Introduction to Biomedical Engineering: *Instrumentation*

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Outline

- Cardiac pacemaker: an example
- Chapter 5 of the textbook:
  - Basic instrumentation system
  - Analog circuit
  - Signal conditioning
  - Instrumentation design
  - Computer-based instrumentation systems
- Noise figure and its measurements
- Quantization and sampling

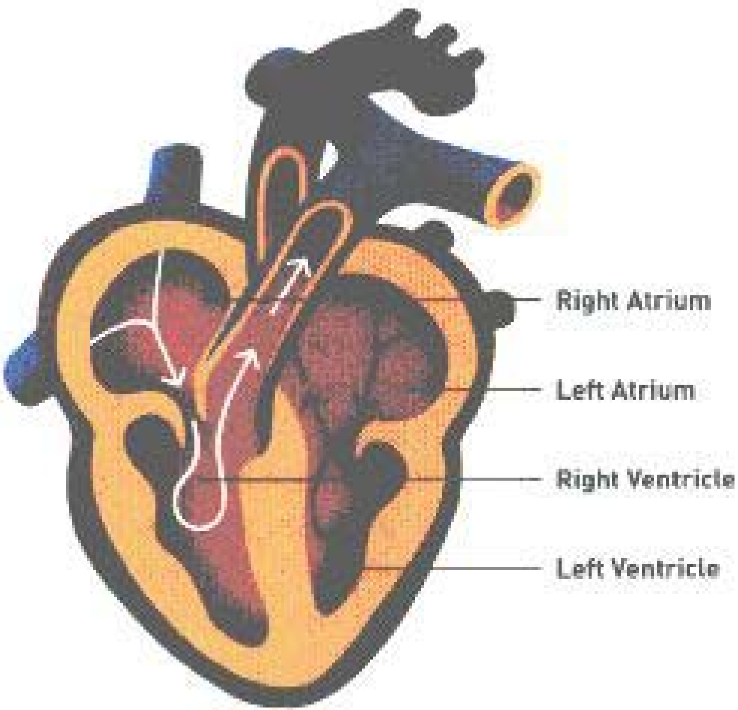
Cardiac Pacemaker: An Example

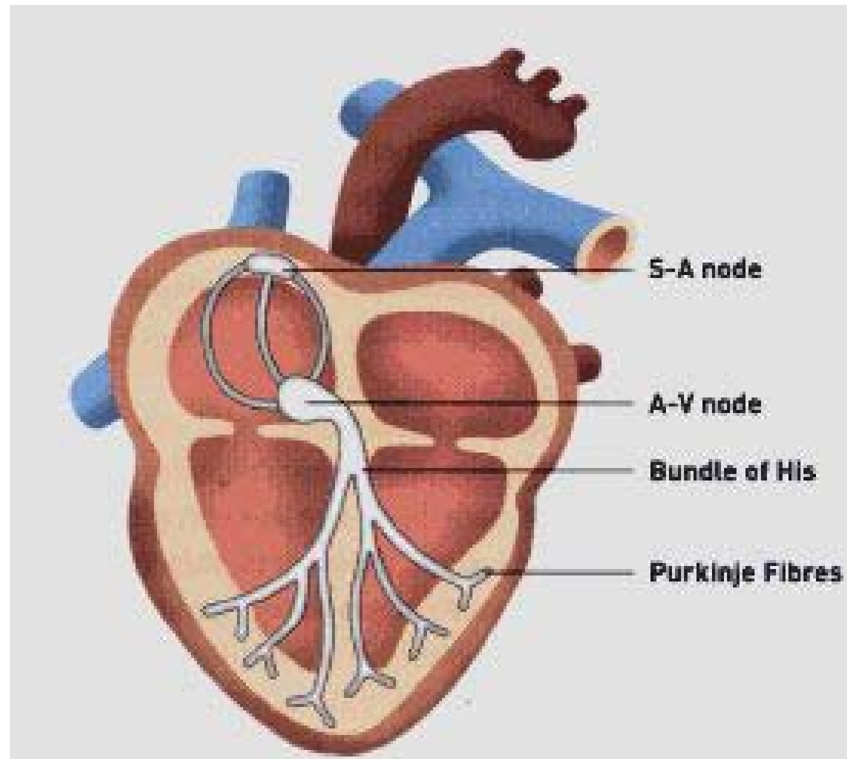
Cardiac Pacemaker

- A small, battery-powered device implanted into the body.
- It monitors the electrical impulses in the heart and, when needed, delivers electrical stimuli to make the heart beat in a more normal rhythm.
- A pacemaker is used when the heart beats too slowly (bradycardia) or has other abnormal rhythms (arrhythmias).

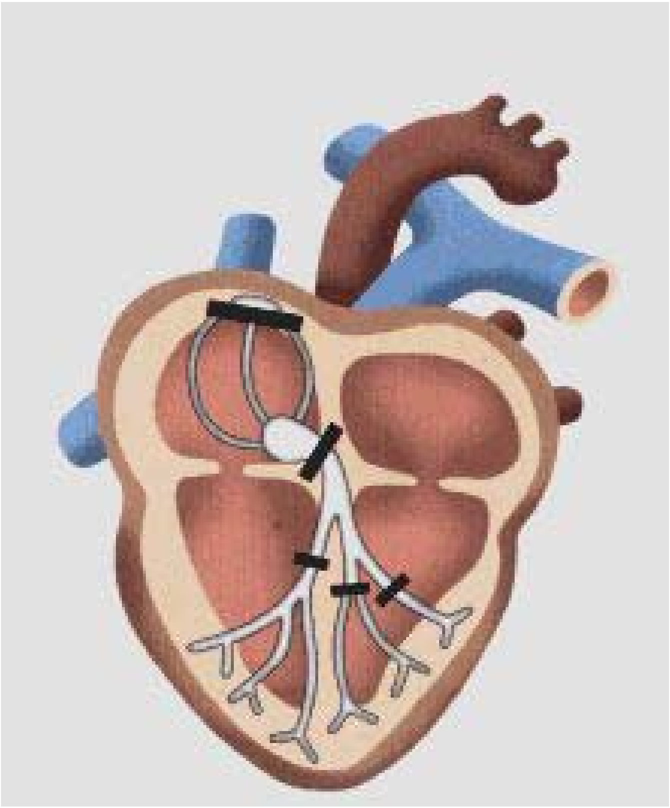
** Chapter 8, Design and development of medical electronic instrumentation, by Prutchi and Norris, John Wiley and Sons, 2005.*

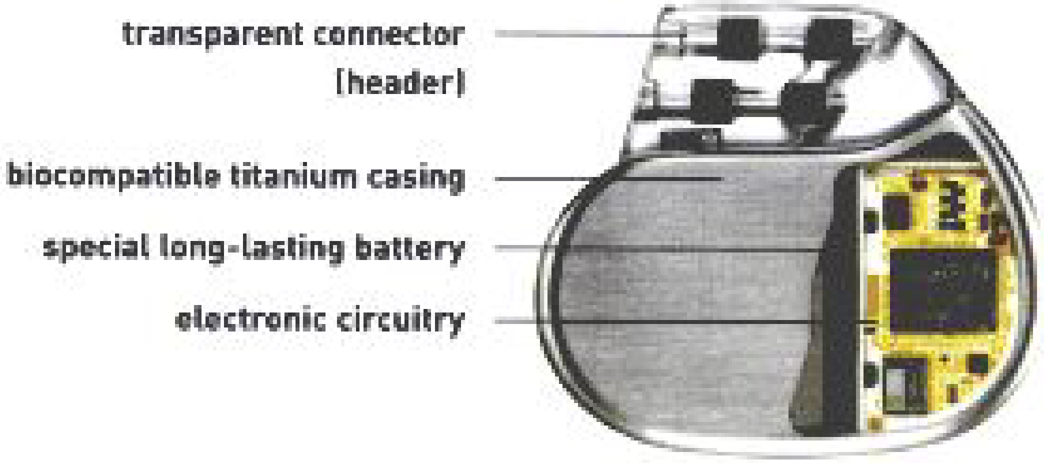
Heart Disorder and Pacemaker



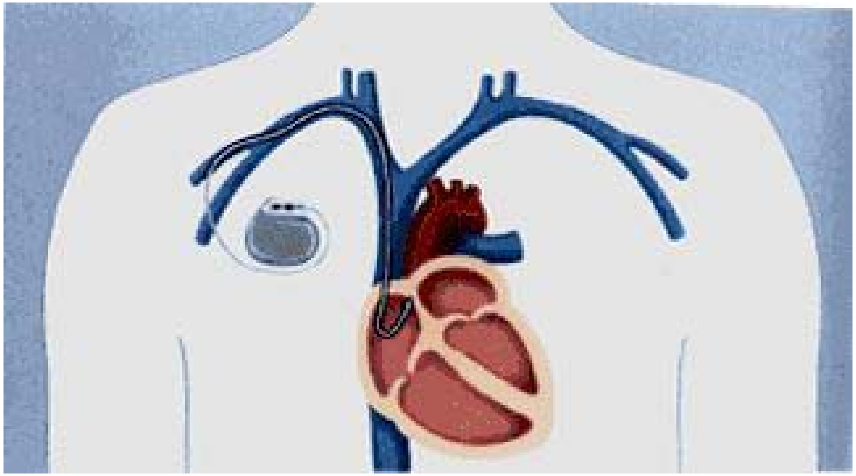


Heart Disorder and Pacemaker

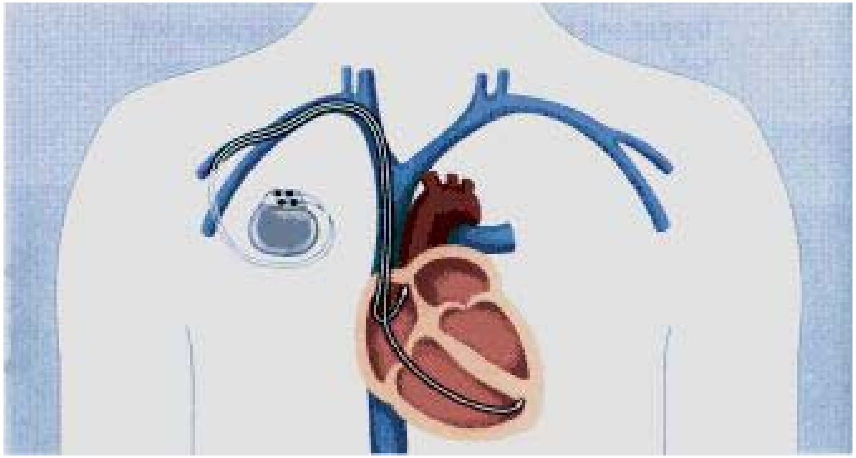




Heart Disorder and Pacemaker



Single Chamber



Dual Chamber

Principles of Cardiac Pacemaker

- Consisting of a battery and electrical circuitry (pulse generator). The circuitry checks the heart rate and produces tiny electrical pulses that keep the heart beating at the correct pace.
- The pacemaker is connected to the heart through one to three insulated wires (leads) that are attached directly to the heart's chambers.

Customized Cardiac Pacemakers

- Rate-Responsive Pacemakers: May be programmed to increase or decrease heart rate to match your activities (i.e. resting or walking).
- Single-Chambered Pacemakers: Use only one lead placed into the right atrium or the right ventricle.
- Dual-Chambered Pacemakers: One is placed in the right atrium, the other in the right ventricle.
- Cardiac Resynchronization Therapy Pacemakers: One is in the right atrium, one is in the right ventricle, and one is placed through the heart's veins to the left ventricle.

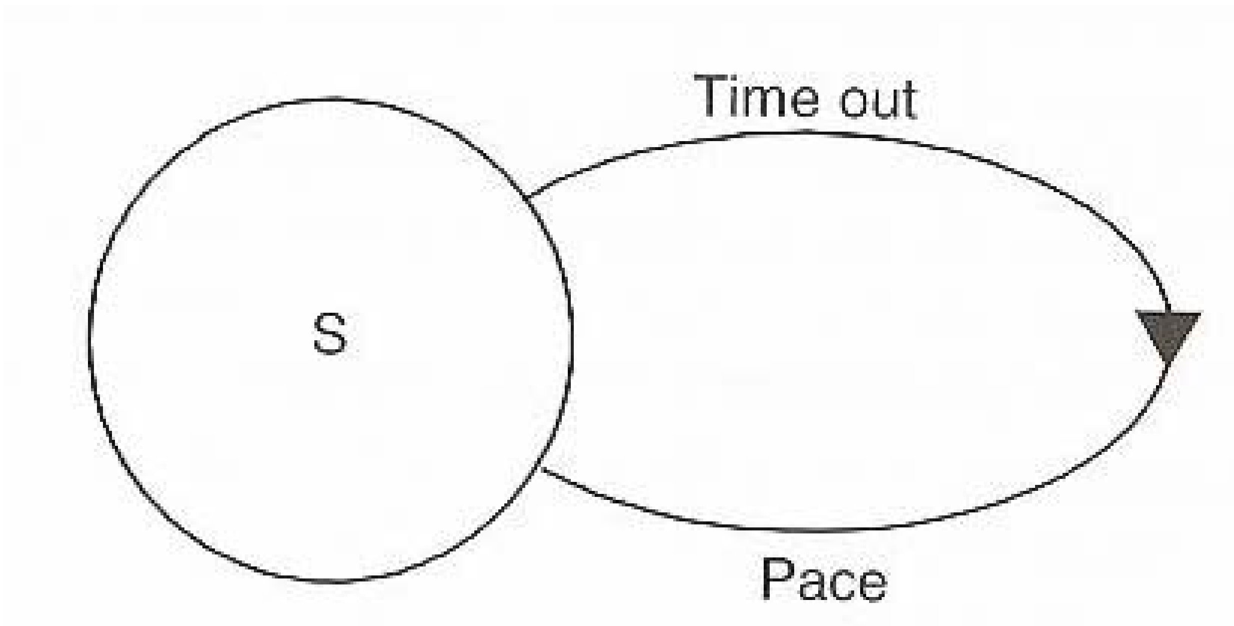
Risks in Surgical Procedures

- Bleeding
- Swelling or bruising under the skin
- Blood clot formation
- Infection
- Blood vessel damage

Electromagnetic Interference

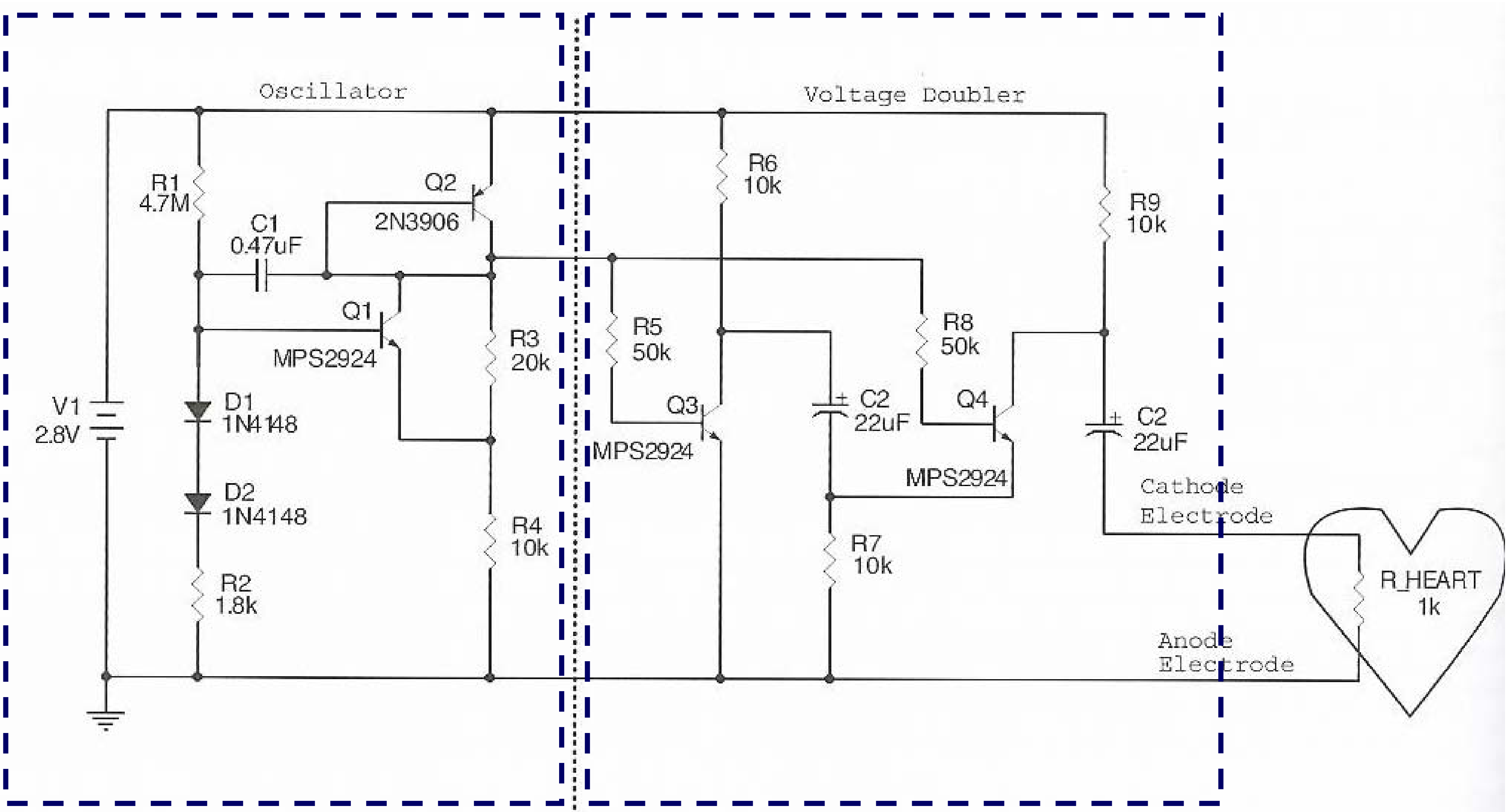
- Household devices and appliances may cause the pacemaker to enter a mode to prevent inappropriate behavior or cause it to stop delivering therapy.
- Some medical equipment can damage your pacemaker.
- Some security devices may temporarily stop your pacemaker from working properly or give you cardiac symptoms.
- Welders and electric generators may stop your pacemaker from working properly.

Pacemaker State Machine: Early Stage

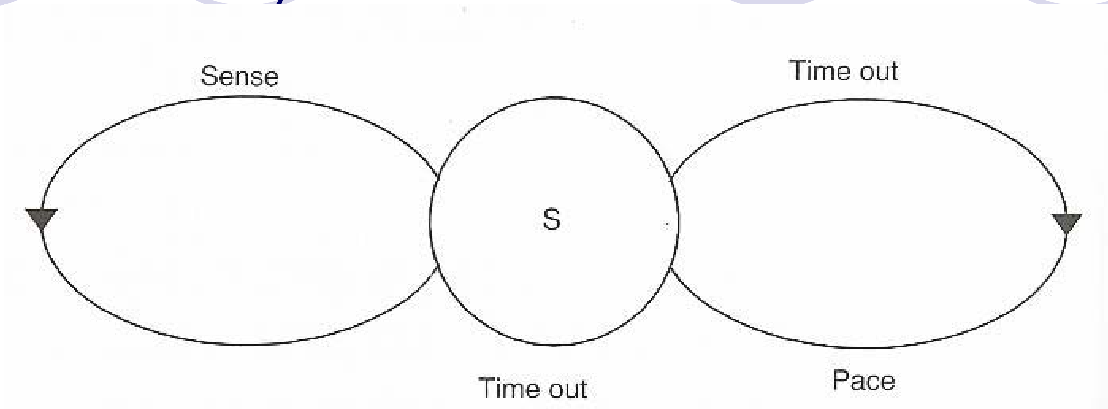


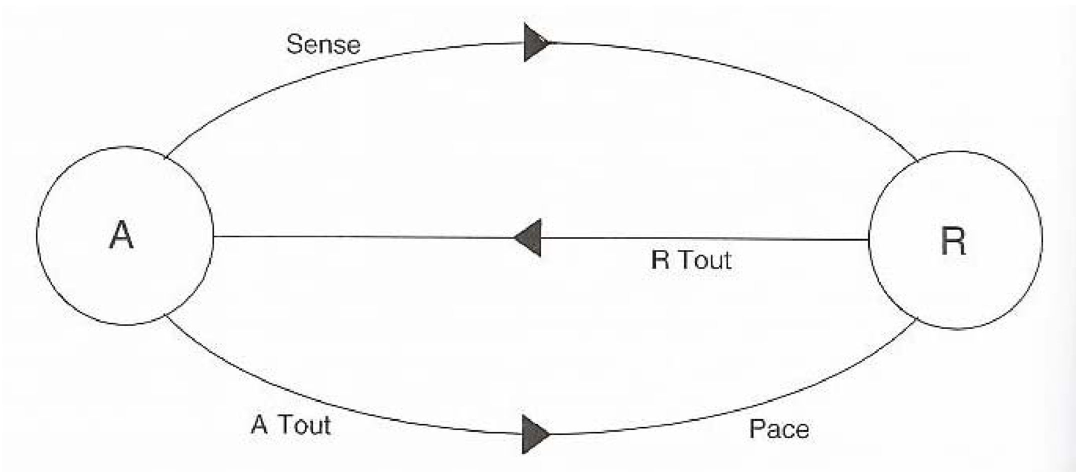
- A pulse is generated every time that a length of time elapses.
- Pulse characteristics (length, shape and duration) can be programmed.

Pacemaker State Machine: Early Stage



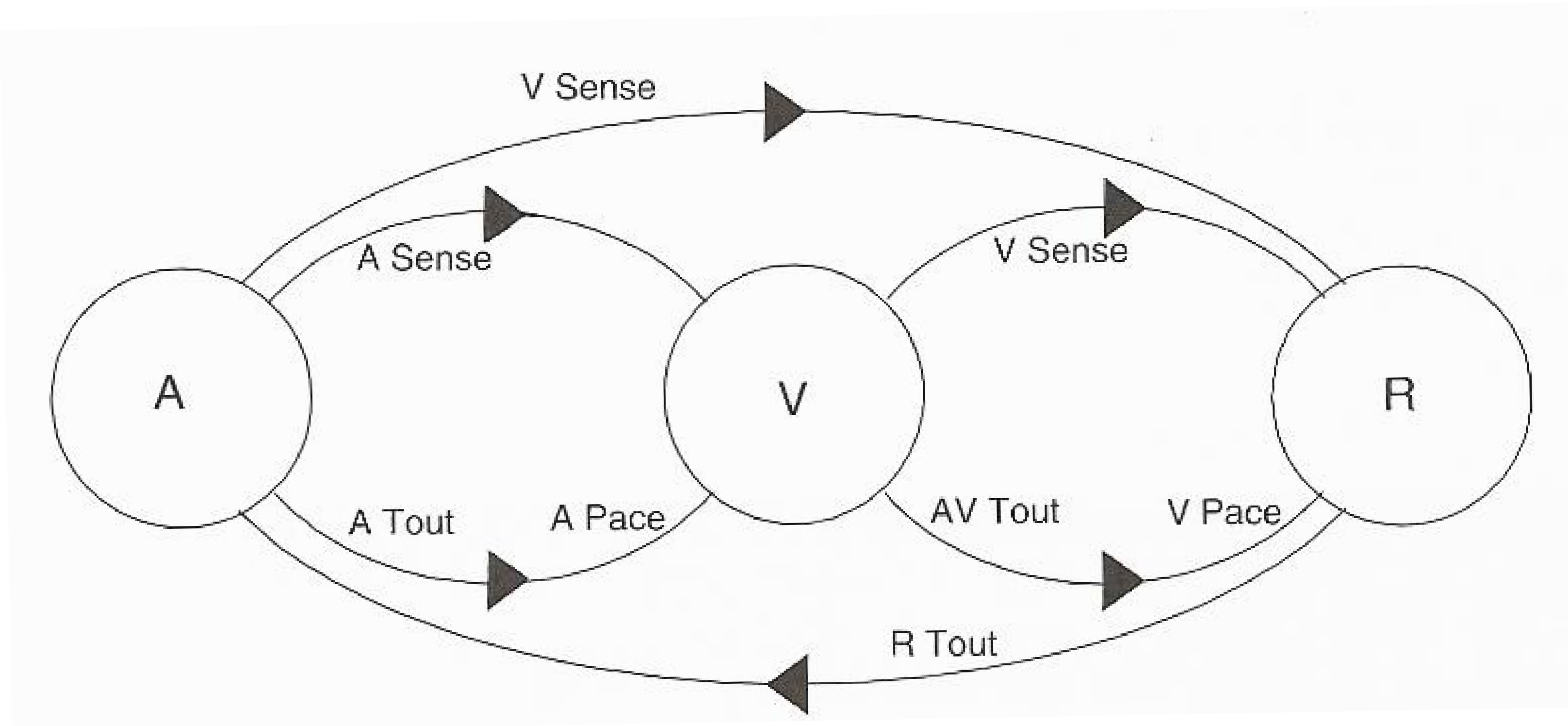
Pacemaker with detection of intrinsic heart activity



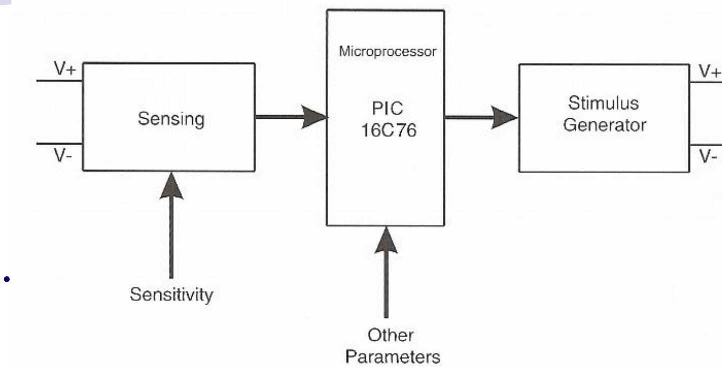


- The stimulus period is the sum of A (alert) time-out and R (refractory) time-out.

