Biopotential Amplifiers

- Basic function
  - to increase the amplitude of a weak electric signal of biological origin (next slide)
  - typically process *voltages*
    - but in some cases also process currents

- Typical bio-amp requirements
  - high input impedance -greater than 10 Mohms
  - safety: protect the organism being studied
    - careful design to prevent macro and microshocks
    - isolation and protection circuitry to limit the current through the electrode to safe level
  - output impedance of the amplifier
    - should be low to drive any external load with minimal distortion
  - gain greater than 1000
    - biopotentials are typically less than a millivolt
  - most biopotential amplifiers are differential
    - signals are recorded using a bipolar electrodes which are symmetrically located
  - high common mode rejection ratio
    - biopotentials ride on a large offset signals
  - rapid calibration of the amplifier in laboratory conditions
  - adjustable gains
    - often the change in scale is automatic
    - therefore calibration of the equipment is very important

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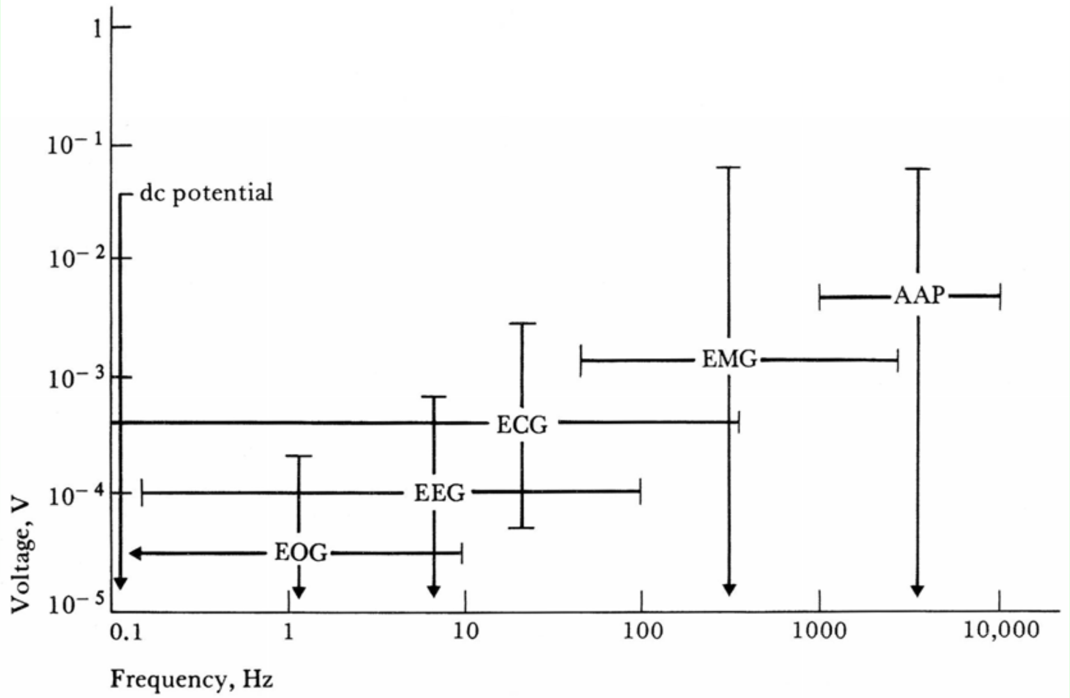
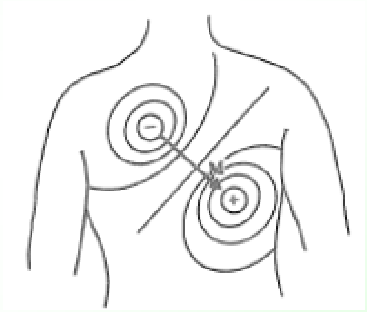
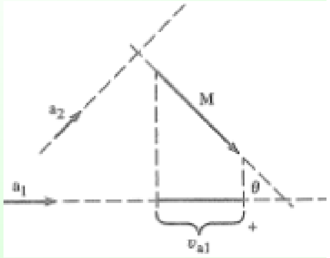
Voltage and Frequency Range for Biopotentials



