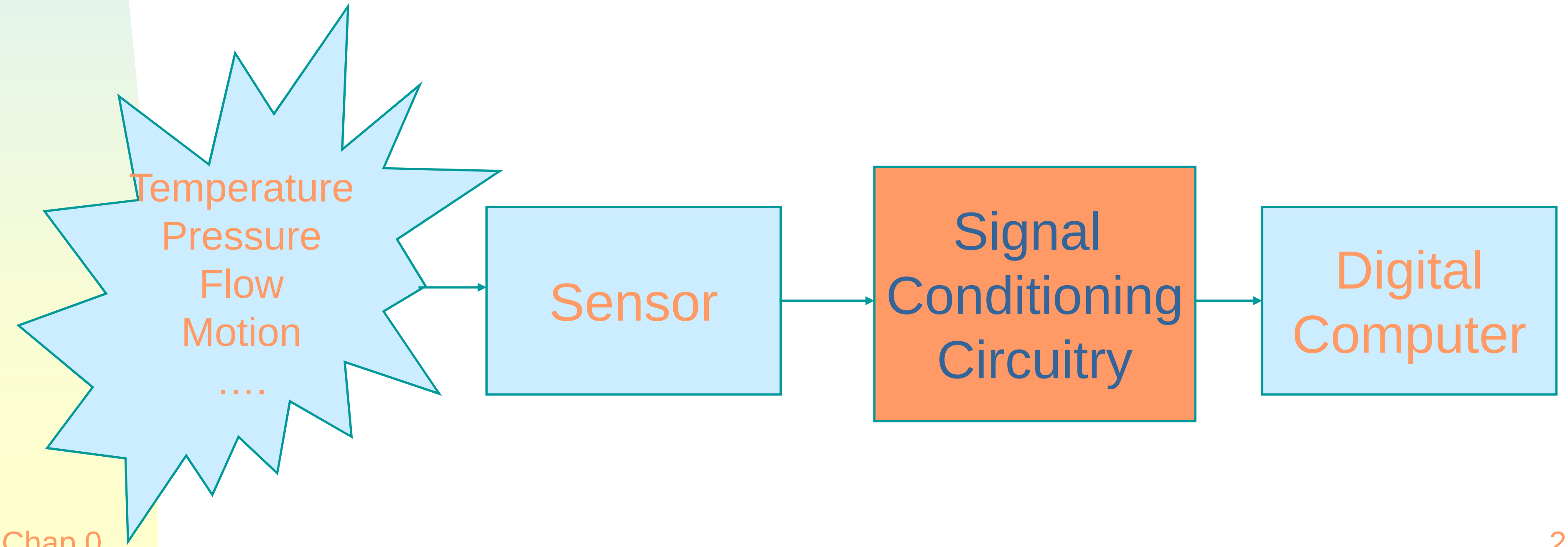
Circuits for sensors

- Ideal OP Amps
- Basic OP Amp Circuit Blocks
- Analog Computation
- Nonlinear OP Amp Applications
- OP Amp Considerations
- Guarding
- Passive Filters
- Active Filters
- VCO(Voltage Controlled Oscillator)

Function of Amplifiers

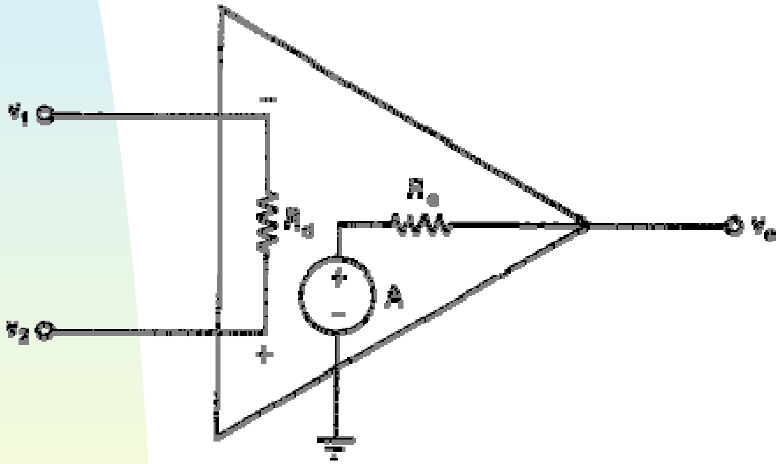
- **Amplifiers provides**
  - GAIN
  - Filtering, Signal processing, Correction for Nonlinearities



Ideal OP Amps

- **Transfer Function = Output / Input**
  - Voltage Amp TF (Gain): $A_v = \frac{v_o}{v_i}$
  - Usually $A_v \geq 1$
  - OP Amp is preferred
    - Easy to use in circuit designed compared to discrete Transistor circuits

Ideal OP Amps (Cont.)



- **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

Ideal OP Amps (Cont.)

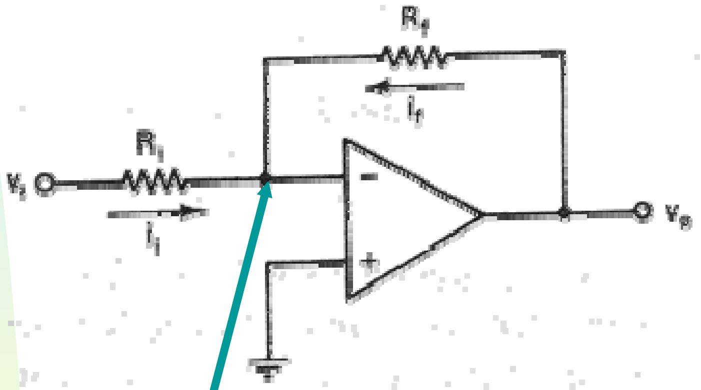
- **Note**
  - ◆ $v_0 = A(v_2 - v_1)$
    - ☞ If $v_0 = \infty$, $A = \infty$ (Typically 100,000)
      - Then $v_2 - v_1 = 0 \Rightarrow v_2 = v_1$
    - ☞ Since $v_2 = v_1$ and $Rd = \infty$
      - We can neglect the current in Rd
- **Rule 1**
  - ◆ When the OP Amp is in linear range the two inputs are at the same voltage
- **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 Electrocardiogram Amplifier**

Inverting Amplifier

- **Inverting Amp with Gain = - Rf / Ri**

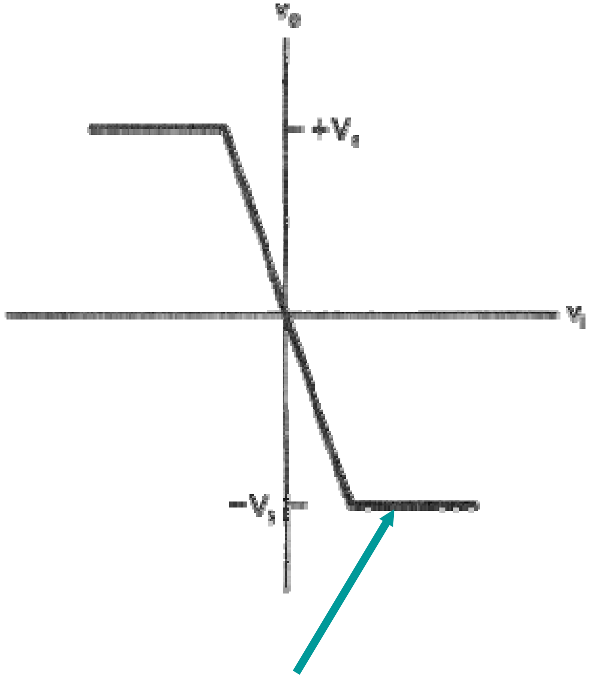


Virtual Ground

- **From Rule 1**
  - $v- = v+ = 0$
- **From Rule 2 & KCL**
  - $i_i + i_f = 0 \Rightarrow i_i = -i_f$
  - From Ohm's law
    - $i_i = v_i / R_i$, , $i_f = v_o / R_f$
  - $v_i / R_i = - v_o / R_f$
    - $v_o / v_i = -R_f / R_i$
- **Inverting Amp Gain**
  - $-R_f / R_i$

Inverting Amplifier (Cont.)