Dual Chamber Pacemaker

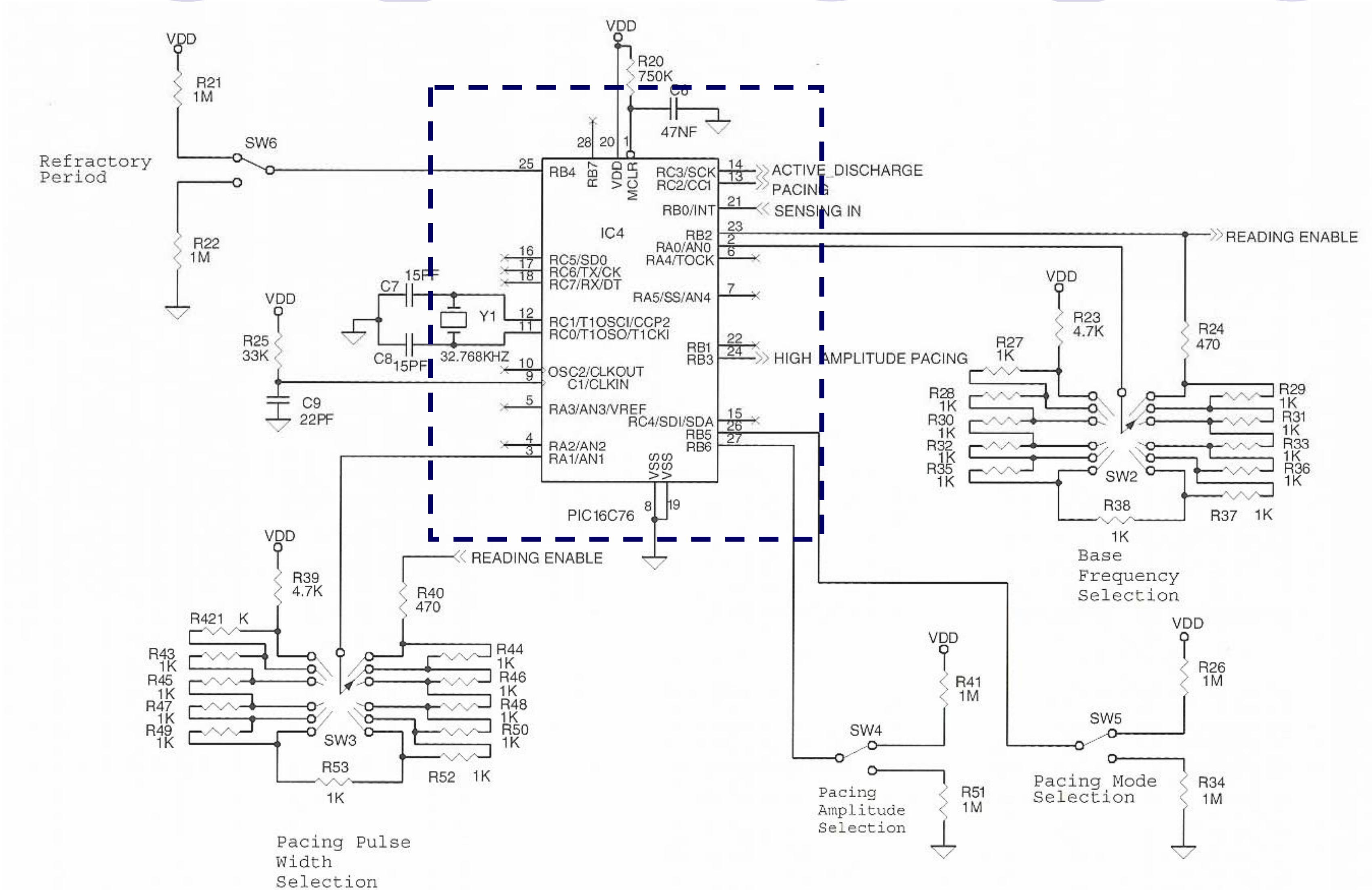


External VVI Pacemaker

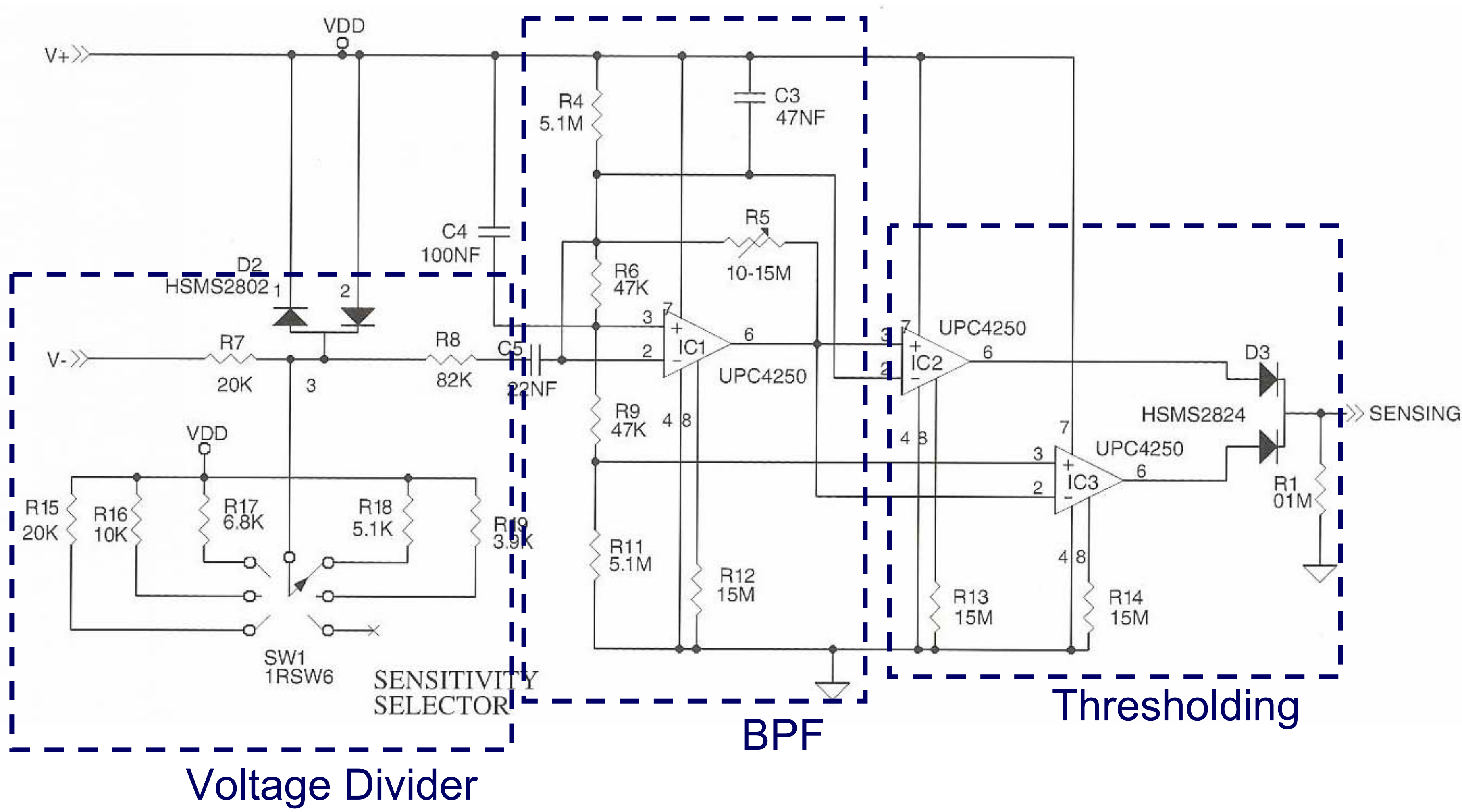


- VVI:
  - V: Pacemaker can stimulate the ventricle.
  - V: Pacemaker can sense the ventricle.
  - I: Ventricle pacing is inhibited whenever the pacemaker detects a timely intrinsic ventricular event.
- Rate: 40, 50, 55, 60, 65, 70, 80, 90, 100, 110, 120, 140 beat/min
- Refractory period: 250, 350 ms.
- Pacing pulse amplitude: battery voltage (3V) and its double (6V).
- Pacing pulse width: 0.125 to 1.5 ms in 0.125-ms steps.
- Ventricular sensing sensitivity: 1.0 to 6.0 mV in 1.0-mV steps.

External VVI Pacemaker

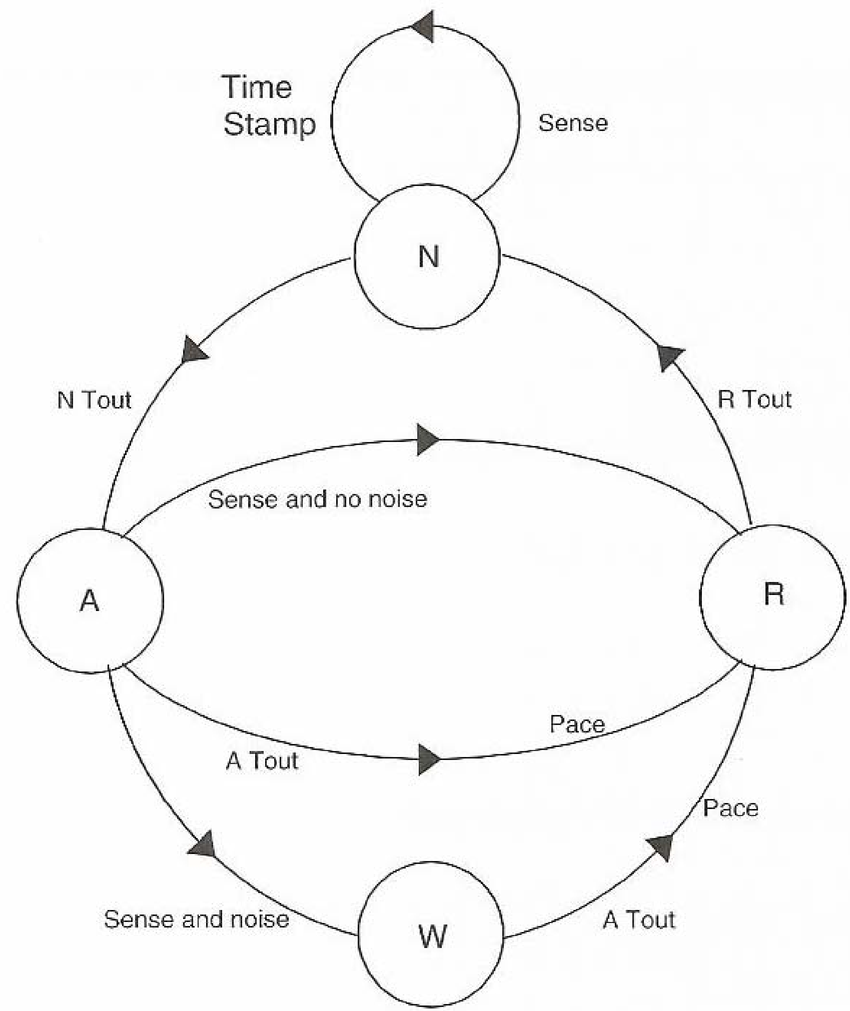


Sense Amplifier Circuit



Enhanced VVI State Machine

- Two new states:
  - N: Noise window with a 100 ms (10 Hz) timeout elapse.
  - W: Difference between a sense event and a time-stamped event is less than 100 ms.



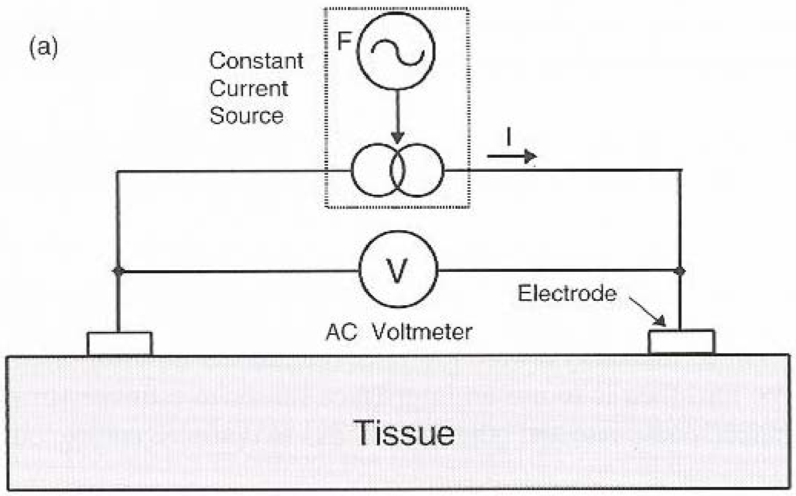
More Issues to Consider

- Power consumption.
- Software testing.
- Noninvasive communication (bidirectional RF link)
- Rate responsiveness.
- …

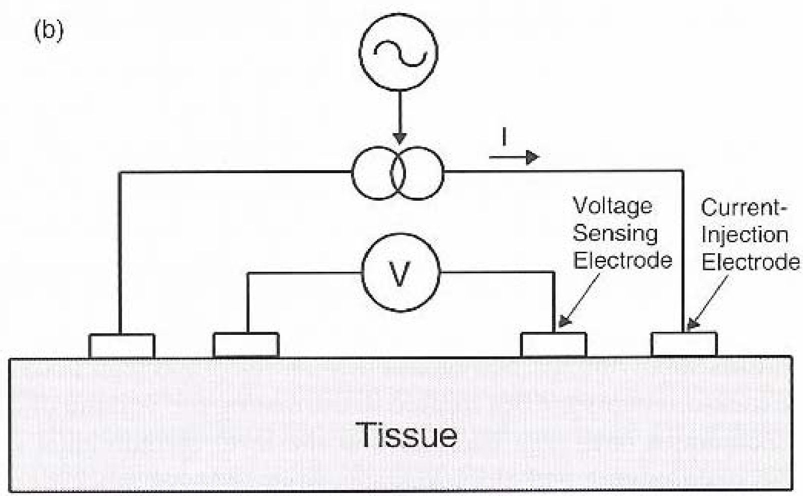
Rate Responsiveness

- Take into account activity level and emotional state.
- Use sensor technologies to determine optimal heart rate.
  - Body movement detection.
  - Minute ventilation (MV): respiration parameter.
- Hemodynamic state improvement: blood pressure and blood flow.
  - Intracardiac impedance measurement: Impedance of tissue reflects the filling state of the blood vessels contained.

Impedance Technique (*Impedance plethysmography*)



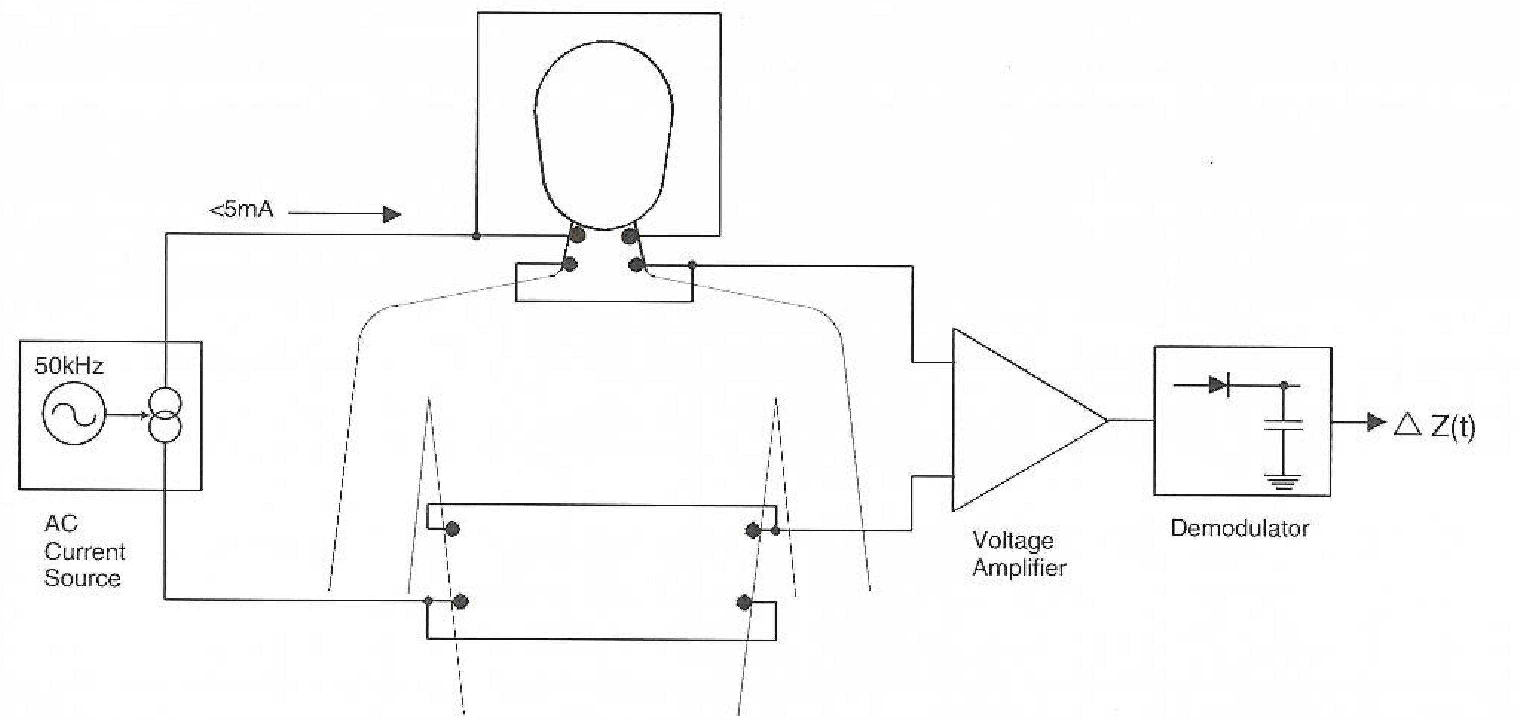
Two-terminal measurement



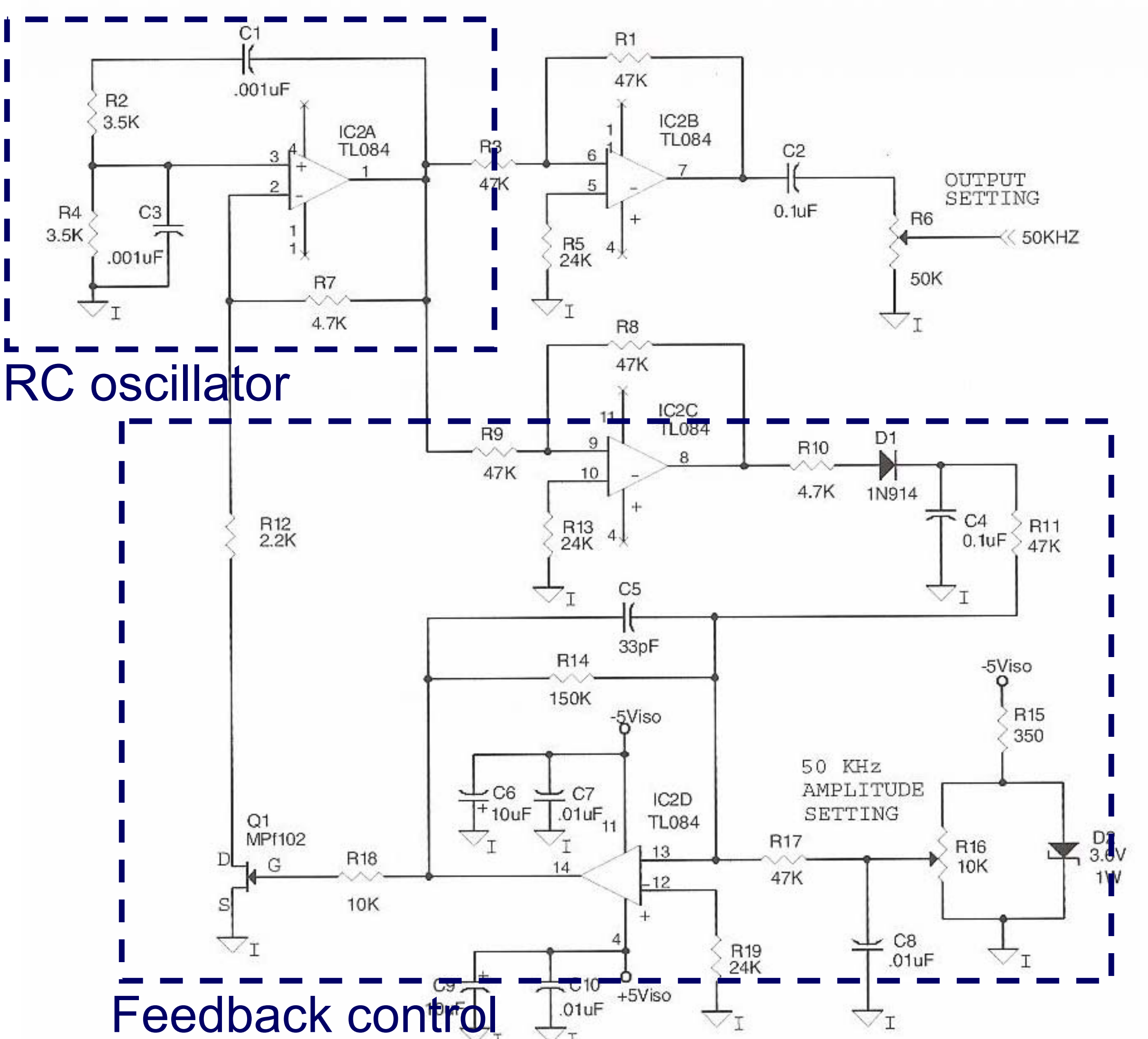
Two-terminal measurement: avoid errors caused by nonlinear potential differences generated at the electrodes

Impedance Cardiograph

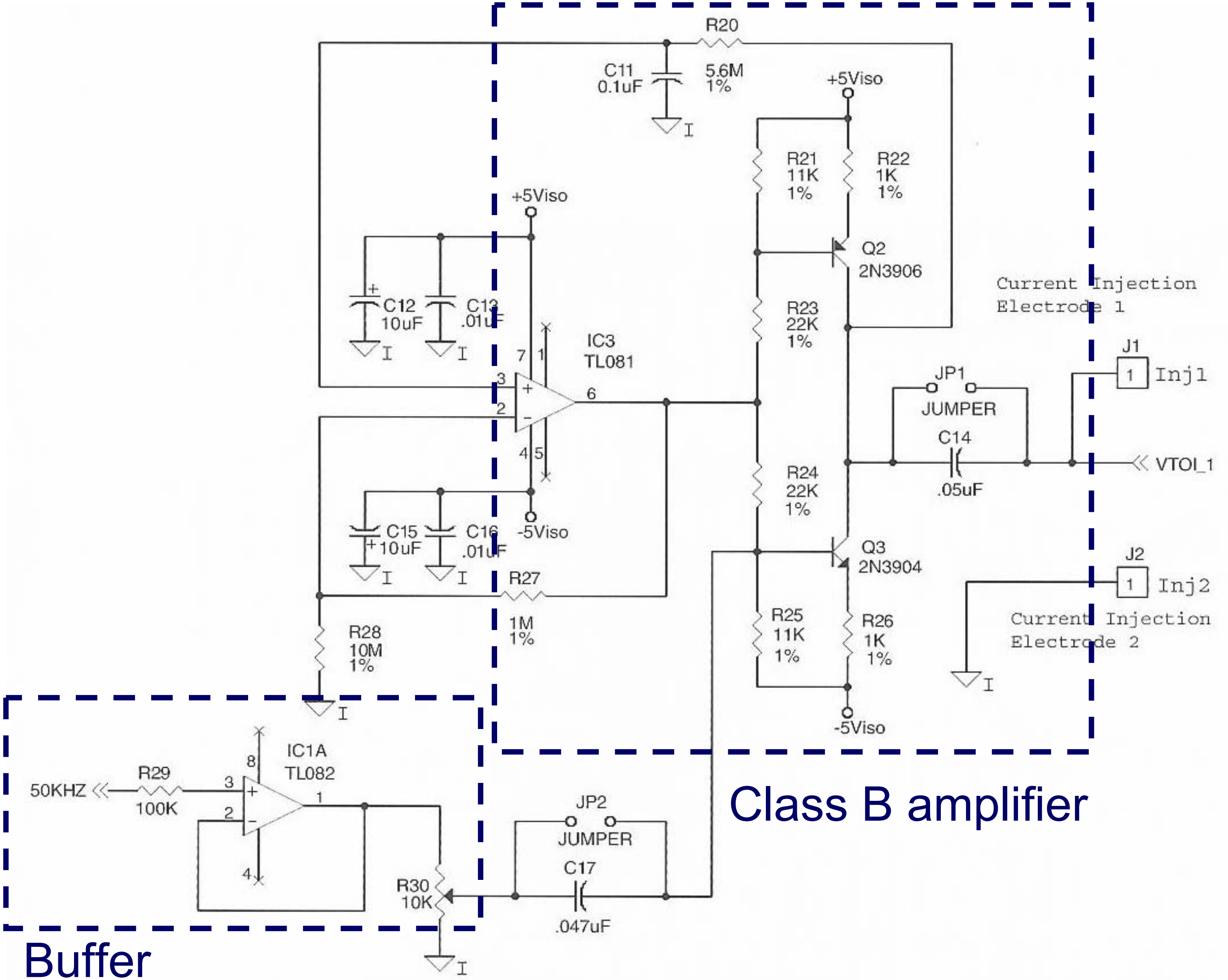
- Majority of the impedance signal is caused by changes in aortic blood volume and blood velocity.