Electrocardiograph amplifiers

- Beating heart generates electric signal
  - monitored to understand heart functions
- Measurements are functions of
  - location at which the signal is detected
  - time-dependence of the signal amplitude
- Different pairs of electrodes at different locations yield different measurements
  - hence placement is standardized
- Electrical model of heart
  - electric dipole located in a partially conducting medium (thorax)
  - dipole represented as a cardiac vector ***M***
    - M is the dipole moment
  - during the cardiac cycle
    - magnitude and direction of the dipole vector will vary
  - electric potentials appears throughout the body and on its surface

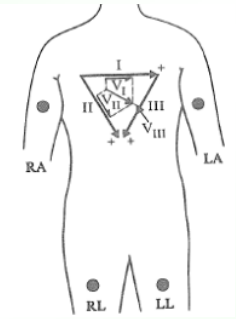




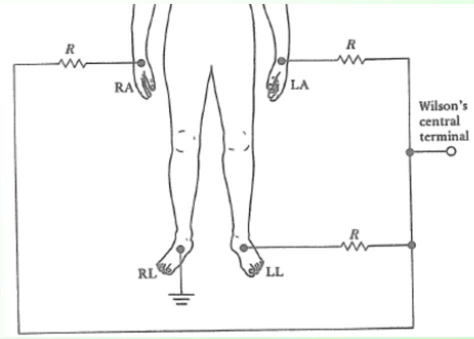
$$v_{a1} = \mathbf{M}\cdot\mathbf{a}_1,\ v_{a1} = |\mathbf{M}|\cos\theta$$

Electrocardiograph Leads

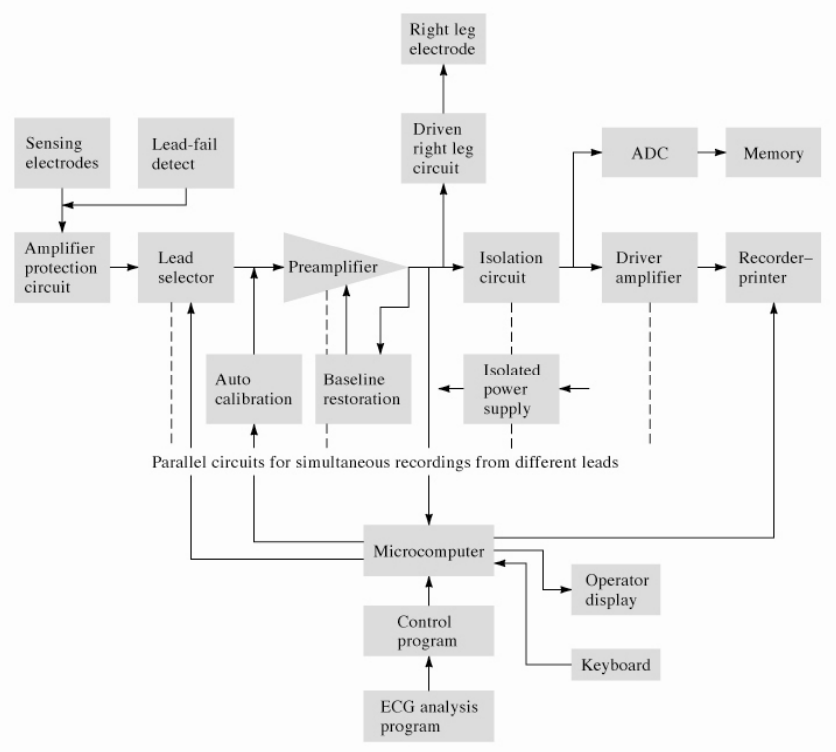
- In clinical electrocardiography
  - more than one lead must be recorded to describe the heart's electric activity fully
  - several leads are taken in the frontal plane and the transverse plane
    - frontal plane: parallel to the back when lying
    - transverse plane: parallel to the ground when standing
- Frontal plane lead placement
  - called *Eindhoven's triangle*



- Additional leads
  - unipolar measurements
    - potential measured at electrodes wrt a reference; average of the 2 electrodes
  - *Wilson central terminal*
    - three limb electrodes connected through equal-valued resistors to a common node
  - augmented leads
    - some nodes disconnected
    - increase the amplitude of measurement using