- **Linear Range**
  - By Power Supply Voltage

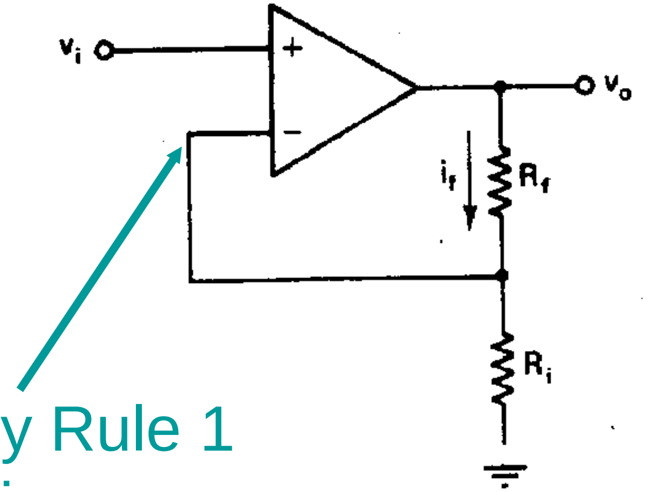


Saturation

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

Noninverting Amplifiers

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

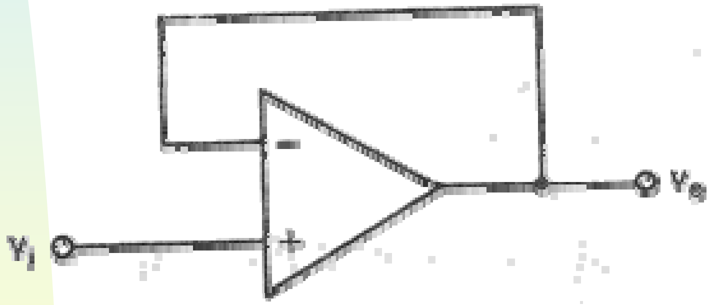


By Rule 1
Vi

- **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

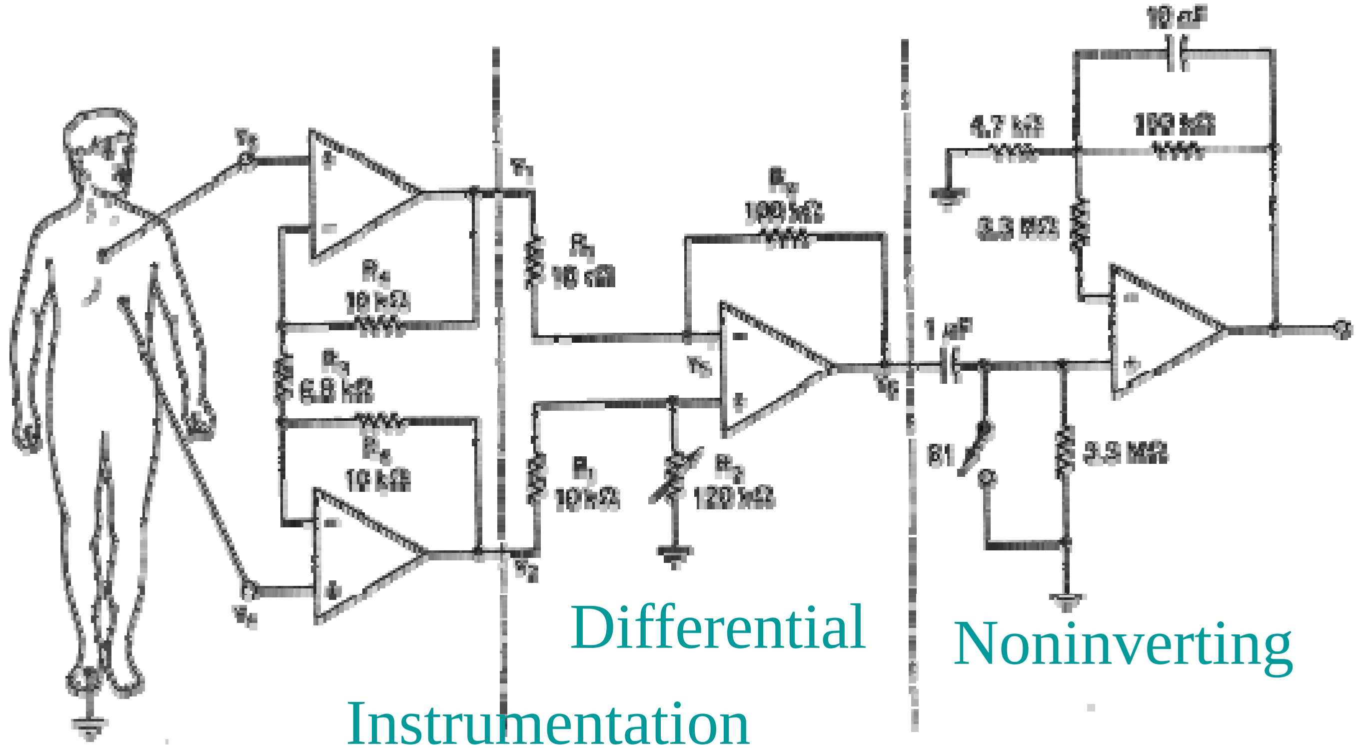
- Verify that the Gain of Unity-Gain Amp is 1



- **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**
- **Electrocardiogram amplifier**

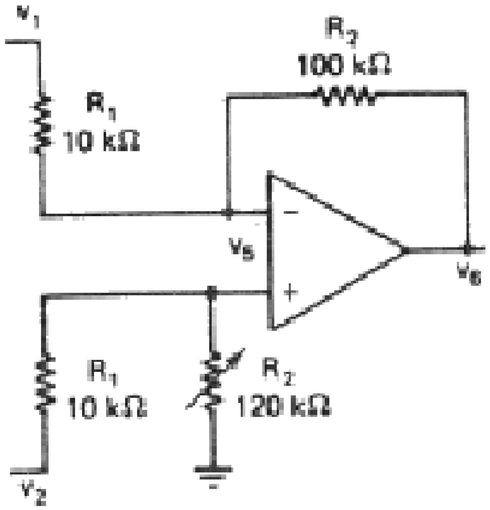


Differential

Noninverting

Instrumentation

Differential Amplifiers (Cont.)



- **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.)

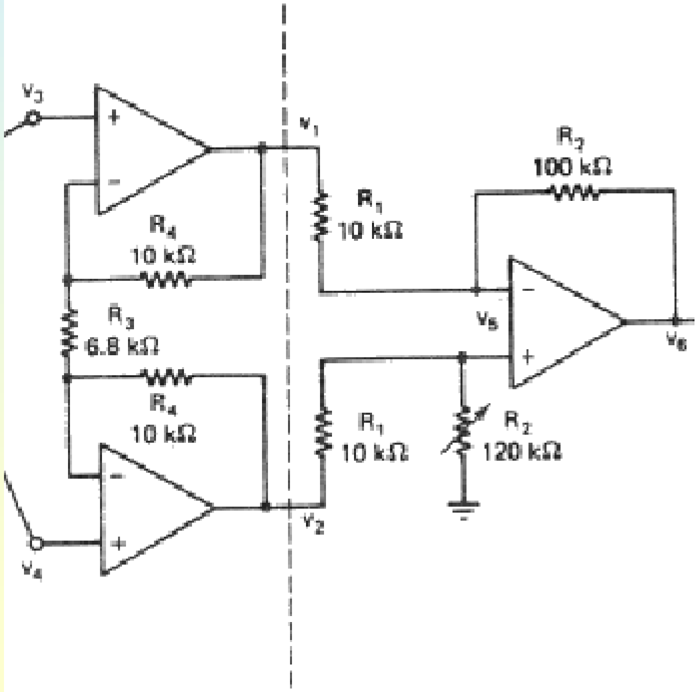
- **CMV (Common Mode Voltage)**
  - If V1 = V2, then V6 = 0
- **CMG (Common Mode Gain) = 0**
- **DG(Differential voltage Gain)**
  - If V1 ≠ V2, then V6 = (V2-V1)*(R2/R1)
- **In practice, CMG ≠ 0**
- **CMRR (Common Mode Rejection Ratio)**
  - Measure of the ability to reject CMV
  - CMRR = DG / CMG
    - The Higher CMRR, the better quality
    - Typically, 100 ~ 10,000
    - 60Hz noise common to V1 and V2 can be rejected

