4. Amplifiers

Operational Amplifier

Instrumentation Amplifier

Analog Computation

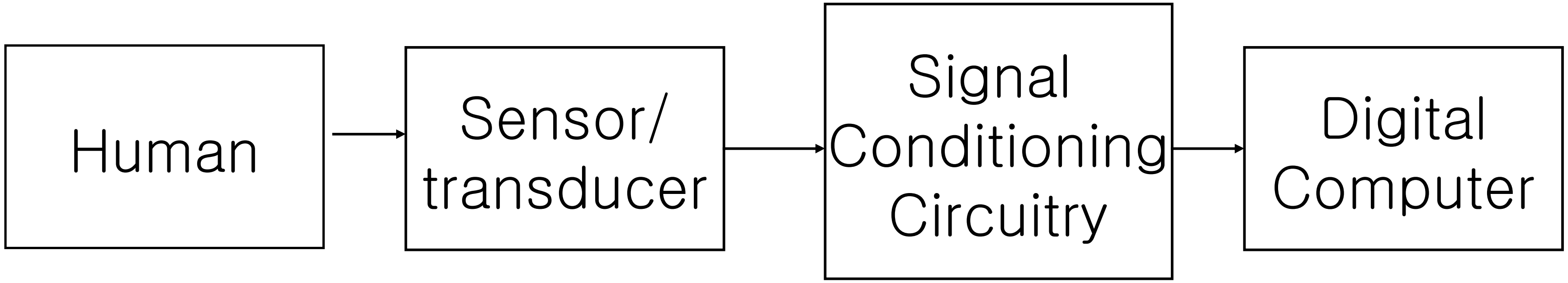
Active Filter

Grounding

Isolation

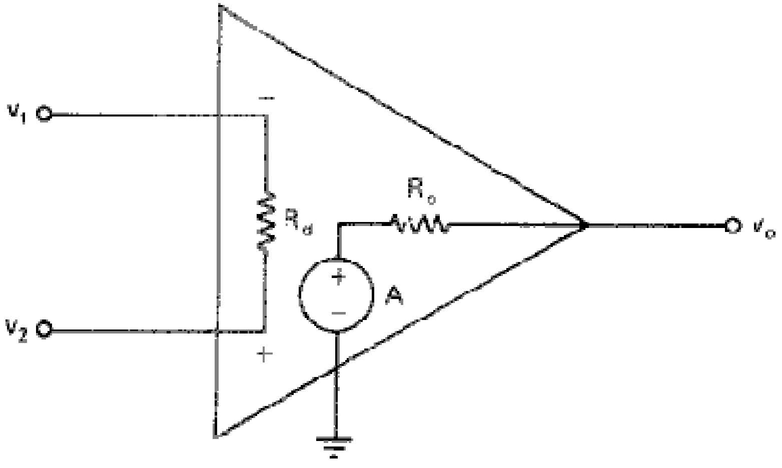
Function of Amplifiers

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



Human → Sensor/ transducer → Signal Conditioning Circuitry → Digital Computer

Ideal Amps

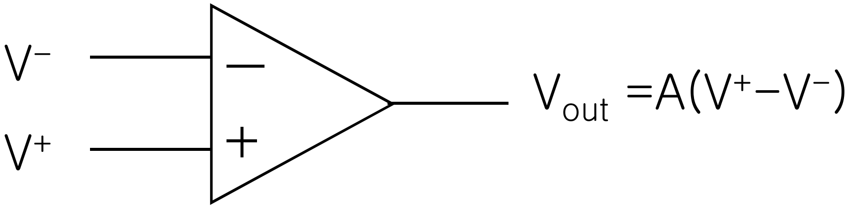


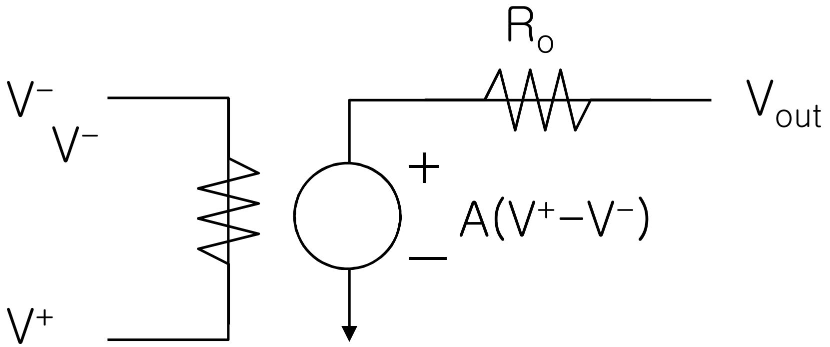
- Assumptions
  - Open loop Gain = Infinity
  - Input Impedance Rd = Infinity
  - Output Impedance Ro = 0
  - Bandwidth = Infinity
    - Infinite Frequency Response
  - v_o=0 when $v_1 = v_2$
    - No Offset Voltage

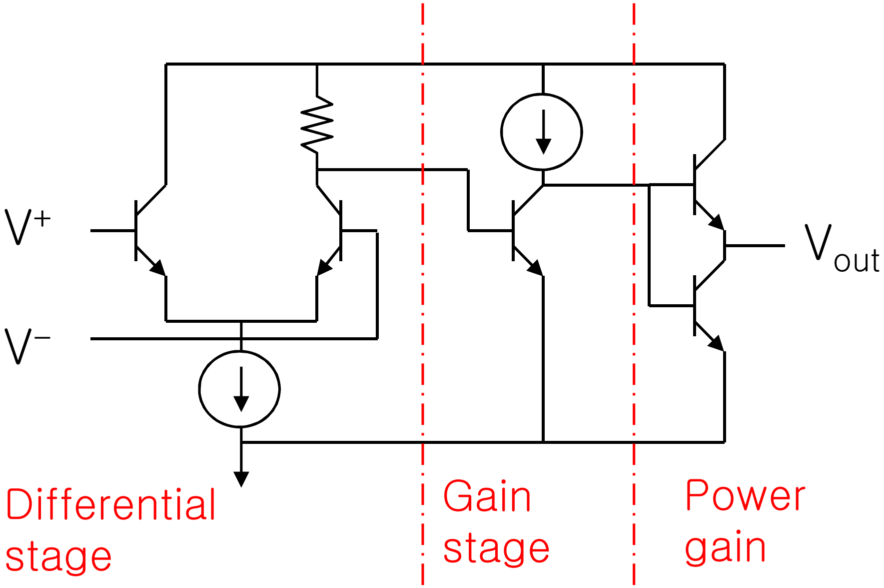
OP Amplifier Properties

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

How do we achieve these properties?







741인 경우

(Stage 1) $R=1.6\text{M}\Omega$
Gain=1200

(Stage 2) V_{tg} gain=220

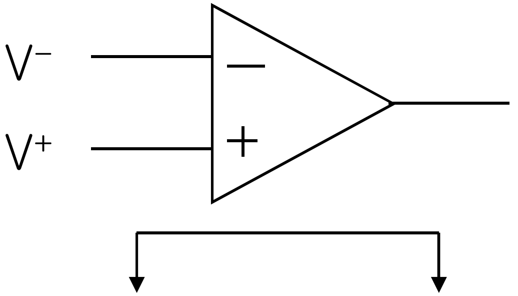
(Stage 3) $Ro=60\Omega$
V_{tg} gain=1

Overall Gain=108dB

Ideal OP Amps

- Note
  - $v_0 = A(v_2 - v_1)$
    - If $v_0 = \infty$, $A = \infty$ (Typically 100,000)
      - Then $v_2 - v_1 = 0 \Rightarrow v_2 = v_1$
    - Since $v_2 = v_1$ and $Rd = \infty$
      - We can neglect the current in Rd
- 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

Thus, The Two rules of Ideal OP Amp.



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

Rule 1: Op Amp의 output이 Linear Stage에 있을 때,

두 input은 동 전위에 있다. (Virtual Ground)

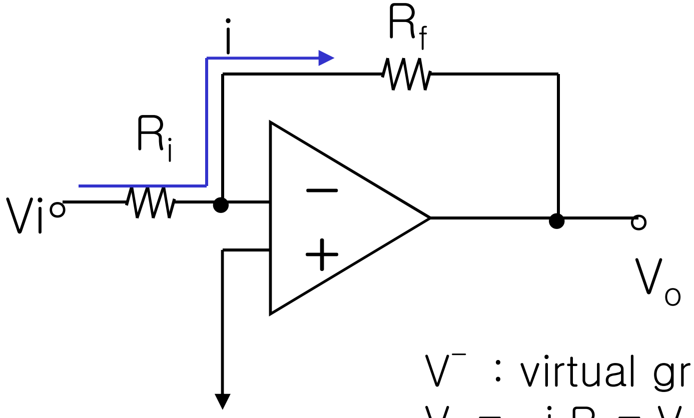
Rule 2: Op Amp의 input 단자에 입력되는 전류는 없다.

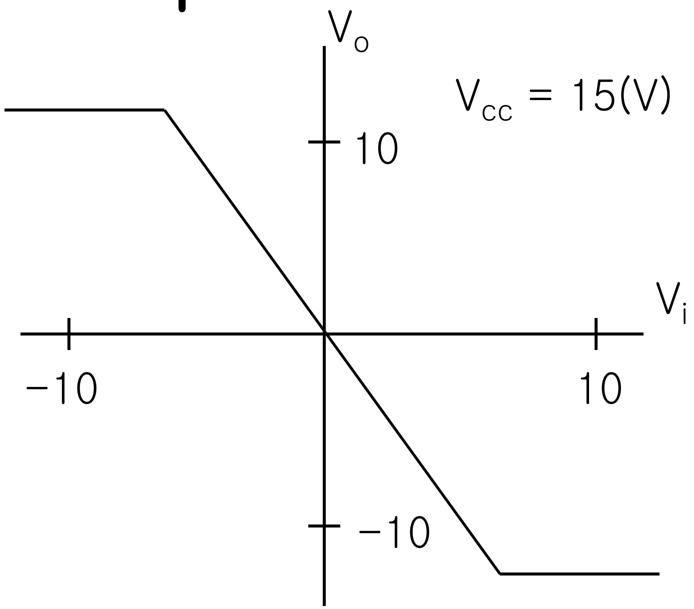
(infinite input impedance)

Basic OP Amp Circuit Blocks

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

Inverting Amp.



