ESE 3400: Medical Devices Lab

Lec 5: September 20, 2023

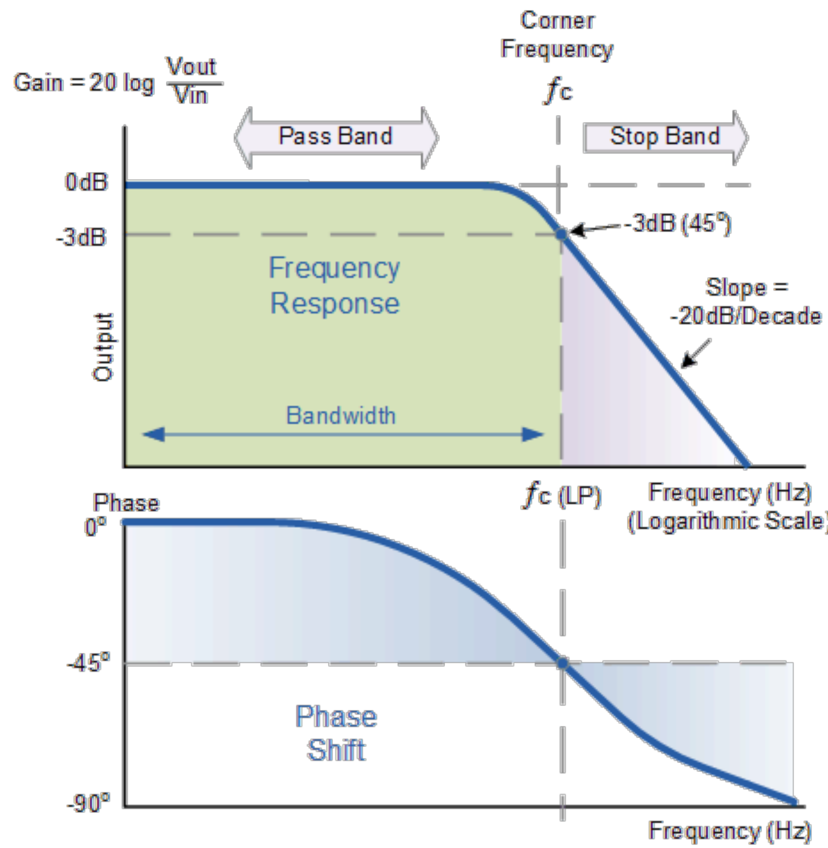
Signal Conditioning/Interface Circuits

Lecture Outline

- Lab 2 Discussion
- Amplification
  - Opamp
  - Practical Opamp Circuits
- Biopotential Amplifier
- Instrumentation Amplifier
- Driven Right Leg System
- Lab 3 Setup
  - LT Spice
  - Amplification and filter schematic

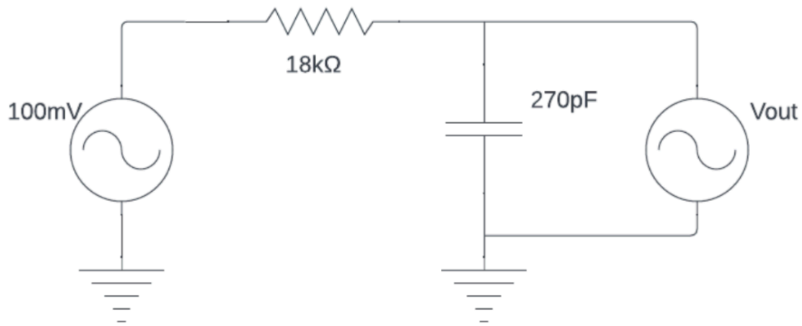
Frequency response of a low pass filter

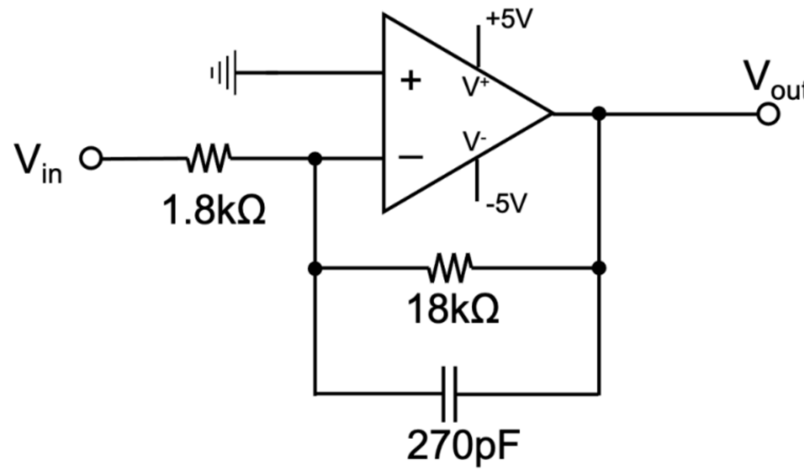
- Gain
- Bandwidth
- Pass band vs stop band
- Corner frequency
- 3dB point
- Roll off



