under test.

Ⓥ : reference 간의 전위차
Rm : reference at Measure
Rc : reference at Computer

Grounding & Instrumentation Amp.

- Ground Loop => safety

  During ExG (x=E,M,C etc.) measurements, a ground loop current can threaten the safety of the patient under measurement.

- Bias current => safety

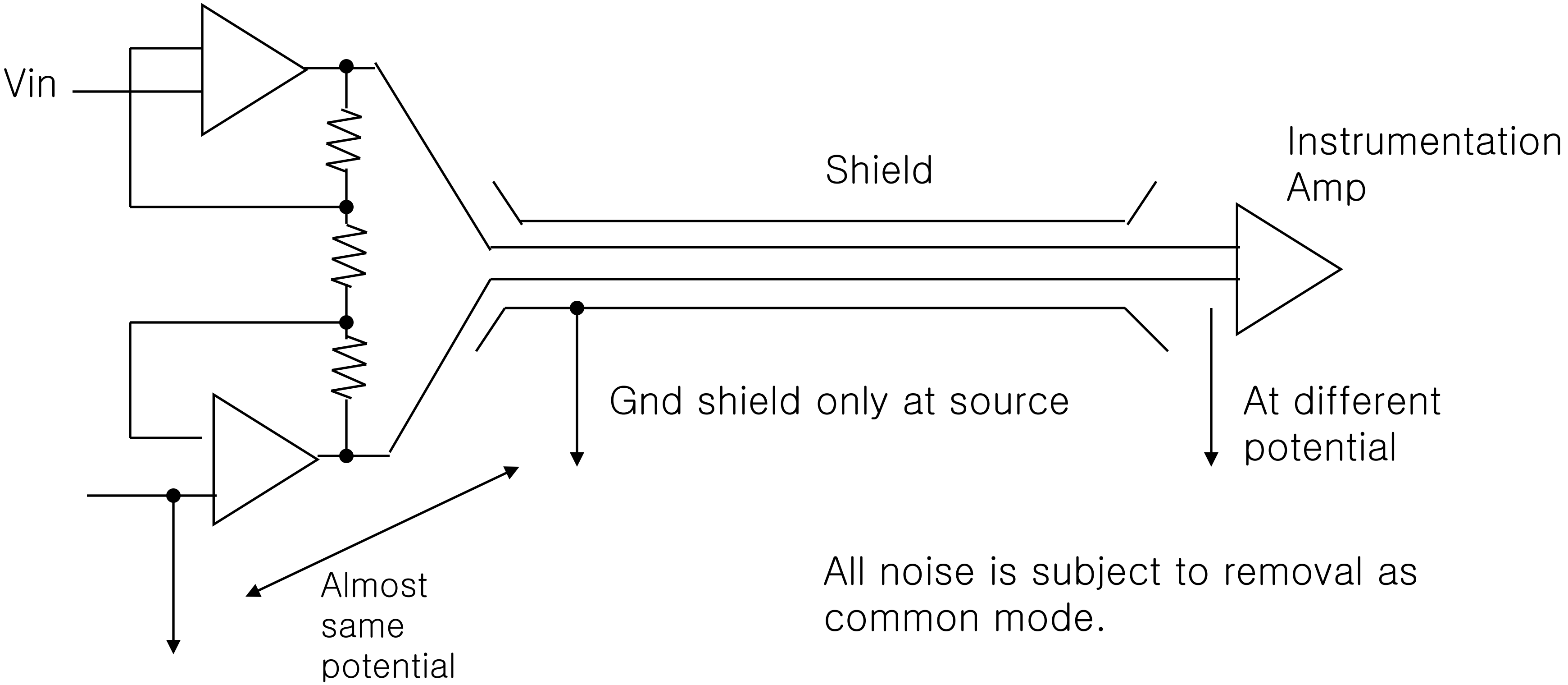
  Devices with particularly small I_B is favored.

  Ex) AD55L max I_B = 75fA

  AD00L max I_B = 10fA

Grounding & Instrumentation Amp.

- **Solution : (I) Differential Transmission :**
- Grounding only at source to prevent the group loop.