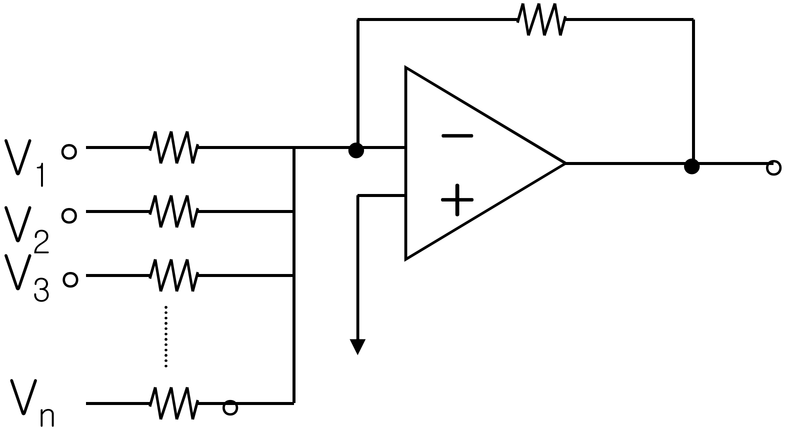


V^- : virtual ground

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

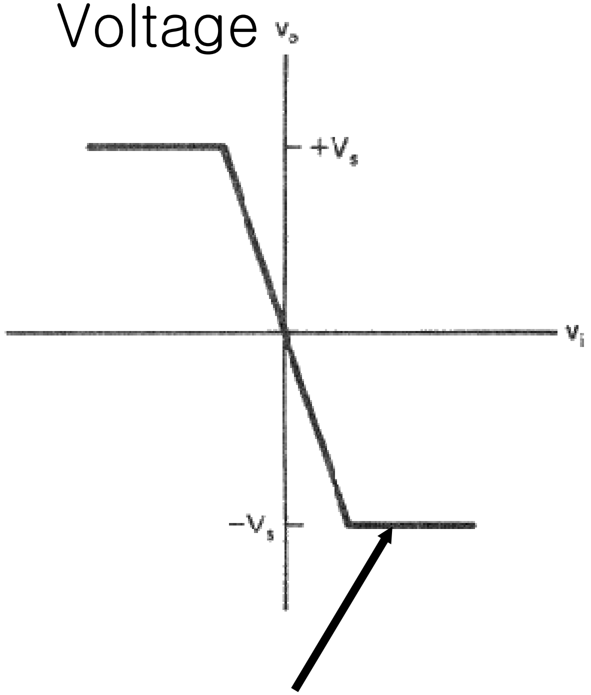
$A_v = -(R_f/ R_i)$

- Summing



Inverting Amplifier (Cont.)

- Linear Range
  - By Power Supply Voltage

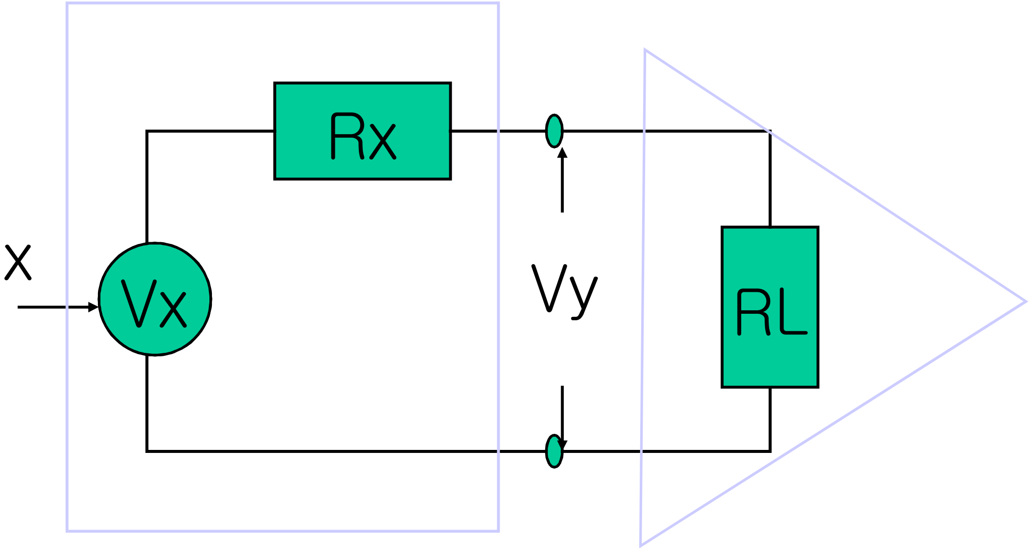


Saturation

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

Why High Input Impedance ?

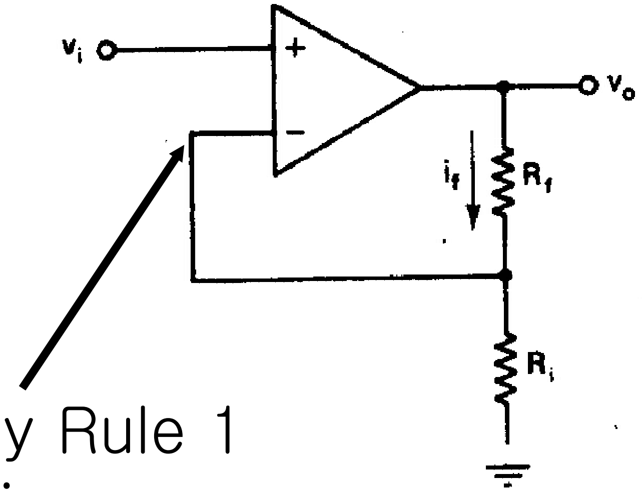
- Concept of Loading
  - 계측기가 Sensor의 출력에 영향을 주고 싶지 않음
  - Sensor의 출력이 amplitude인 경우에만 중요함. Frequency 혹은 Digital 출력인 경우에는 영향 없음



- Open Loop Output
  - Vx
- Voltage Drop by Load
  - Vy = Vx − Vx × Rx / (RL + Rx)
- Let RL >> Rx
  - Vy = Vx
  - Amp 혹은 계측기의 영향을 제거할 수 있음

Noninverting Amplifiers

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

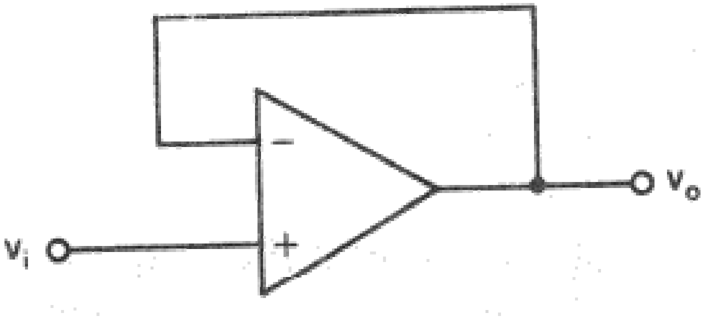


By Rule 1
Vi

- 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

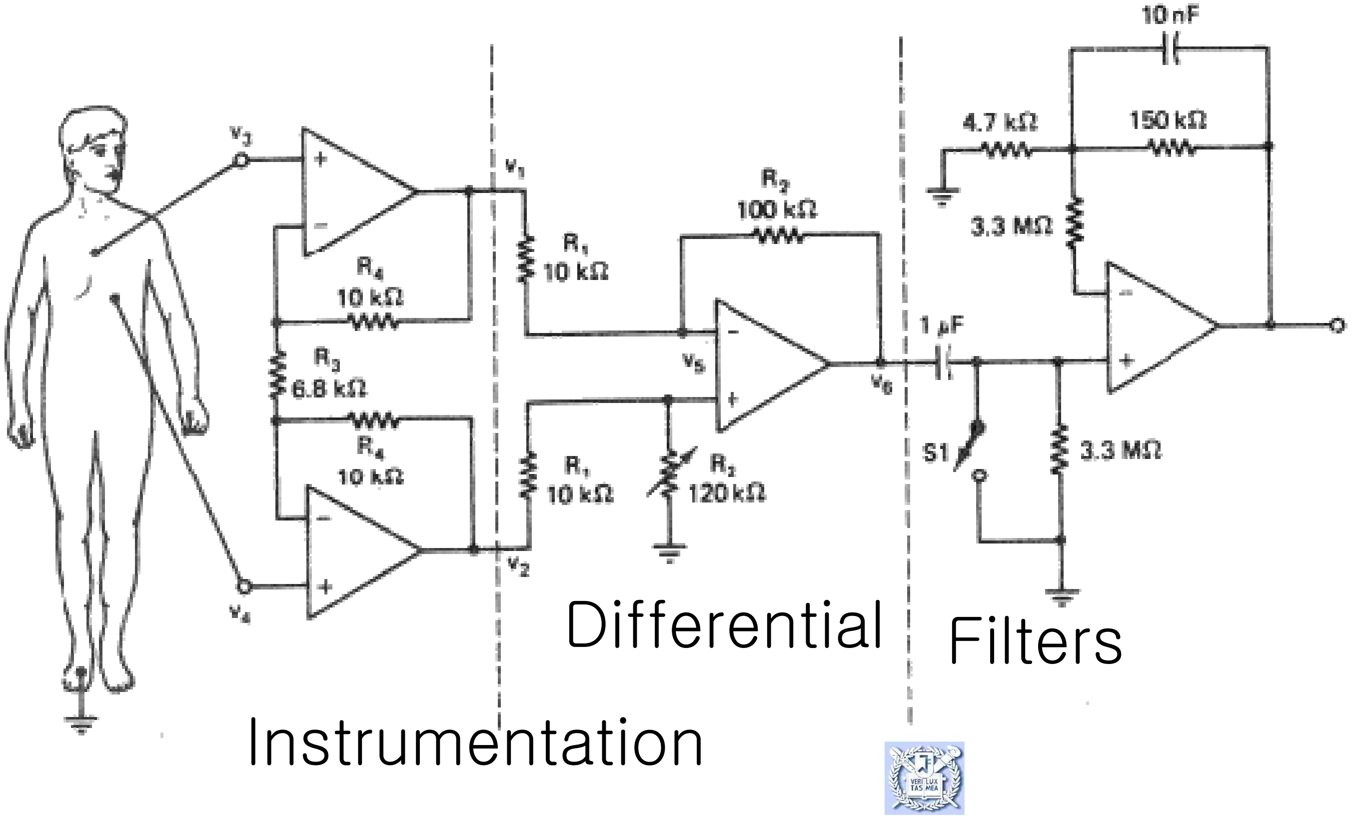
- Homework #2-1
  - Verify that the Gain of Unity-Gain Amp is 1



- 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

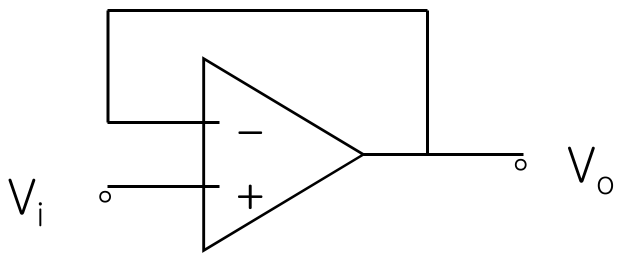
Differential Amplifiers

- Combination of Inverting and Noninverting Amp
- Can reject 60Hz interference
- Example Use of Diff. Amp. In ECG amplifier



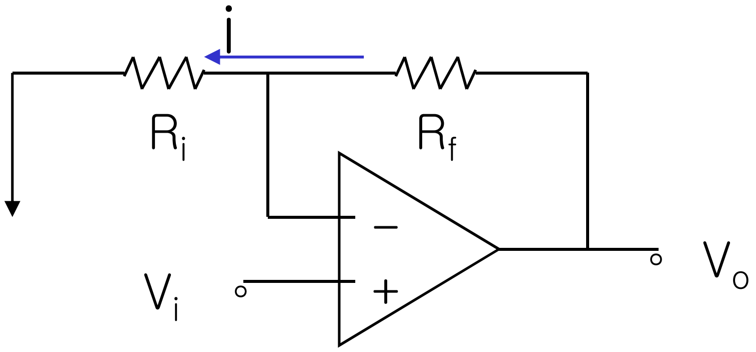
Non Inverting Amp.

- Follower



Buffer, Impedance Converter

- Non-inverting Amp.