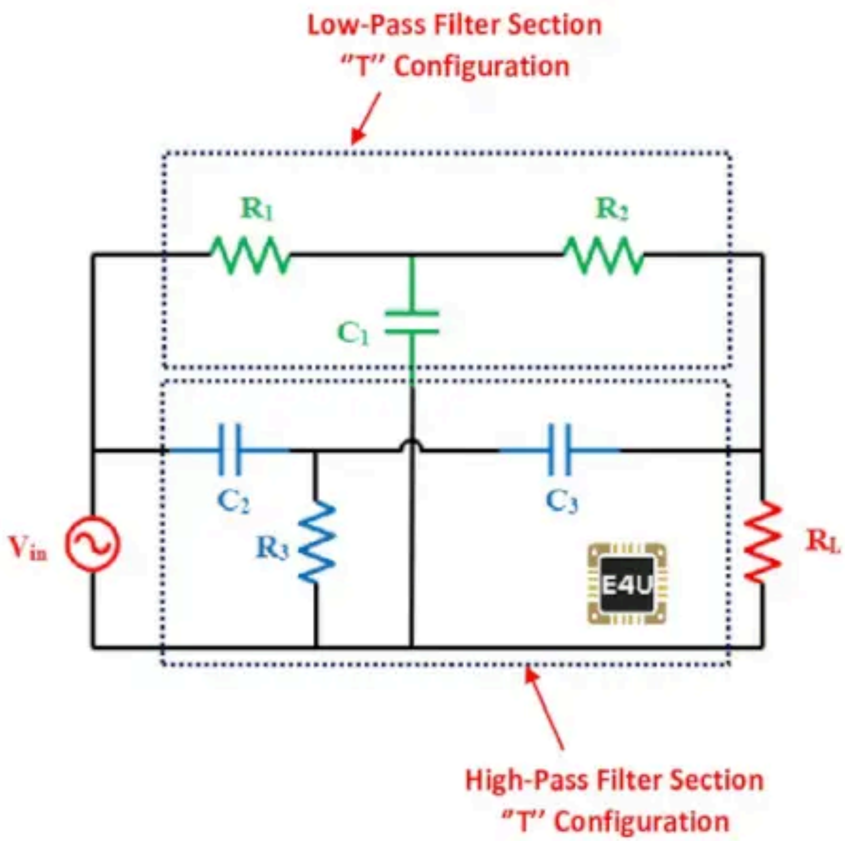
https://www.electronics-tutorials.ws/filter/filter_2.html

Passive LPF vs. Active LPF w/ Gain



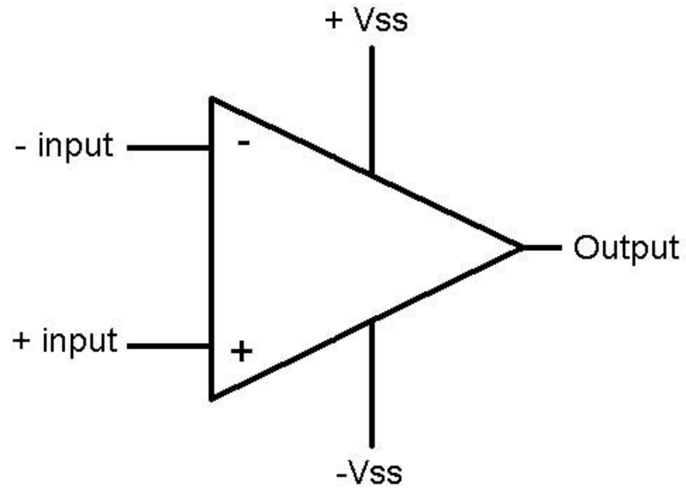


Notch Filter 3dB Cutoffs



Amplification

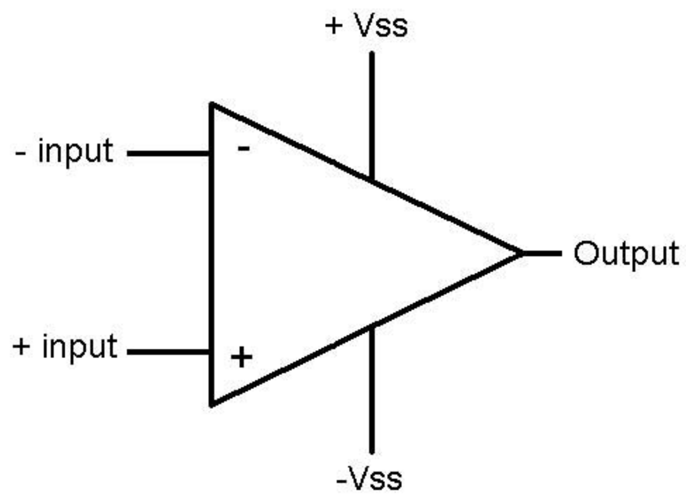
- Sensor outputs may (read: amost always) need amplification for any sort of acquisition and data analysis
- Use operational amplifier to do this
  - Amplifies differential input: Out = $A(V_{in+}-V_{in-})$, where A is large



Opamp

Ideal Opamp

- The ideal opamp characterized by seven properties
  - Knowledge of these properties is sufficient to design and analyze a large number of useful circuits

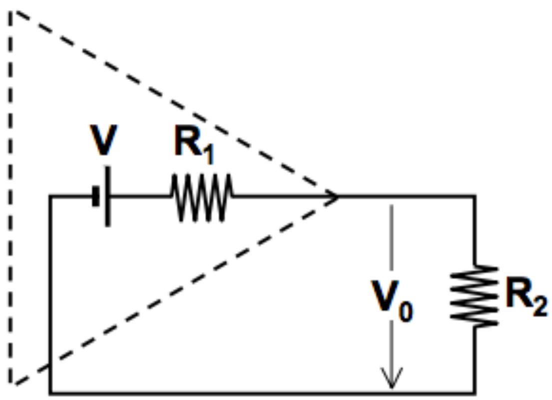


Basic Opamp Properties

- Property No.1: Infinite Open-Loop Gain
  - Open-Loop Gain A_{VOL} is the gain of the opamp without positive or negative feedback
  - In the ideal opamp A_{VOL} is infinite
    - Typical values range from 20,000 to 200,000 in real devices
- Property No.2: Infinite Input Impedance
  - Input impedance is the ratio of input voltage to input current, $Z_{in}=V_{in}/I_{in}$
  - When Z_{in} is infinite, the input current $I_{in}=0$
    - High-grade opamps can have input impedance in the TΩ range
    - Some low-grade opamps, on the other hand, can have mA input currents

Basic Opamp Properties

- Property No. 3: Zero Output Impedance
  - The ideal opamp acts as a perfect internal voltage source with no internal resistance
    - This internal resistance is in series with the load, reducing the output voltage available to the load
    - Real opamps have output-impedance in the 10-20Ω range
  - Example