Vin

Shield

Instrumentation
Amp

Gnd shield only at source

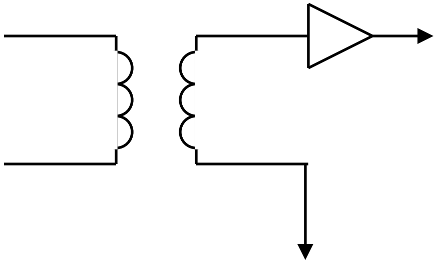
At different
potential

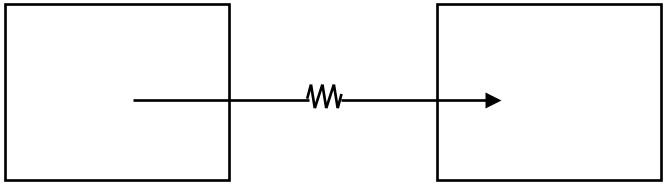
Almost
same
potential

All noise is subject to removal as
common mode.

Grounding & Instrumentation Amp.

- Solution(II) : Isolation between Measure and Computer stations.
  - By transformer

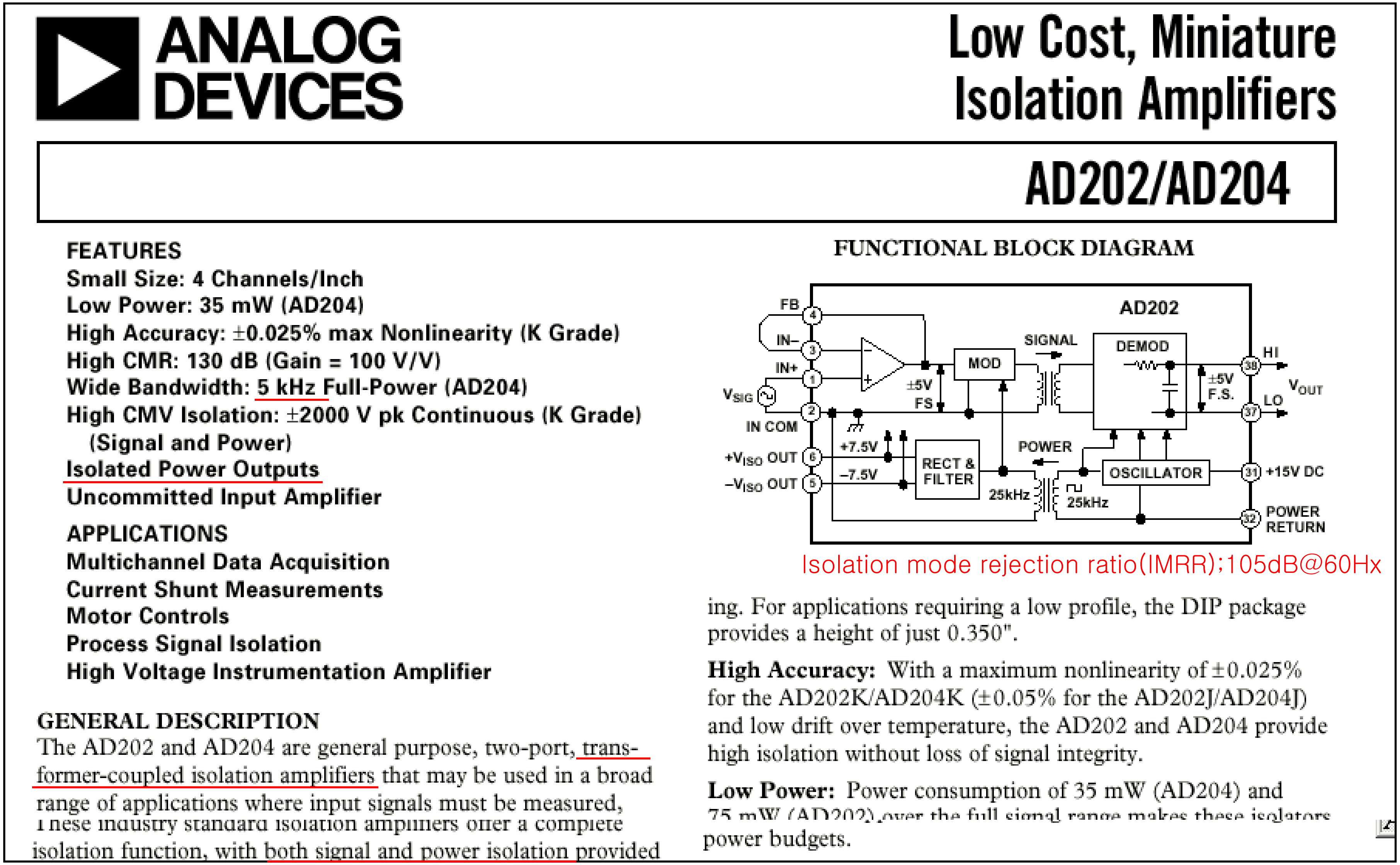




Optics, RF ....