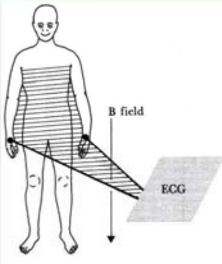


Functional blocks of electrocardiograph



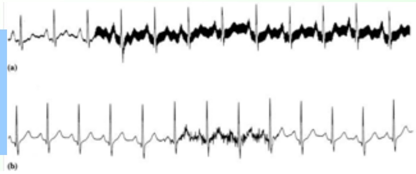
Problems in ECG Measurement

- Frequency distortion
  - if filter specification does not match the frequency content of biopotential
  - then the result is high and low frequency distortion
- Saturation or cutoff distortion
  - high electrode offset voltage or improperly calibrated amplifiers can drive the amplifier into saturation
    - then the peaks of QRS waveforms are cut off
- Ground loops
  - if two monitoring instruments are placed at disjoint ground points
  - then small current could flow through the patient’s body
- Electric/magnetic field coupling
  - open lead wires (floating connections) pick up EMI
  - long leads produce loop that picks up EMI (induces loop current)
- Interference from power lines (common mode interference)
  - can couple onto ECG signal



60Hz supply noise

Coupled to ECG



Interference Reduction Techniques

Common-mode voltages can be responsible for much of the interference in biopotential amplifiers.

- Solution 1:
  - amplifier with a very high common-mode rejection

- Solution 2:
  - eliminate the source of interference

Ways to eliminate interference

- Use shielding techniques
  - electrostatic shielding: Place a grounded conducting plane between the source of the electric field and the measurement system
    - very important for EEG measurement
- Magnetic shield
  - use high permeability materials (sheet steel)
- Use twisted cables to reduce magnetic flux, reduce lead loop area

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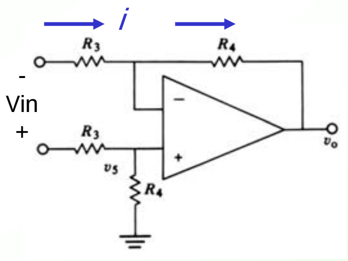
Differential Amplifier

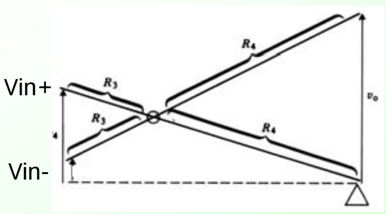


- One-amp differential amplifier
  - gain determination
    - Rule 1: virtual short at op-amp inputs
    - Rule 2: no current into op-amp

$$v_5 = \frac{v_{in+}R_4}{R_3 + R_4} \qquad i = \frac{v_{in-} - v_5}{R_3} = \frac{v_5 - v_o}{R_4}$$

$$\rightarrow \quad v_o = \frac{(v_{in+} - v_{in-})R_4}{R_3}$$

Gain of differential amplifier (not gain of op-amp) $\frac{v_o}{v_{in}} = \frac{R_4}{R_3}$ = Gd



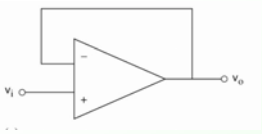
- characteristics
  - no common mode gain, Gc = 1
  - input resistance of the diff. amp is lower than ideal op-amp
    - OK for low resistance sources (like Wheatstone bridge), but not good for many biomedical applications

common mode rejection ratio: $\text{CMRR} = \frac{G_d}{G_c}$

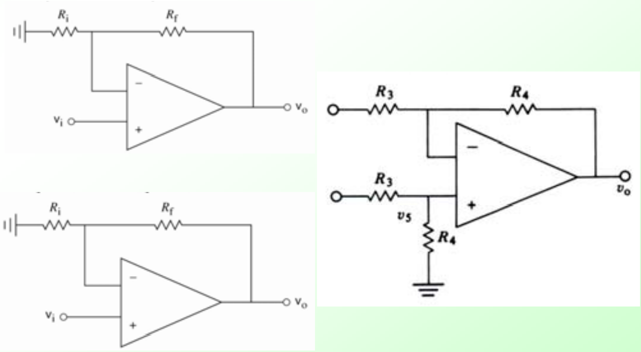
Differential Amplifier

- How do we fix low input resistance of 1-op-amp diff amp?