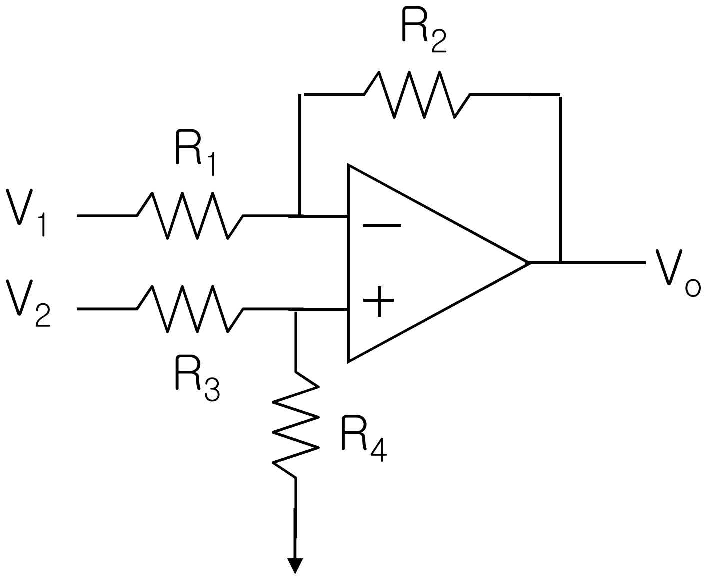
$$\left.\begin{array}{l} V_o = i \bullet (R_i + R_f) \\ V_i = i \bullet R_i \end{array}\right] \rightarrow A_v = \frac{R_i + R_f}{R_i}$$

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.



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

$V^{+}=V^{-}$로부터

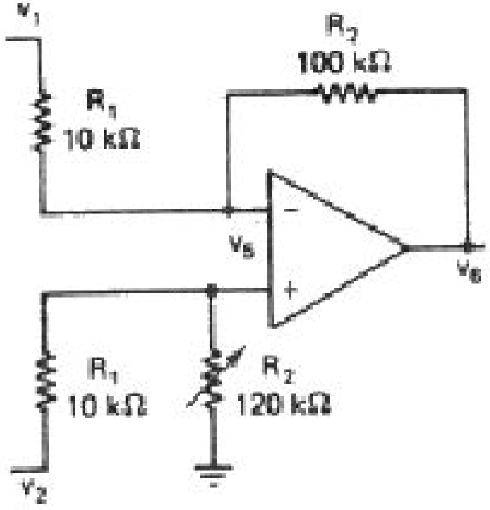
$$V_o = \frac{R_4}{R_3+R_4}\left(1+\frac{R_2}{R_1}\right)V_2 - \frac{R_2}{R_1}V_1$$

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

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

CMRR= G_d / G_c

Another look at the gain

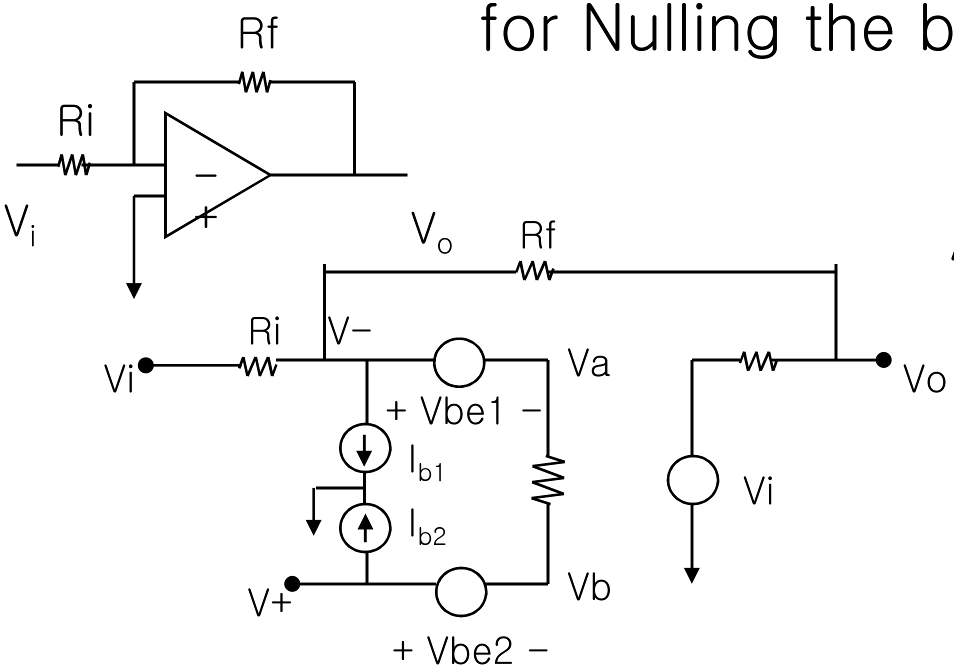


- Gain of Differential Amp
  - By Rule 2
    - $V5 = I2 * R2$
    - $V2 = I2 * R1 + V5 = V5 * R1 / R2 + V5$
    - $V5 = R2 * V2 / (R1 + R2)$
  - By Rule 1
    - $V1 = R1 * I1 + V5$
    - $V5 = R2 * I1 + V6$
    - $V6 = (V2 - V1) * R2 / R1$

Differential Amplifiers (Cont.)

- CMV (Common Mode Voltage)
  - If V1 = V2, then V6 = 0
- CMG (Common Mode Gain) = 0
- DG(Differential voltage Gain)
  - If V1 $\neq$ V2, then V6 = (V2−V1)*(R2/R1)
- In practice, CMG $\neq$ 0
- 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

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



Assume

$V^+ = V^-$

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

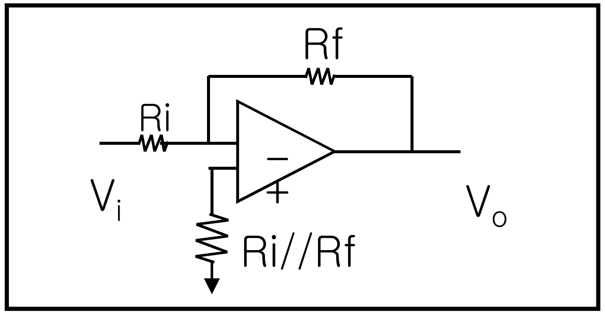
$$\frac{Vo - V^-}{Rf} + \frac{Vi - V^-}{Ri} = Ib \quad \text{(eq 1)}$$

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

Comparing eq 1 and 2,

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

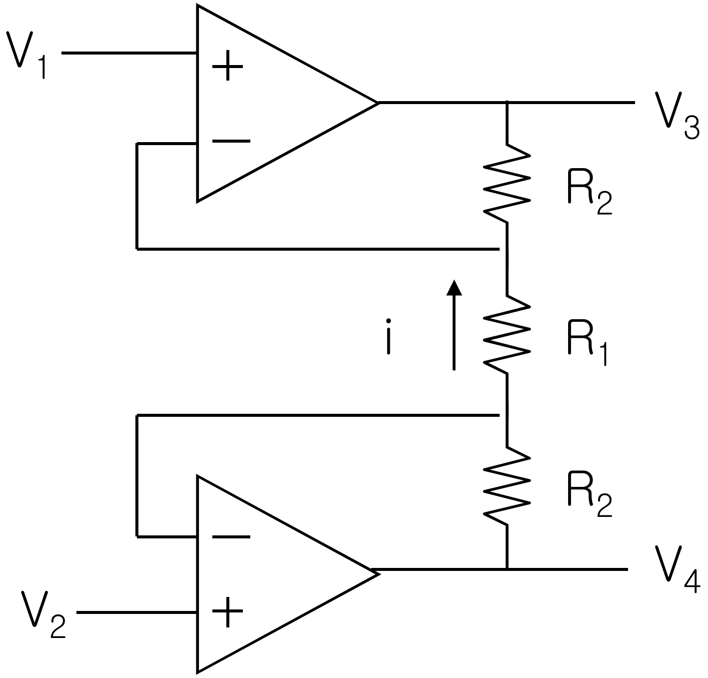
This condition can be satisfied by the next circuit.



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

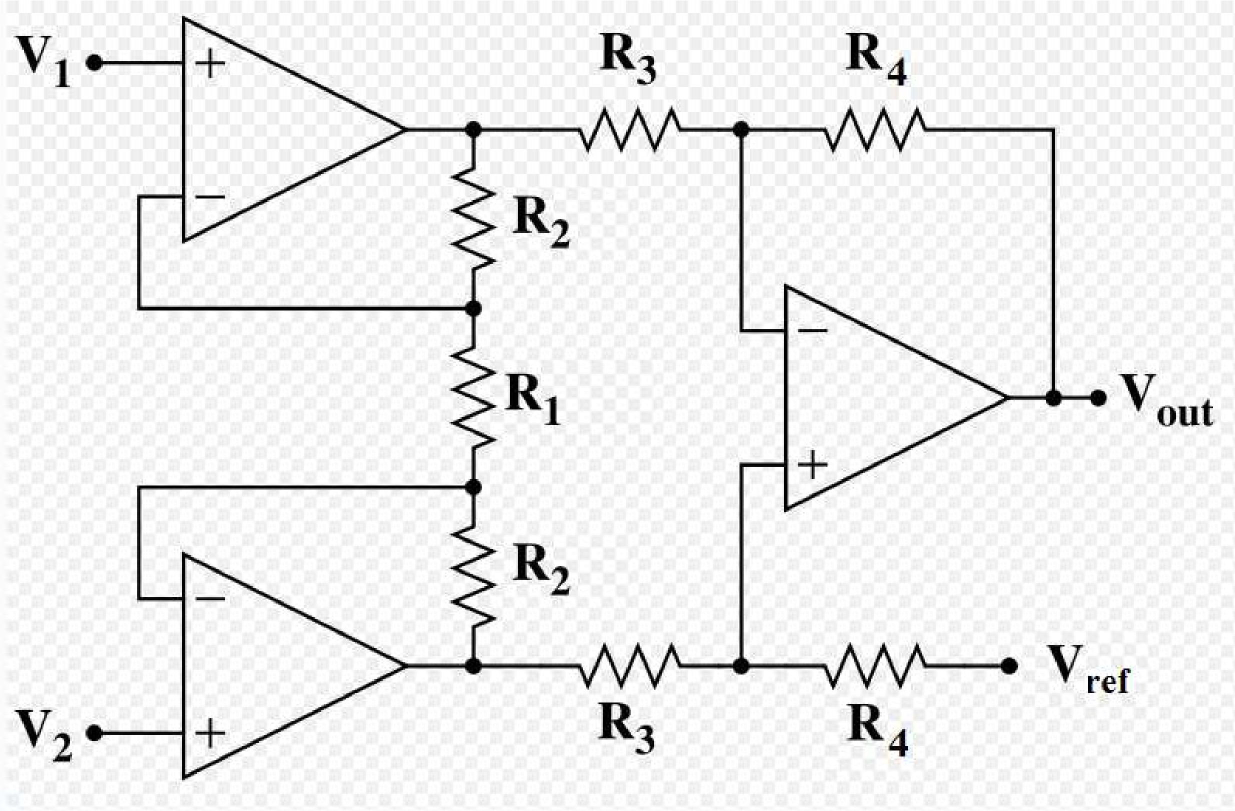
If $V_1 \neq V_2$ (DMG)
→ $i=(V_2-V_1)/R_1$

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

Complete Design of Instrumentation Amp.