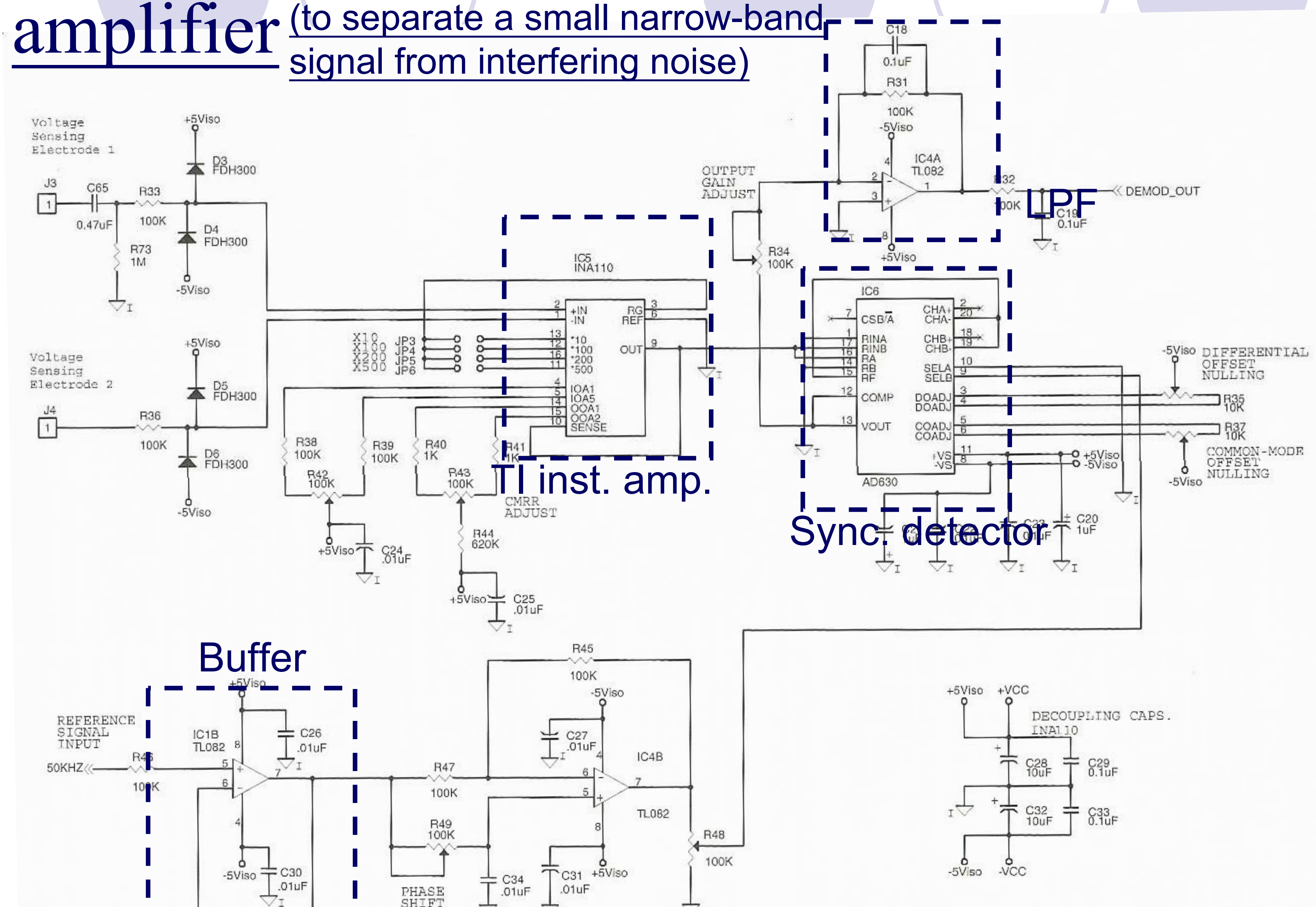
Impedance Cardiograph: 50-KHz sinusoidal oscillator



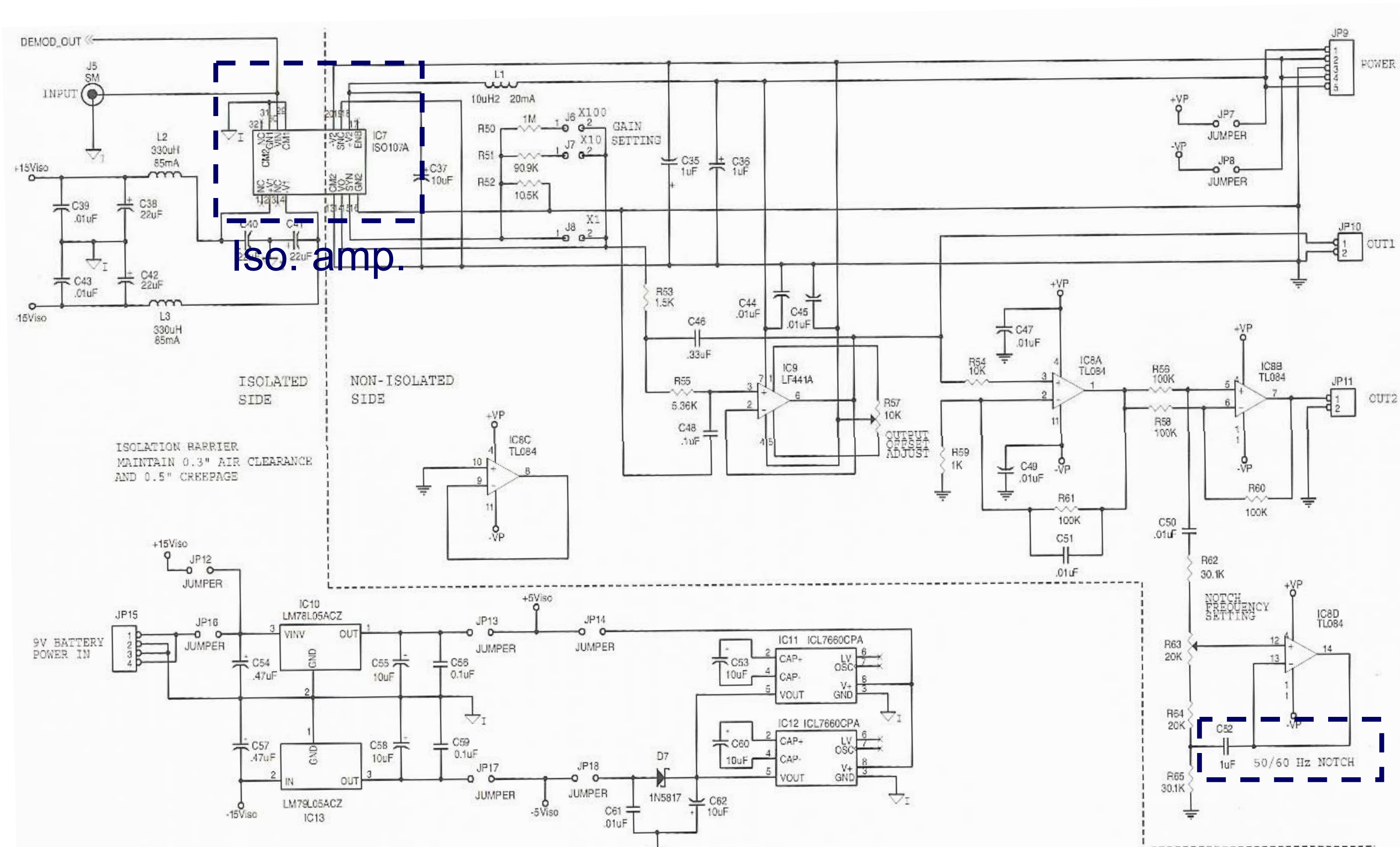
Impedance Cardiograph: Voltage-controlled current source



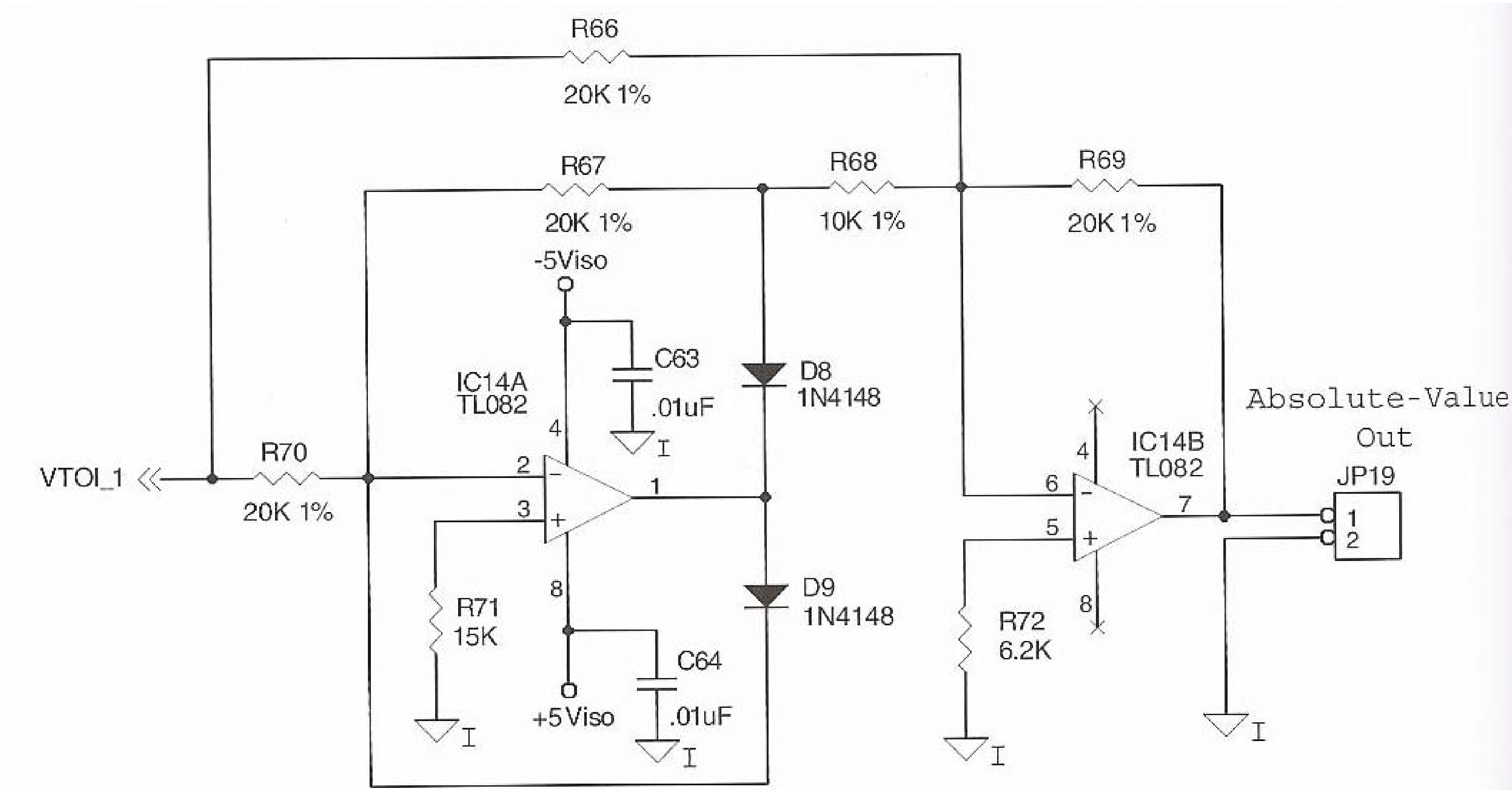
Impedance Cardiograph: Lock-in amplifier (to separate a small narrow-band signal from interfering noise)



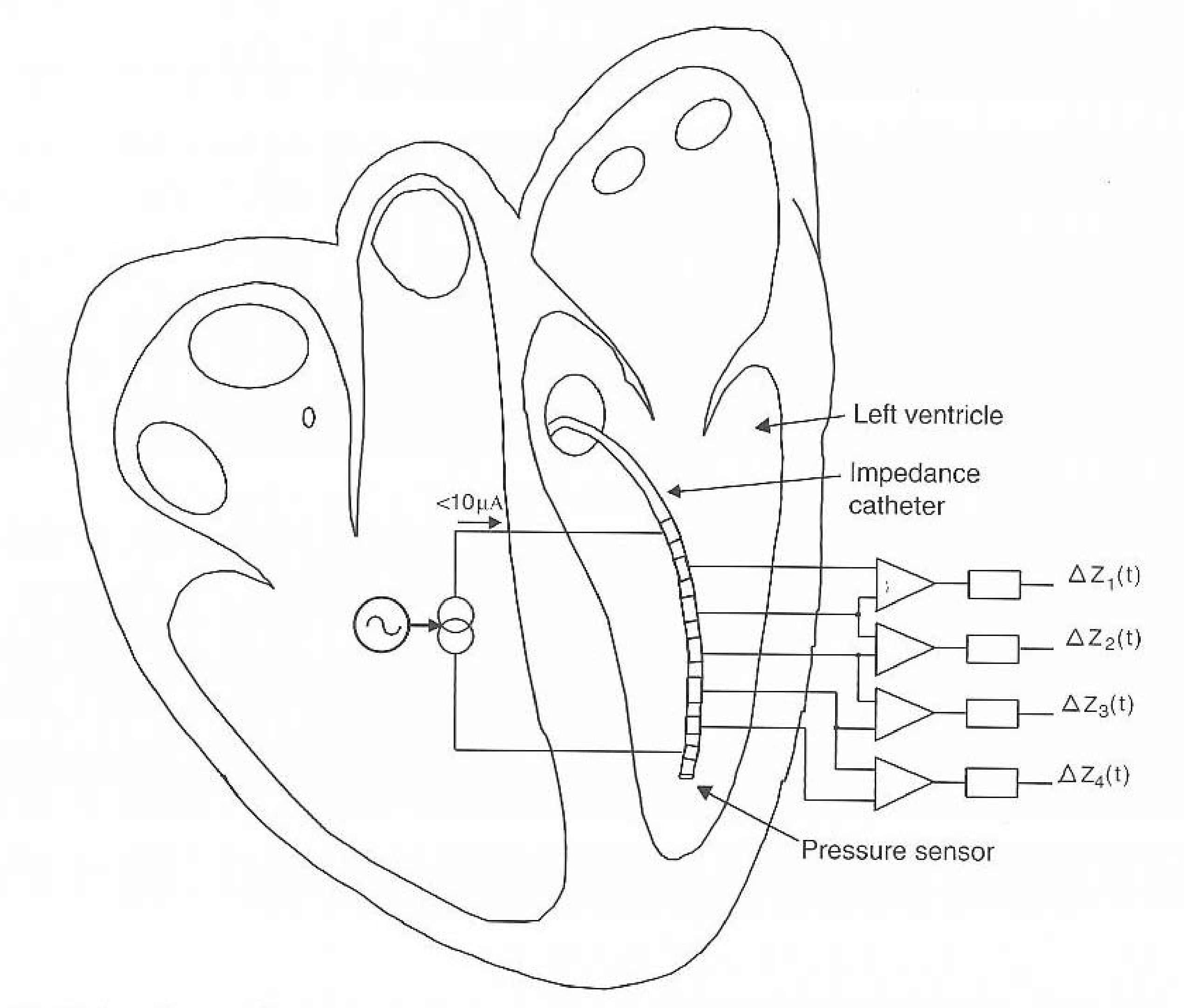
Impedance Cardiograph: Isolation and Notch Filtering



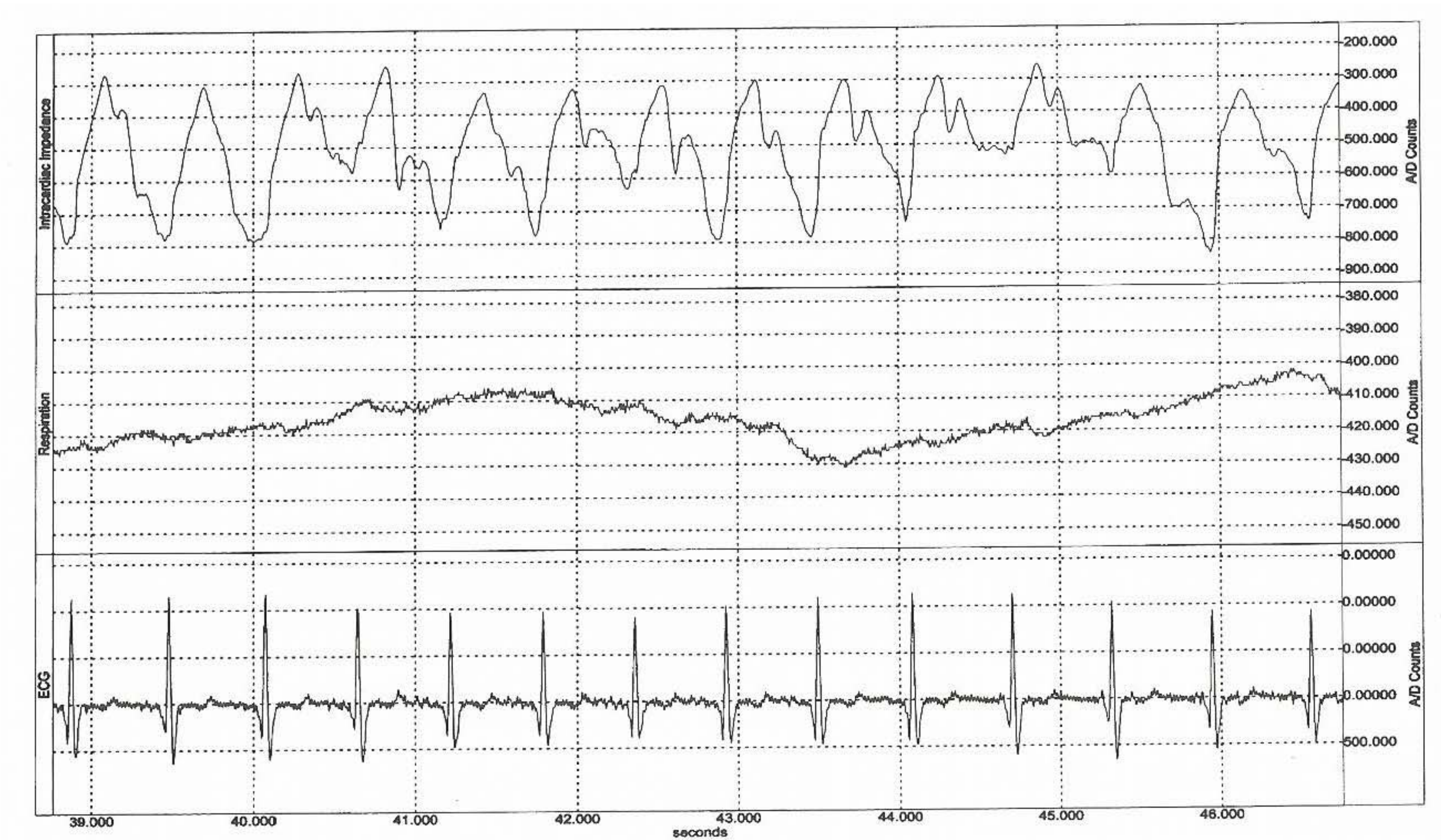
Impedance Cardiograph: Full-Wave Rectifier



Ventricle Volume Measurement

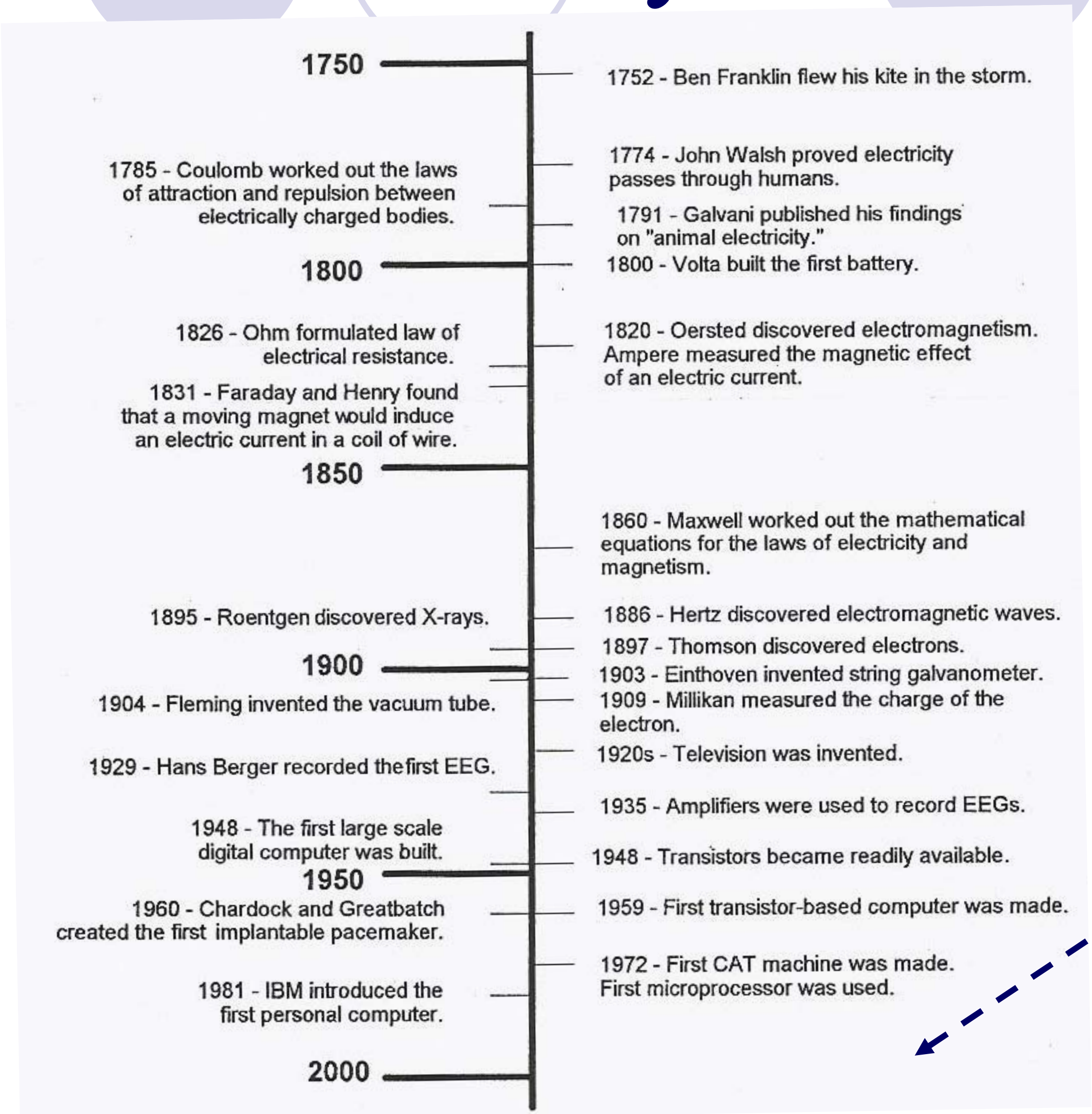


Intracardiac Impedance Signals



Chapter 5: Bioinstrumentation

A Brief History



真正精采
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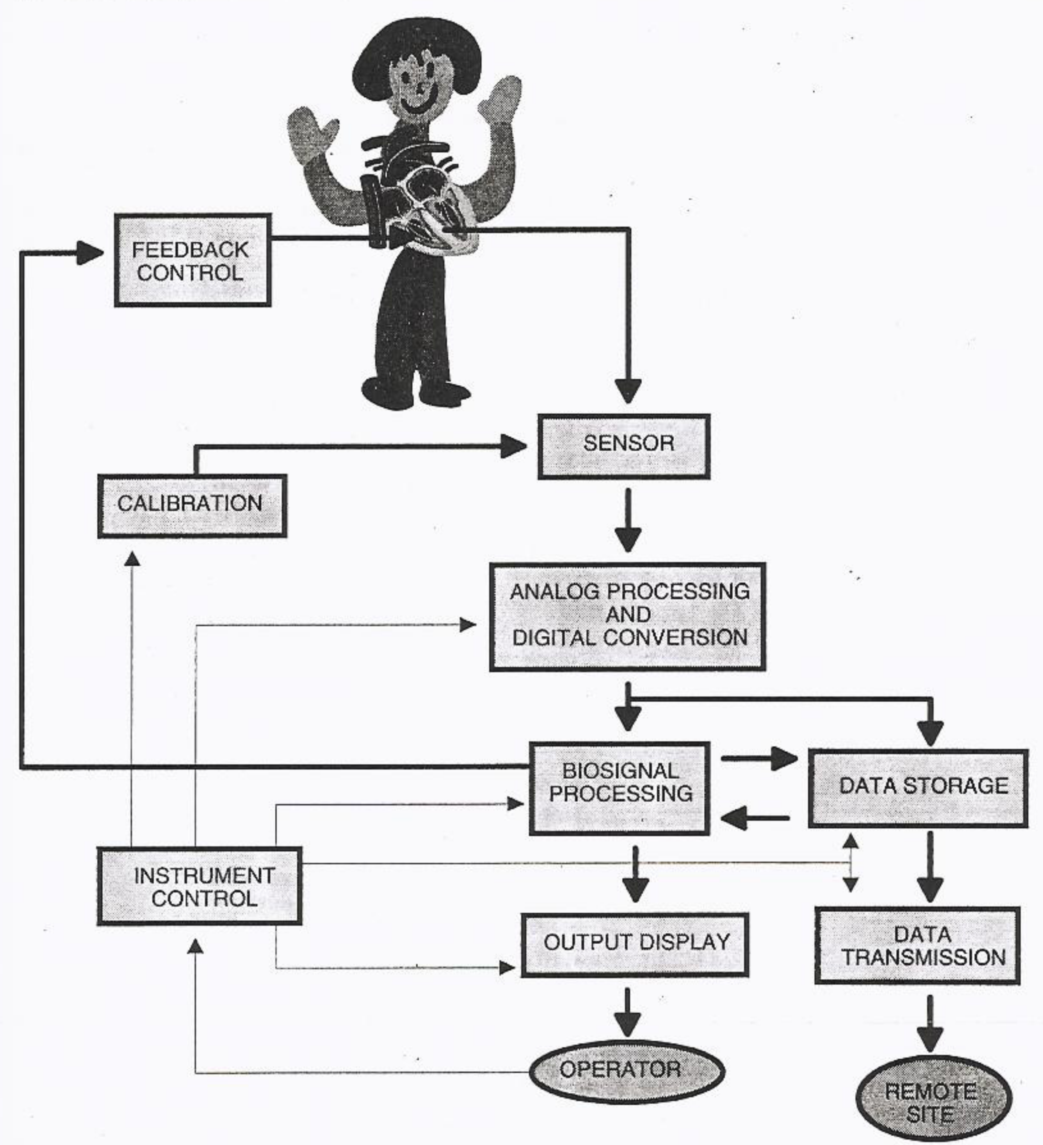
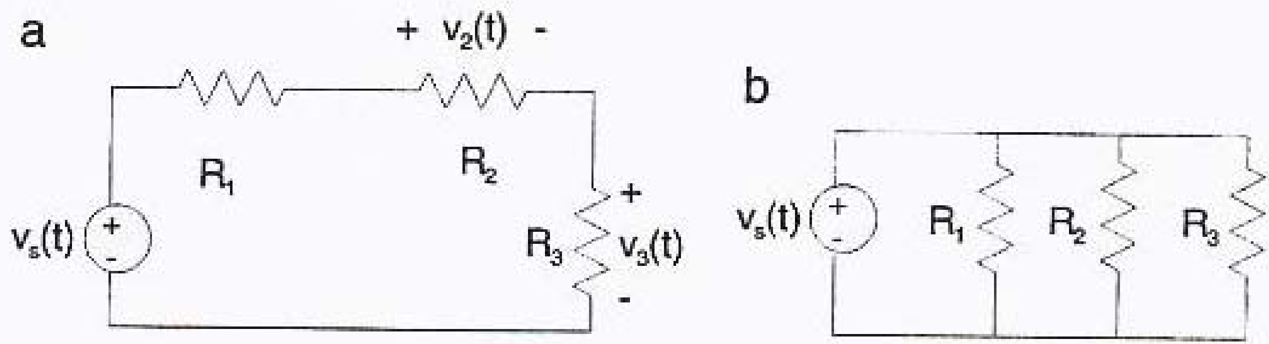
Basic Instrumentation System