Instrumentation Amplifiers

- **One OP Amp Differential Amplifier**
  - Input Impedance is not so High
    - Good for Low impedance source
      - Strain gage Bridge
    - Bad for High impedance source
- **Instrumentation Amplifier**
  - Differential Amp with High Input Impedance and Low Output Impedance
  - Two Noninvering Amp + One Differential Amp

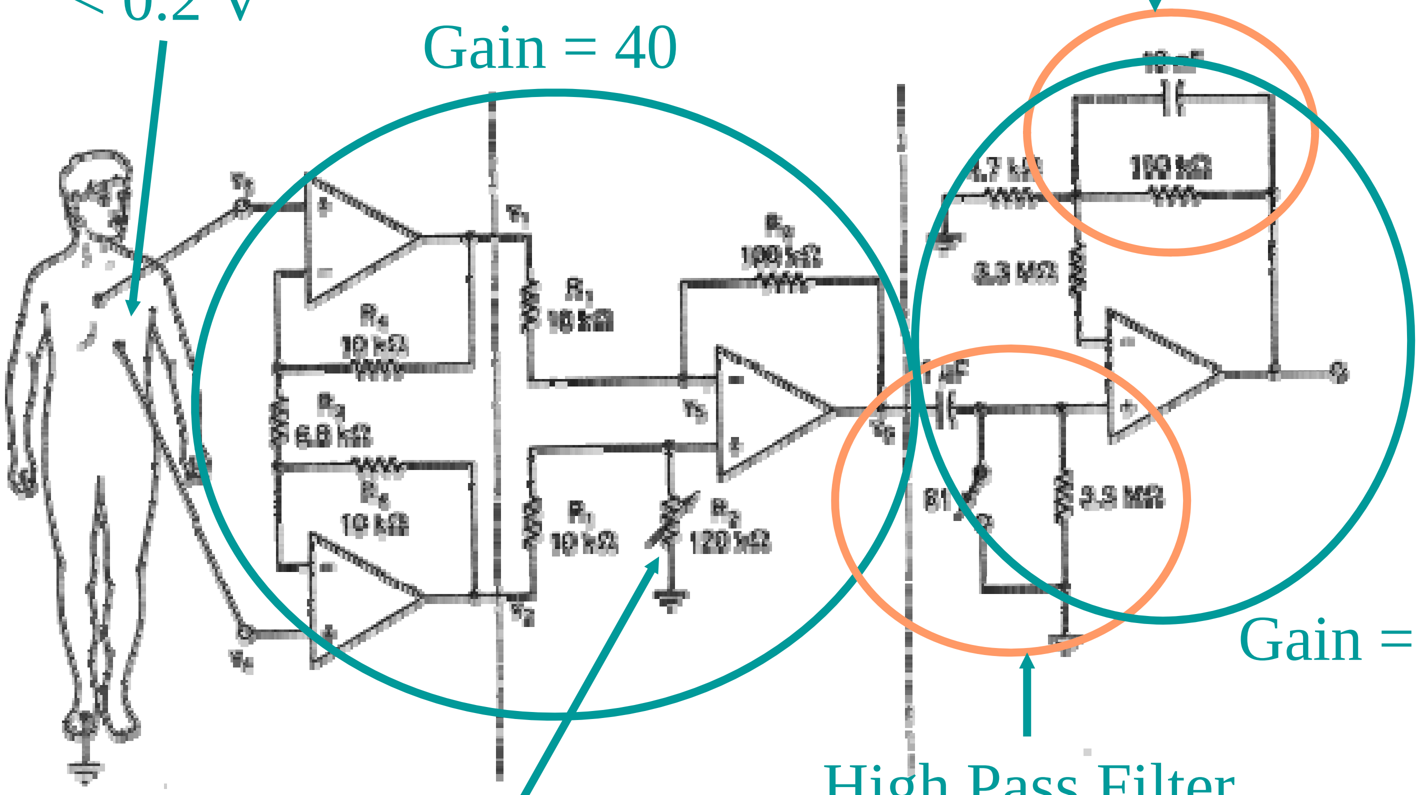
Instrumentation Amplifiers (Cont.)

- **Instrumentation Amp = Noninverting Amp + Differential Amp**



- We have:
  - 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**

The Electrocardiogram Amplifier



Low Pass Filter
< 100Hz

< 0.2 V

Gain = 40

Gain = 32

Maximize CMRR

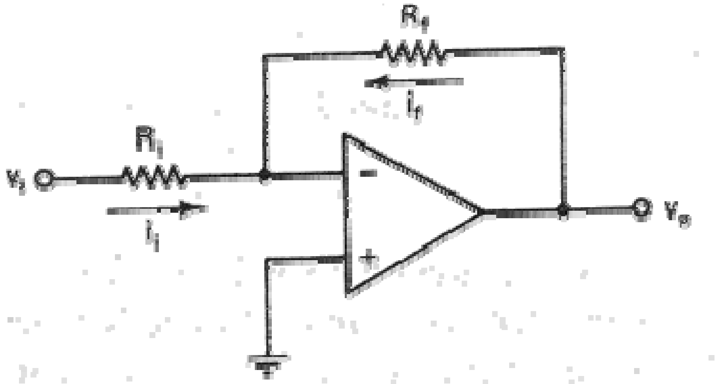
High Pass Filter
>0.05Hz

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

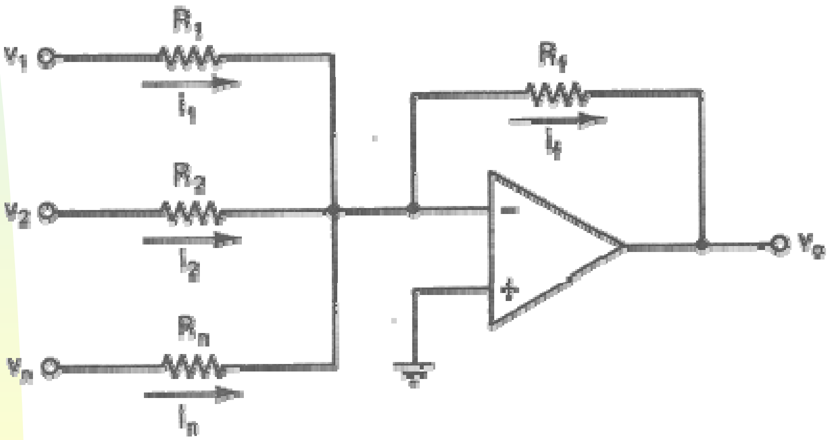
- **Inverting Amp with Gain = - Rf / Ri**



- **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)

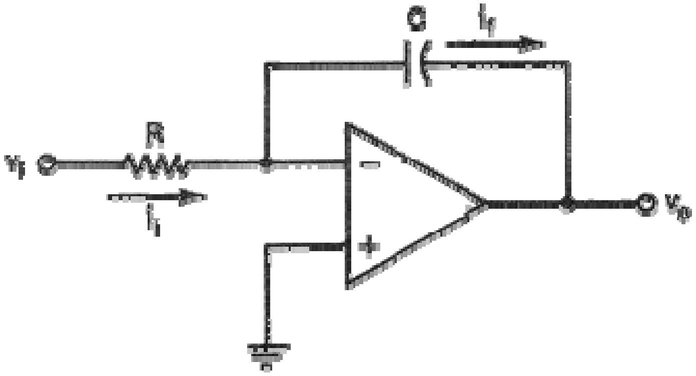
- **Adder**
  - Inverter with Several inputs