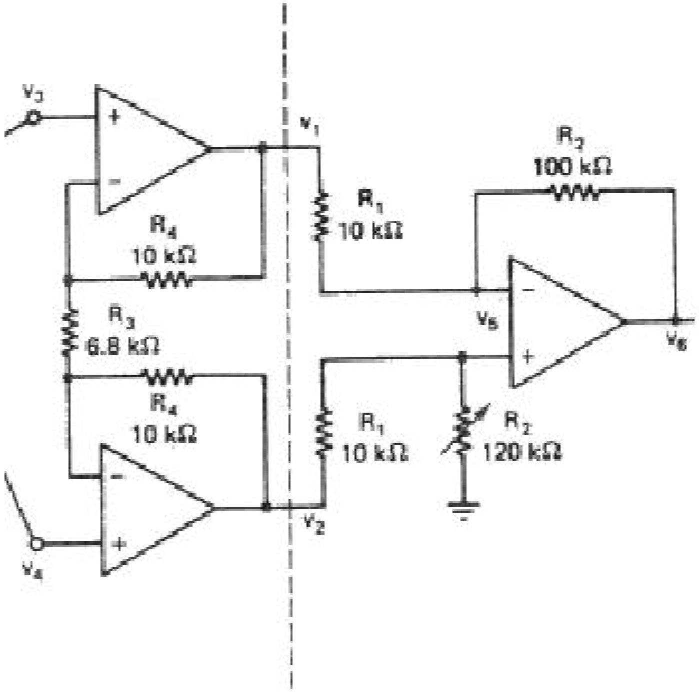
$$V_{out} - V_{ref} = G(v_2 - v_1)$$

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



Instrumentation Amplifiers (Cont.)

- Instrumentation Amp = Noninverting Amp + Differential Amp



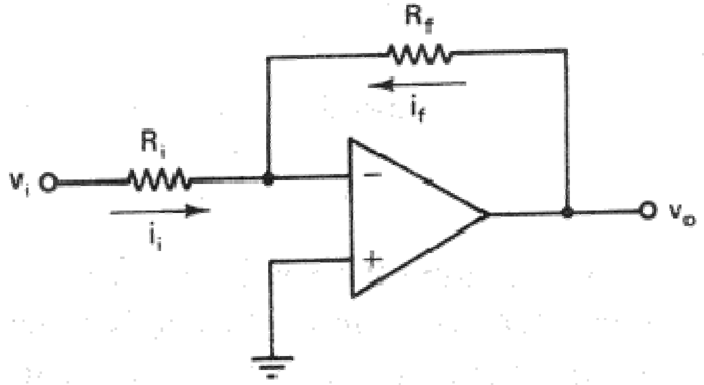
  - DG = (V1−V2) / (V3−V4)
    = (2*R4 + R3) / R3
  - V6 = (V3−V4)*DG*R2 / R1
- First Stage CMRR
  - CMRR = DG/CMG = DG
- Overall CMG = 0
  - High CMRR
- High Input Impedance
- Gain is adjustable by changing R3

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

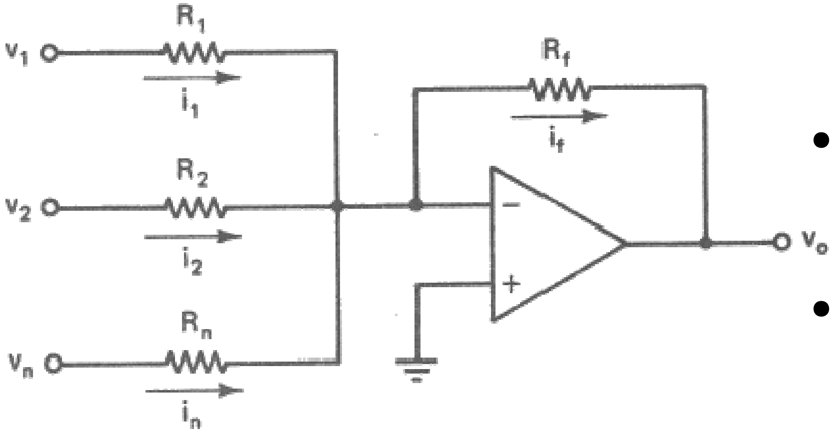
- Inverting Amp with Gain = − Rf / Ri



- 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

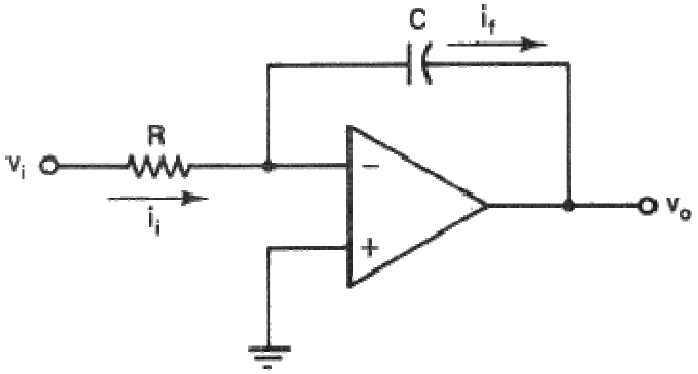


- Vo = −Rf(V1/R1 + V2/R2 +⋯ + Vn/Rn)
  - If = I1 + I2 + In
  - I1 = V1/R1, ⋯
  - Vo = −If * Rf
- Rf determines overall Gain
- Ri determines weighting factor and input impedance

Integrator

- Self homework
  - Show that

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

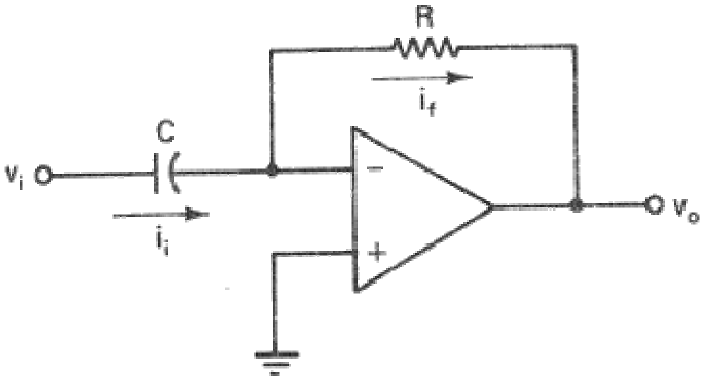


- Drawbacks
  - Vo will reach saturation voltage, if Vi is left connected indefinitely
    - Integrator operates as an open-loop amplifier for DC inputs

Differentiators

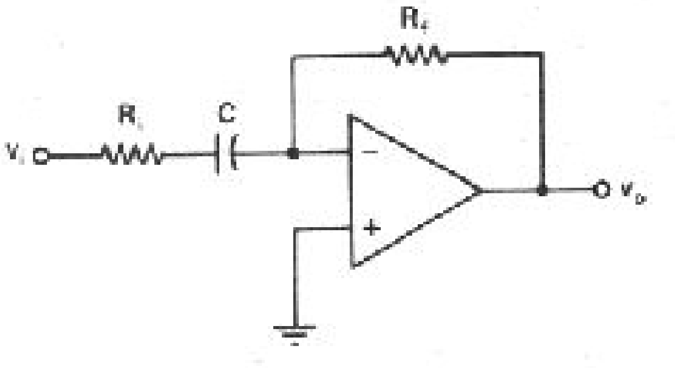
- Self Homework
- Show that

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



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

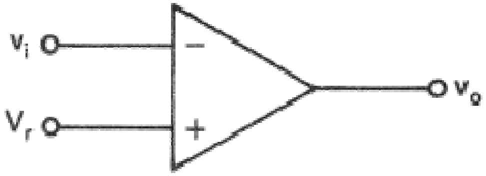
$$R_i = \sqrt{\frac{R}{A_0\omega_0 C}}$$

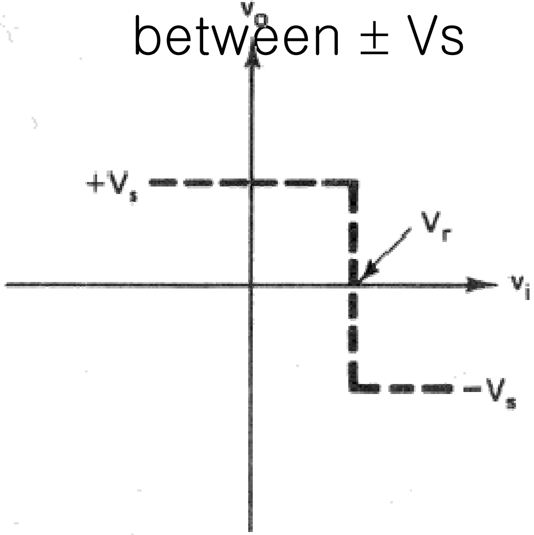


Comparators

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

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





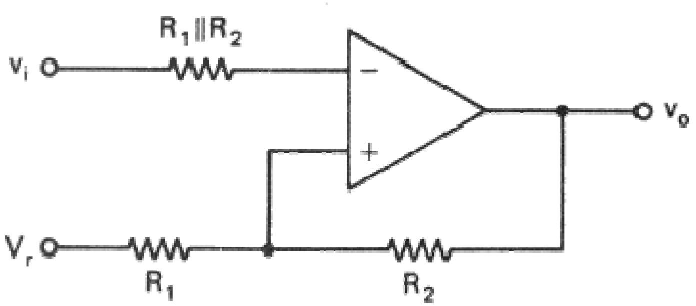
Comparators with Hysteresis

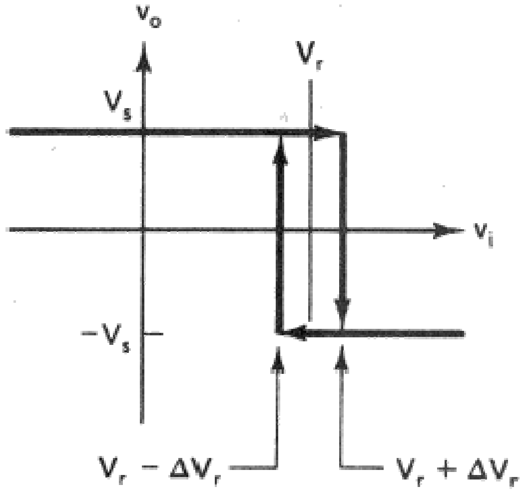
- Positive Feedback
  - Hysteresis loop
  - Can remove the effect of Small Noise
    - Reduce Fluctuation

- Homework
  - Show that

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

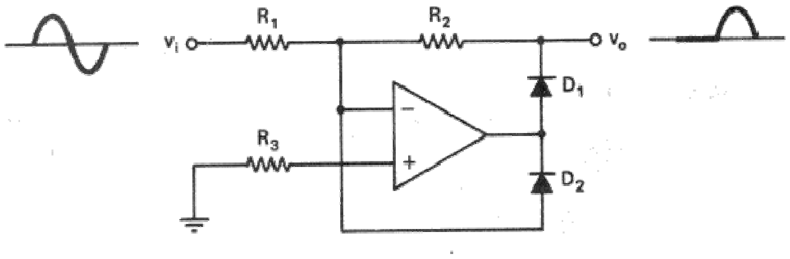
$$V_r - \Delta V_r = V_r + \frac{(-V_S - V_r)R_1}{R_1 + R_2}$$