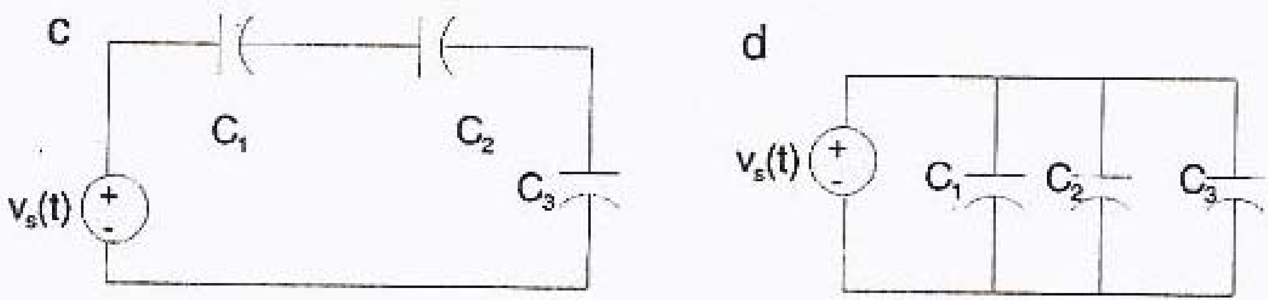
5.3 Analog Circuits

Simple Circuits and Voltage Divider

$$R_{EQ} = \sum_{i=1}^{N} R_i \qquad\qquad G_{EQ} = \sum_{i=1}^{N} G_i$$

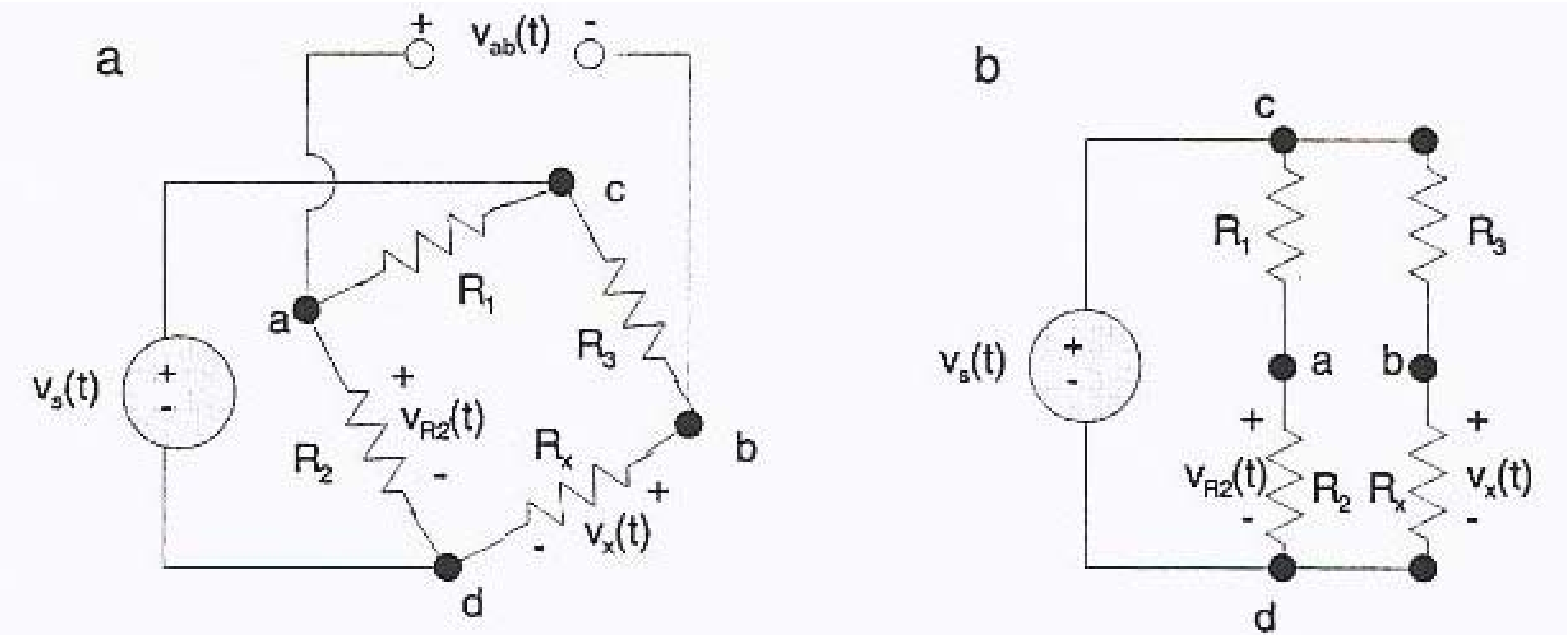


$$v_2(t) = \frac{R_2}{R_1 + R_2 + R_3} v(t) \qquad\qquad v_3(t) = \frac{R_3}{R_1 + R_2 + R_3} v(t)$$



Wheatstone Bridge

$$v_{ab}(t) = v_{R_2}(t) - v_{R_x}(t) = v_s(t)\left(\frac{R_2}{R_1 + R_2} - \frac{R_x}{R_3 + R_x}\right)$$



(Example Problem 5.1)

Time-Varying Signals

- Sinusoidal signals: amplitude, frequency and phase.

$$v_1(t) = V_1 \cos(\omega t + \theta)$$

$$f = \frac{\omega}{2\pi}$$

- Phasor:

$$\hat{V}_1 = V_1 e^{j\theta} = V_1 \angle \theta$$

- Impedance:

$$\hat{V}_1 = Z\hat{I}$$

(Example Problem 5.2)

Impedance

$$Z_R = R$$

$$Z_L = j\omega L$$

$$Z_C = \frac{1}{j\omega C}$$

- Example: *R*, *C*, *L* in series.

$$Z = R + j\omega L + \frac{1}{j\omega C} = R + j\left(\omega L - \frac{1}{\omega C}\right)$$

Laplace Domain

- Definition

$$L\{f(t)\} = F(s) = \int_{0^-}^{\infty} f(t)e^{-st}\,dt$$

$$s = \sigma + j\omega$$

- s-domain impedance

$$Z_R(s) = \frac{V(s)}{I(s)} = R$$

$$Z_L(s) = sL$$

$$Z_C(s) = \frac{1}{sC}$$

Laplace Domain Circuit Analysis

- Differential equation → Algebraic equation
- KVL and KCL still apply
- Series and parallel:

$$Z_{EQ}(s) = \sum_{i=1}^{N} Z_i(s)$$

$$\frac{1}{Z_{EQ}(s)} = \sum_{i=1}^{N} \frac{1}{Z_i(s)}$$

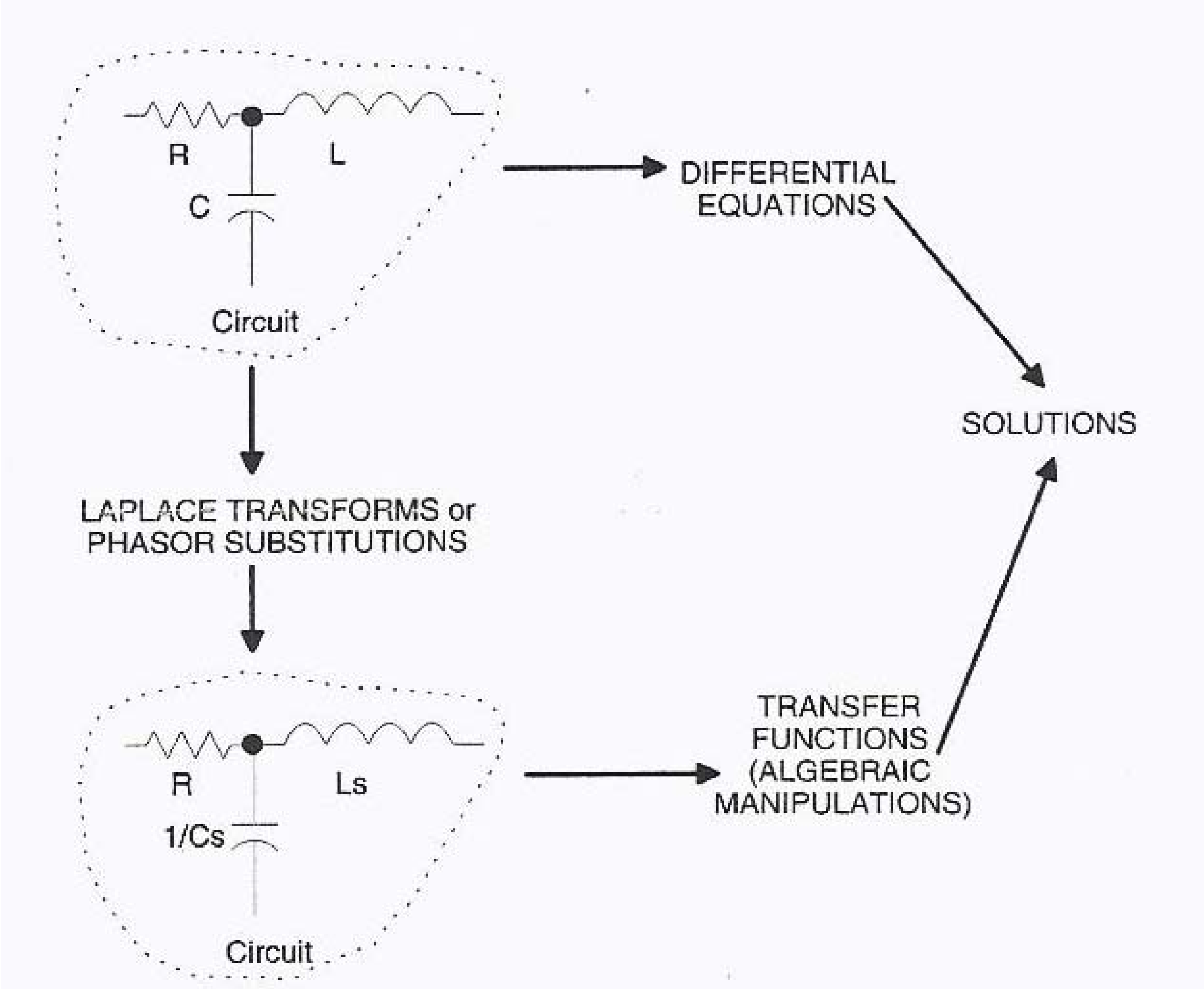
Laplace Transform Properties

Operation	Time Function	Laplace Transform
Linear combination	$Af(t) + Bg(t)$	$AF(s) + BG(s)$
Multiplication by e^{-at}	$e^{-at}f(t)$	$F(s + a)$
Multiplication by t	$tf(t)$	$-dF(s)/ds$
Time delay	$f(t - t_0)u(t - t_0)$	$e^{-st_0}F(s)$
Differentiation	$f'(t)$	$sF(s) - f(0^-)$
	$f''(t)$	$s^2F(s) - sf(0^-) - f'(0^-)$
Integration	$\int_{0^-}^{t} f(\lambda)\, d\lambda$	$\frac{1}{s} F(s)$

Laplace Transform Pairs

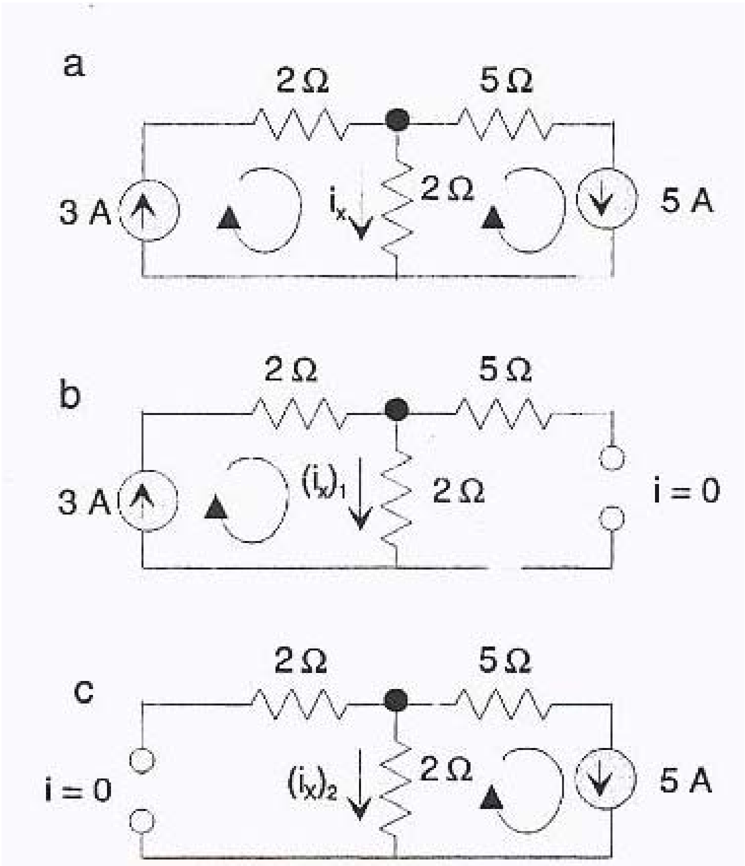
$f(t)$	$F(s)$
A	$\frac{A}{s}$
$u(t) - u(t - D)$	$\frac{1 - e^{-sD}}{s}$
t	$\frac{1}{s^2}$
t^r	$\frac{r!}{s^{r+1}}$
e^{-at}	$\frac{1}{s + a}$
te^{-at}	$\frac{1}{(s + a)^2}$
$t^r e^{-at}$	$\frac{r!}{(s + a)^{r+1}}$
$\sin \beta t$	$\frac{\beta}{s^2 + \beta^2}$
$\cos (\beta t + \phi)$	$\frac{s \cos \phi - \beta \sin \phi}{s^2 + \beta^2}$
$e^{-at} \cos (\beta t + \phi)$	$\frac{(s + a) \cos \phi - \beta \sin \phi}{(s + a)^2 + \beta^2}$

Laplace Transform for Circuit Analysis



Superposition

- In linear circuits with multiple sources, the combination of the sources is the sum of each of them taken once at a time.
- Example problem 5.4:

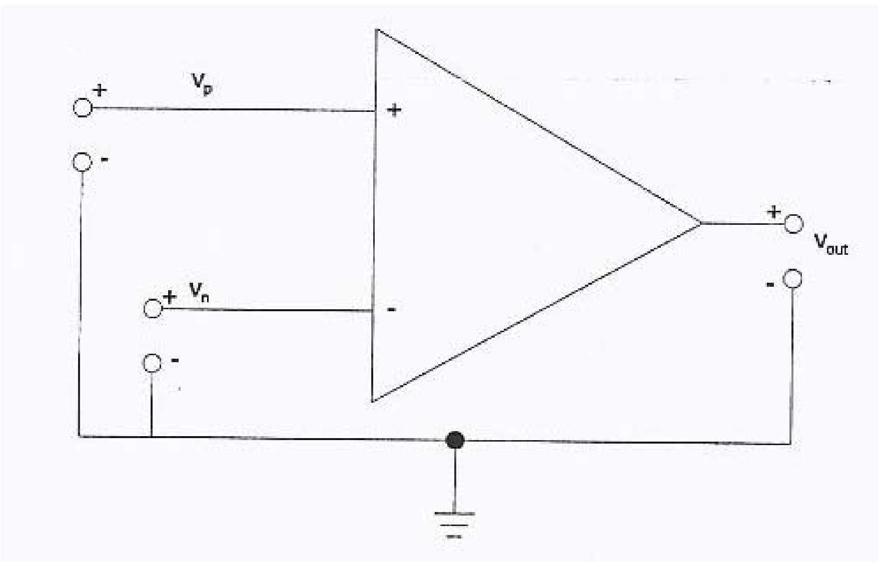


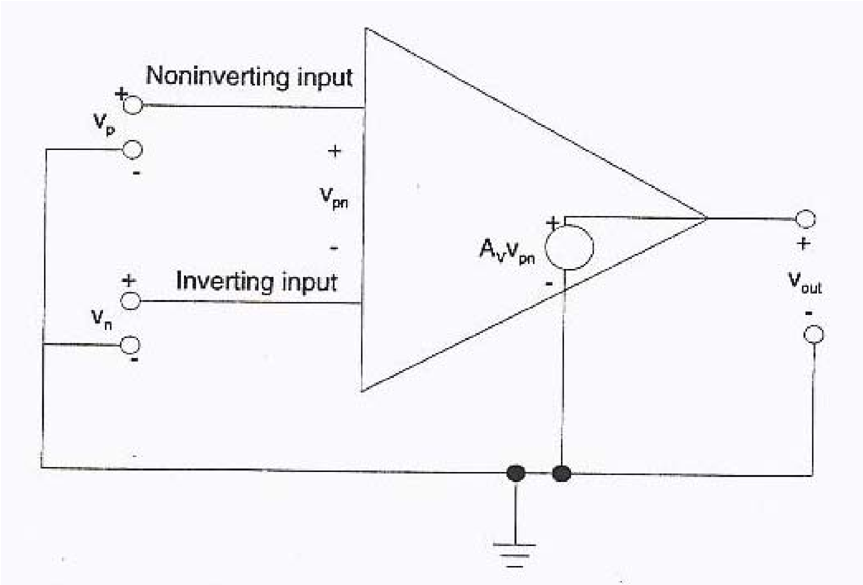
5.4 Signal Conditioning

Operational Amplifiers

Operational Amplifiers

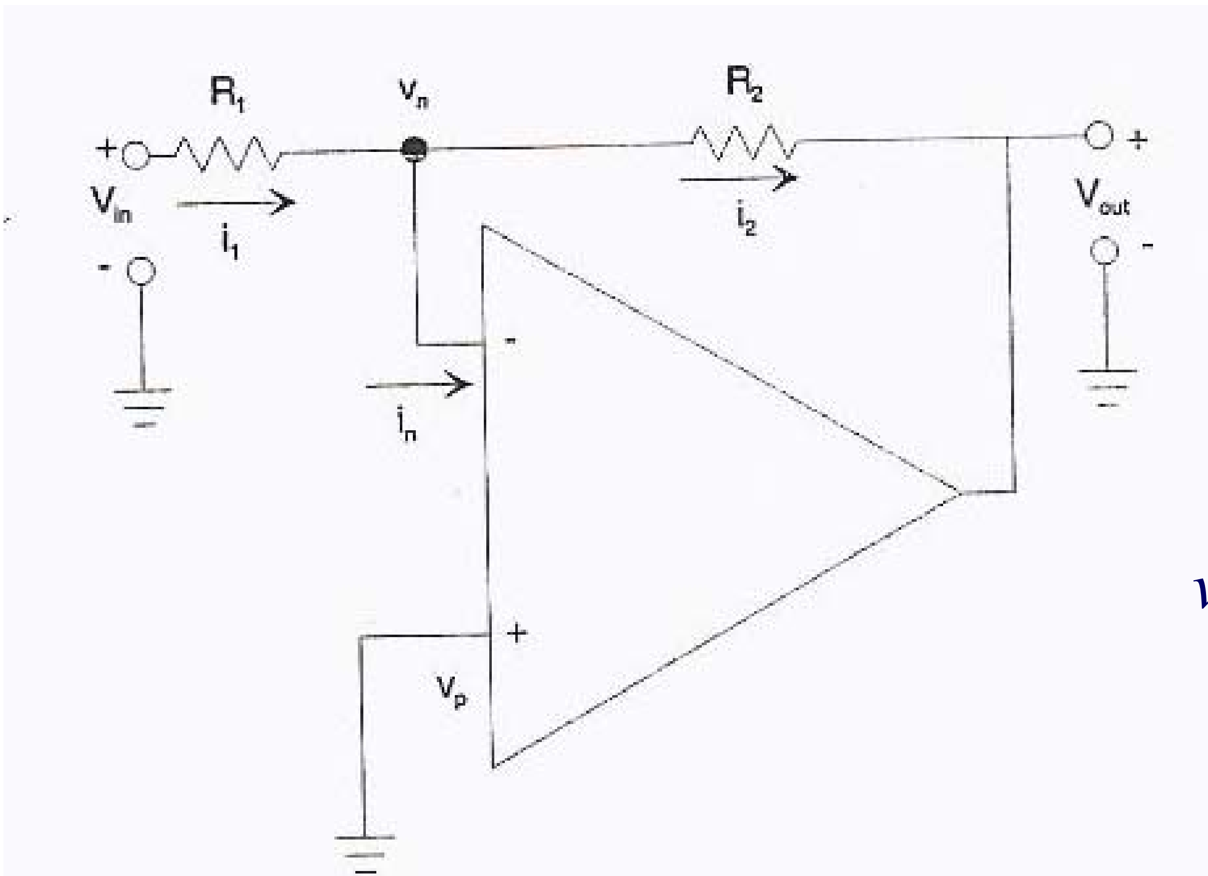
$$v_{OUT} = A_v(v_p - v_n); \; A_v : \text{open - loop voltage gain}$$





- Ideal op-amps:
  - No current flows into the two terminals
  - Open-loop gain is infinite, *vp=vn*.

Inverting Amplifier



$$v_{OUT} = v_{in}\left(-\frac{R_2}{R_1}\right)$$

$$G(\text{gain}) = -\frac{R_2}{R_1}$$

Example Problem 5.5

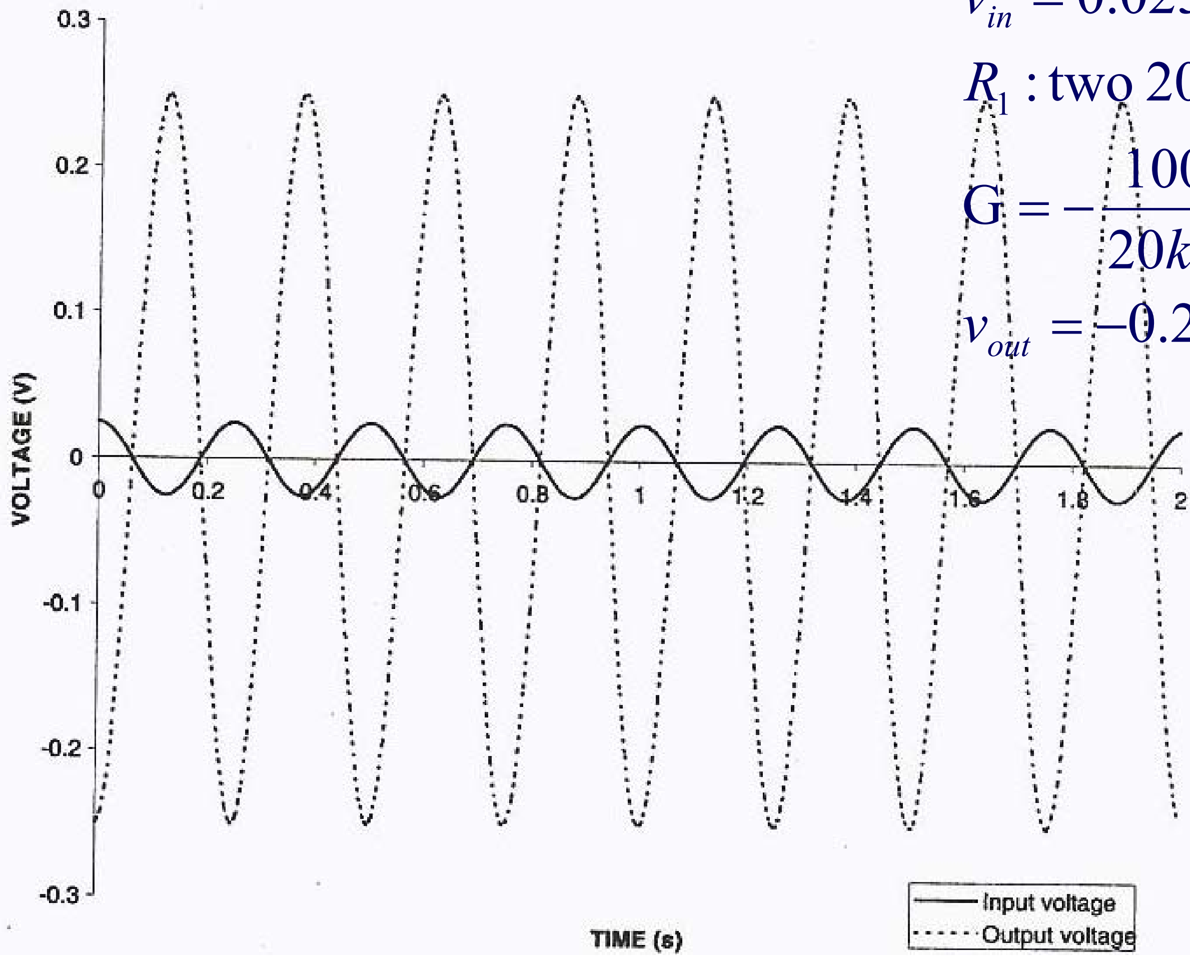
$$R_2 = 100k\Omega$$

$$v_{in} = 0.025\cos(25t)$$

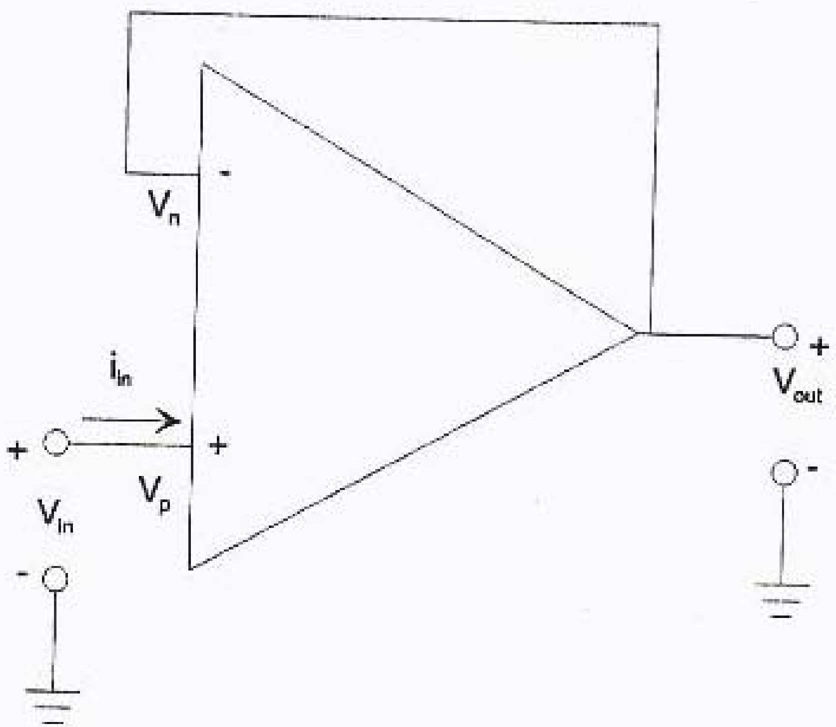
R_1 : two $20k\Omega$ resistors in parallel

$$G = -\frac{100k\Omega}{20k\Omega/2} = -10$$

$$v_{out} = -0.25\cos(25t)$$



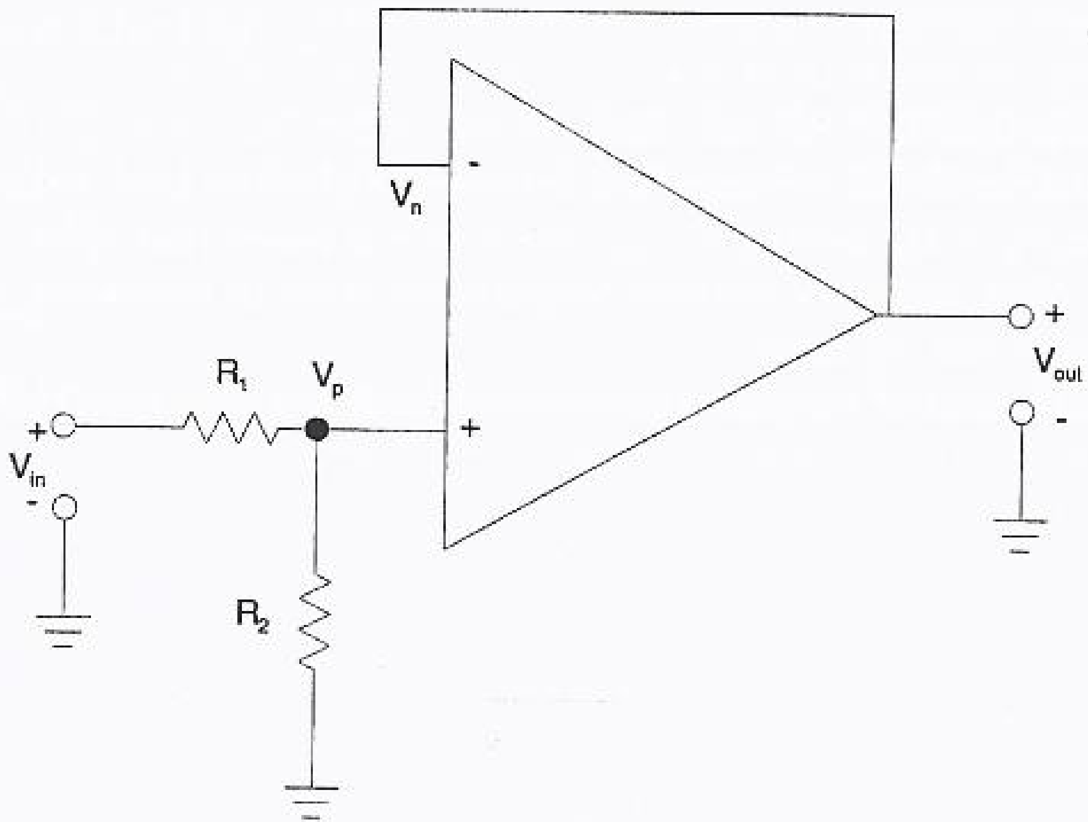
Unity Buffer (G=1)