- Option 1: Add voltage follower to each input
  - Problem: ?

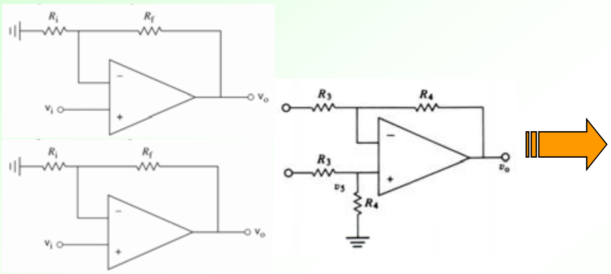


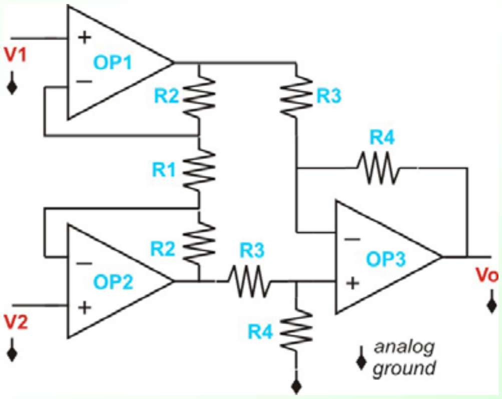
- Option 2: Add non-inverting amp at each input
  - Provides additional gain
  - Problem: ?



Instrumentation Amplifier

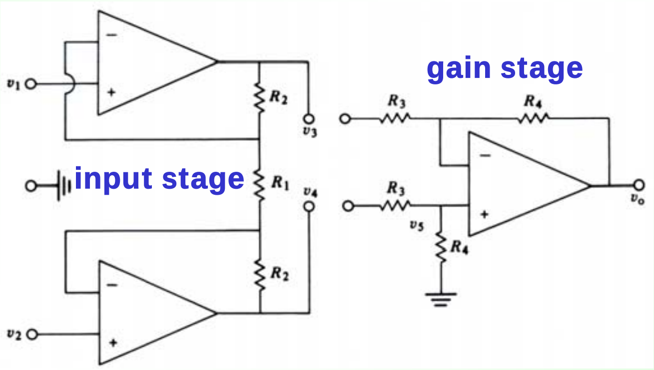
- Better option:
  - connect Ri's of input amps together
  - eliminate ground connection





- This 3-op-amp circuit is called an ***instrumentation amplifier***
- Input stage characteristics
  - low common-mode gain -rejects common mode voltages (noise)
  - high input impedance
  - input stage gain adjusted by R_1 $G_d = \frac{v_3 - v_4}{v_1 - v_2} = \frac{2R_2 + R_1}{R_1}$

Instrumentation Amplifier



gain stage

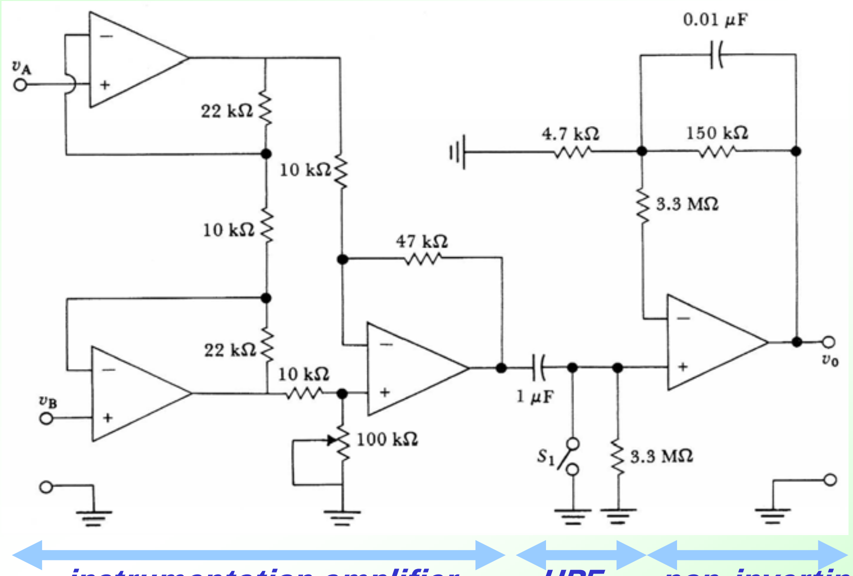
input stage

- Input stage
  - high input impedance
    - buffers gain stage
  - no common mode gain
  - can have differential gain
- Gain stage
  - differential gain, low input impedance
- Overall amplifier
  - amplifies only the differential component
    - high common mode rejection ratio
  - high input impedance suitable for biopotential electrodes with high output impedance