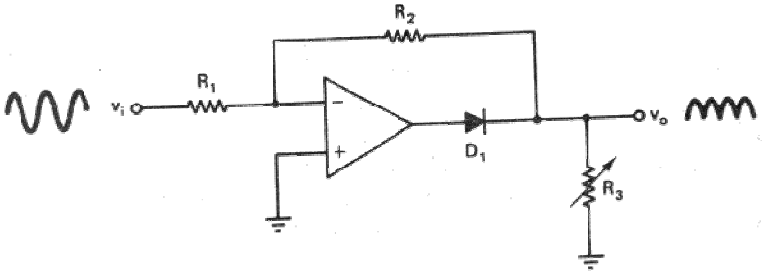


Rectifiers

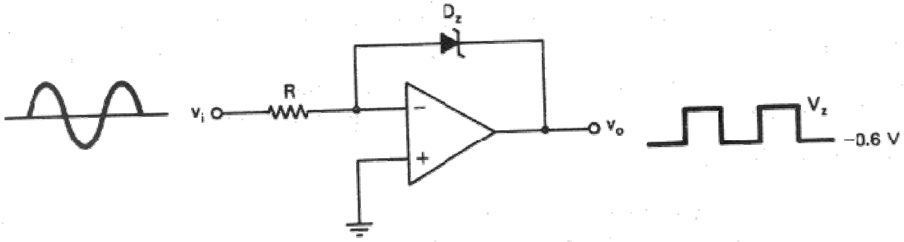
- Precision Half Wave Rectifier



- 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

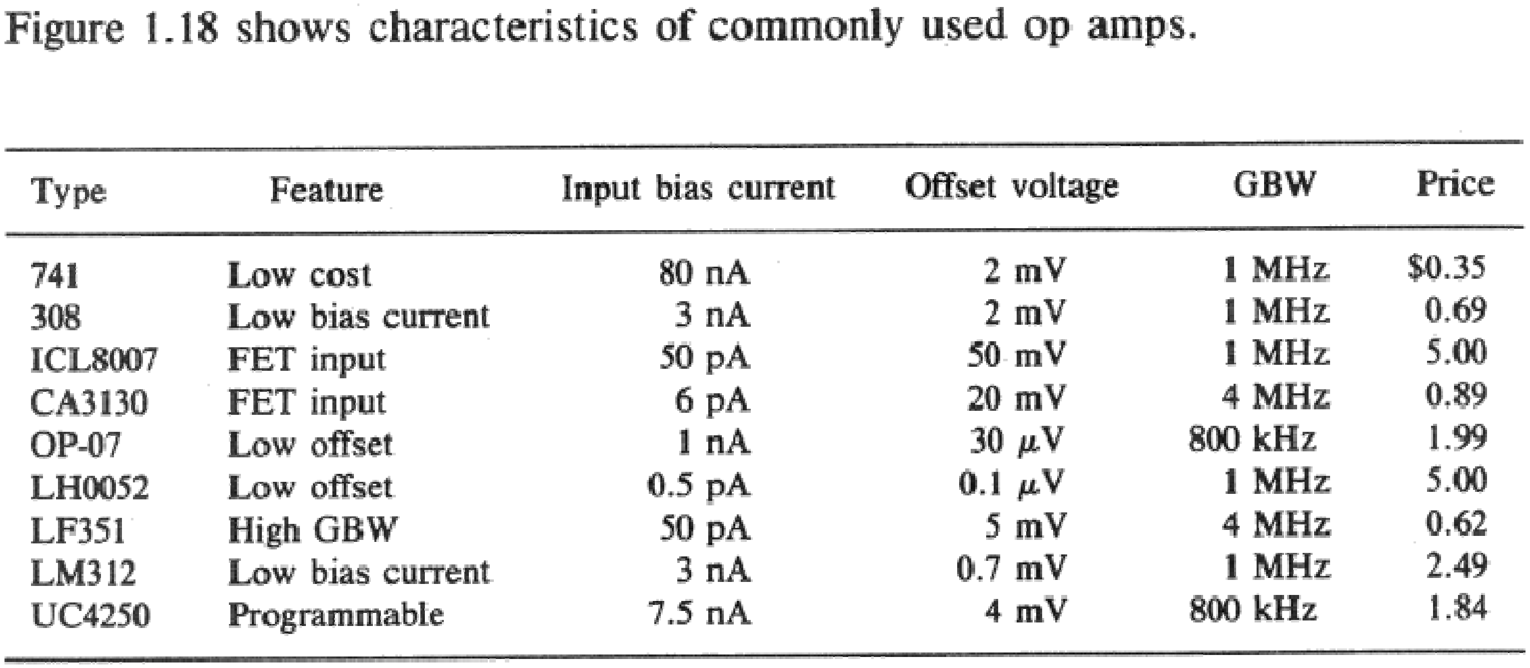


Figure 1.18 shows characteristics of commonly used op amps.

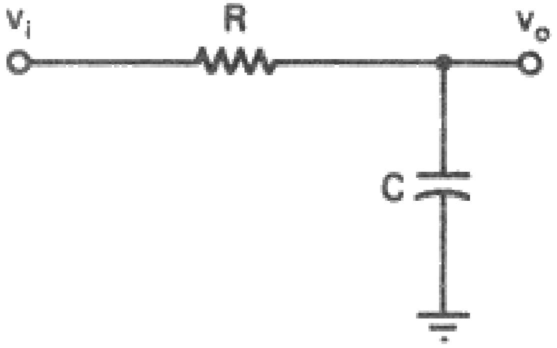
Type	Feature	Input bias current	Offset voltage	GBW	Price
741	Low cost	80 nA	2 mV	1 MHz	\$0.35
308	Low bias current	3 nA	2 mV	1 MHz	0.69
ICL8007	FET input	50 pA	50 mV	1 MHz	5.00
CA3130	FET input	6 pA	20 mV	4 MHz	0.89
OP-07	Low offset	1 nA	30 μV	800 kHz	1.99
LH0052	Low offset	0.5 pA	0.1 μV	1 MHz	5.00
LF351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

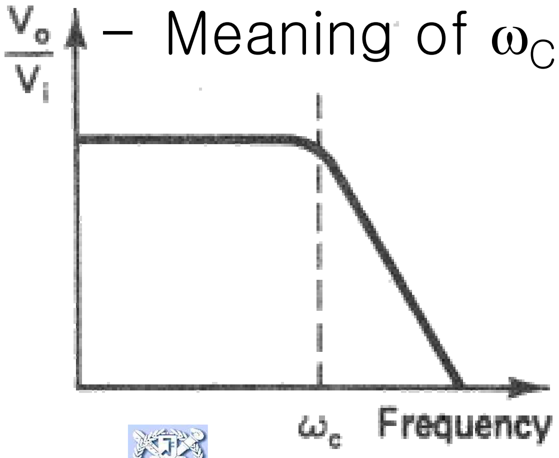
- Pass desired Audio signal and reject undesired RF
- Order of Filter
  - Number of C and L



-
  - 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

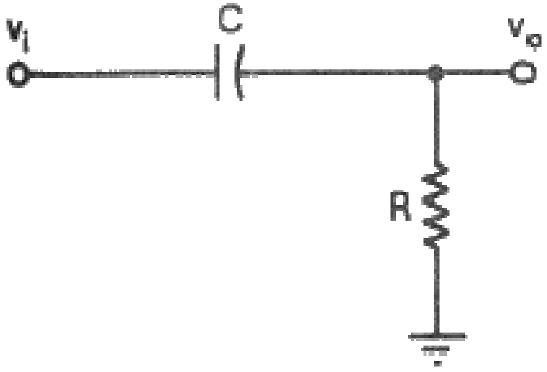
- Pass desired High frequency signal and reject undesired low frequency signal

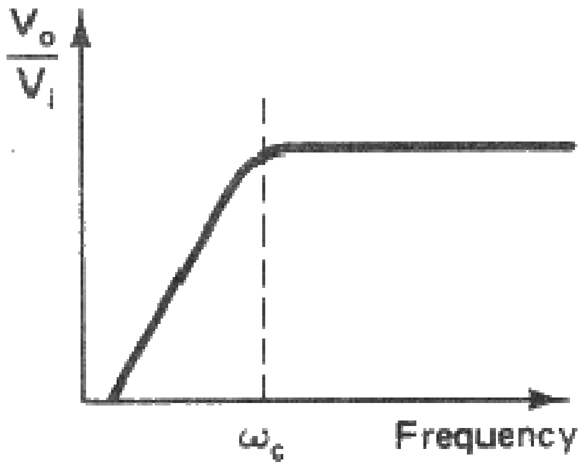
◆ Show that

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

◆ 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

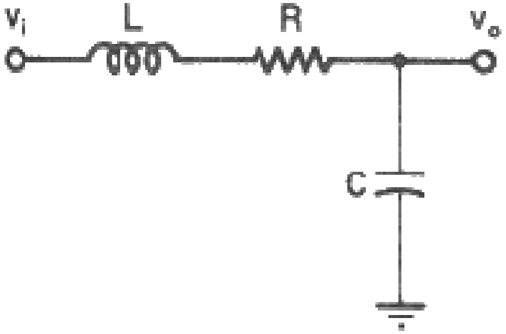
◆ Show that

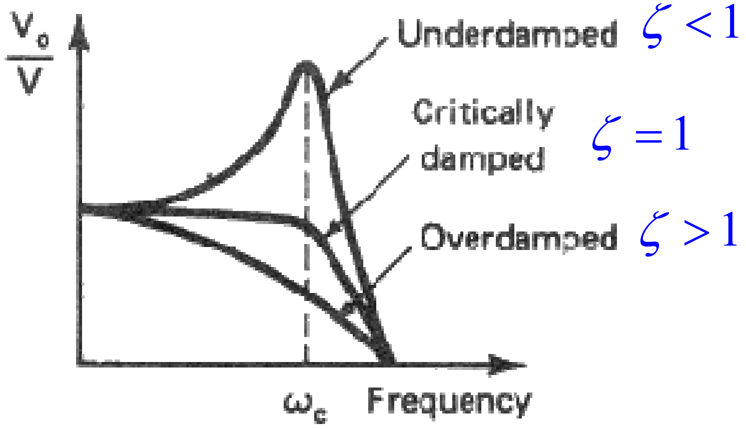
$$\frac{V_o}{V_i} = \frac{1}{(j\omega/\omega_c)^2 + (2\zeta j\omega/\omega_c) + 1}$$

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

◆ Meaning of Quality factor

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





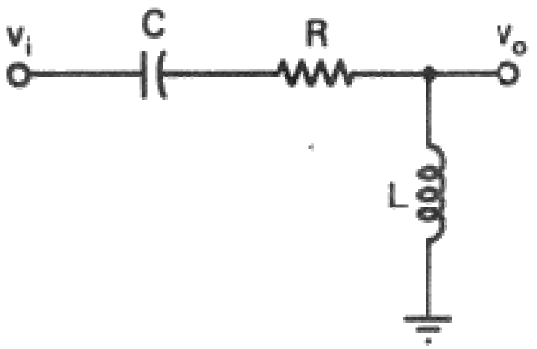
Passive second-order High pass Filter

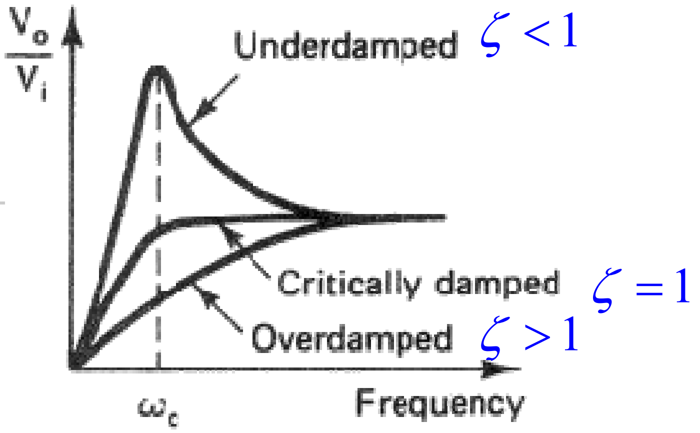
- To increase the attenuation of transfer function
- Order of Filter
  - ◆ Number of C and L