$$v_{out} = v_{in}$$

$$G = 1$$

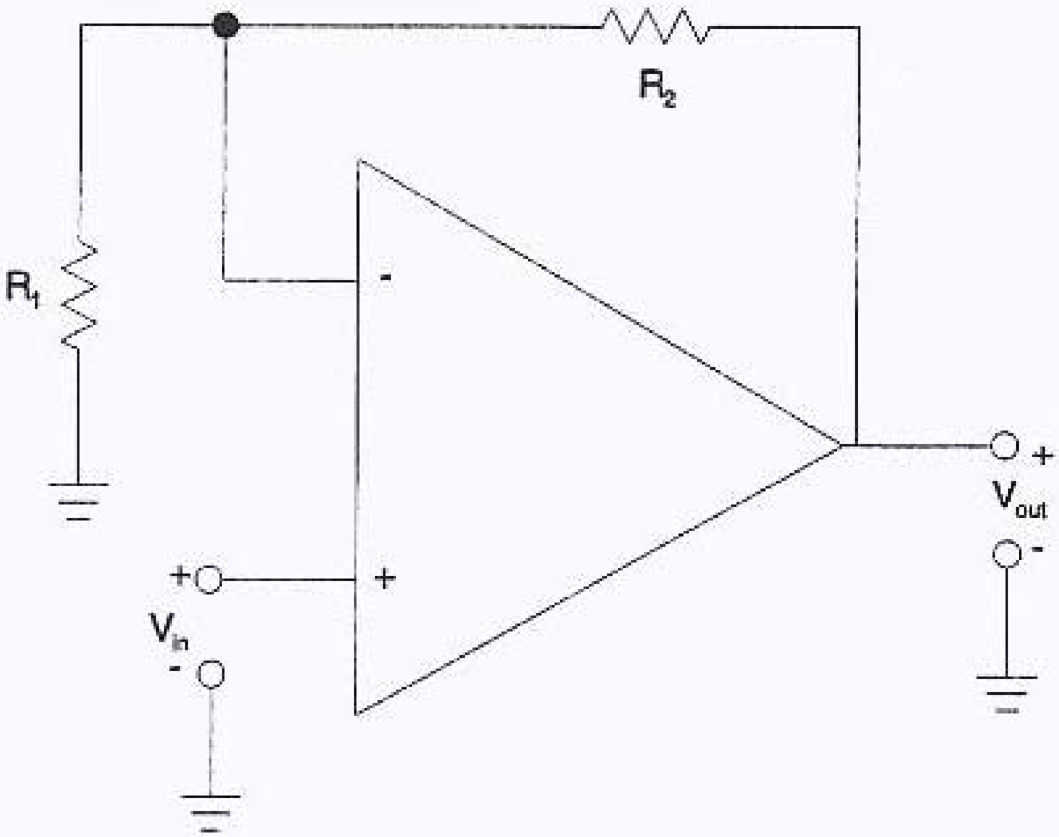
Voltage Follower in a Voltage Divider



$$v_{out} = v_{in} \frac{R_2}{R_1 + R_2}$$

$$G = \frac{R_2}{R_1 + R_2}$$

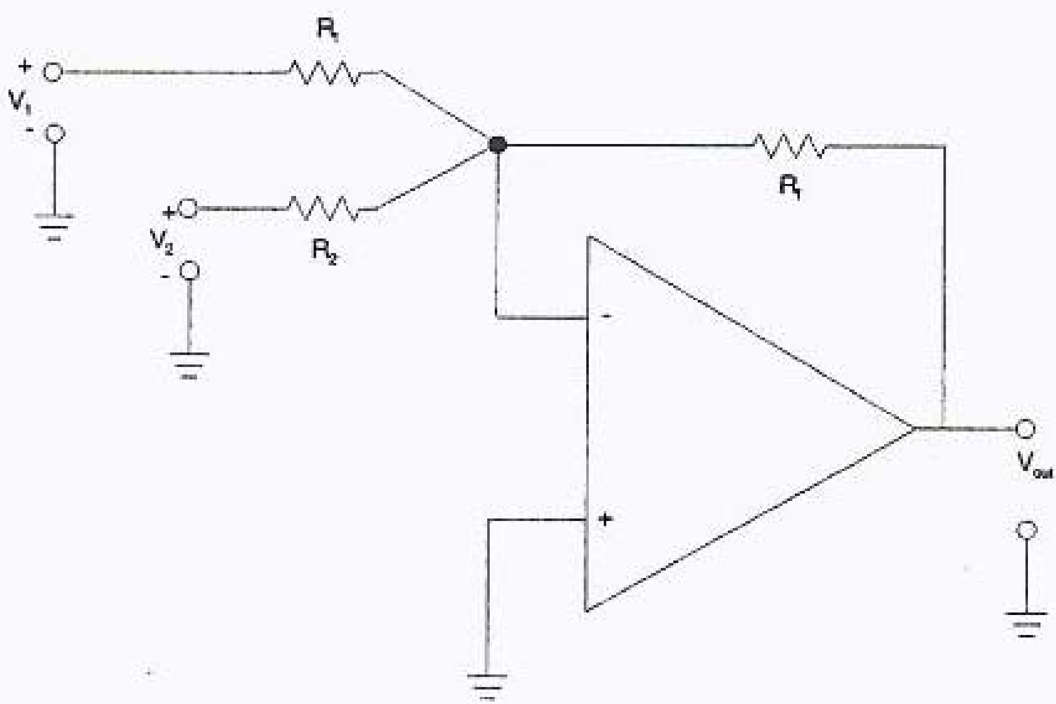
Non-Inverting Amplifier



$$v_{out} = \left(\frac{R_1 + R_2}{R_1}\right) v_{in}$$

$$G = \frac{R_1 + R_2}{R_1}$$

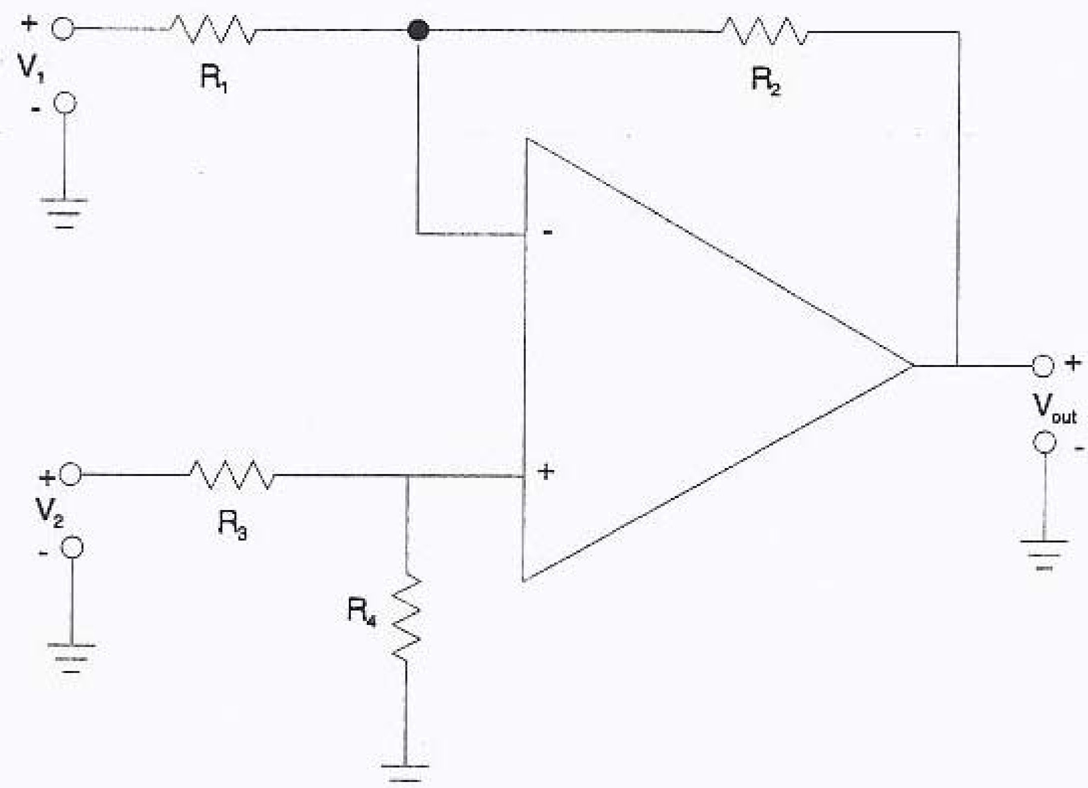
Inverting Summer



$$v_{out} = \left(\frac{-R_f}{R_1}\right)v_1 + \left(\frac{-R_f}{R_2}\right)v_2$$

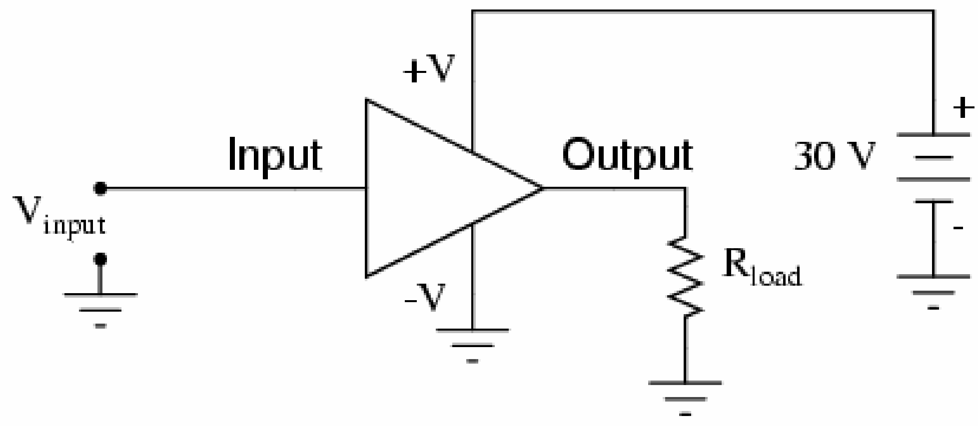
Subtractor

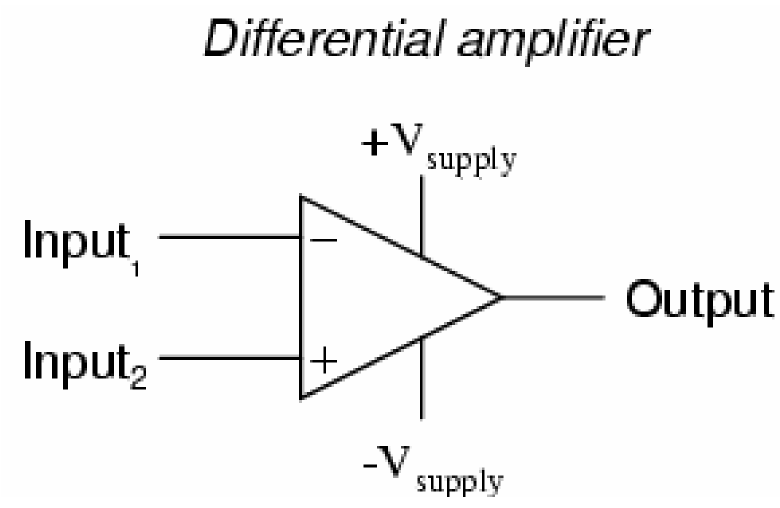
$$v_{out} = \left(\frac{-R_2}{R_1}\right)v_1 + \left[\left(\frac{R_1 + R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right)\right]v_2$$



Single-Ended and Differential Amplifiers

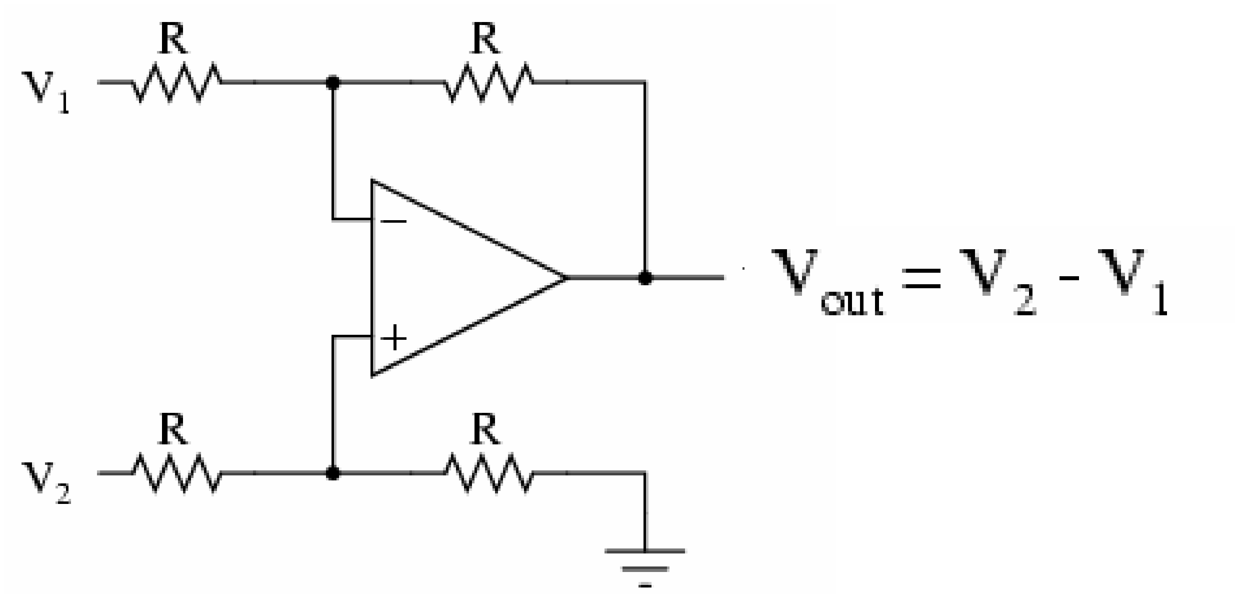
Single end amplifier





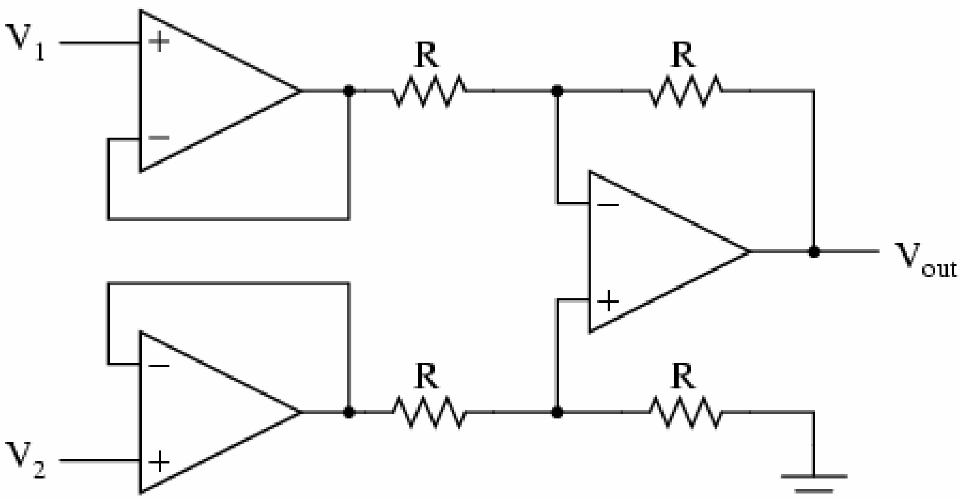
Differential Amplifier with Feedback

- An op-amp with no feedback is already a differential amplifier. However, its gain cannot be controlled, and it is generally too high.
- we can construct an op-amp circuit maintaining both voltage inputs, yet with a controlled gain set by external resistors.

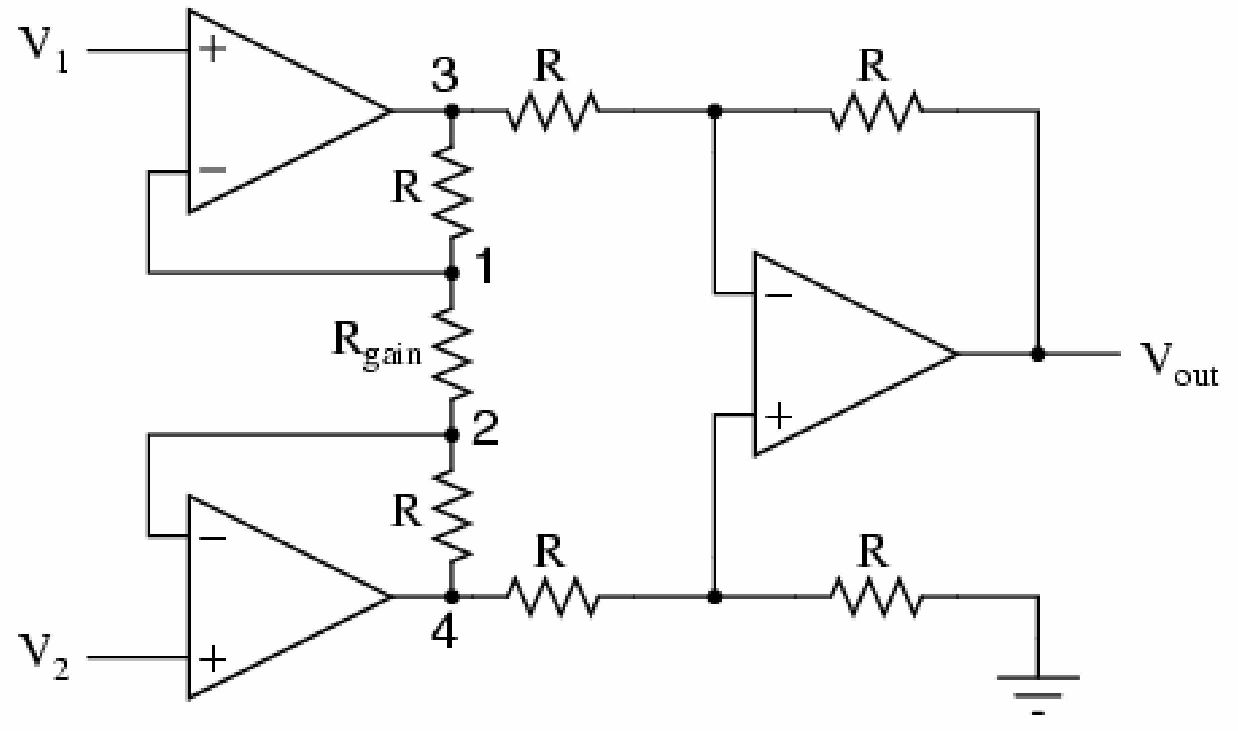


Differential Amplifier with Feedback

- For a differential gain of anything other than 1, we would have to adjust the resistances in *both* upper and lower voltage dividers.
- Another limitation of this amplifier design is the fact that its input impedances are rather low. Each input voltage source has to drive current through a resistance. All we need to do is "buffer" each input voltage signal through a voltage follower.



Instrumentation Amplifier



$$V_{3\text{-}4} = (V_2 - V_1)\left(1 + \frac{2R}{R_{gain}}\right) \qquad A_V = \left(1 + \frac{2R}{R_{gain}}\right)$$

Simple gain control

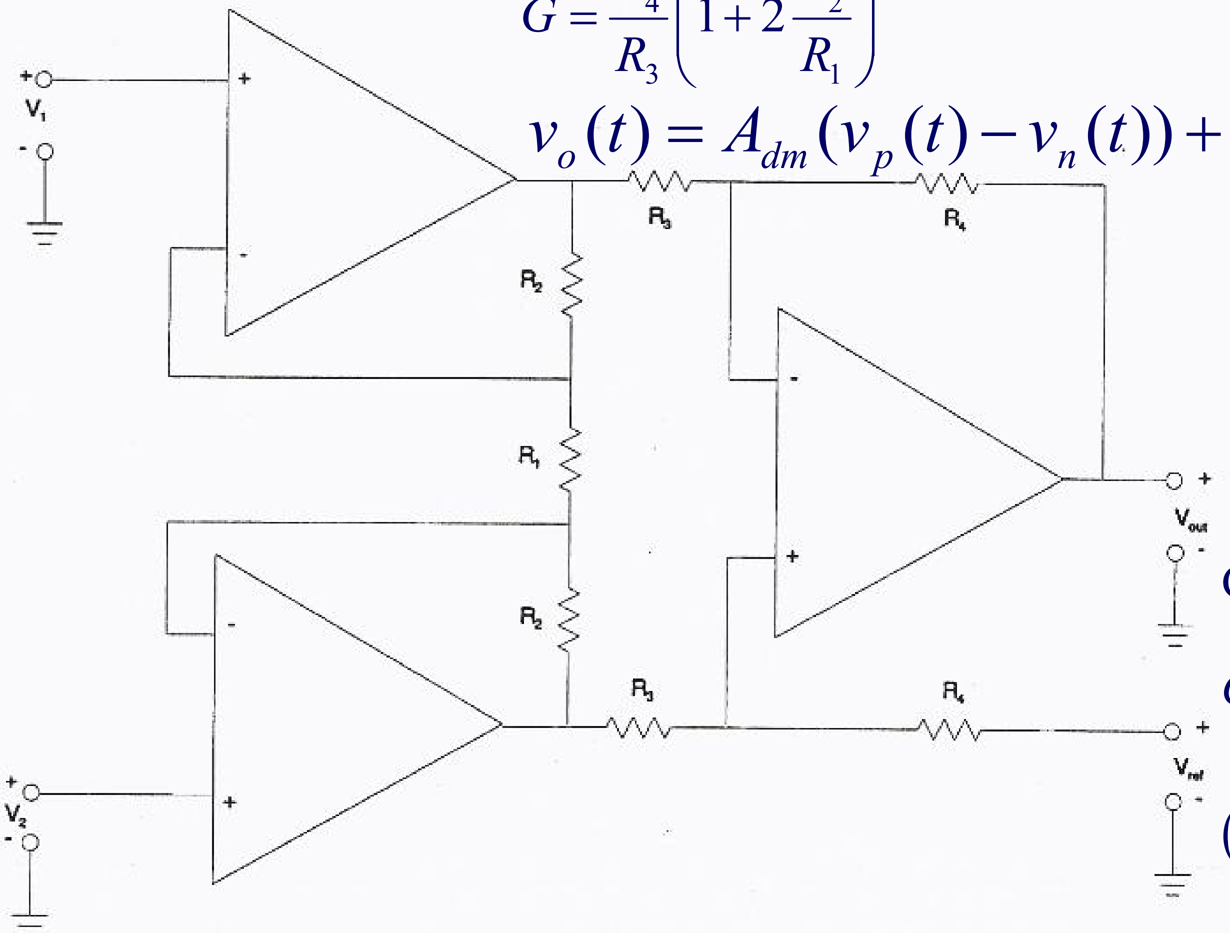
Instrumentation Amplifier

- High input impedance and common-mode signal rejection.