- **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**

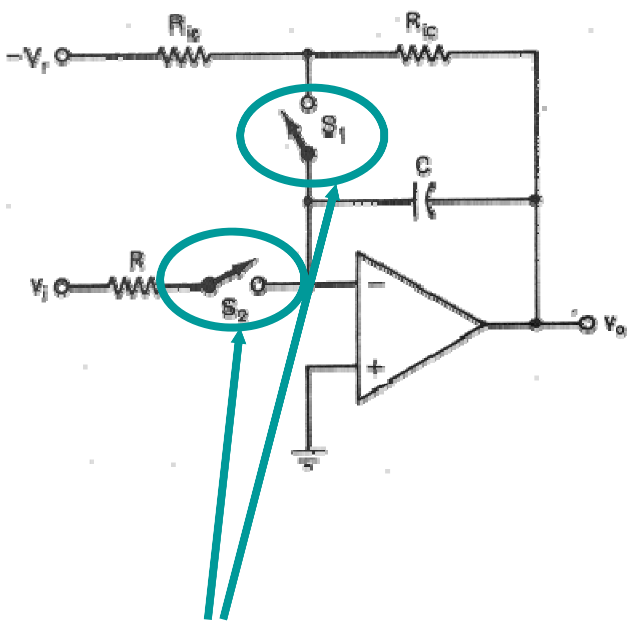
Integrator

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

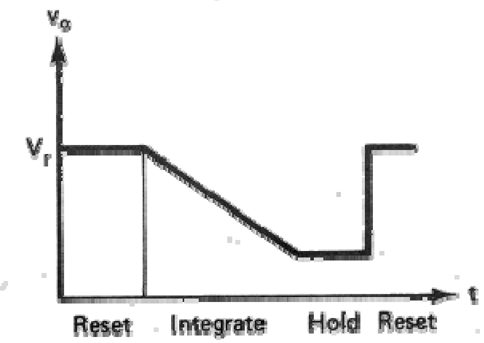


- **Drawbacks**
  - Vo will reach saturation voltage, if Vi is left connected indefinitely
    - Integrator operates as an open-loop amplifier for DC inputs

Practical Integrator



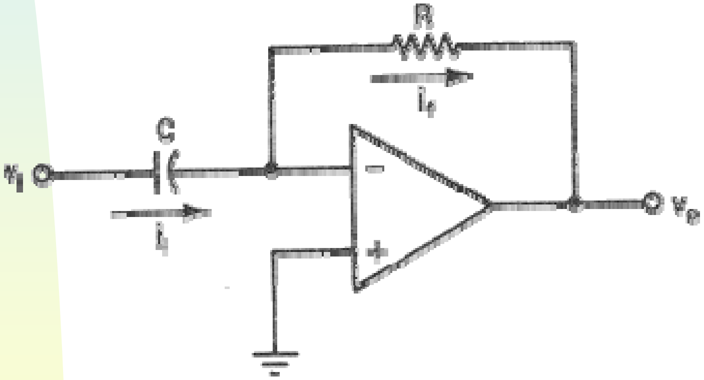
Controlled By
Relay or
Solid State Switch or
Analog Switch



- **Reset**
  - S1 Closed, S0 Open
    - Inverter
    - C is initialized to Vr
- **Integrate**
  - S1 Open, S0 Closed
- **Hold**
  - S1 Open, S0 Open
  - Keeps Vo constant
    - Read and Process

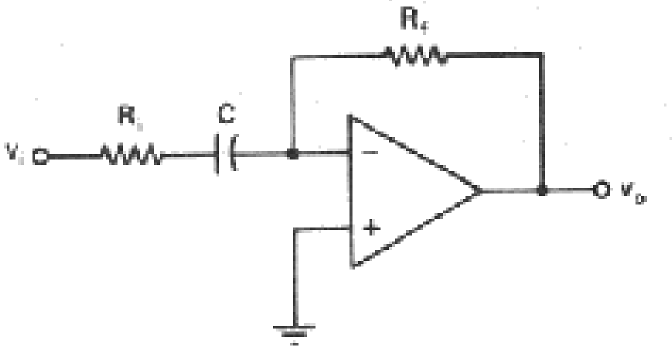
Differentiators

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



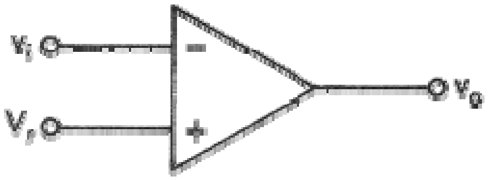
- **Drawbacks**
  - Instability at High frequencies
- **Practical Differentiator**
  - To Stable

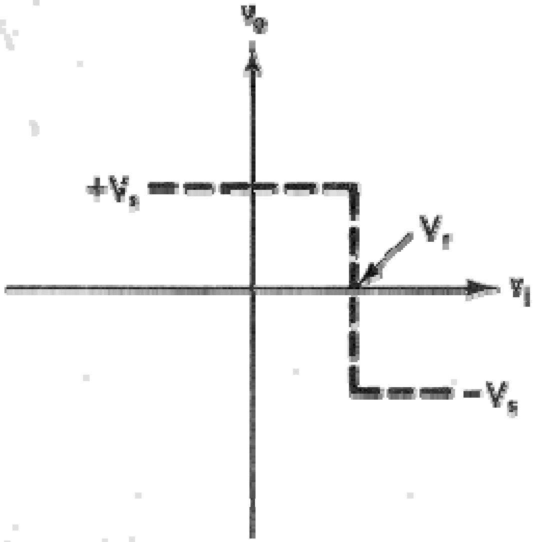
$$R_i = \sqrt{\frac{R}{A_0\omega_0 C}}$$



Comparators

- **Compare Two Inputs**
  - Vi > Vr
    - Vo = -Vs
  - Vi < Vr
    - Vo = Vs
- **Drawbacks**
  - If Vi = Vr + small noise
    - Rapid fluctuation between ± Vs



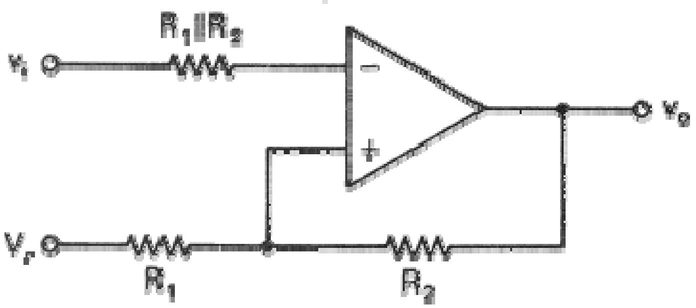


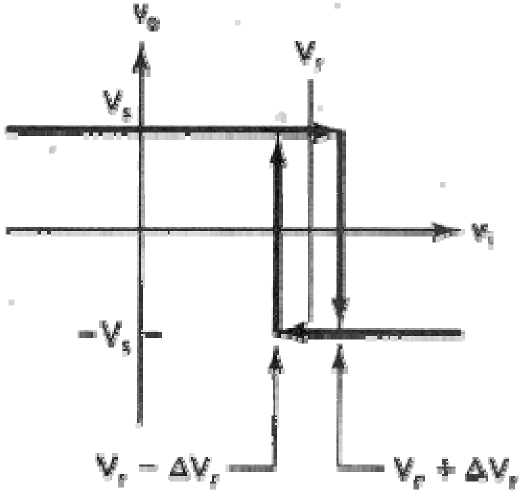
Comparators with Hysteresis

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

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

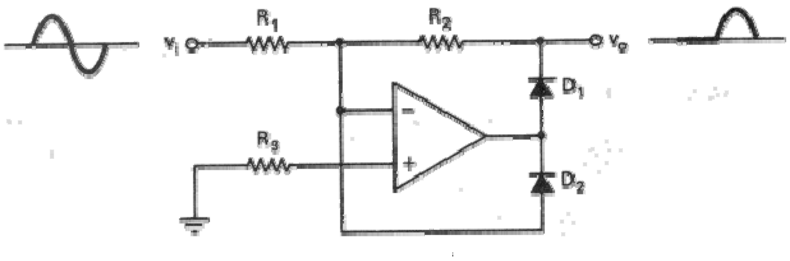
$$V_r - \Delta V_r = V_r + \frac{(-V_S - V_r)R_1}{R_1 + R_2}$$