◆ Show that

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

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

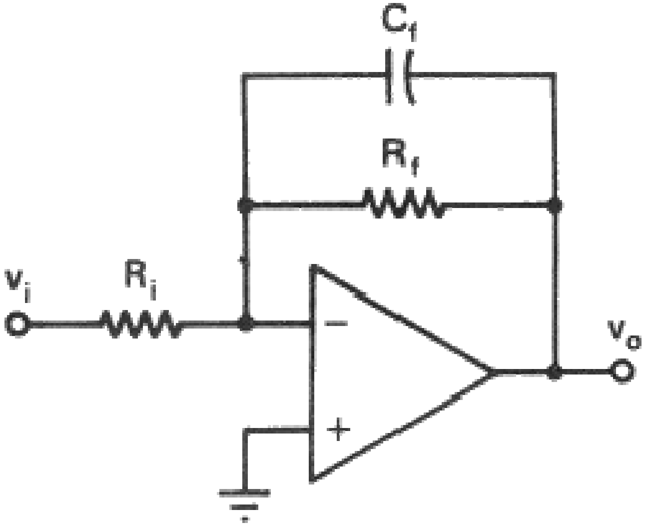


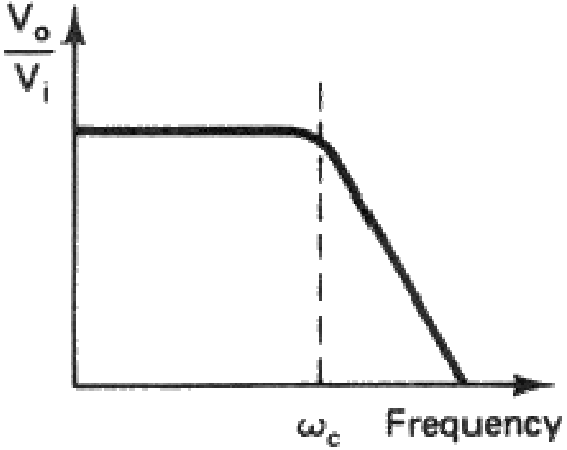


Active First-order Low Pass Filter

- Inverting Amp + Feedback Capacitor

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

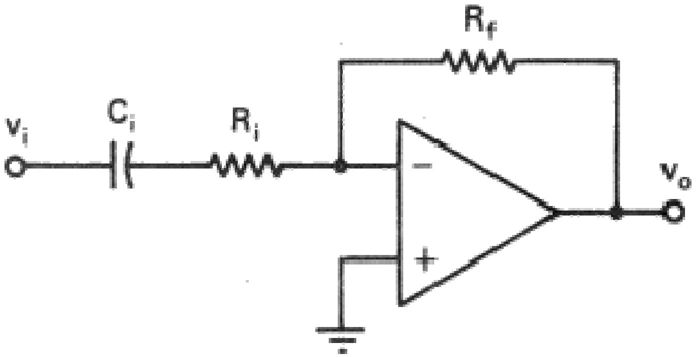


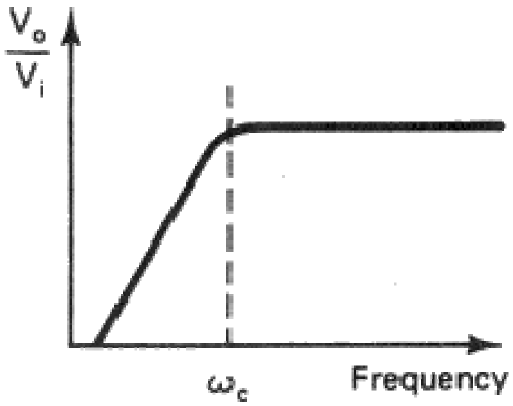


Active First-order High Pass Filter

- Inverting Amp + Input Capacitor

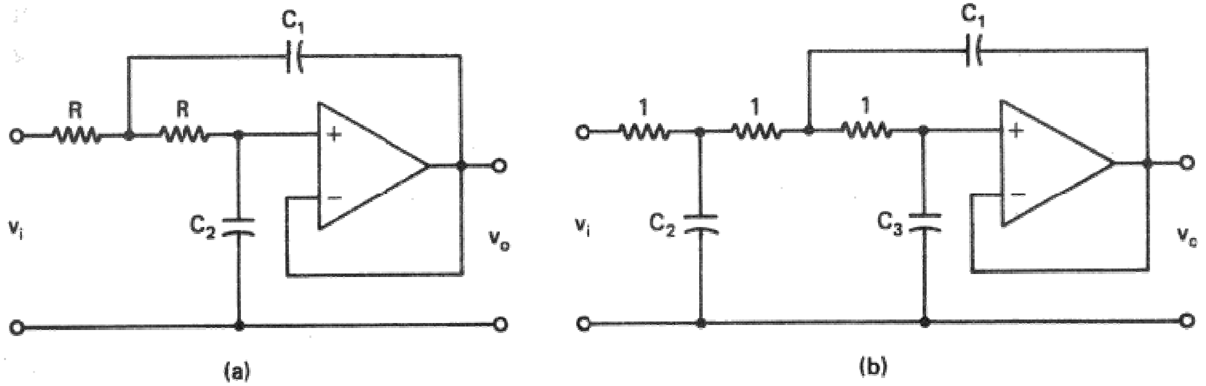
- Identical frequency response with Passive filter
- Very Low Output impedance
  - Negligible Loading Effect





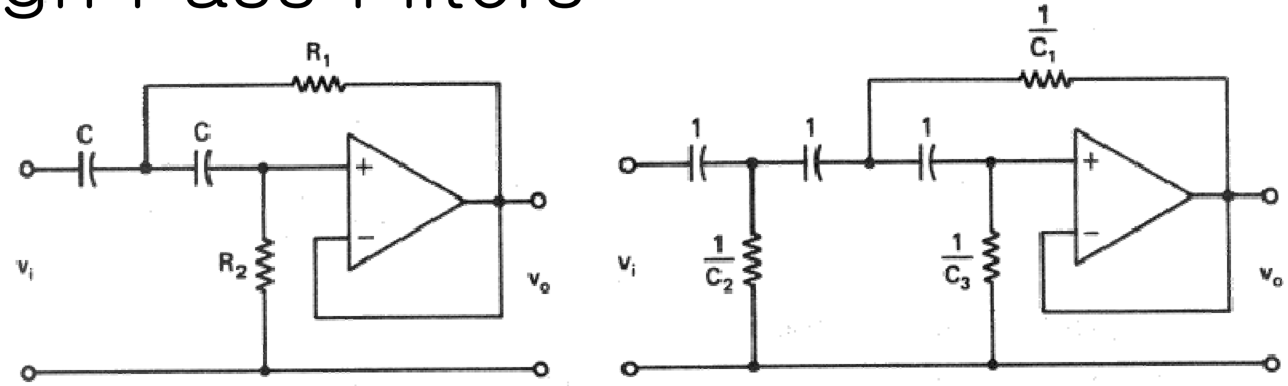
Active High-order Filters

- Low Pass Filters



(a) (b)