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

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

$$v_o(t) = A_{dm}(v_p(t) - v_n(t)) + A_{cm}(v_p(t) + v_n(t))$$



Common - mode rejection rati

$$CMRR = \frac{|A_{dm}|}{A_{cm}}$$

$$(CMRR)_{dB} = 20\log_{10}\left|\frac{A_{dm}}{A_{cm}}\right|$$

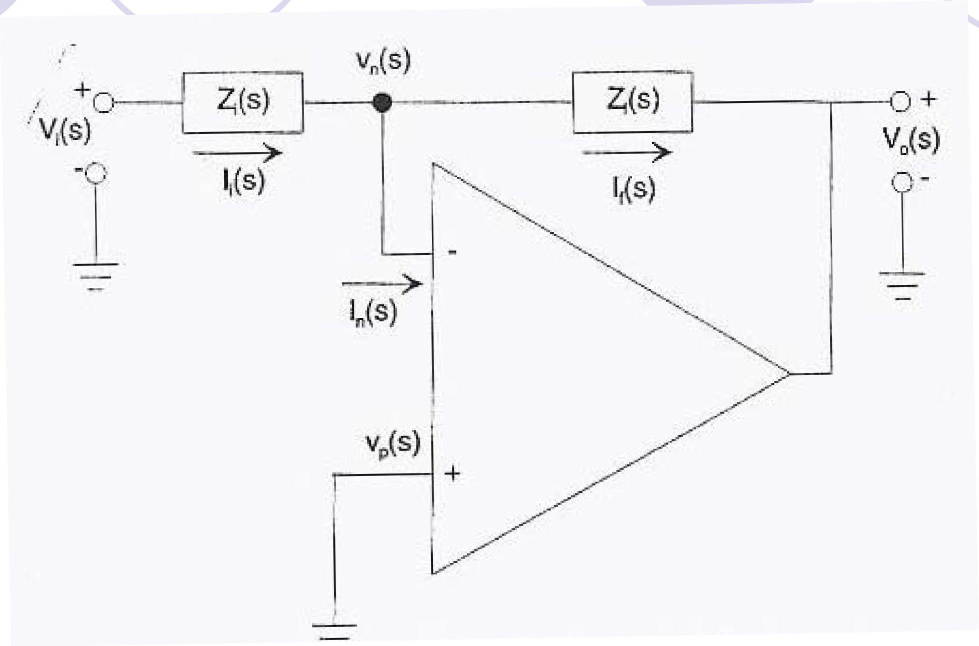
Transfer Functions and Complex Impedance

Transfer Function

- Input/output amplitude/phase relationship as a function of frequency.

$$T(s) = \frac{V_{out}(s)}{V_{in}(s)}$$

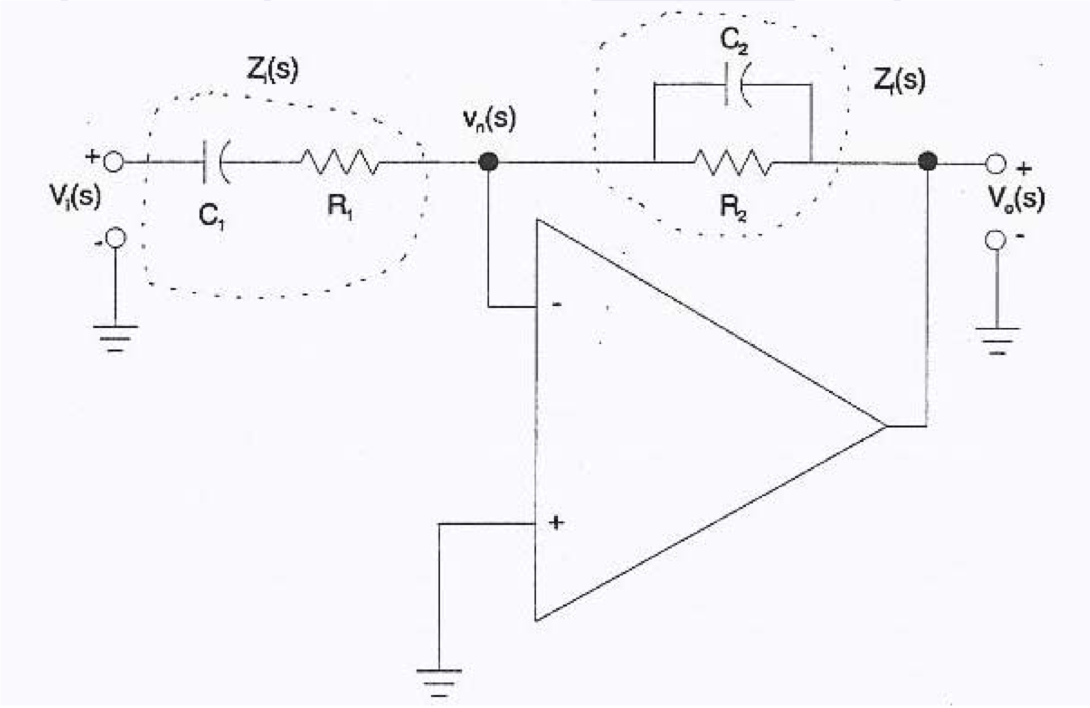
Transfer Function



$$\frac{V_{out}(s)}{V_{in}(s)} = -\frac{Z_f(s)}{Z_i(s)}$$

Refer to Fig. 5.10 (inverting amplifier)

Example Problem 5.6



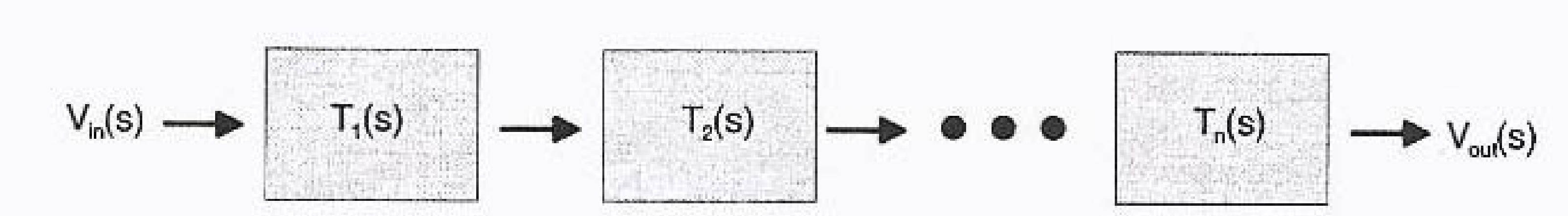
$$Z_i = \frac{R_1 C_1 + 1}{sC_1}, Z_f(s) = \frac{R_2}{R_2 C_2 s + 1}$$

$$T(s) = \frac{1}{R_1 C_2} \frac{s}{\left(s + \frac{1}{R_1 C_1}\right)\left(s + \frac{1}{R_2 C_2}\right)}$$

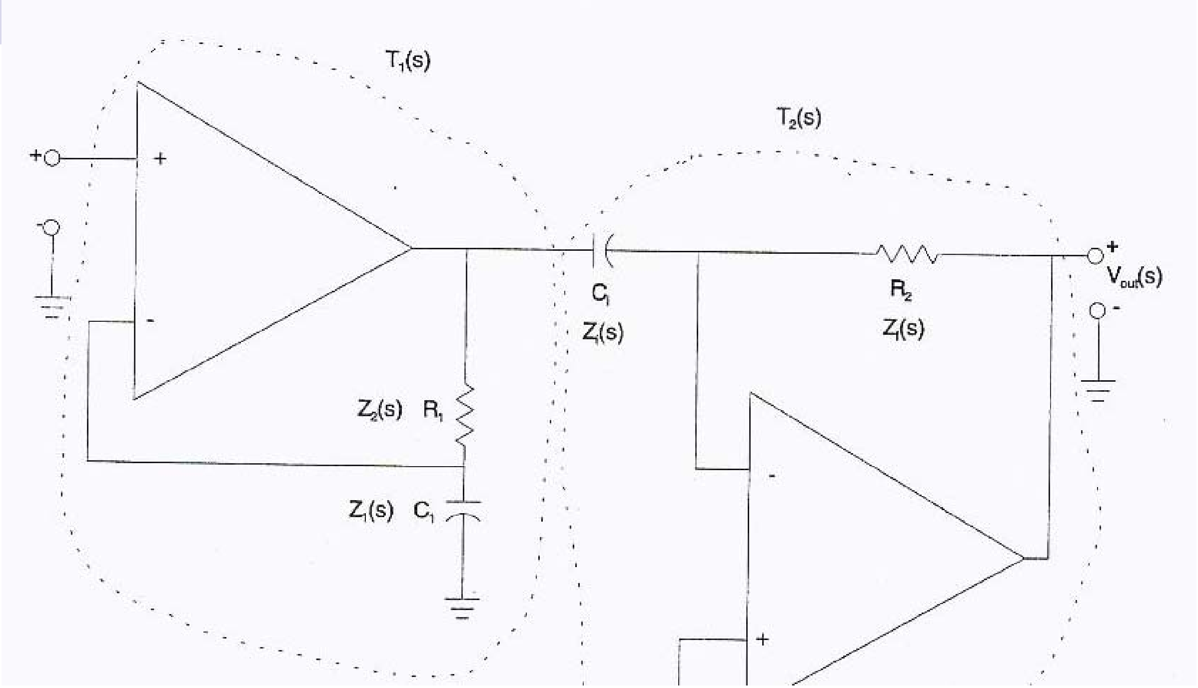
Cascaded Transfer Function

- Op-amp at input (input current is 0)
- Op-amp at output (current independent of the output voltage)

$$T(s) = T_1(s)T_2(s)\cdots T_n(s)$$



Example Problem 5.7



$$T_1(s) = \frac{Z_2(s) + Z_1(s)}{Z_1(s)} = R_1C_1s + 1$$

$$T_2(s) = \frac{Z_f(s)}{Z_i(s)} = -R_2C_2s$$

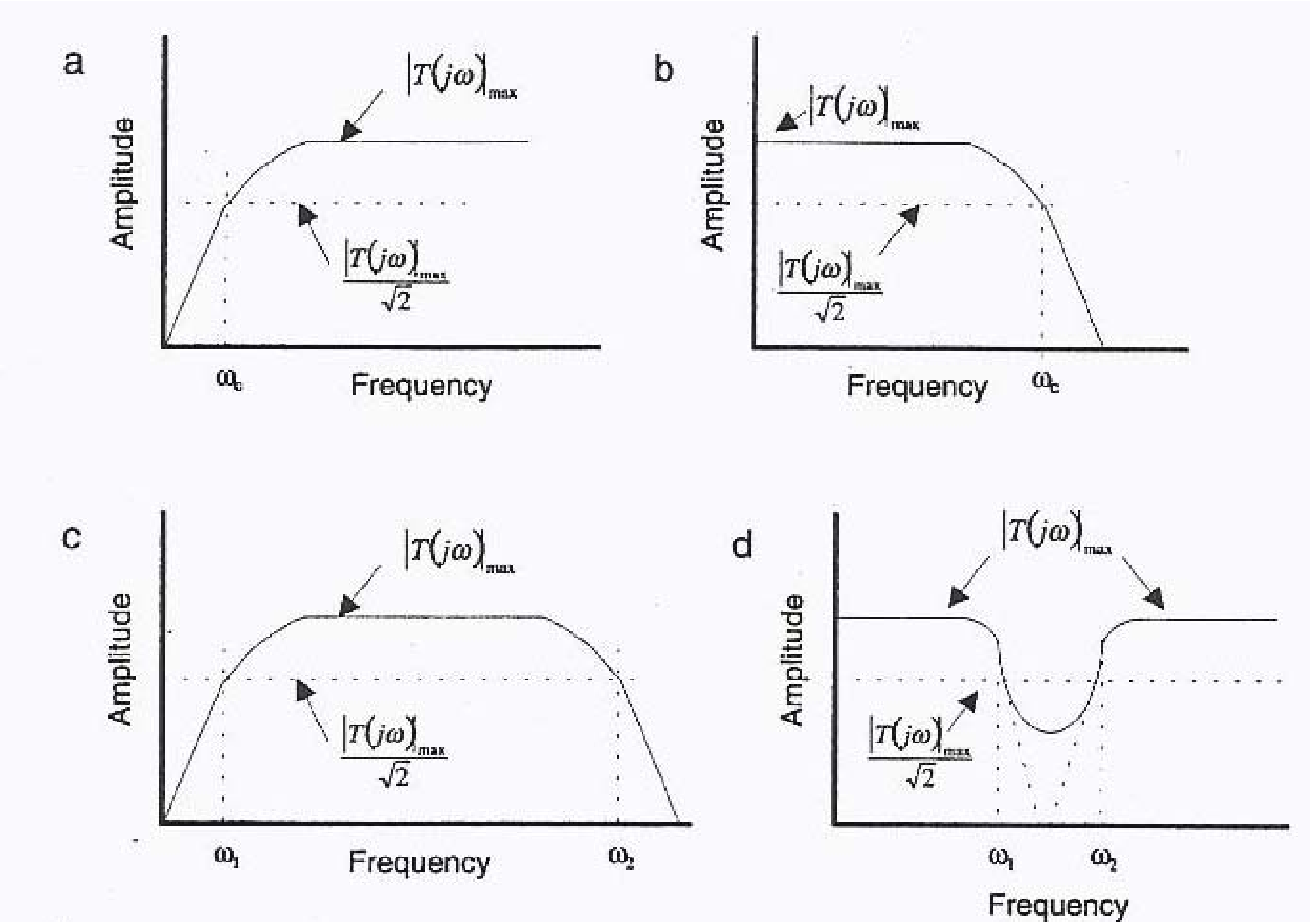
$$T(s) = T_1(s)T_2(s) = (R_1C_1s + 1)(-R_2C_2s)$$

Filters and Frequency Response

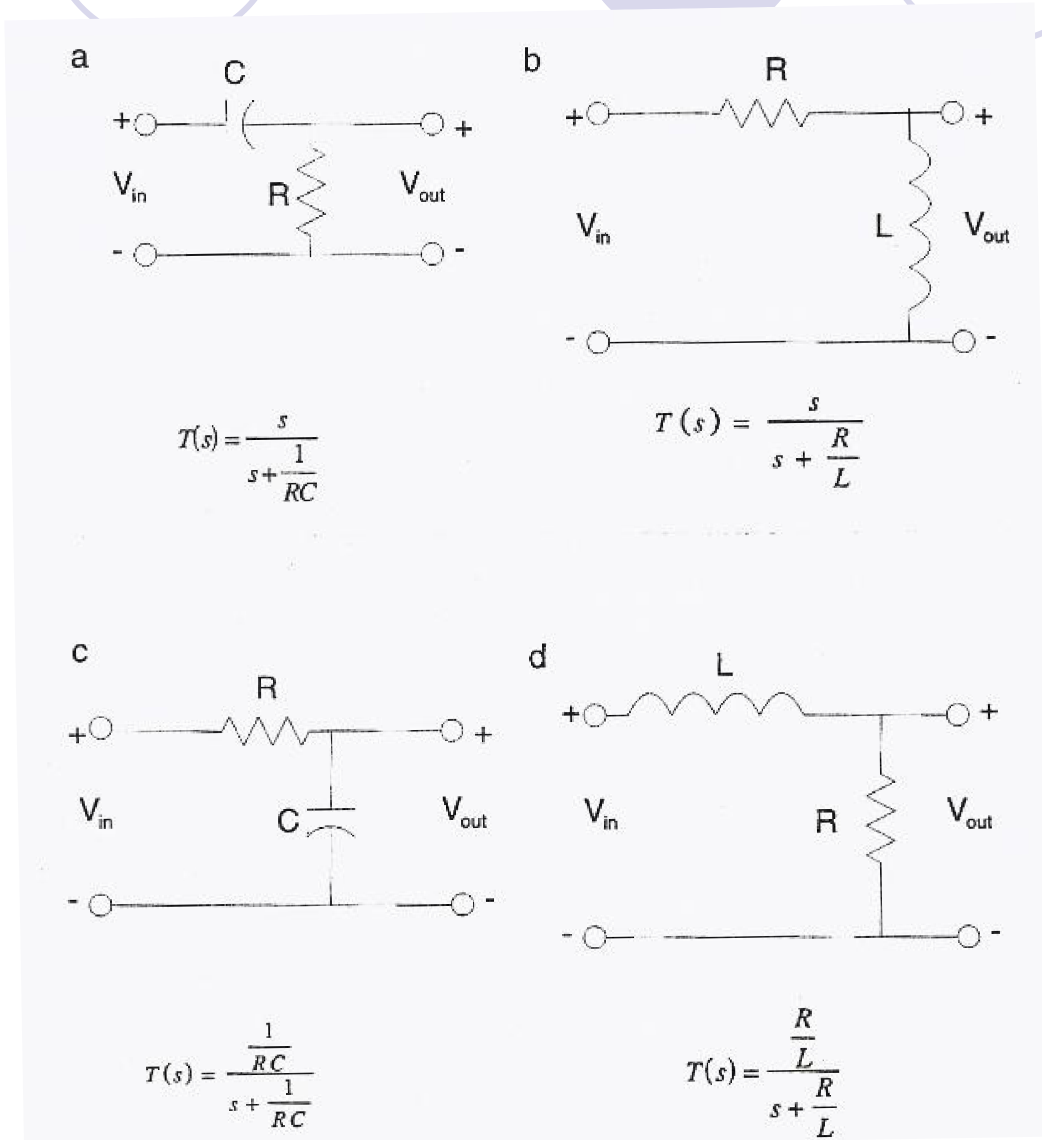
Filters

- Used to modify the frequency content of input signals.
- Use cut-off frequencies to specify the pass band and stop band.
- Common filter type:
  - Low-pass
  - High-pass
  - Band-pass
  - Band-stop

Common Filter Types



First-Order Filters



Transfer Function

$$T(s) = K\frac{(s+z_1)(s+z_2)\cdots}{(s+p_1)(s+p_2)\cdots} = K_d\frac{\left(1+\frac{s}{z_1}\right)\left(1+\frac{s}{z_2}\right)\cdots}{\left(1+\frac{s}{p_1}\right)\left(1+\frac{s}{p_2}\right)\cdots}$$

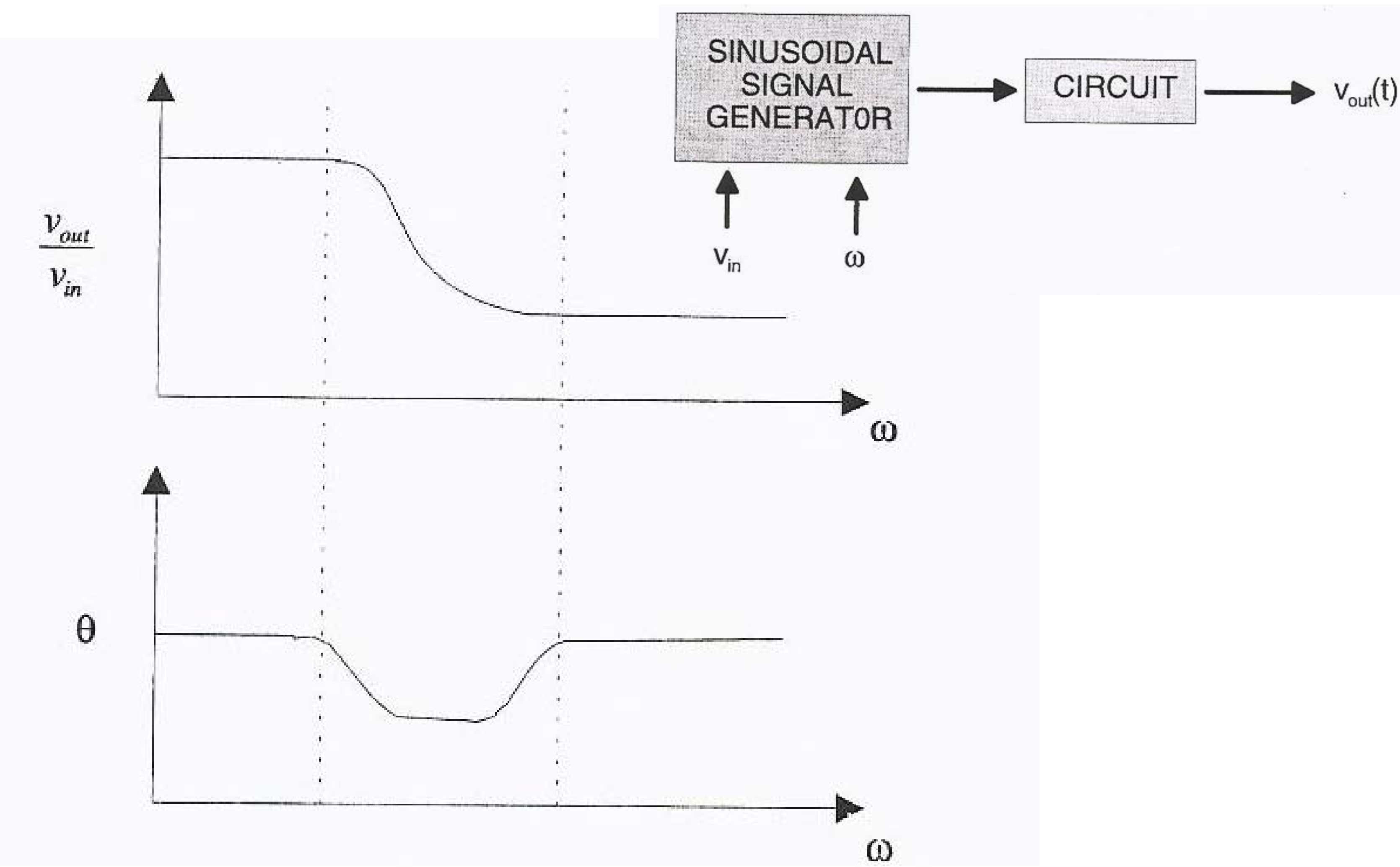
$$s = j\omega = j2\pi f$$

$$T(j\omega) = K_d\frac{\left(1+\frac{j\omega}{z_1}\right)\left(1+\frac{j\omega}{z_2}\right)\cdots}{\left(1+\frac{j\omega}{p_1}\right)\left(1+\frac{j\omega}{p_2}\right)\cdots} = \left|T(j\omega)\right|e^{j\theta_T(\omega)}$$

$\left|T(j\omega)\right|$: magnitude response, $\theta_T(\omega)$: phase response

$$T(j0) = K_d, \left|T(j\omega_c)\right| = \frac{\left|T(j\omega)\right|_{\max}}{\sqrt{2}}$$

Frequency Response



Example Problem 5.8

$$T(s) = K\frac{(s+\alpha)}{(s+\beta)}, \alpha = 10, \beta = 1, K = 0.1$$

$$T(j\omega) = \frac{\left(1+\frac{j\omega}{10}\right)}{\left(1+\frac{j\omega}{1}\right)}$$

$$|T(j0)| = 1, |T(j1)| = 0.707, |T(j10)| = 0.141, |T(j\infty) = 0.1|$$

A low pass filter with the cutoff at $\omega_c = 1$, DC gain $= 1$

When $\alpha \geq 10\beta, \omega_c \approx \beta$

5.5 Instrumentation Design

Instrumentation Design

- Sensors
- Signal amplification
- Noise reduction
- Anti-aliasing filter
- A/D conversion
- Digital signal processing
- Display
- …

Voltage and Frequency Ranges of Human Signals

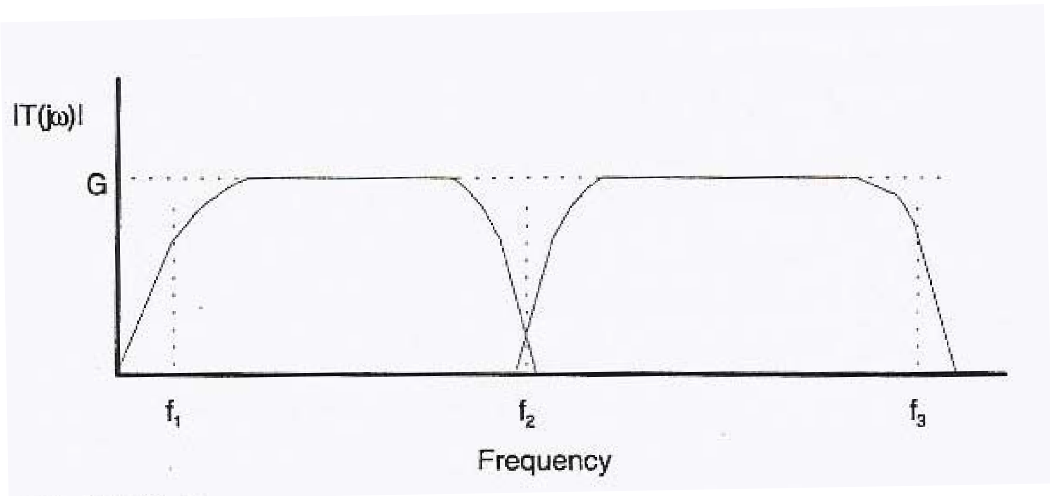
Parameter	Voltage	Frequency (Hz)
ECG (skin)	0.5-4 mV	0.01-250
EEG (scalp)	5-200 μV	DC-150
EGG (skin)	10-1000 μV	DC-1
EGG (stomach)	0.5-80 mV	DC-1
EMG (needle)	0.1-5 mV	DC-10,000
EOG (contact)	50-3500 μV	DC-50
ERG (contact)	0-900 μV	DC-50
Nerve	0.01-3 mV	DC-10,000

Signal Amplification

- Gain up to 10^7.
- Cascade of amplifiers, each has a gain of 10-10,000.
- DC offset must be removed (HPF with a cutoff at 1.0 Hz)

Noise Reduction

- Interference from power line, radio,…etc.
- Reduction through filtering, careful wiring and shielding.
- Power-line noise is in the signal frequency range, can be reduced by a band-stop (notch) filter.



$$\mathrm{SNR} = 20\log_{10}\left[\frac{V_{s(rms)}}{V_{n(rms)}}\right]$$

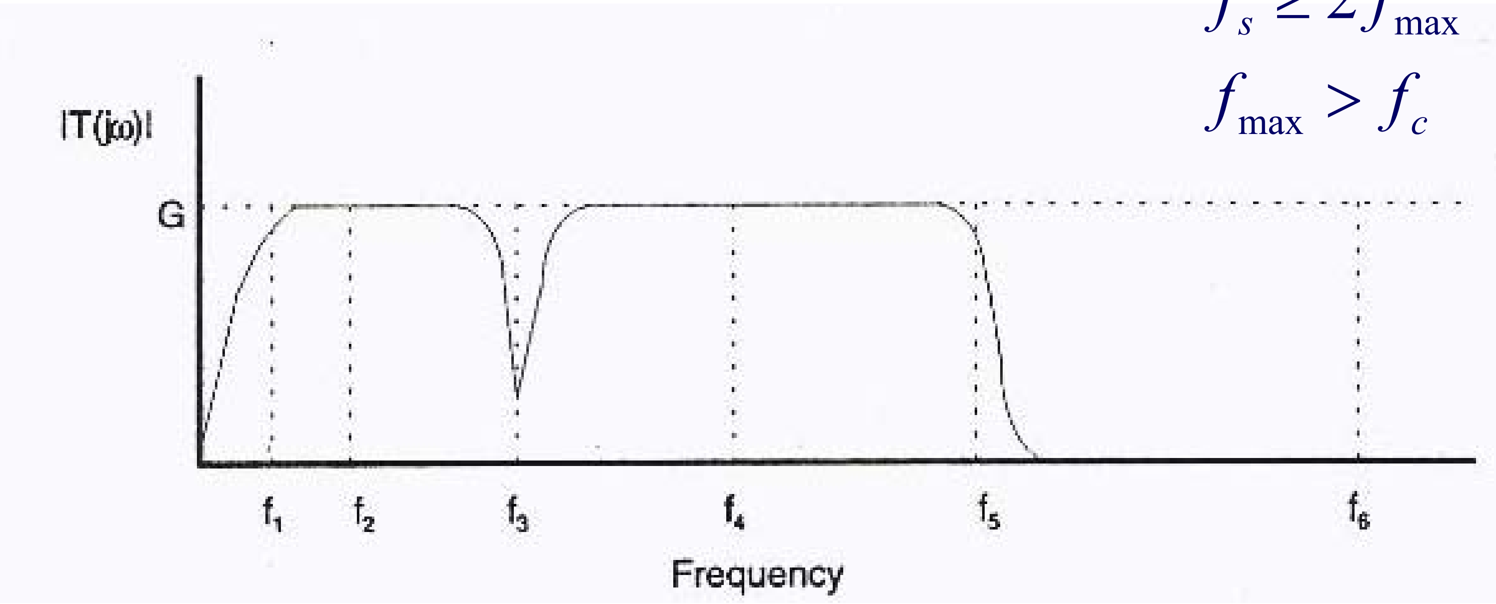
$$V_{i(rms)} = \left[\frac{1}{T}\int v_i^2(t)dt\right]^{\frac{1}{2}}$$