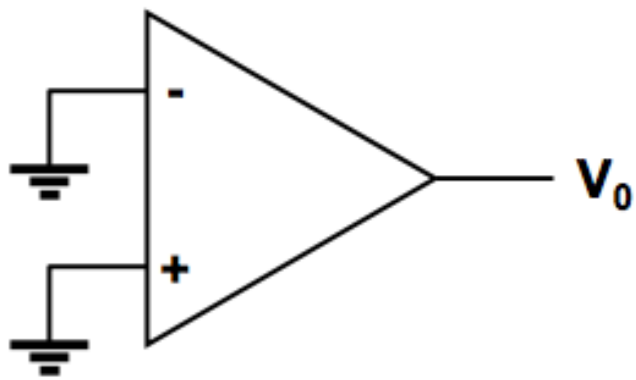
$$V_0 = \frac{VR_2}{R_1 + R_2}$$

Basic Opamp Properties

- Property No. 4: Zero Noise Contribution
  - In the ideal opamp, zero noise voltage is produced internally
    - That is, any noise at the output must have been at the input as well
  - Practical opamp are affected by several noise sources, such as resistive and semiconductor noise
    - These effects can have considerable effects in low signal-level applications

Basic Opamp Properties

- Property No. 5: Zero output Offset
  - The output offset is the output voltage of an amplifier when both inputs are grounded
  - The ideal opamp has zero output offset, but real opamps have some amount of output offset voltage

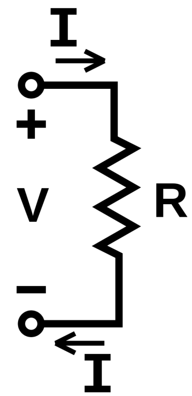


Basic Opamp Properties

- Property No. 6: Infinite Bandwidth
  - The ideal opamp will amplify all signals from DC to the highest AC frequencies
  - In real opamps, the bandwidth is rather limited
    - This limitation is specified by the Gain-Bandwidth product
      - $GBW = f_{3dB} * Gain_{3dB}$
    - Some opamps, such as the 741 family, have very limited bandwidth of up to a few KHz
- Property No. 7: Differential Inputs Stick Together*
  - In the ideal opamp, a voltage applied to one input also appears at the other input
  - *when connected in feedback

Ohm's Law and Kirchoff's Laws

- Ohm's Law
  - V = IR



- KCL – Kirchoff's Current Law
  - The sum of the currents into a node = 0
- KVL – Kirchoff's Voltage Law
  - The sum of the voltage differences around any closed loop in a circuit must be zero

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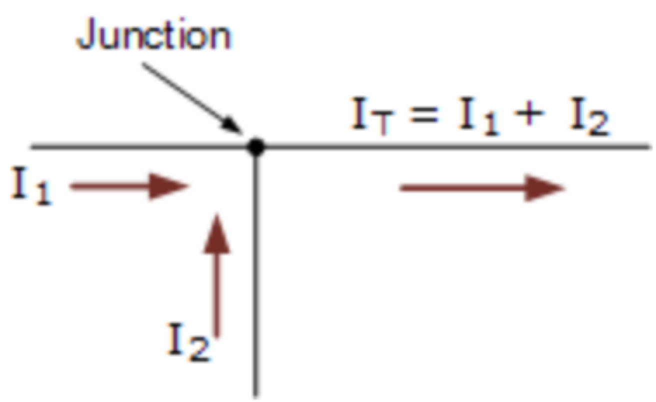

KVL

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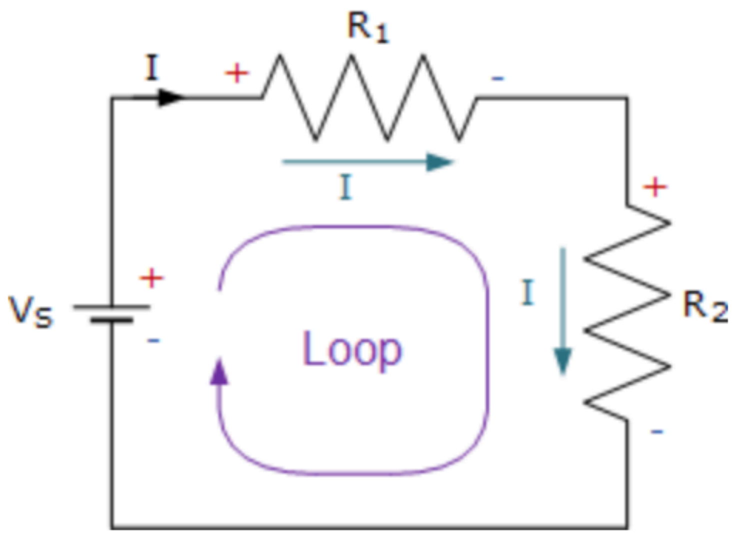
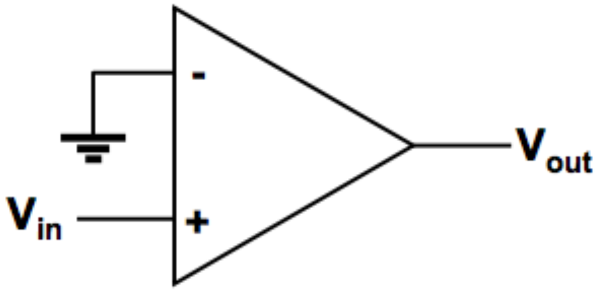
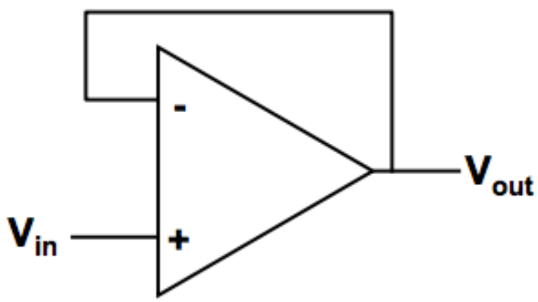


Opamp Practical Circuits

- A)