total differential gain

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

ECG Amplifier



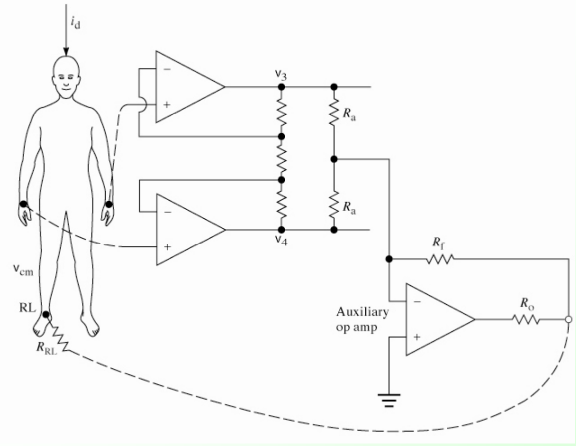
instrumentation amplifier ***HPF*** ***non-inverting amp***

With 776 op amps, the circuit was found to have a CMRR of 86 dB at 100 Hz and a noise level of 40 mV peak to peak at the output. The frequency response was 0.04 to 150 Hz for ±3 dB and was flat over 4 to 40 Hz. The total gain is 25 (instrument amp) x 32 (non-inverting amp) = 800.

Driven Right Leg System

- Motivation
  - reduce interference in amplifier
  - improve patient safety

- Approach
  - patient right leg tied to output of an auxiliary amp rather than ground
  - common mode voltage on body sensed by averaging resistors, Ra's & fed back to right leg
  - provides negative feedback to reduce common mode voltage
  - if high voltage appears between patient and ground, auxiliary amp effectively un-grounds the patient to stop current flow



Driven Right Leg System: Example

- **Problem**: Determine the common-mode voltage v_{cm} on the patient in the driven-right-leg circuit of Slide 13 when a displacement current i_d flows to the patient from the power lines. Choose appropriate values for the resistances in the circuit so that the common-mode voltage is minimal and there is only a high-resistance path to ground when the auxiliary operational amplifier saturates.
- What is v_{cm} for this circuit when i_d=0.2µA?
- **Answer**: The equivalent circuit is shown here. Note that because the common-mode gain of the input stage is 1, and because the input stage as shown has a very high input impedance, v_{cm} at the input is isolated from the output circuit. R_{RL} represents the resistance of the right-leg electrode. Summing the currents at the negative input of the operational amplifier, we get

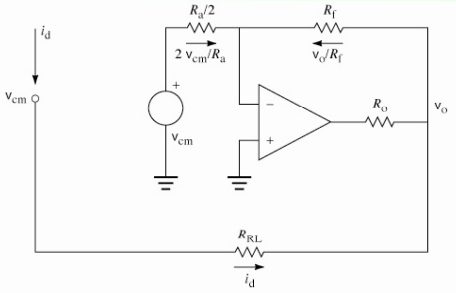
$$\frac{2v_{cm}}{R_a} + \frac{v_o}{R_f} = 0$$

  - this gives

$$v_o = -\frac{2R_f}{R_a} v_{cm} \quad 1 \qquad \text{but} \qquad v_{cm} = R_{RL} i_d + v_o \quad 2$$

  - thus, substituting (1) into (2) yields

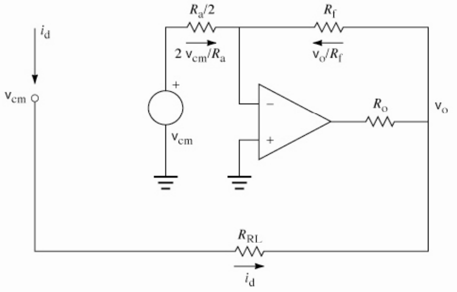
$$v_{cm} = \frac{R_{RL} i_d}{1 + 2R_f/R_a}$$