Frequency Aliasing

- Sampling theorem, Nyquist theorem
- LPF for anti-aliasing

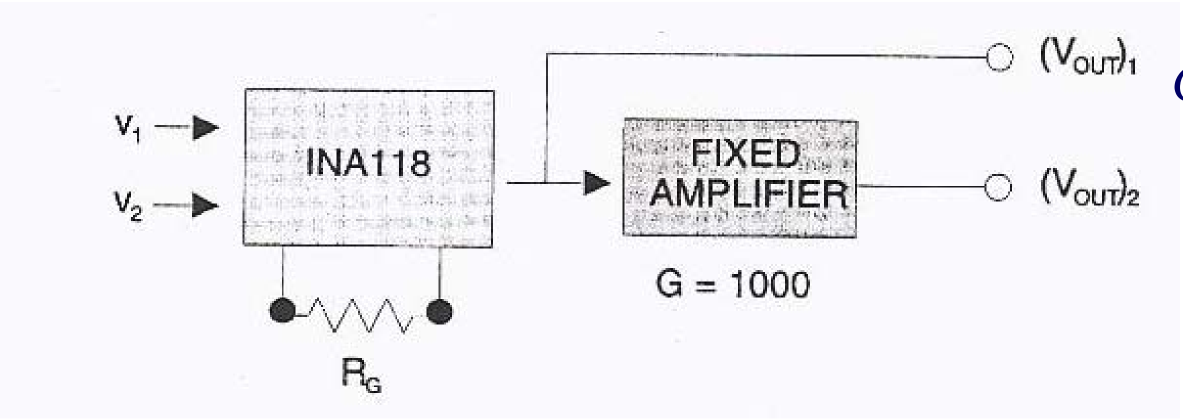
$$f_s \geq 2f_{\max}$$

$$f_{\max} > f_c$$



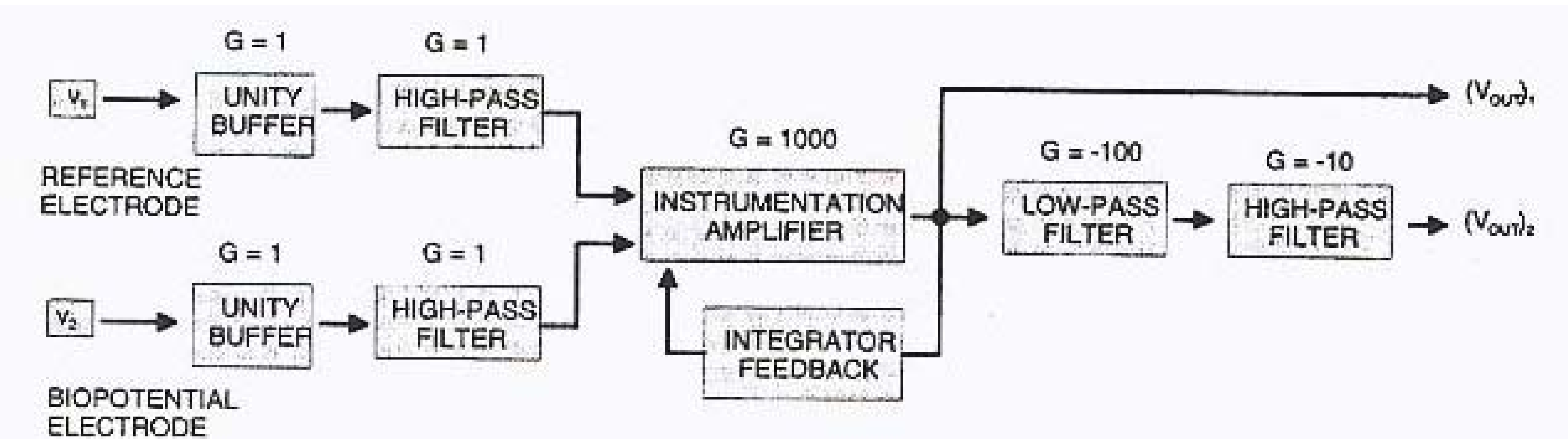
Design of a Differential Biopotential Amplifier (an Example)

- Input signal: 0.5 μV to 500 mV.
- Output voltages matches A/D converter's dynamic range (e.g., ±5V).
- Fist stage gain: 1, 10, 100, 1000, and 10,000
- Second stage gain: 1000 (optional)

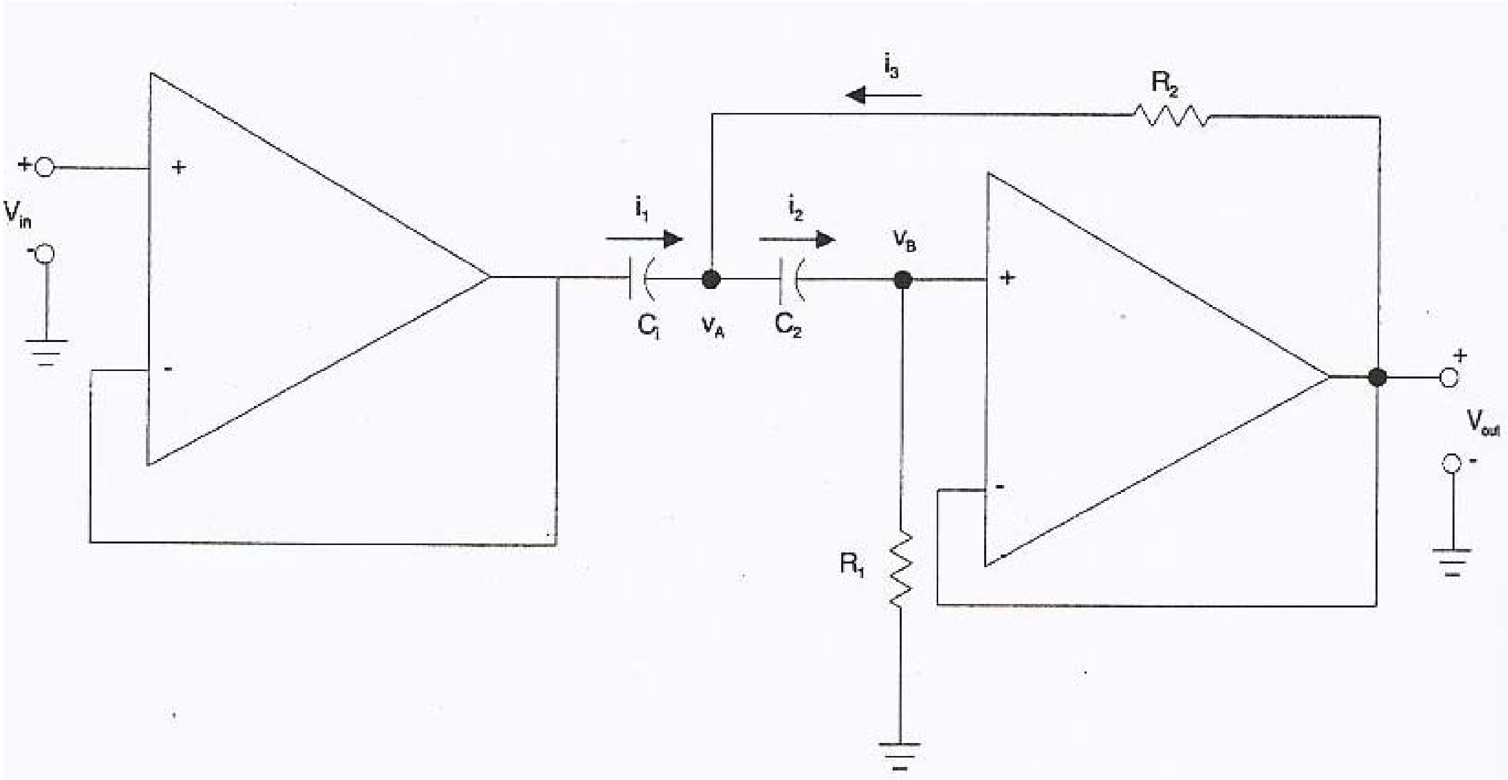


$$G = 1 + \frac{50{,}000}{R_G}$$

Block Diagram



Unity Buffer and High-Pass Filter

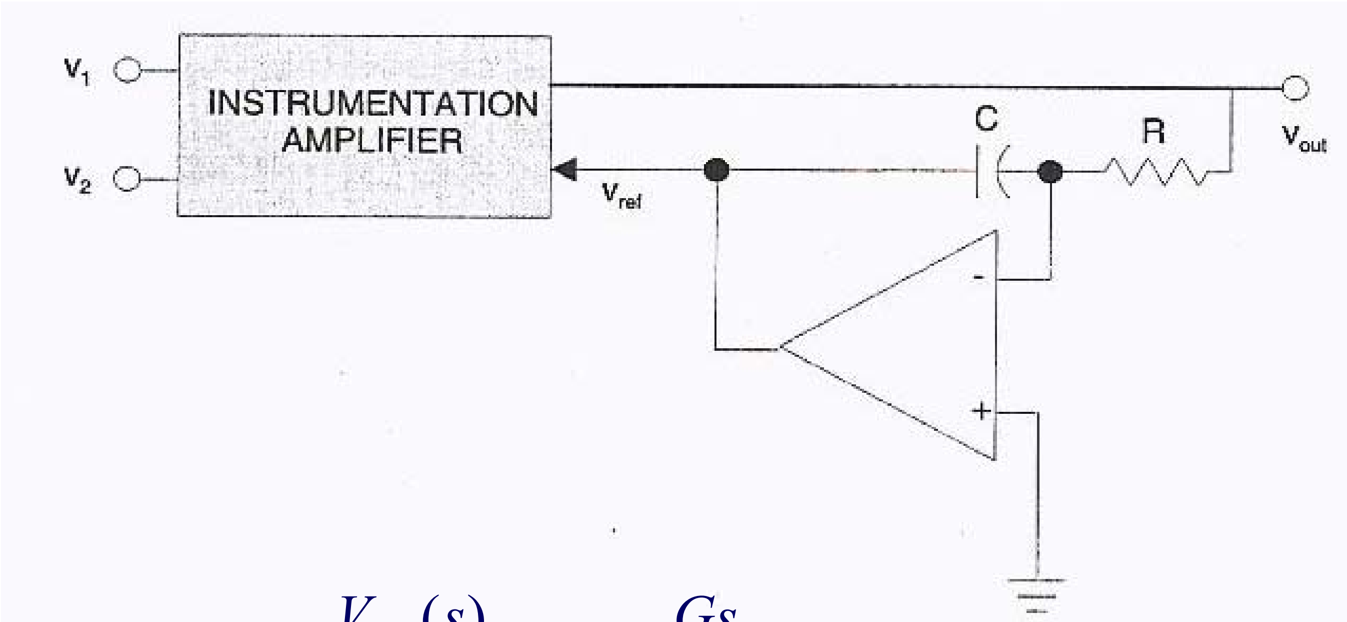


Buffer

2nd Order HPF

Instrumentation Amplifier with Integrator Feedback

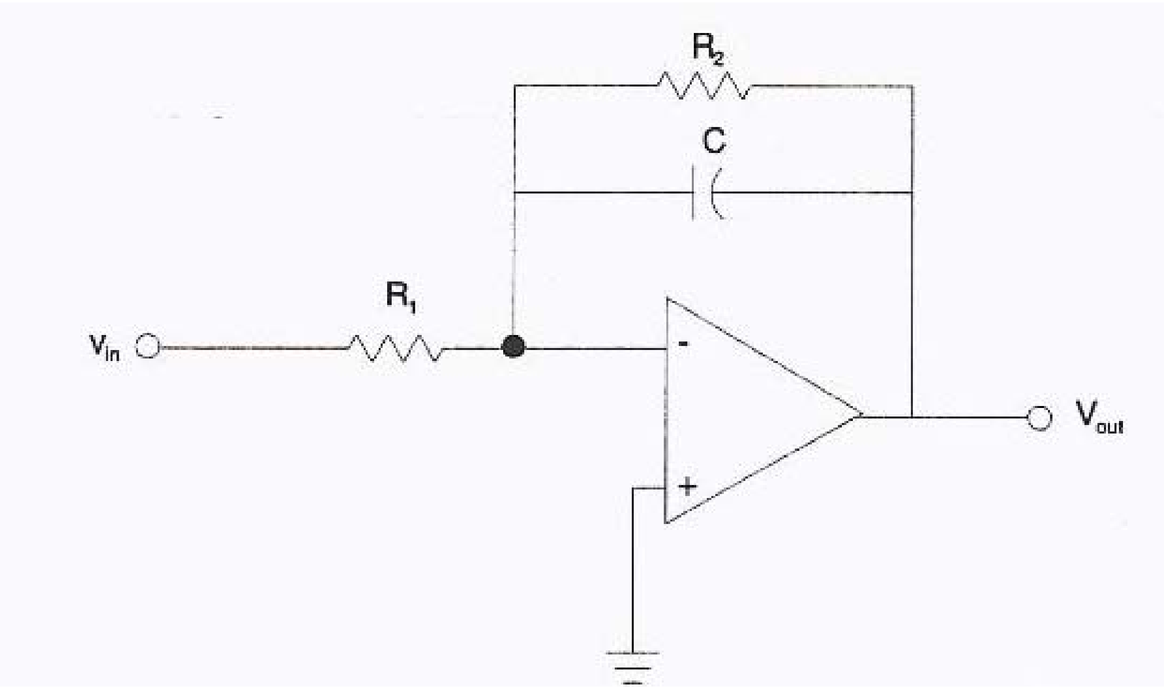
- Additional stage for removing DC offset.



$$\frac{V_{out}(s)}{V_2(s)-V_1(s)}=\frac{Gs}{s+\frac{1}{RC}}$$

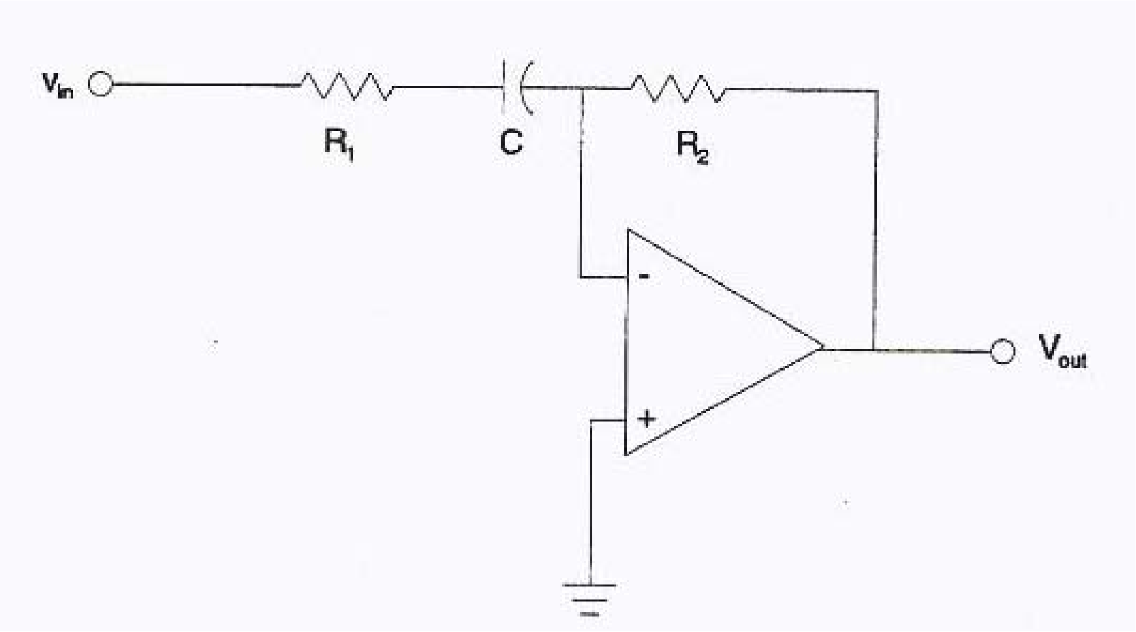
1st Order HPF

Low-Pass Filter



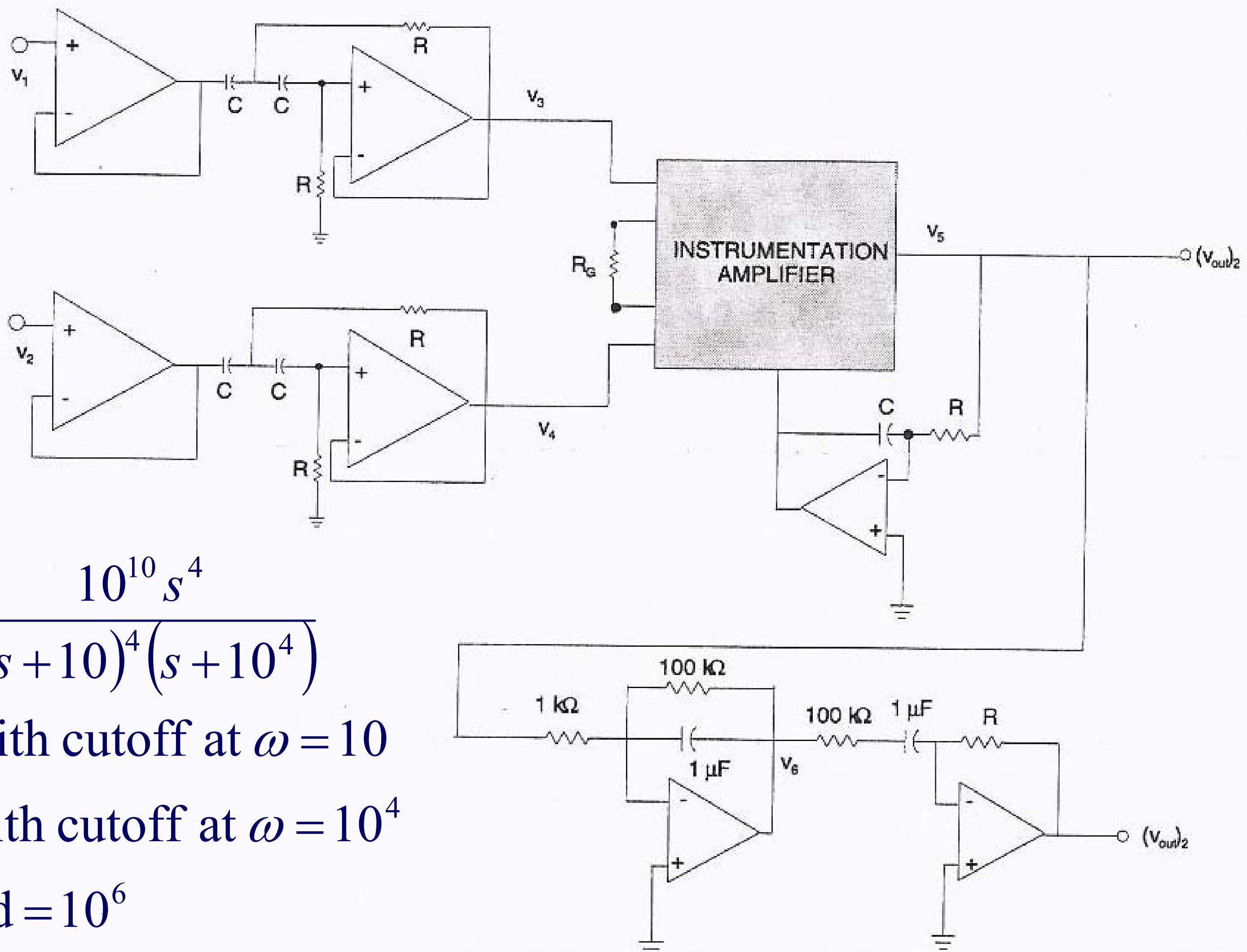
1st Order LPF

Final High-Pass Filter



1st Order HPF

Complete Design



$$\frac{\left(V_{out}(s)\right)_2}{V_2(s)-V_1(s)}=\frac{10^{10}s^4}{(s+10)^4\left(s+10^4\right)}$$

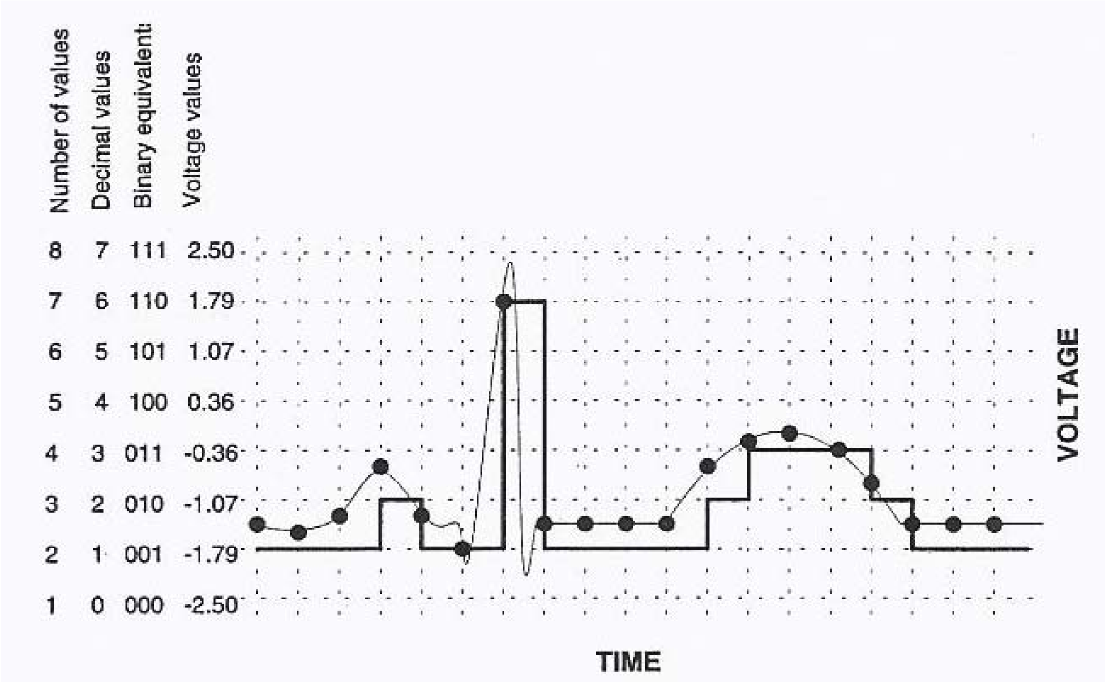
4th order LPF with cutoff at $\omega = 10$

1st order HPF with cutoff at $\omega = 10^4$

Gain in passband $= 10^6$

A/D Conversion

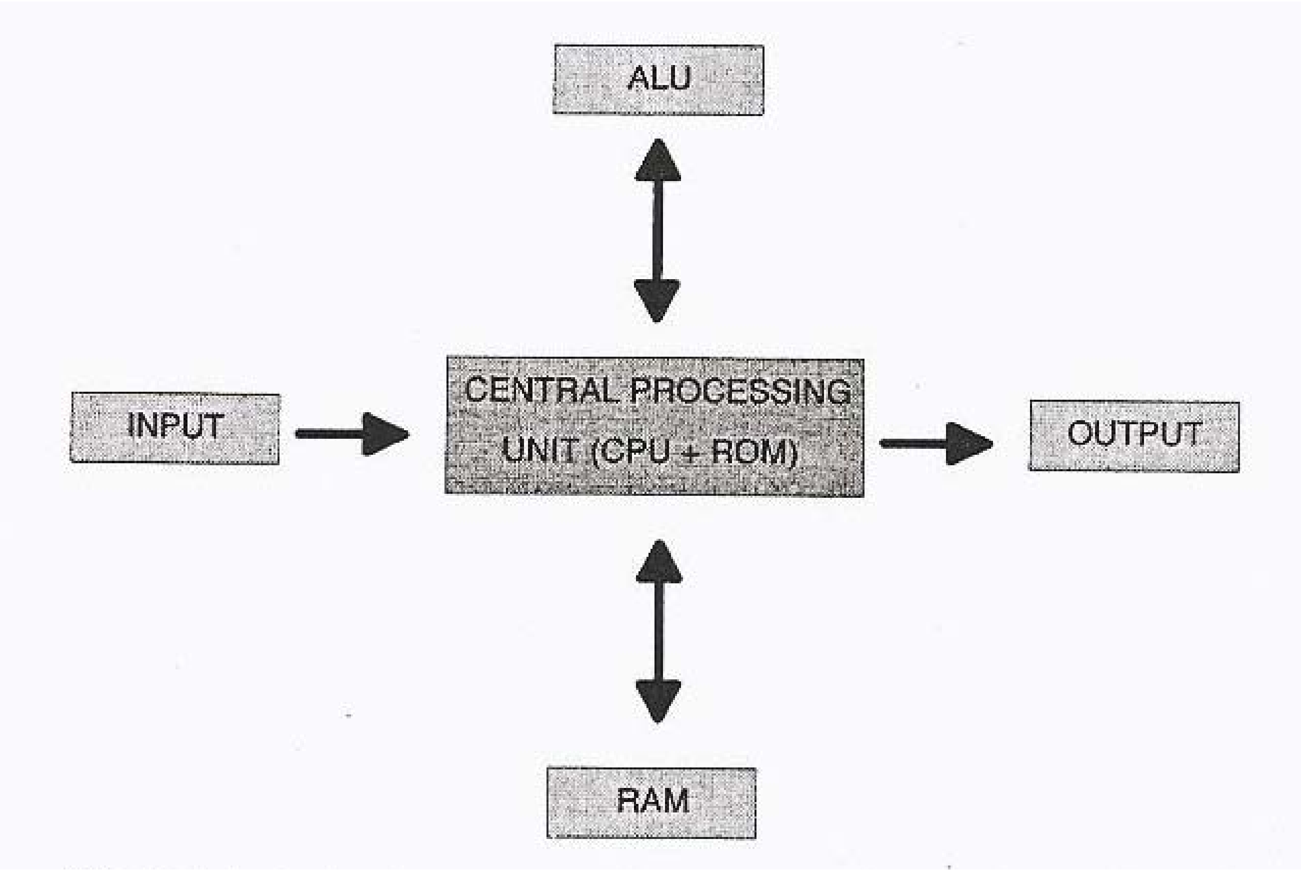
- Sampling rate (Samples/sec)
- Amplitude resolution (number of bits)
- Signal amplification to match input range



5.6 Computer-Based Instrumentation Systems

Computers and Programming Languages

- You should all be familiar with these,…



Noise Figure

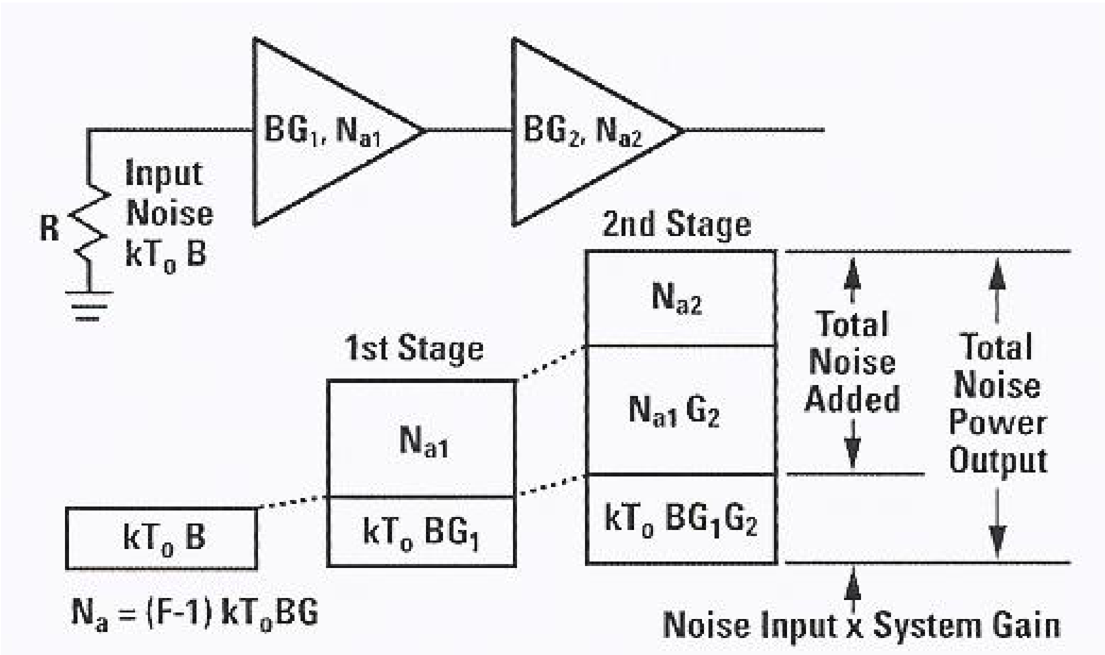
Noise and Noise Figure

- Noise figure is a system parameter to characterize the ability to process low-level signals.
- It can be used for individual system components or the entire system.
- Sources of noise include thermal noise and shot noise.
- Random noise is often treated as if it all were caused by thermal noise, characterized by a noise temperature.