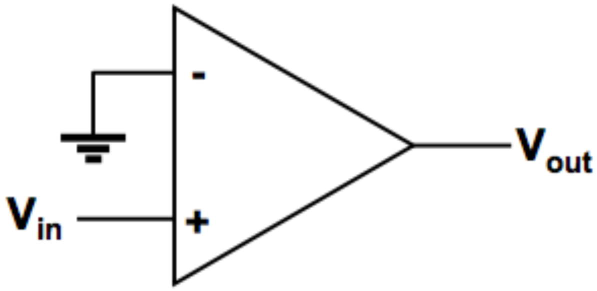


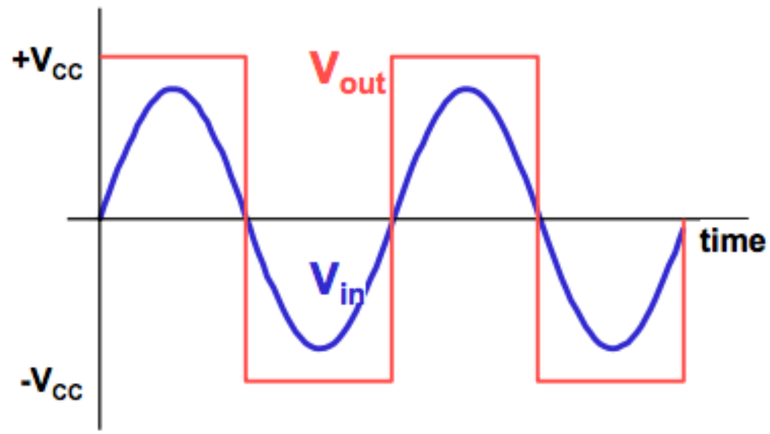
- B)



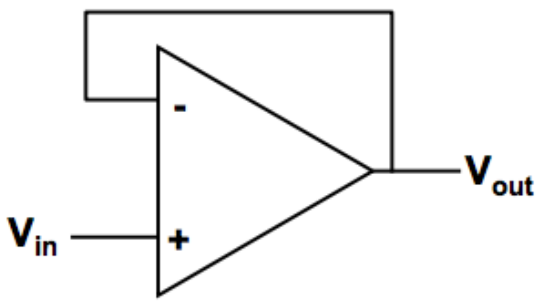
Opamp Practical Circuits

- A) Voltage comparator





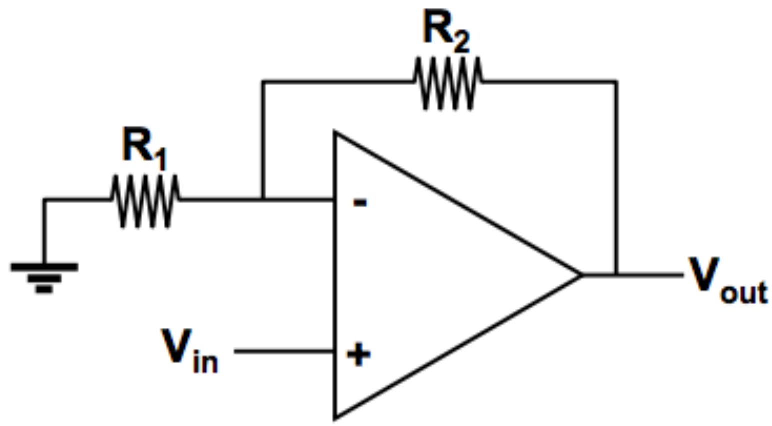
- B) Voltage follower (Buffer)



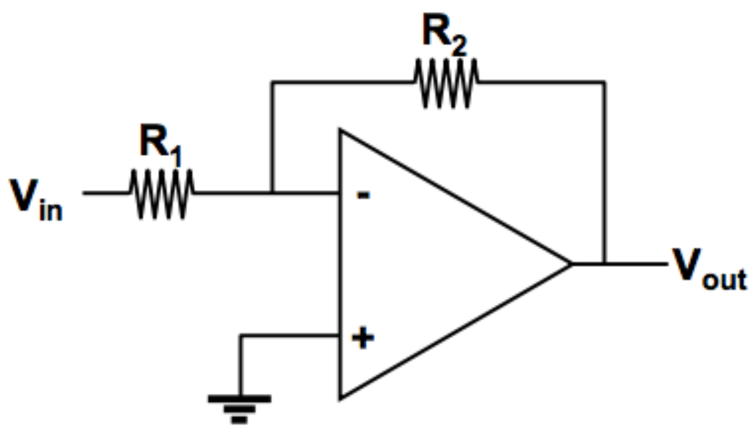
$$V_{out} = V_{in}$$

Opamp Practical Circuits

- C)

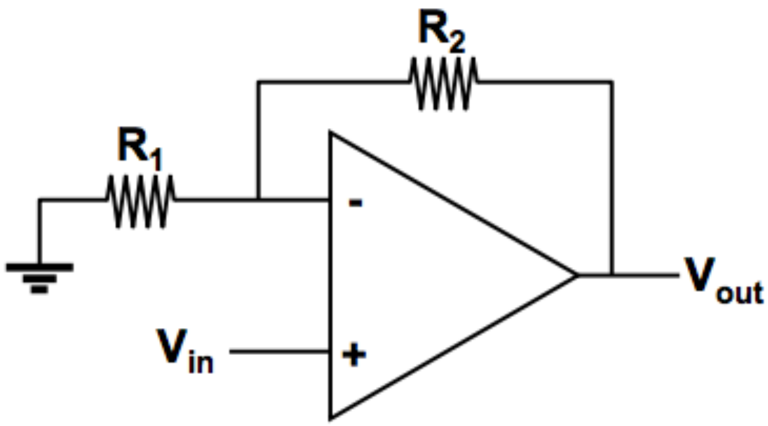


- D)