- 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

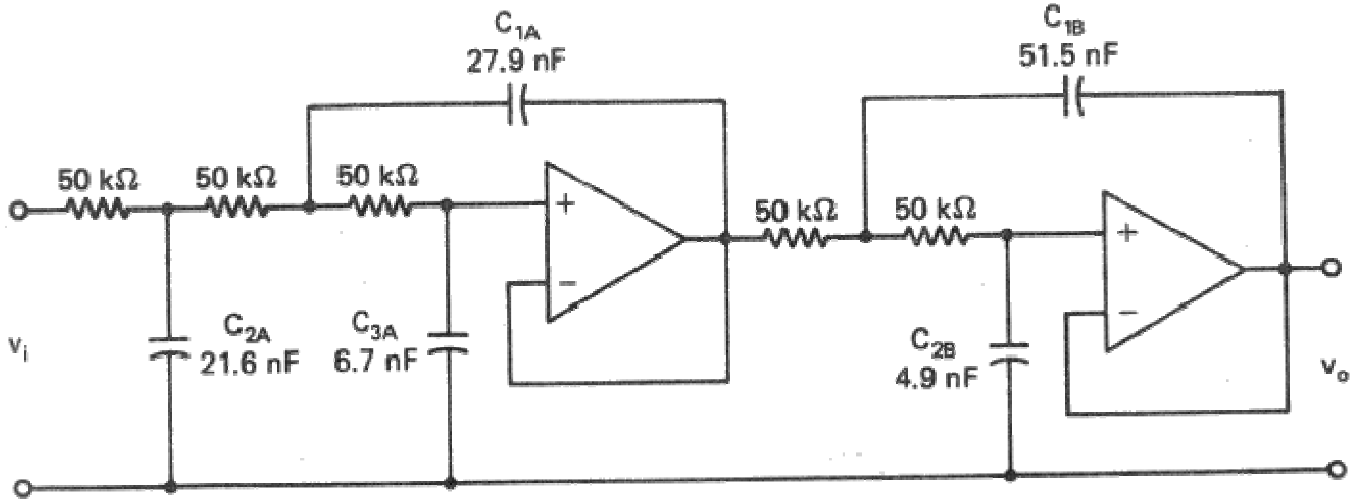
Filter Design Table

- C when $\omega_0 = R_0 = 1$

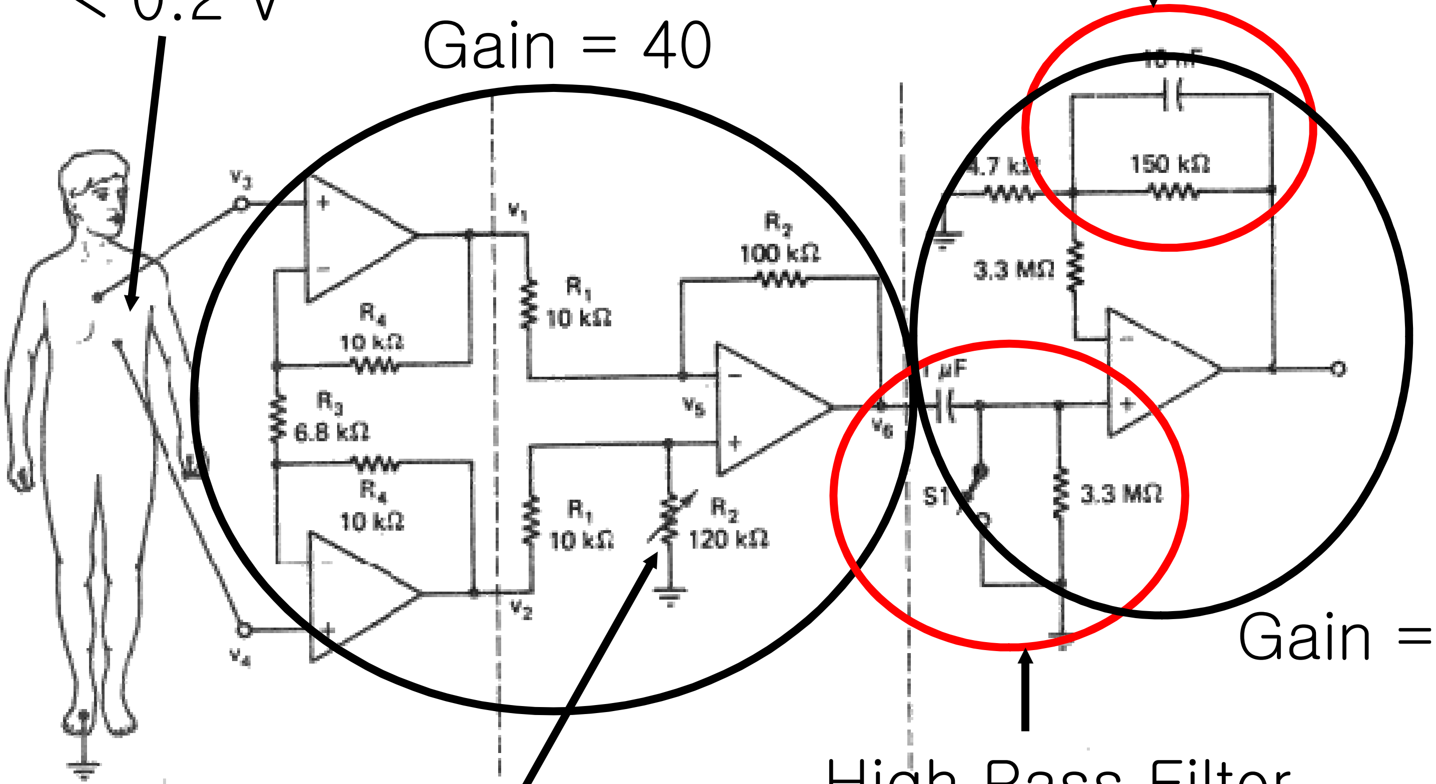
Poles	C_1	C_2	C_3	C_1	C_2	C_3
	Bessel			Butterworth		
2	9.066 −1	6.799 −1		1.414 +0	7.071 −1	
3	1.423 +0	9.880 −1	2.538 −1	3.546 +0	1.392 +0	2.024 −1
4	7.351 −1	6.746 −1		1.082 +0	9.241 −1	
	1.012 +0	3.900 −1		2.613 +0	3.825 −1	
5	1.009 +0	8.712 −1	3.095 −1	1.753 +0	1.354 +0	4.214 −1
	1.041 +0	3.098 −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

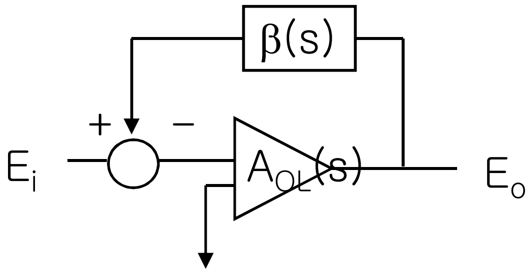
Gain = 40

Gain = 32

Maximize CMRR

High Pass Filter
>0.05Hz

Frequency Stability



$A_{CL}(S) = Eo/Ei = A_{OL}(S)/(1+ A_{OL}(s)\ \beta(s))$

$= A_{oL}(s)/(1+A_L(S))$

Instability : $A_L(s) = A_{OL}(s)B(s) = 1\angle 180 = -1$ 일때.

Critical condition : $A_{OL}(jw) = \{1/\ \beta(jw)\}\angle 180$

즉,

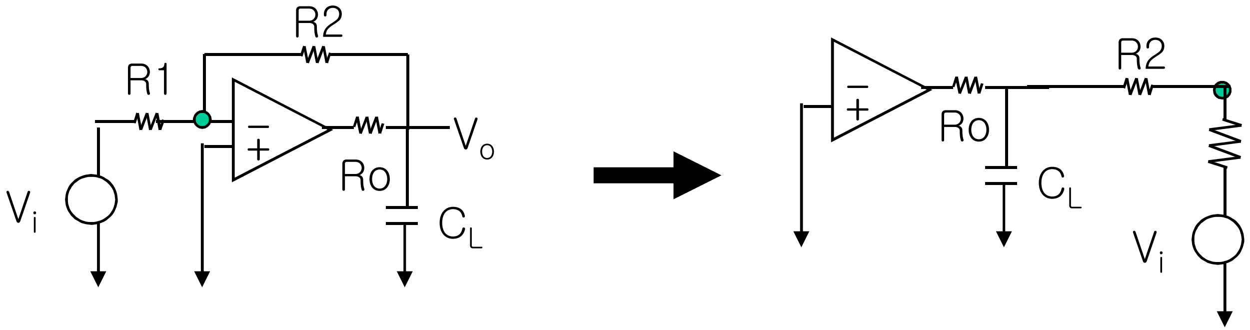
$|A_{oL}(jw)| = 1/|\ \beta(jw)|$이고 $\Phi_{OL} - \Phi_{CL} = 180^\circ$

가 되는 freq.에서 oscillation

Frequency Stability

- 흔히 우리는 $|A_L(jw)| = |A_{oL}(jw)\beta(jw)| = 1$이 되는 w를 구하고 이 때의 $A_L(jw)$의 phase를 보아, 이것이 +180°로부터 떨어진 정도를 측정하며 이를 Φ_M (Phase margin) 이라고 한다.
  - $\Phi_M \sim 90°$ 정도일 때 stable system
  - Φ_M 은 크면 클수록 유리하다.