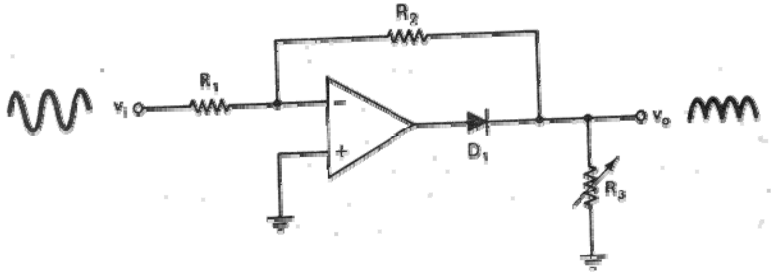


Rectifiers

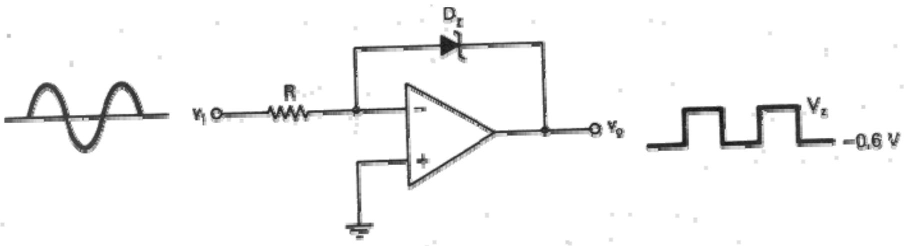
- **Precision Half Wave Rectifier**



- **Precision Full Wave Rectifier**



- **Limiters**



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

Guarding

- **Elimination of Surface Leakage Currents**
- **Elimination of Common Mode Signals**

- **Very important in practice**
  - But skip in this course

Passive Filters

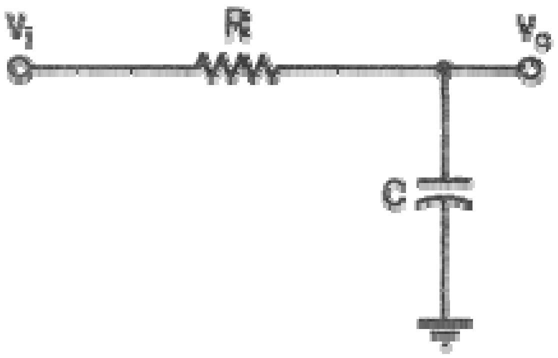
- **Passive Circuits**
  - Contains only passive elements
    - Registers, Capacitors and Inductors
  - Examples
    - Bridge Circuit
    - Voltage Divider
    - Filters
- **Filters**
  - Eliminate unwanted signal from the loop
  - Low Pass, High Pass, Band Pass, Notch, …

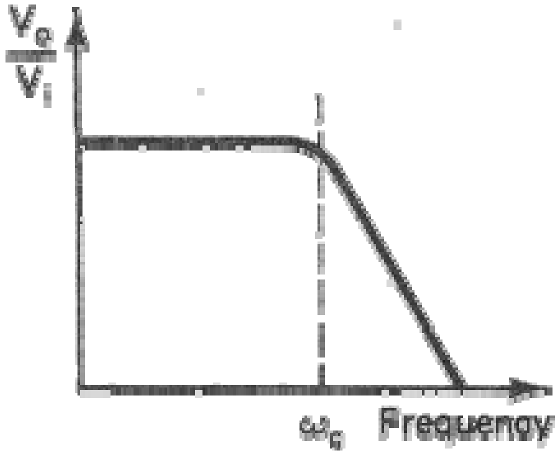
Passive first-order Low pass Filter

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

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

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



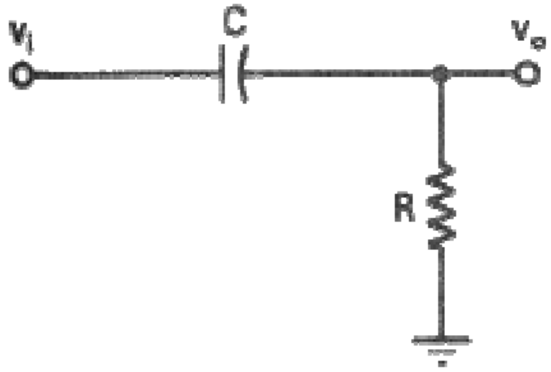


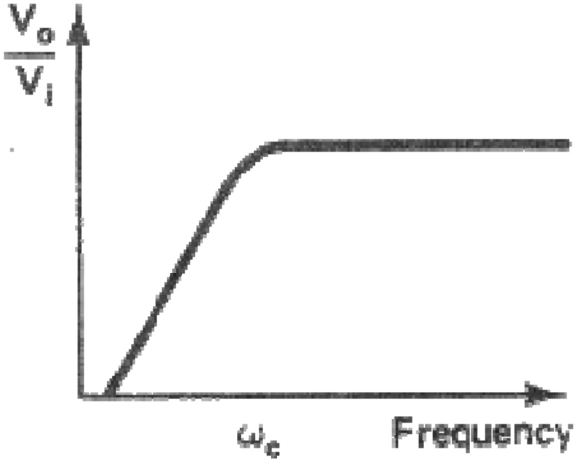
Passive first-order High pass Filter

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

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

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





Passive second-order Low pass Filter

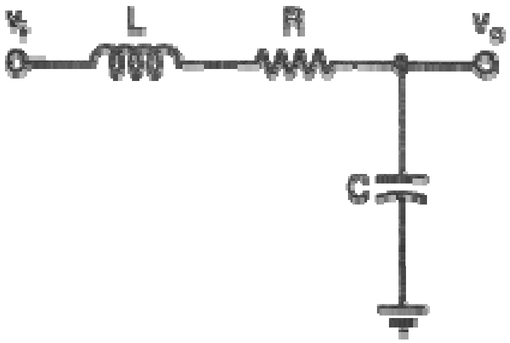
- **To increase the attenuation of transfer function**
- **Order of Filter**
  - Number of C and L

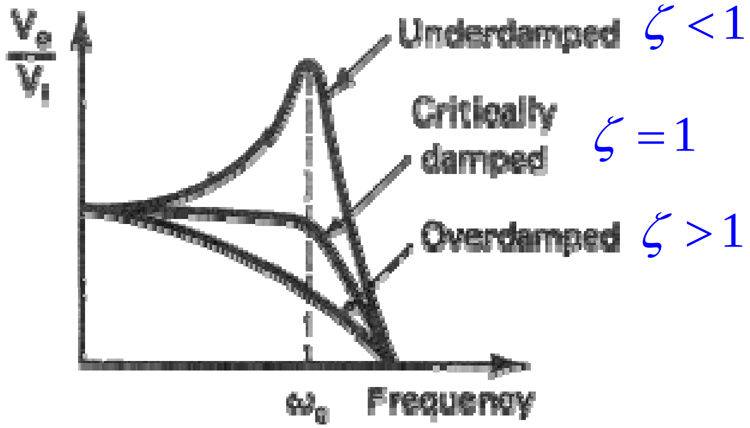
$$\frac{V_o}{V_i}=\frac{1}{(j\omega/\omega_c)^2+(2\zeta j\omega/\omega_c)+1}$$