Example continued

- The effective resistance between the right leg and ground is the resistance of the right-leg electrode divided by 1 plus the gain of the auxiliary operational-amplifier circuit. When the amplifier saturates, as would occur during a large transient v_{cm}, its output appears as the saturation voltage v_s. The right leg is now connected to ground through this source and the parallel resistances R_f and Ro. To limit the current, R_f and Ro should be large. Values as high as 5 MΩ are used.
- When the amplifier is not saturated, we would like v_{cm} to be as small as possible or, in other words, to be an effective low-resistance path to ground. This can be achieved by making R_f large and Ra relatively small. R_f can be equal to Ro, but Ra can be much smaller.
- A typical value of Ra would be 25 kΩ. A worst-case electrode resistance R_{RL} would be 100 kΩ. The effective resistance between the right leg and ground would then be

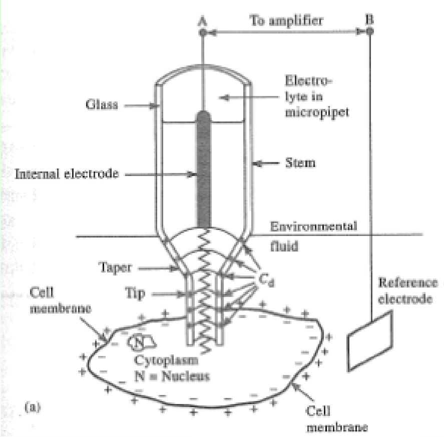
$$\frac{100\,\mathrm{k\Omega}}{1+\dfrac{2\times 5\ \mathrm{M\Omega}}{25\ \mathrm{k\Omega}}} = 249\ \Omega$$

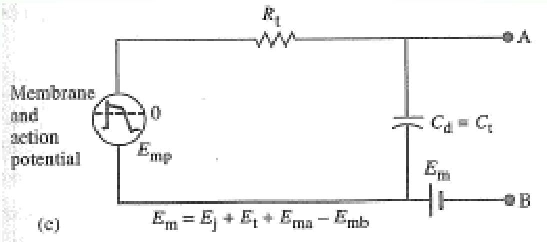


- For the 0.2 μA displacement current, the common-mode voltage is

$$v_{cm} = 249\ \Omega \times 0.2\ \mu\mathrm{A} = 50\ \mu\mathrm{V}$$

Compensation of electrode artifacts





- Microelectrodes detect potentials on the order of 50-100mV.
-Small size implies high source impedance which also results in a large shunting capacitance.
- Degraded frequency response.

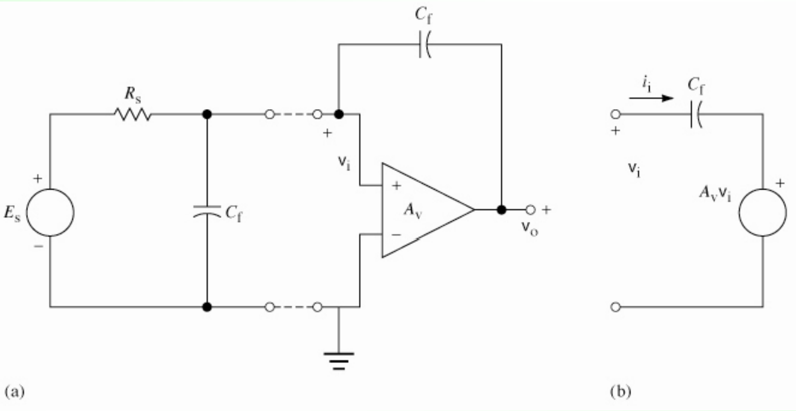
Compensation of electrode artifacts

$$v_i = \frac{1}{C_f}\int i_1 dt + A_v v_i$$

- Compensate large shunt capacitance using a positive feedback

-Circuit below realizes a negative capacitance

$$v_i = \frac{1}{(1-A_v)C_f}\int i_1 dt$$



- Total capacitance

$$C = C_s + (1-A_v)C_f$$

- Compensation criteria

$$C_s = (A_v - 1)C_f$$