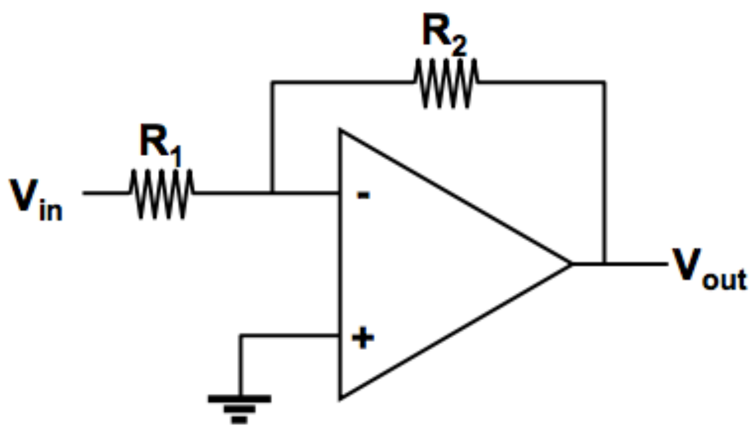
Opamp Practical Circuits

- C) Non-inverting amplifier



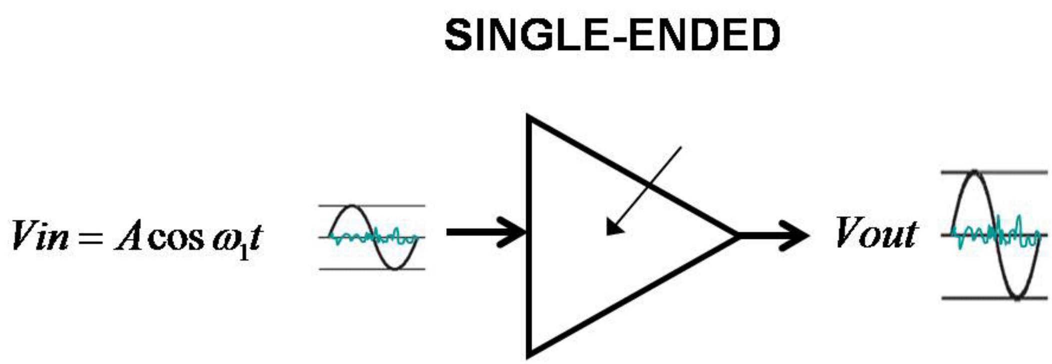
$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