  - Optical coupling :optical isolator : (LED/LD)-PD combination
  - Radio link
    - Signal – Modulator – Transmitter …– Receiver – Demodulator

Datasheet



ANALOG DEVICES

Low Cost, Miniature Isolation Amplifiers

AD202/AD204

FEATURES
- Small Size: 4 Channels/Inch
- Low Power: 35 mW (AD204)
- High Accuracy: ±0.025% max Nonlinearity (K Grade)
- High CMR: 130 dB (Gain = 100 V/V)
- Wide Bandwidth: 5 kHz Full-Power (AD204)
- High CMV Isolation: ±2000 V pk Continuous (K Grade) (Signal and Power)
- Isolated Power Outputs
- Uncommitted Input Amplifier

APPLICATIONS
- Multichannel Data Acquisition
- Current Shunt Measurements
- Motor Controls
- Process Signal Isolation
- High Voltage Instrumentation Amplifier

FUNCTIONAL BLOCK DIAGRAM

Isolation mode rejection ratio(IMRR);105dB@60Hx

GENERAL DESCRIPTION

The AD202 and AD204 are general purpose, two-port, transformer-coupled isolation amplifiers that may be used in a broad range of applications where input signals must be measured,

These industry standard isolation amplifiers offer a complete isolation function, with both signal and power isolation provided

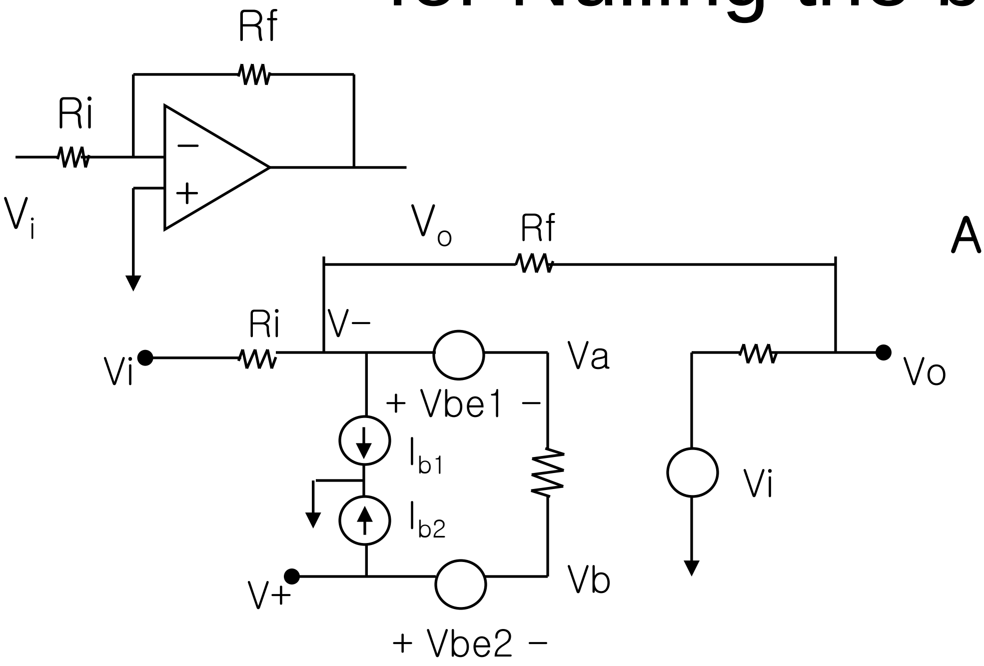
ing. For applications requiring a low profile, the DIP package provides a height of just 0.350".

High Accuracy: With a maximum nonlinearity of ±0.025% for the AD202K/AD204K (±0.05% for the AD202J/AD204J) and low drift over temperature, the AD202 and AD204 provide high isolation without loss of signal integrity.

Low Power: Power consumption of 35 mW (AD204) and 75 mW (AD202) over the full signal range makes these isolators

power budgets.

Choice of resistors (R3 and R4) for Nulling the bias current



Assume

$$V^+ = V^-$$

$$I_{b1} = I_{b2} = I_b$$

$$\frac{Vo - V^-}{Rf} + \frac{Vi - V^-}{Ri} = Ib \quad \text{(eq 1)}$$

Ideally we want, $Vo/Rf = -Vi/Ri$ (eq 2)

Comparing eq 1 and 2,

$$I_b + V^+ /(Rf//Ri) = 0$$

This condition can be satisfied by the next circuit.