$$v_{rms} = \sqrt{4BT(\Delta f)R}$$

Noise Figure

$$NF = \frac{(S_i / N_i)^2}{(S_o / N_o)^2} \qquad NF_i = \frac{(S_{i-1} / N_{i-1})^2}{(S_i / N_i)^2}$$



Noise Figure

$$NF_i = \frac{\left(S_{i-1}/N_{i-1}\right)^2}{\left(S_i/N_i\right)^2} = \frac{\left(S_{i-1}/N_{i-1}\right)^2}{\left(G_i S_{i-1}\right)^2 / \left(\left(G_i N_{i-1}\right)^2 + N_i^2\right)} = \frac{\left(G_i N_{i-1}\right)^2 + N_i^2}{\left(G_i N_{i-1}\right)^2}$$

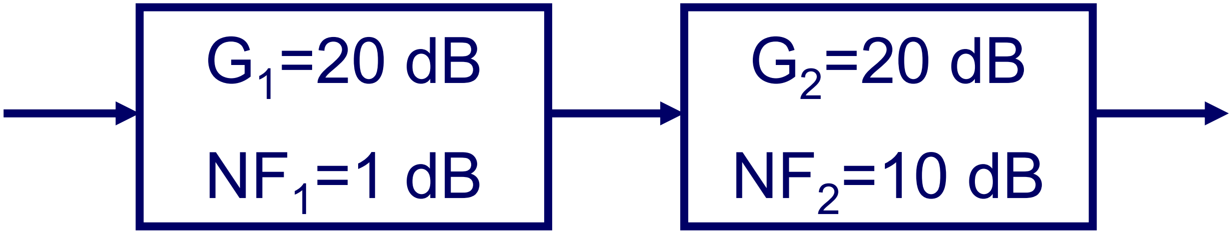
For 2 stages, the output noise figure is:

$$NF = NF_1 + \frac{\left(NF_2 - 1\right)}{G_1^2}$$

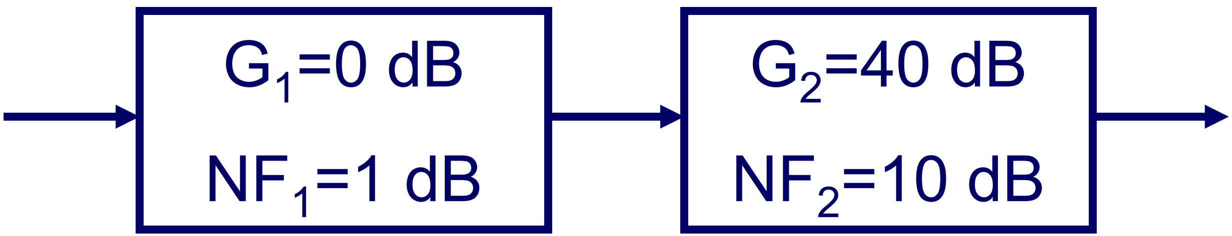
General Case:

$$NF = NF_1 + \sum_{i=2}^{N} \frac{NF_i - 1}{\prod_{j=2}^{i} G_j^2}$$

Noise Figure: Example



$$NF = 10\log_{10}\left[1.26 + \frac{9}{100}\right] = 1.3dB$$



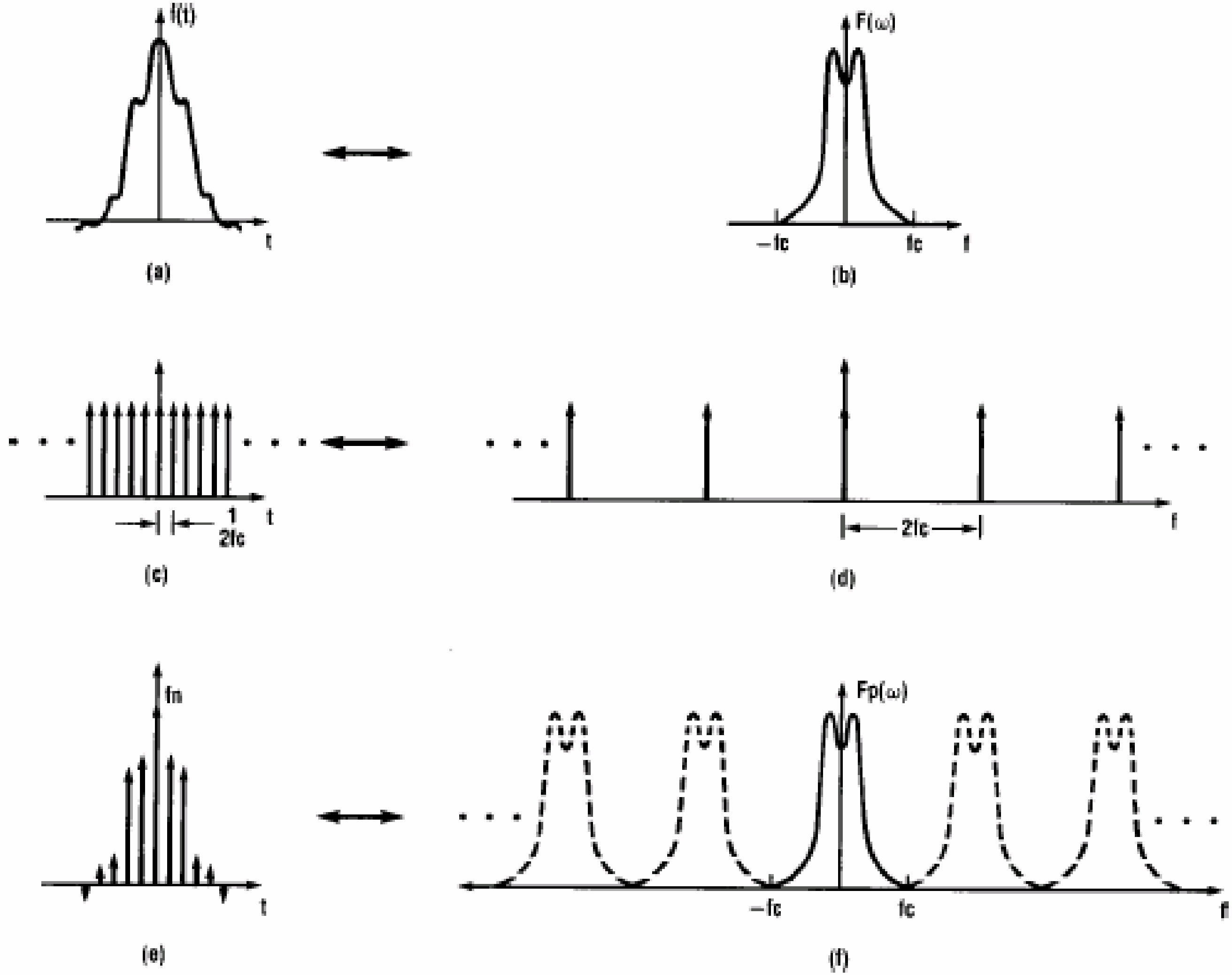
$$NF = 10\log_{10}\left[1.26 + 9\right] = 10.1dB$$

Noise Figure Considerations

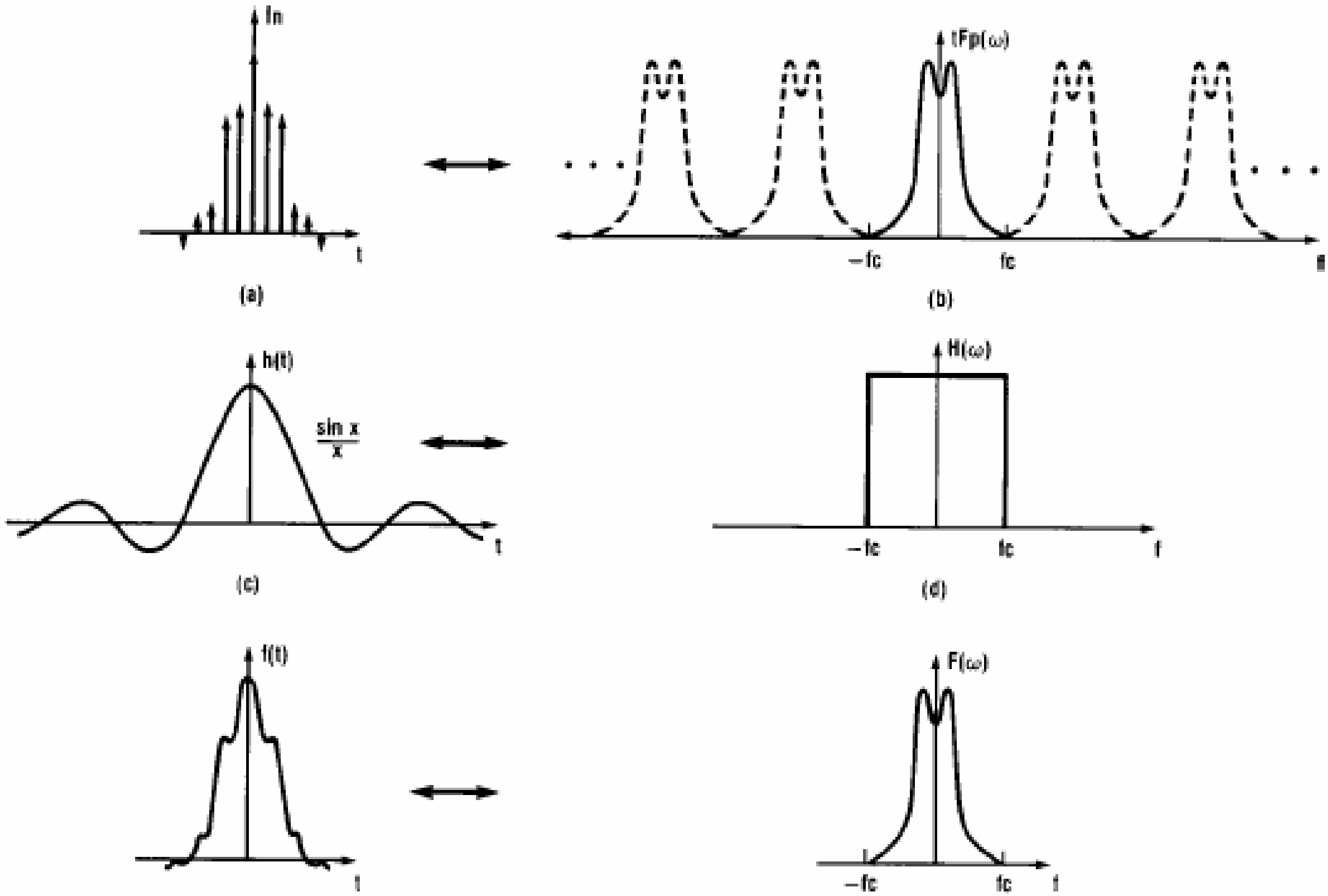
- The first low noise amplifier should have some gain, otherwise the noise characteristics of later amplifier stages matter.
- Never let the total gain get close to unity at any point in the chain, otherwise the noise characteristics of the entire chain are dominated by the amplifier at the that stage.

Quantization and Sampling

Sampling

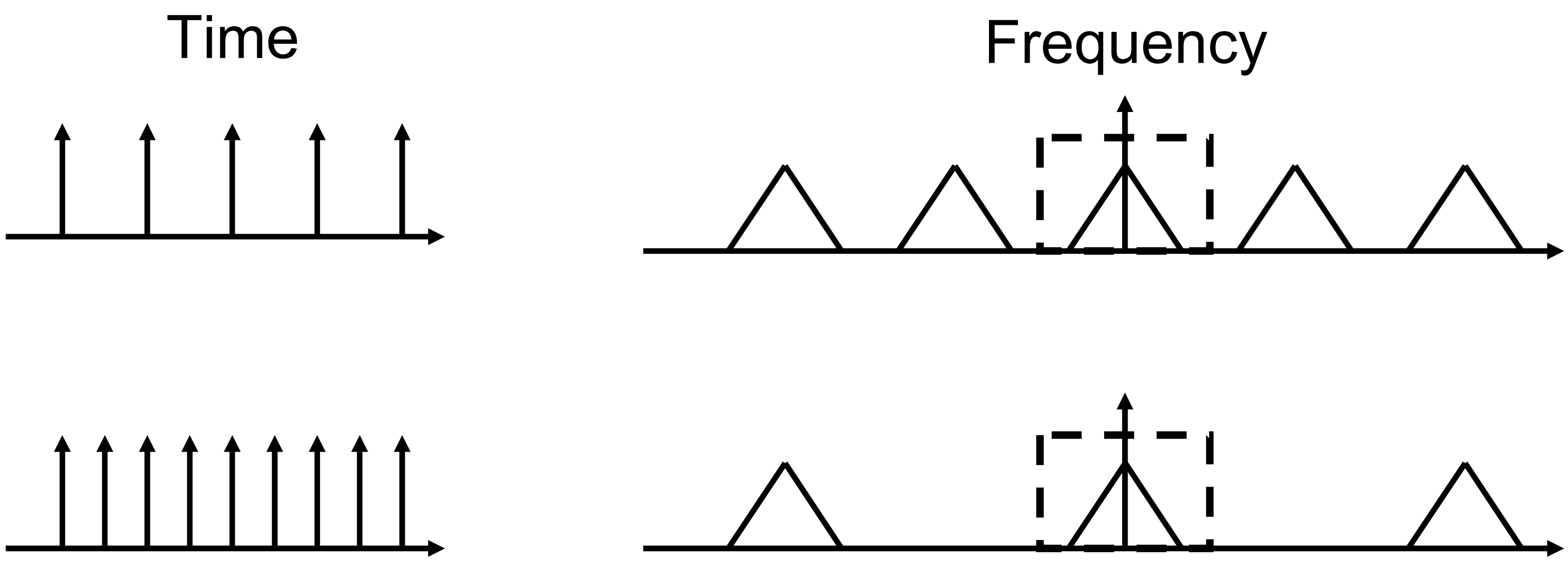


Reconstruction



Oversampling

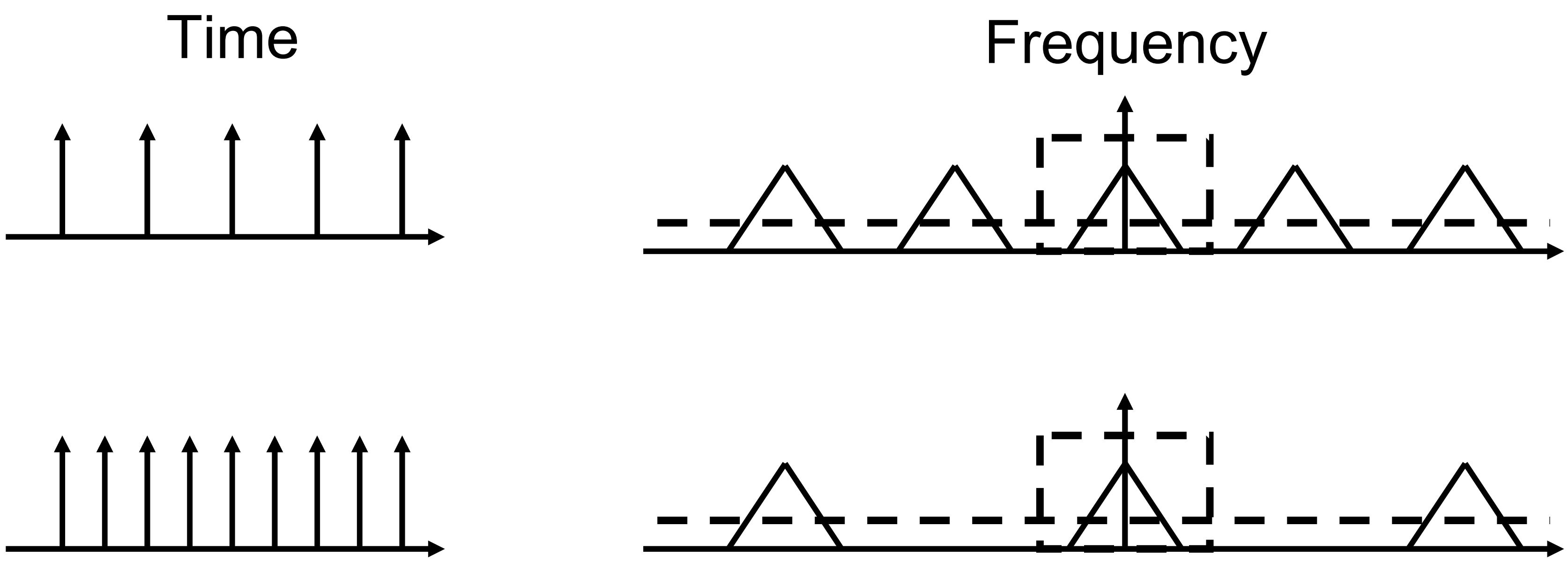
- Is oversampling a total waste?



- Yes, if there is no noise.

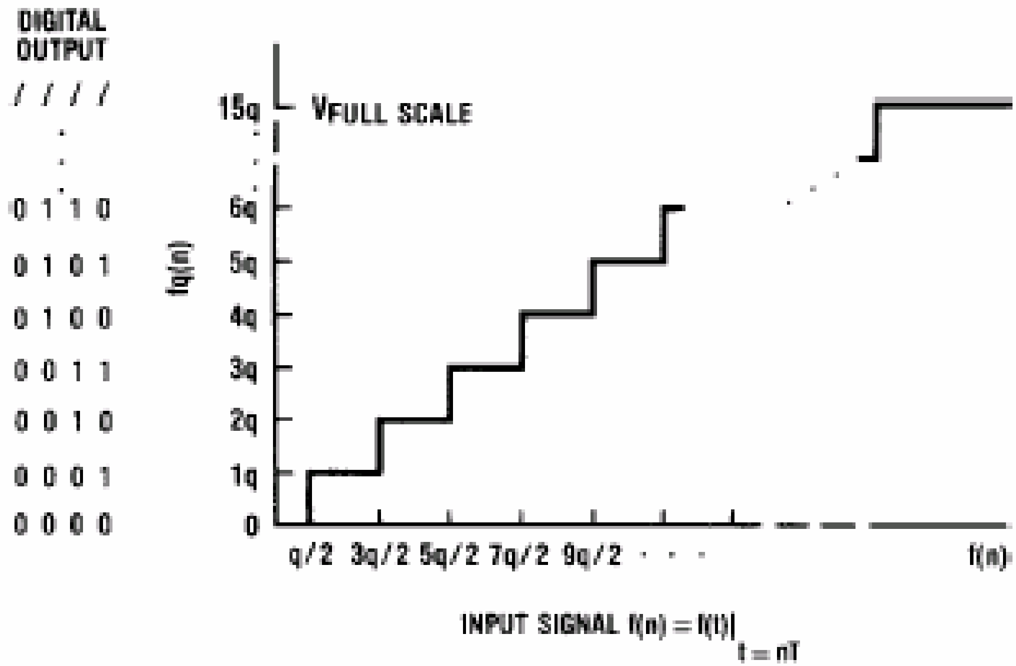
Oversampling

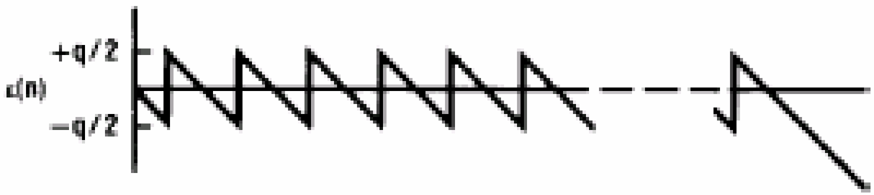
- When the data is noisy, it is not band-limited anymore.



- Signal averaging can be done to reduce noise.

Quantization and Oversampling

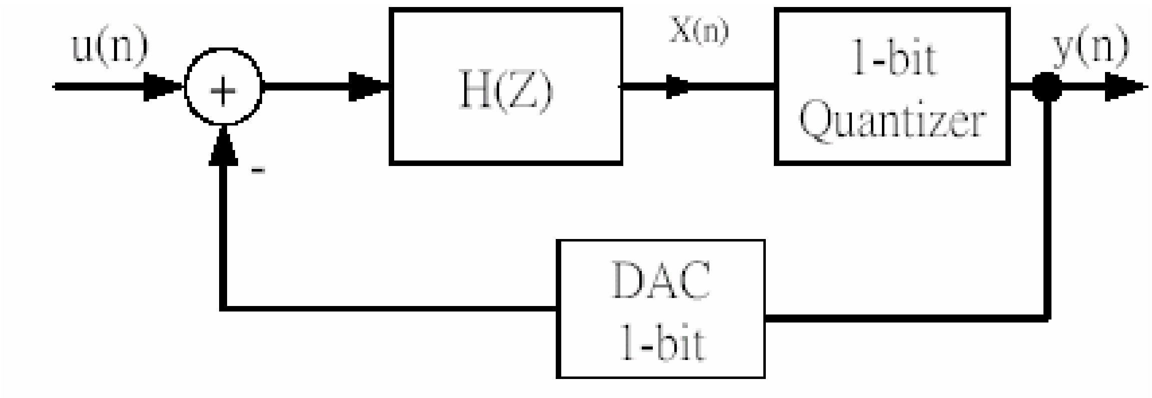


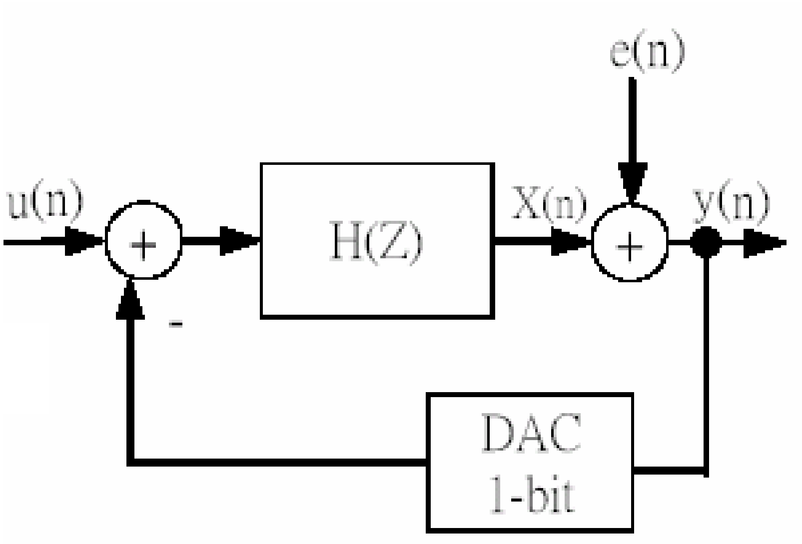


Quantization and Oversampling

- Quantization: An additional bit improves the signal-to-quantization-noise by 6 dB.
- For uniform (white) noise, oversampling by 2 improves the signal-to-noise ratio by 3 dB (equivalently 0.5).
- What if we can “shape” the noise?

Noise Shaped ΔΣ Modulator





Signal and Noise Transfer Function

Signal transfer function $S_{TF}(z) \equiv \frac{Y(z)}{U(z)} = \frac{H(z)}{1+H(z)}$

Noise transfer function $N_{TF}(z) \equiv \frac{Y(z)}{E(z)} = \frac{1}{1+H(z)}$

$H(z)=\frac{z^{-1}}{1-z^{-1}}$ (Noniverting Forward-Euler SC integrator)

$\Rightarrow S_{TF}(z)=\frac{H(z)}{1+H(z)} = z^{-1}$

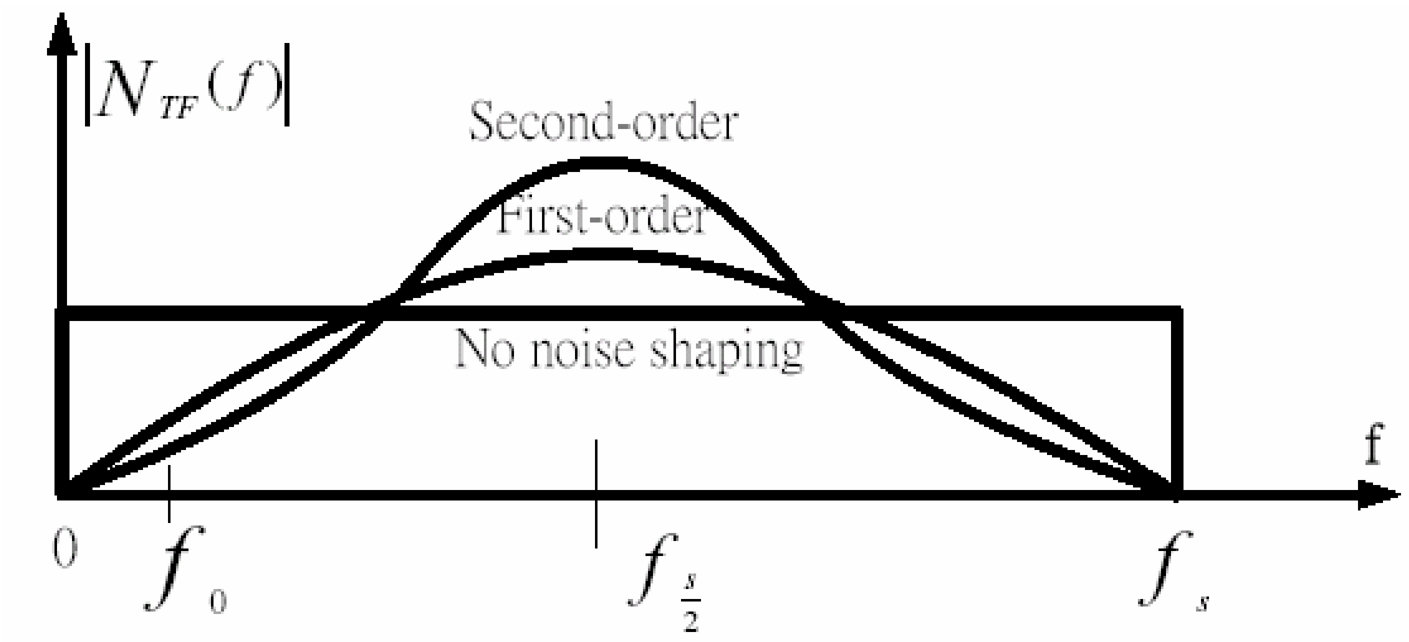
$N_{TF}(z)=\frac{1}{1+H(z)} = (1-z^{-1})$ $z=e^{j\omega T}=e^{j2\pi f/fs}$

$N_{TF}(f)=1-e^{-j2\pi f/fs}=\sin(\frac{\pi f}{f_s})\times(2j)\times(e^{-j\pi f/fs})$

$|N_{TF}(f)| = 2\sin(\frac{\pi f}{f_s})$

Noise Shaping Transfer Functions

- For first order noise shaping, 1.5 bits (9 dB) is gained when the sampling frequency is doubles.
- For second order noise shaping, 2.5 bits (15 dB) is gained when the sampling frequency is doubles.



Noise Shaping and Reconstruction