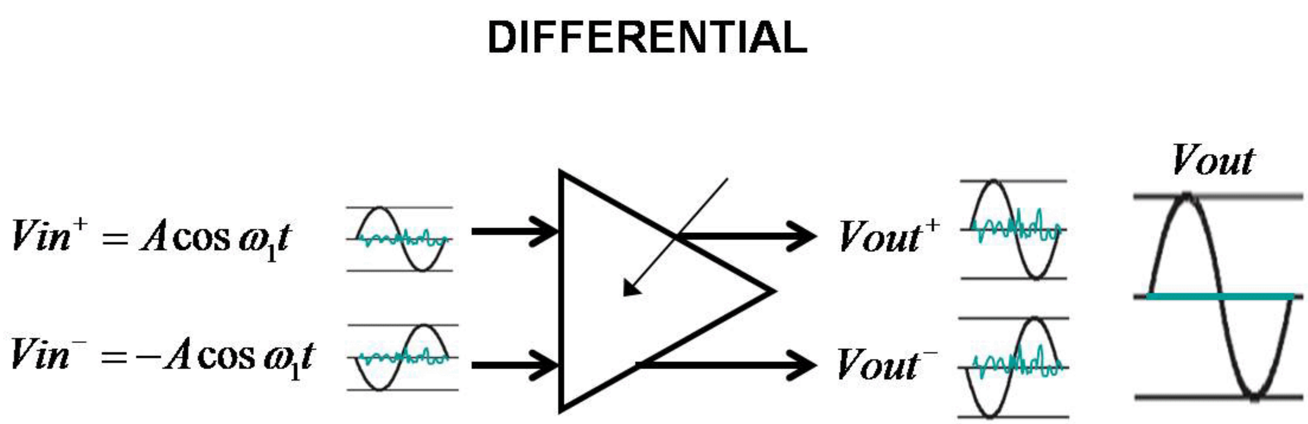
- D) Inverting amplifier



$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

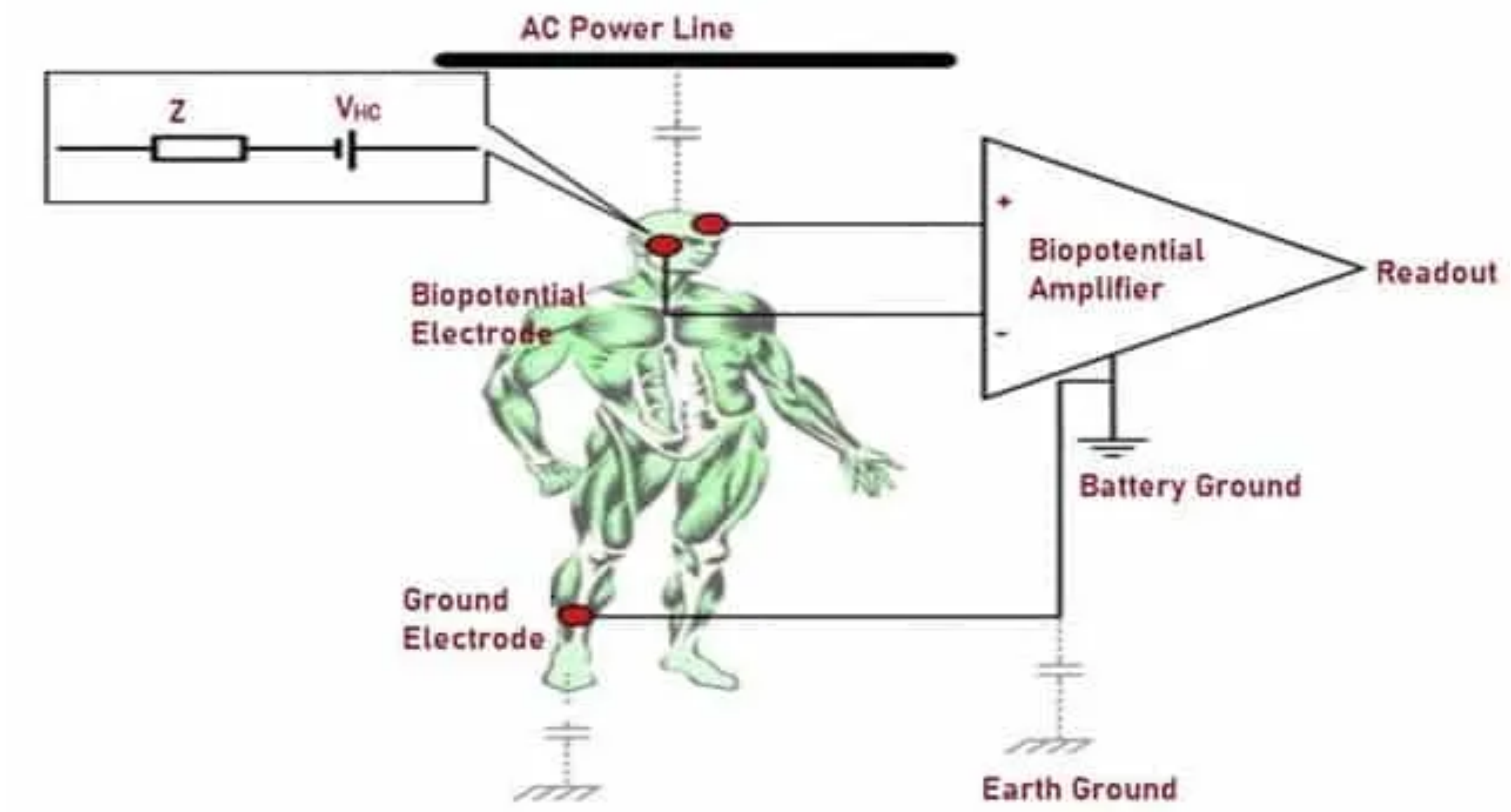
Common Mode and Differential Mode





Biopotential Amplifier

- Differential amplifier



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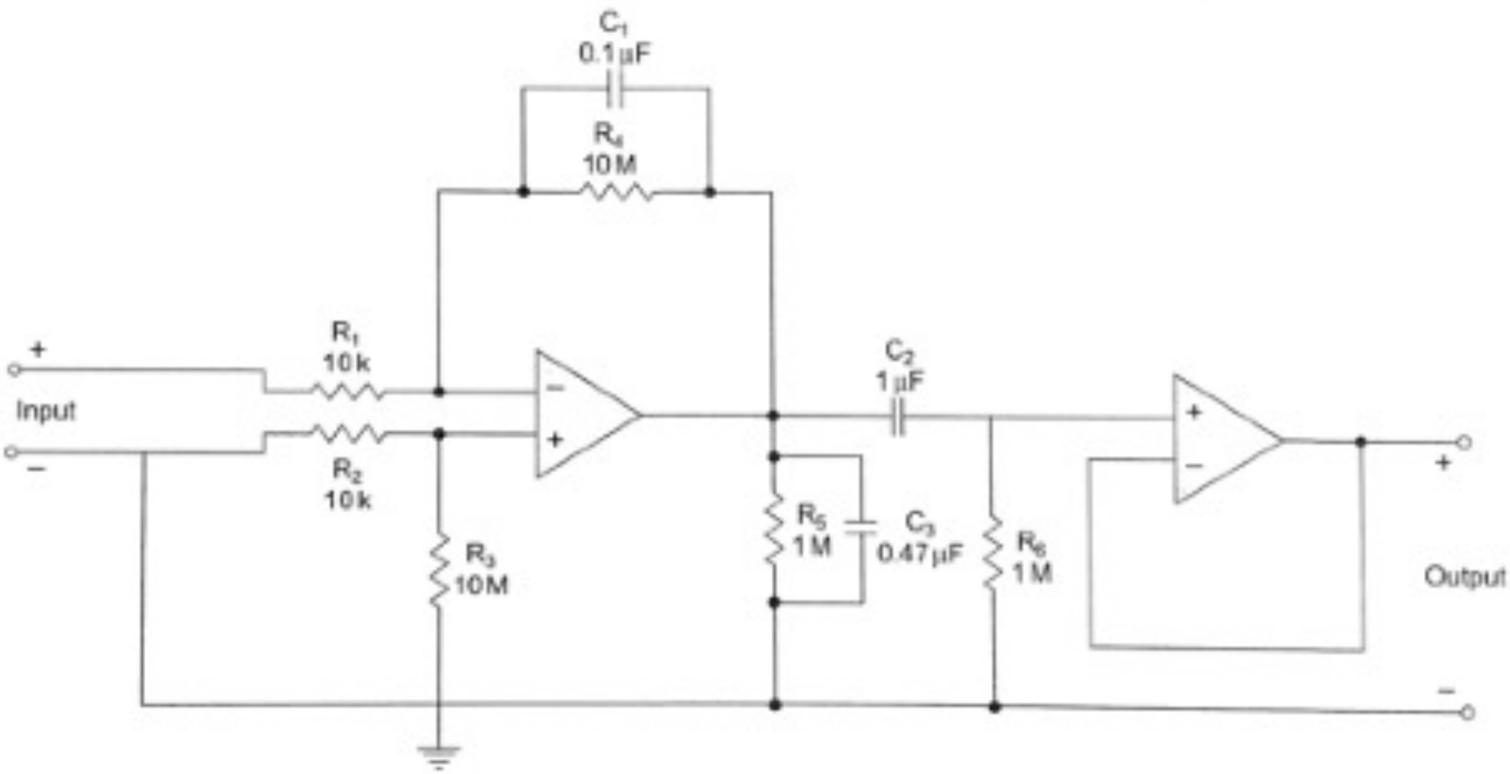