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

- Meaning of Quality factor

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



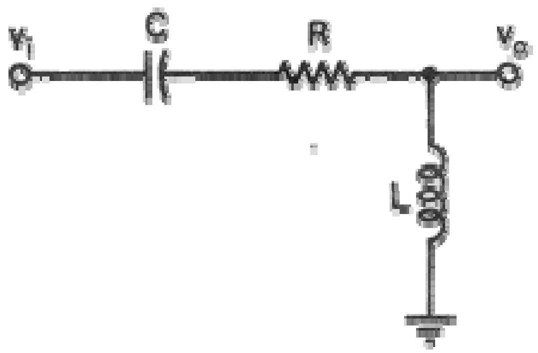


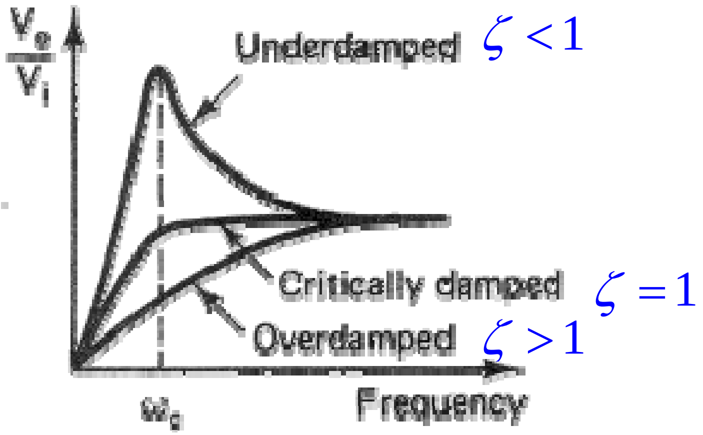
Passive second-order High pass Filter

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

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

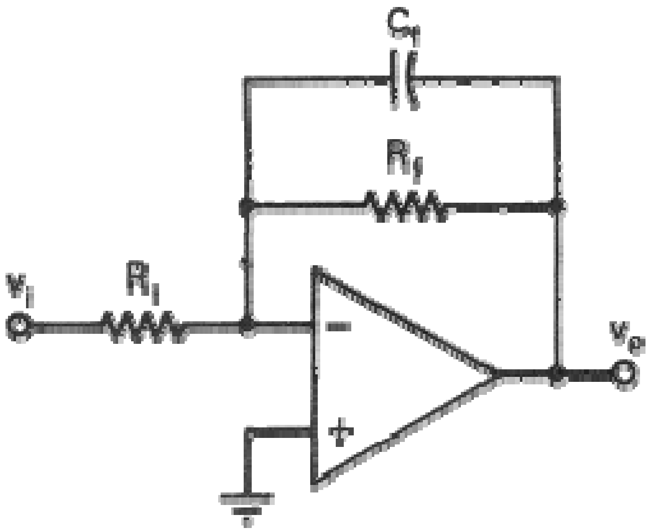
$$\omega_c = \sqrt{\frac{1}{LC}}, \zeta = \frac{R}{2}\sqrt{\frac{C}{L}}$$



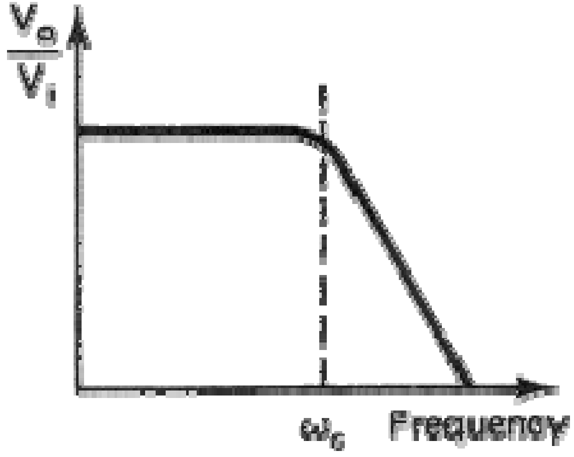


Active First-order Low Pass Filter

- **Inverting Amp + Feedback Capacitor**

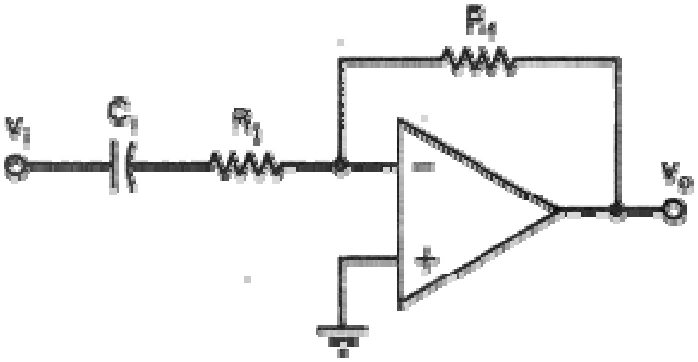


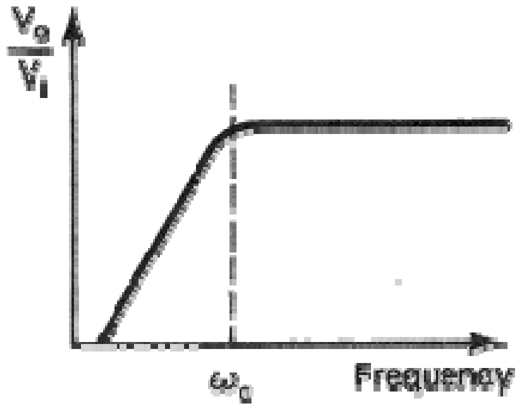
- **Identical frequency response with Passive filter**
- **Very Low Output impedance**
    - Negligible Loading Effect



Active First-order High Pass Filter

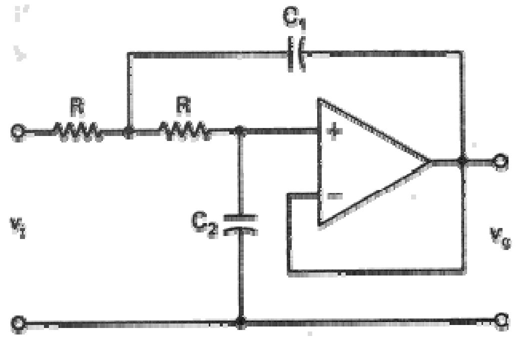
- **Inverting Amp + Input Capacitor**
- **Identical frequency response with Passive filter**
- **Very Low Output impedance**
  - Negligible Loading Effect





Active High-order Filters

- **Low Pass Filters**



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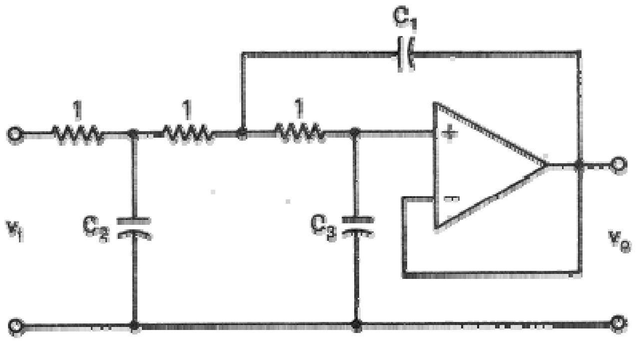
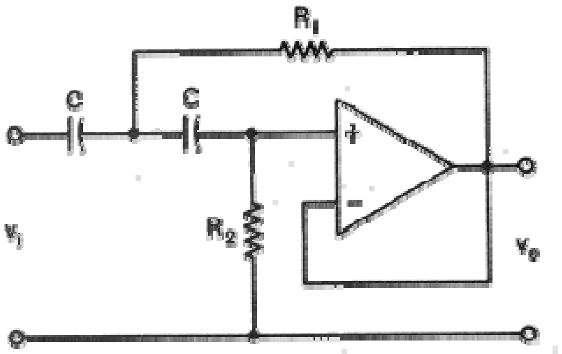
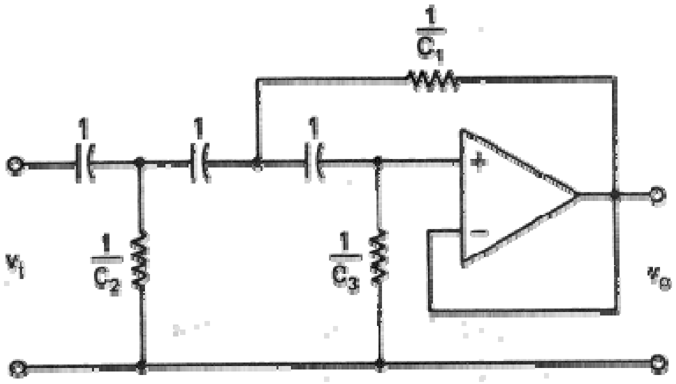


(b)