- OP Amp 의 경우



A_{oL}에 feedback 되는 양

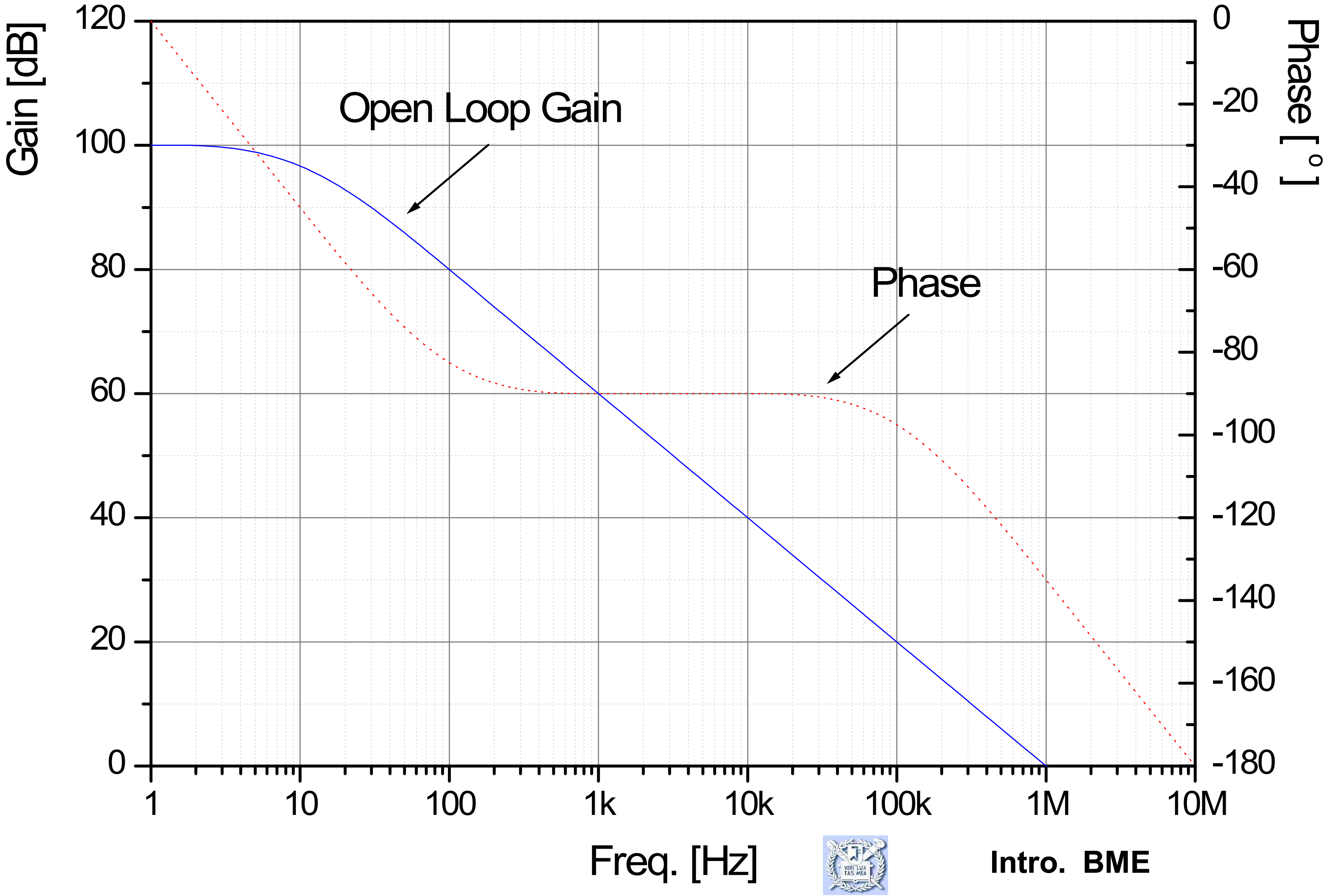
$C_L=0$, Vi 가 없을 때,

$\beta = R1/(R0+R2+R1) \approx R1/(R2+R1)$

즉 $A_{oL}(jw)$에 $\beta = R1/(R2+R1)$을 곱해 $A_L(jw)$를 구하고

이의 Bode Diagram 에서 Φ_M을 구한다

Frequency Stability



Interference

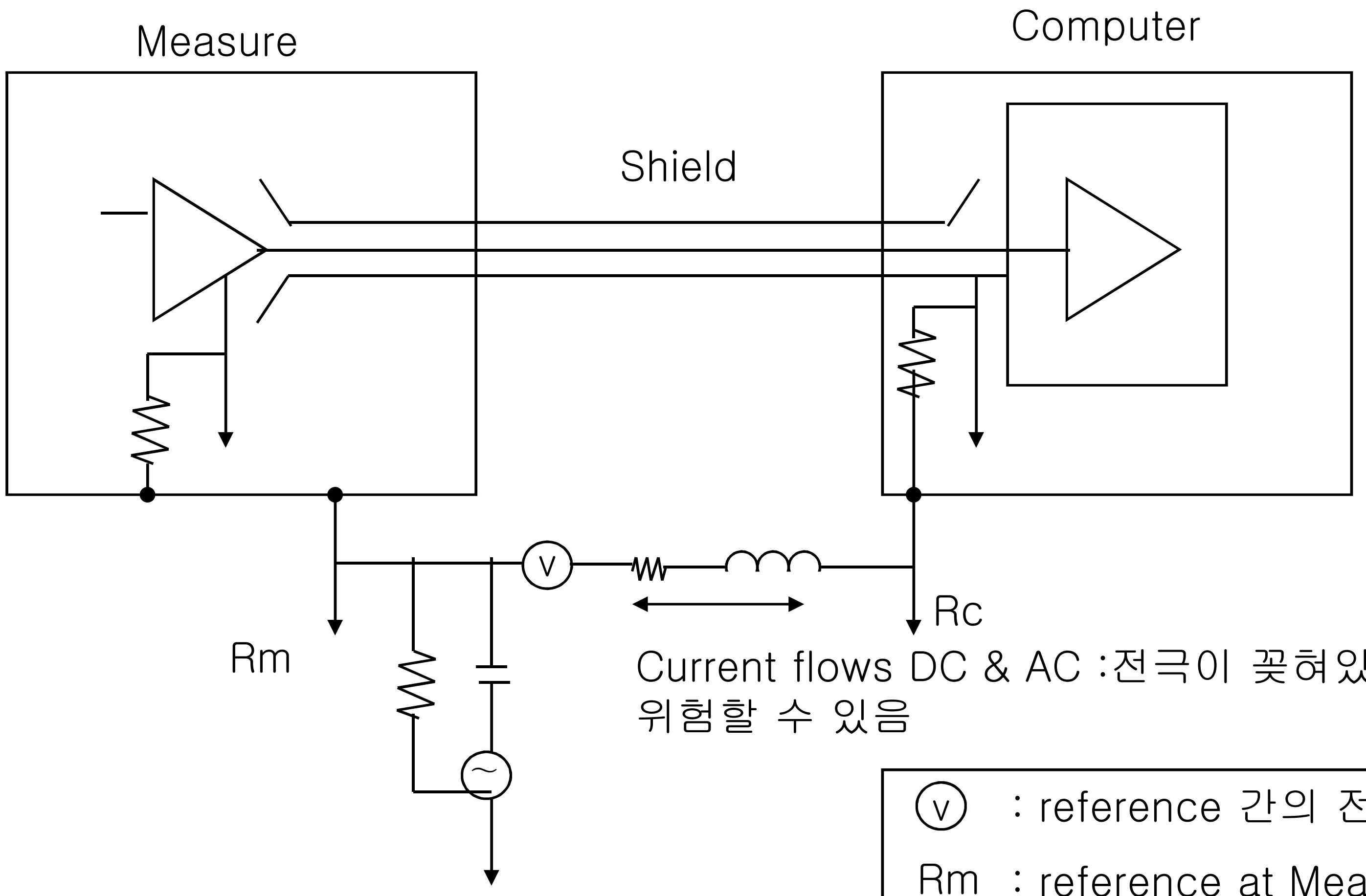
- Noise : random
- Interference : not random, comes from a known source

- 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 flows DC & AC :전극이 꽂혀있는 환자에게 위험할 수 있음

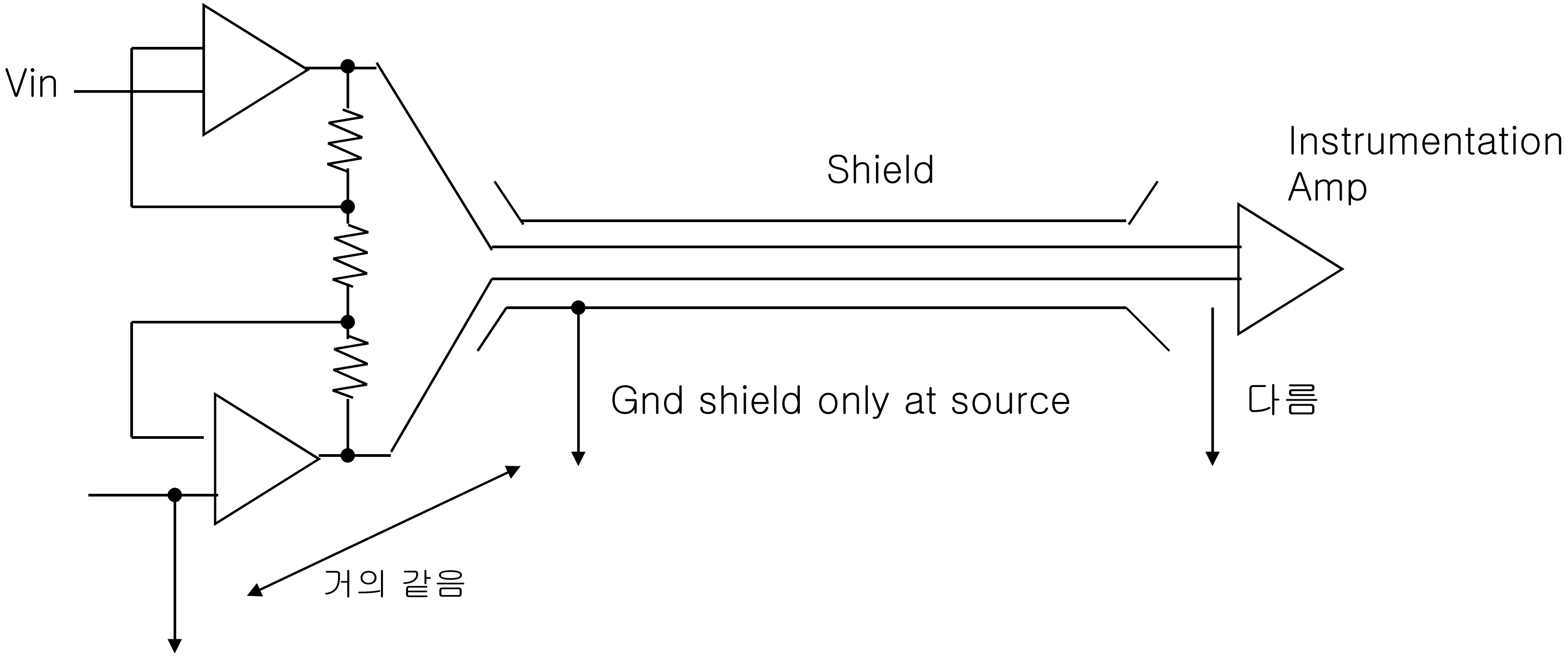
Ⓥ : reference 간의 전위차

Rm : reference at Measure

Rc : reference at Computer

Grounding & Instrumentation Amp.

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



모든 noise는 common mode로 처리

Grounding & Instrumentation Amp.

- Ground Loop => safety

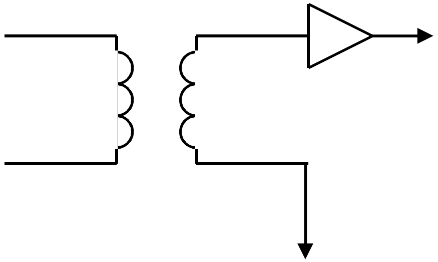
  ECG 측정시 ground loop current는 전극이 꽂혀있는
  환자를 통하여 흐르게 되므로 위험

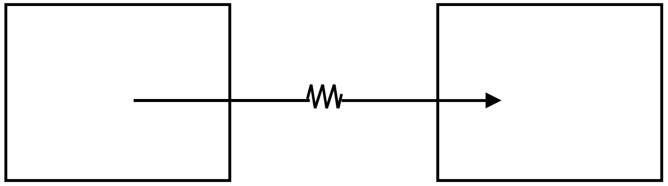
- Bias current => safety

  특별히 I_B가 작은 소자
  Ex) AD55L max I_B = 75fA
  AD00L max I_B = 10fA

Grounding & Instrumentation Amp.

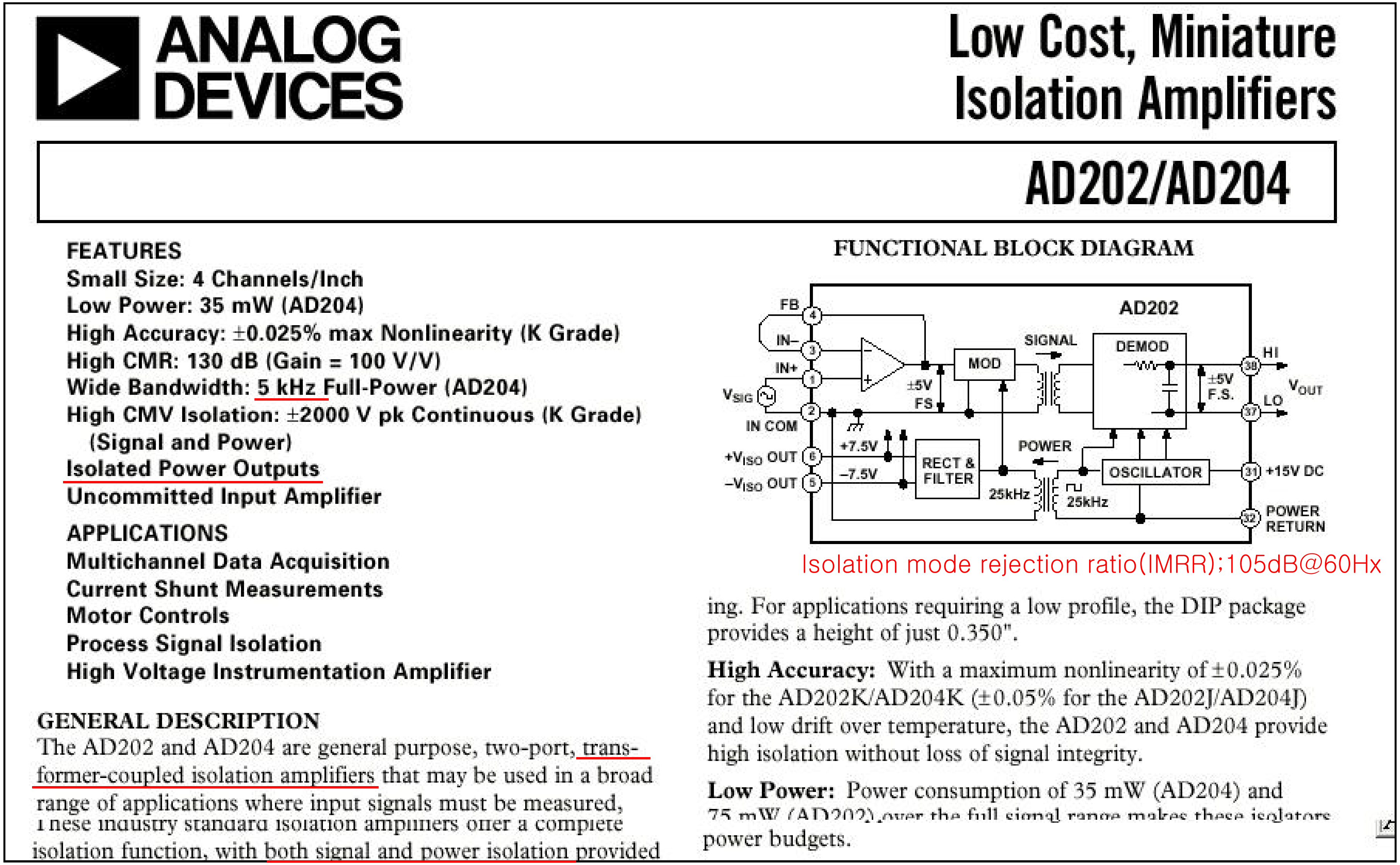
- Solution(II) : Isolation between Measure and Computer stations.
  - By transformer





Optics, RF ....

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



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

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

FUNCTIONAL BLOCK DIAGRAM

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

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.