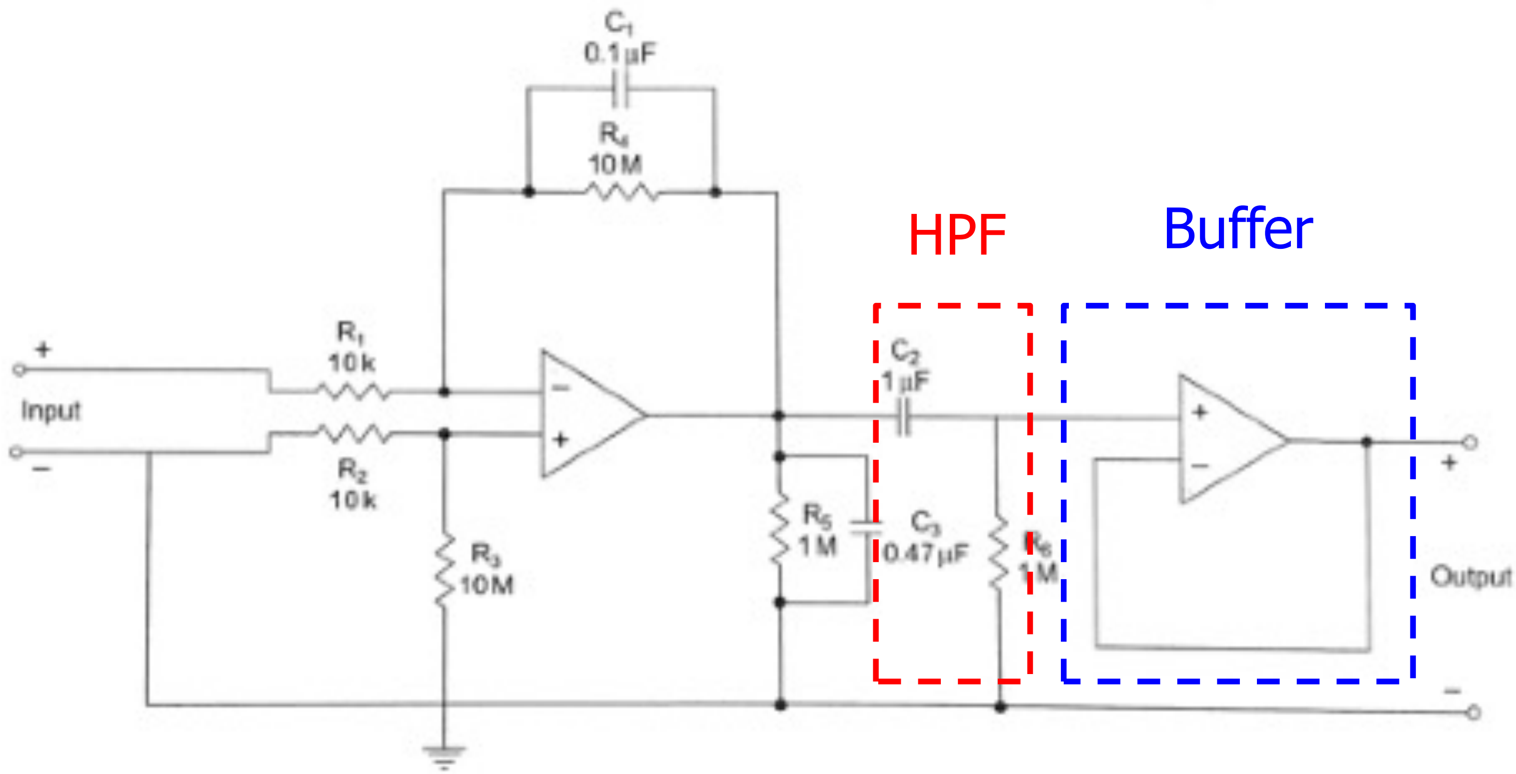
FIGURE 1.20

Differential biopotential amplifier.

Adapted from Prutchi and Norris (2005).