- **High Pass Filters**



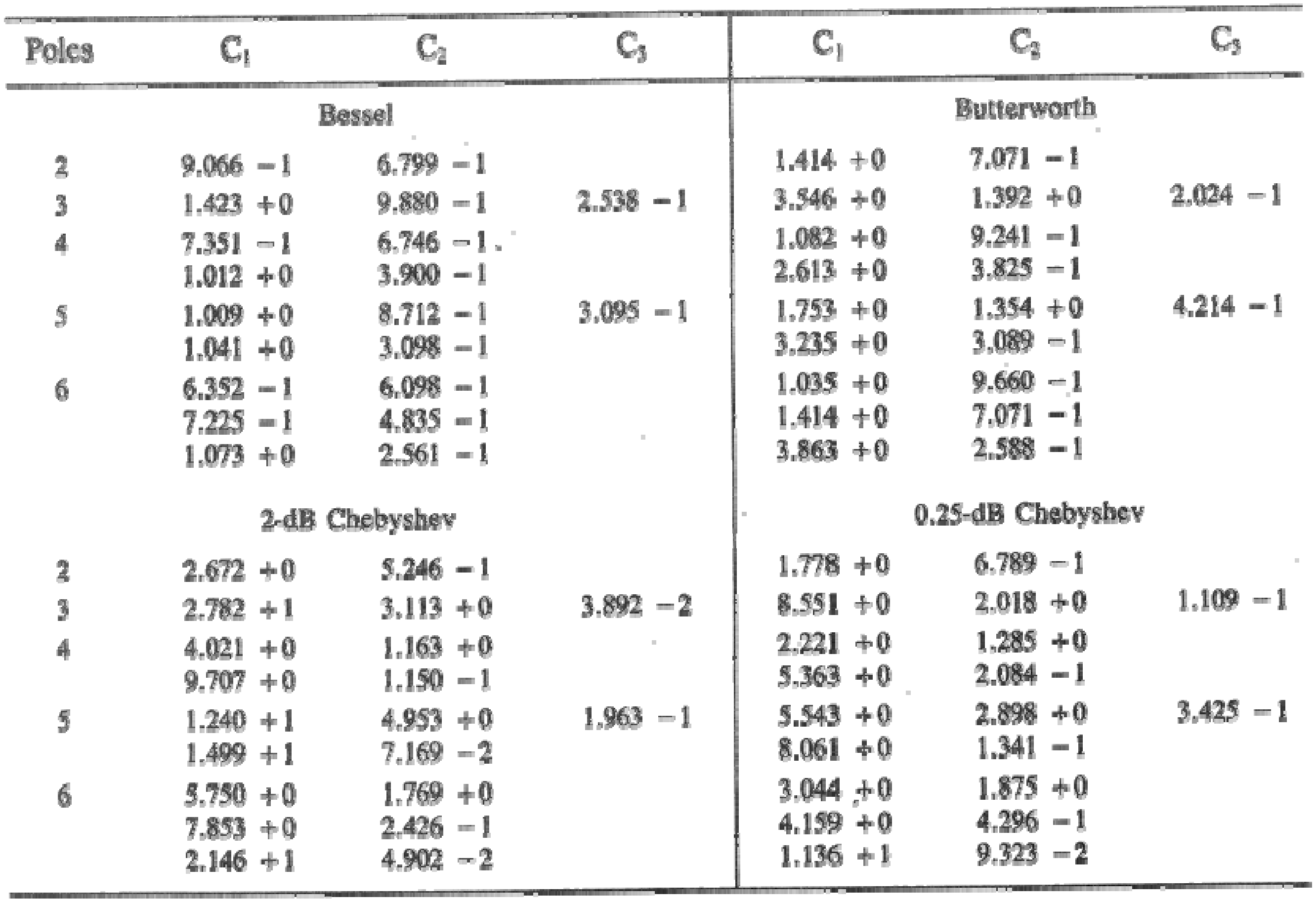


Bandpass and Band-reject Filters

- **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

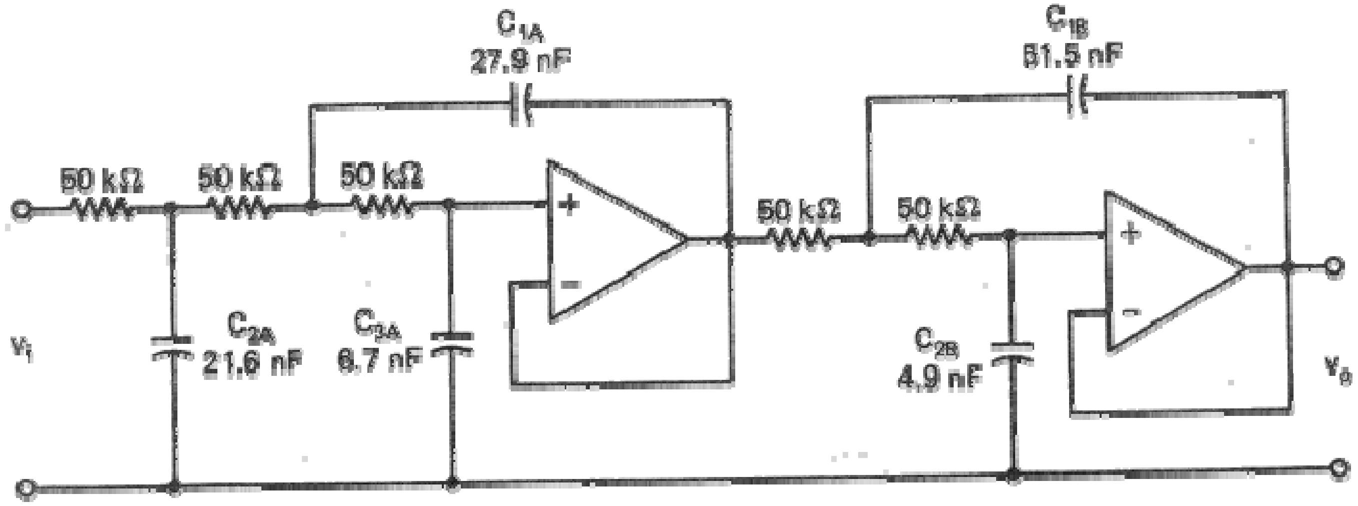
- **C when $\omega_0 = R_0 = 1$**



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	

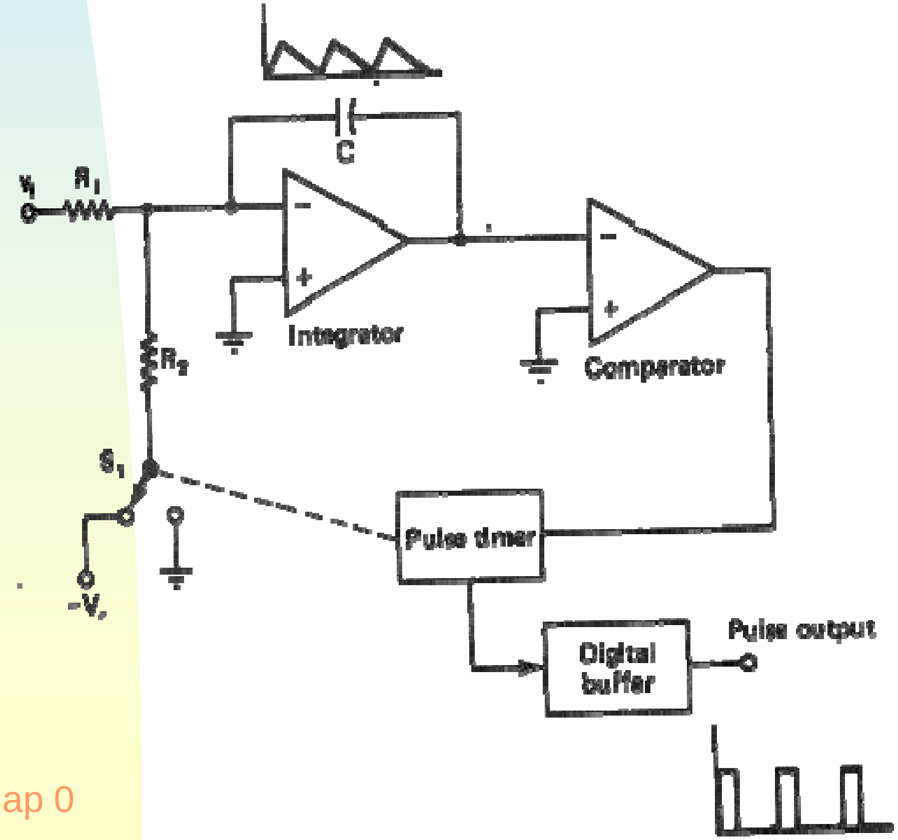
Filter Design Example

- **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 ?
    - $C_{1A} = (\omega_0\, R_0\, C_0\,) / (\omega\, R)$
      $= 1 \text{x} 1 \text{x} 1.753 / 2\pi \text{x} 200 \text{x} 50\text{K} = 27.9\ \text{nF}$
    - $C_{2A} = 21.6$ nF, $C_{3A} = 6.7$ nF, $C_{1B} = 51.5$ nF, $C_{2B} = 4.9$ nF



VCO(Voltage Controlled Oscillator)

- **VCO = Voltage to Frequency(V/F) Converter**



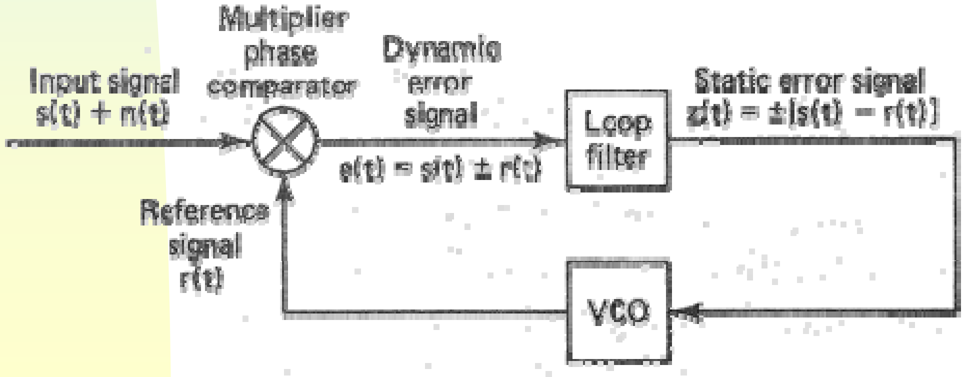
- **VCO converts an input voltage to a series of output digital pulses whose frequency is proportional to the input voltage**
- **Applications**
  - ◆ ADC
  - ◆ Digital Transmission
  - ◆ Telemetry
  - ◆ Digital Voltmeter

VCO (Cont.)

- **Module form**
  - Better linearity, Lower Gain drift, Higher full-scale frequencies than IC
- **Monolithic IC form**
  - Less expensive, Small size
  - Lower drift, Better flexibility of frequency range
- **Examples**
  - LM331
    - Low cost VCO from National Semiconductor
    - Maximum nonlinearity 0.01% over 1 ~ 100KHz
  - CD4046B
    - PLL contains VCO
    - Maximum nonlinearity 1.0% over 1 ~ 400MHz

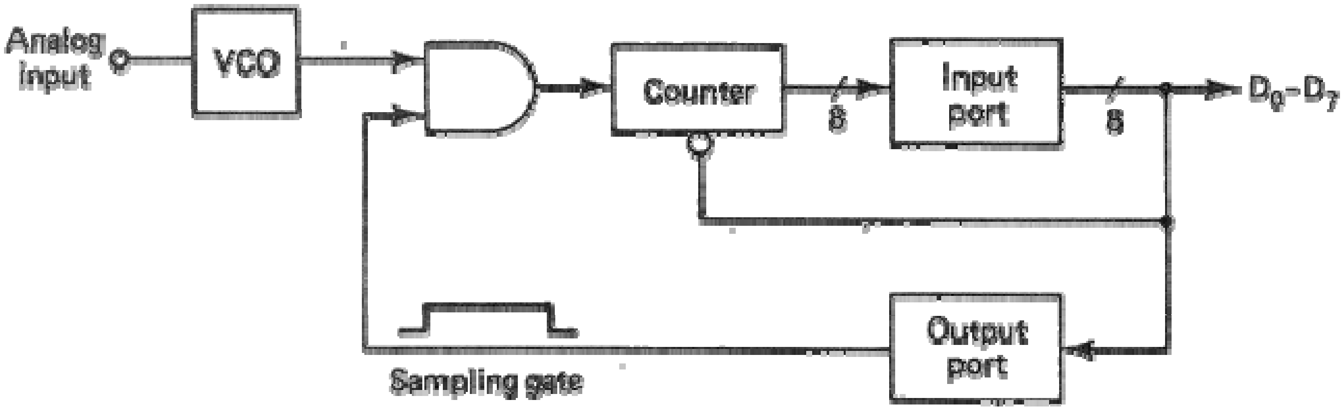
PLL(Phase Locked Loop)

- **VCO is commonly used in PLL**
- **Applications**
  - Communications
  - Radar
  - Time and frequency control
  - Instrumentation system
- **Control loop**
  - Goal
    - Minimize z(t)
      → s(t) = r(t)
  - Change r(t) until z(t)=0
    - s(t) can be obtained By reading r(t)



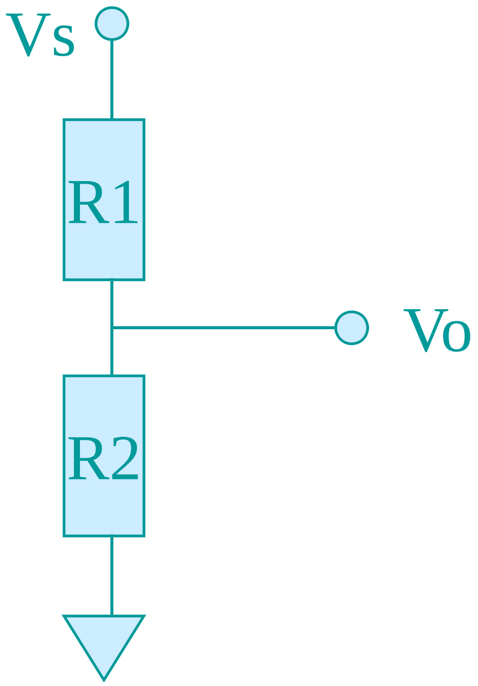
VCO Interfacing

- **Output of VCO**
  - Digital pulses whose frequency is proportional to input voltage
- **# of pulse / Duration**
  - Duration
    - Controlled by Sampling Gate
  - # of Pulse
    - Counted in Counter



Divider Circuit

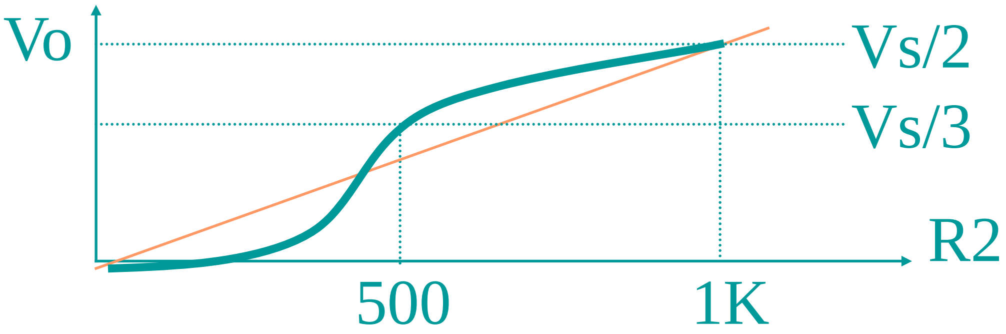
- **Convert Register Variations to Voltage Variations**



- **Output Voltage**
  - Vo = {R2 / (R1 + R2)} Vs

Divider Circuit: Drawbacks

- **Vo is not linearly changed**
  - Ex: Vs = 5V, R1 = 1KΩ, R2 = 0 ~ 1KΩ(Sensor)



- **Output Impedance(R1 || R2) is not so High**
- **Large Power Consumption**

Divider Circuit: Example

- **R1 = 10KΩ, R2 = (4K ~ 12KΩ), Vs = 5V**
  - Maximum Vo = 5 {12 / (10+12)} = 2.73V
  - Minimum Vo = 5 { 4 / (10 + 4)} = 1.43V
  - Maximum Z = (10K || 12K) = 120/22 KΩ
  - Minimum Z = (10K || 4K) = 40/14 KΩ
  - Maximum Power = $(Vo)^2/R2$

    $= (2.73)^2/12K = 0.62mW$
  - Minimum Power = $(1.43)^2/4K = 0.51mW$