Biopotential Amplifier

- Differential amplifier



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Biopotential Amplifier

- Differential amplifier

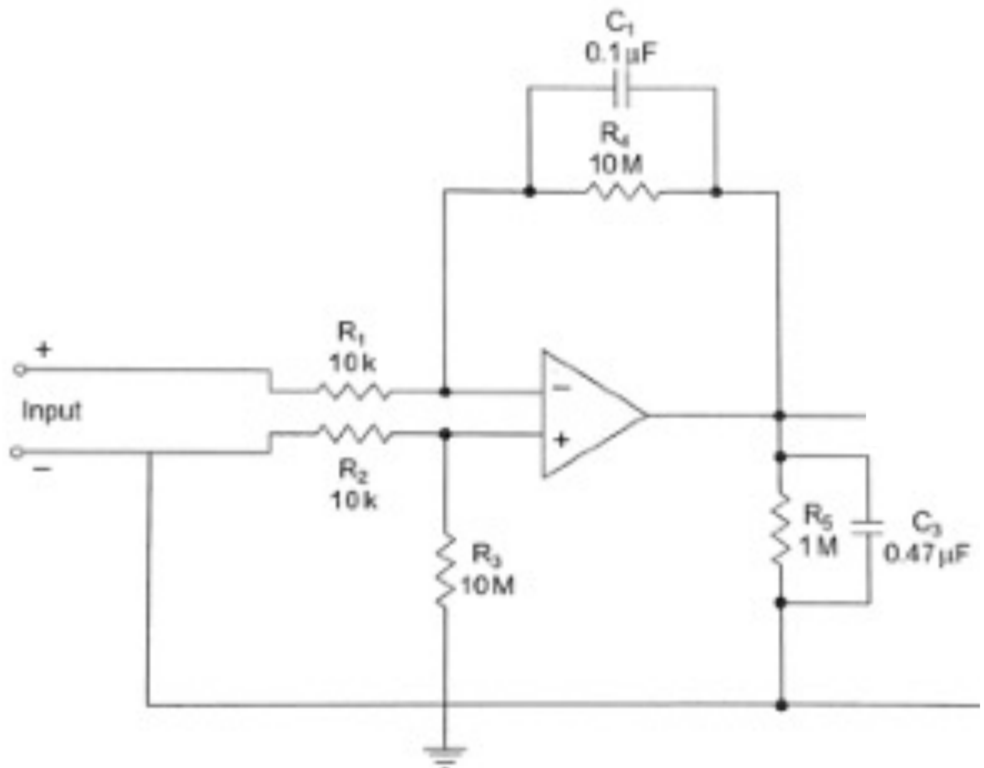
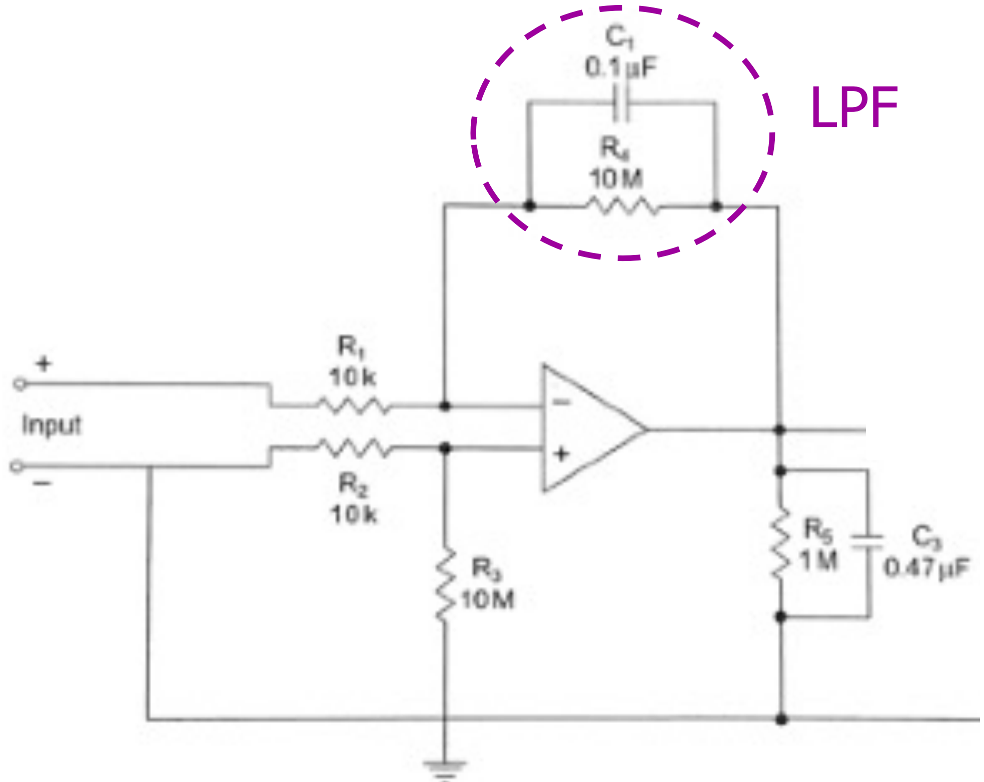


FIGURE 1.20

Differential biopotential amplifier.

Biopotential Amplifier

- Differential amplifier



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Biopotential Amplifier

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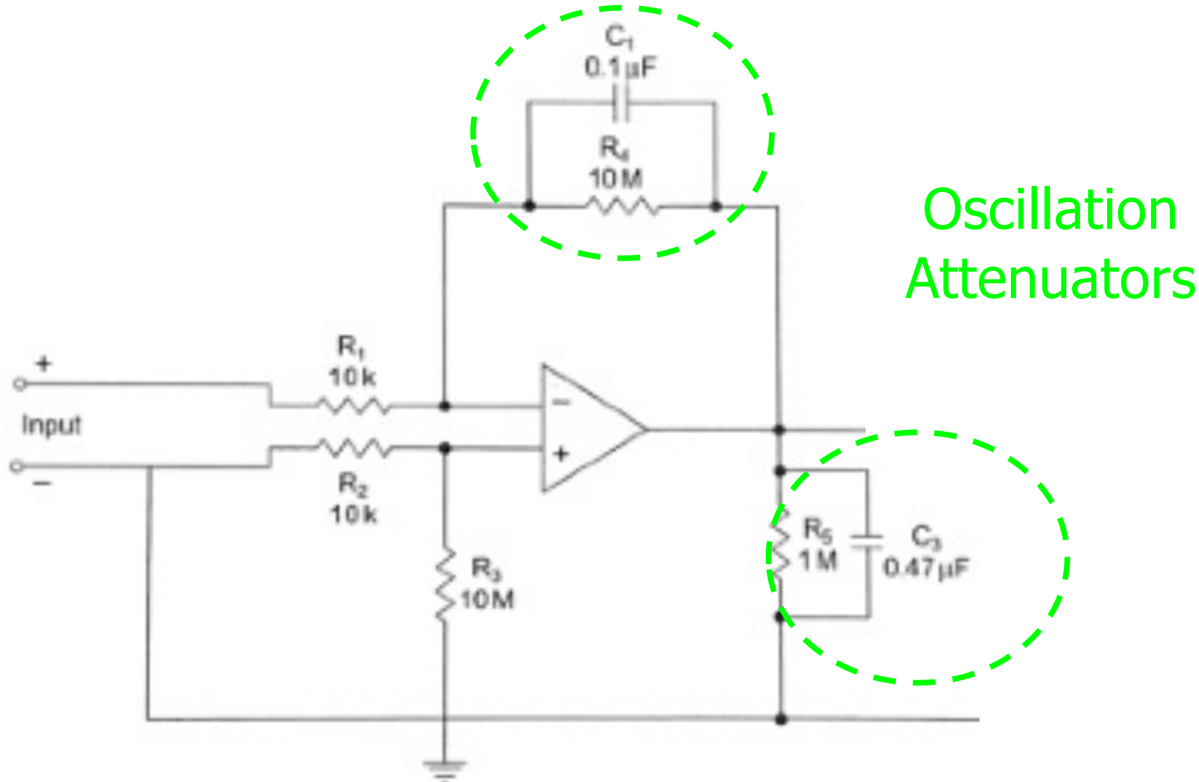


FIGURE 1.20

Differential biopotential amplifier.

Biopotential Amplifier

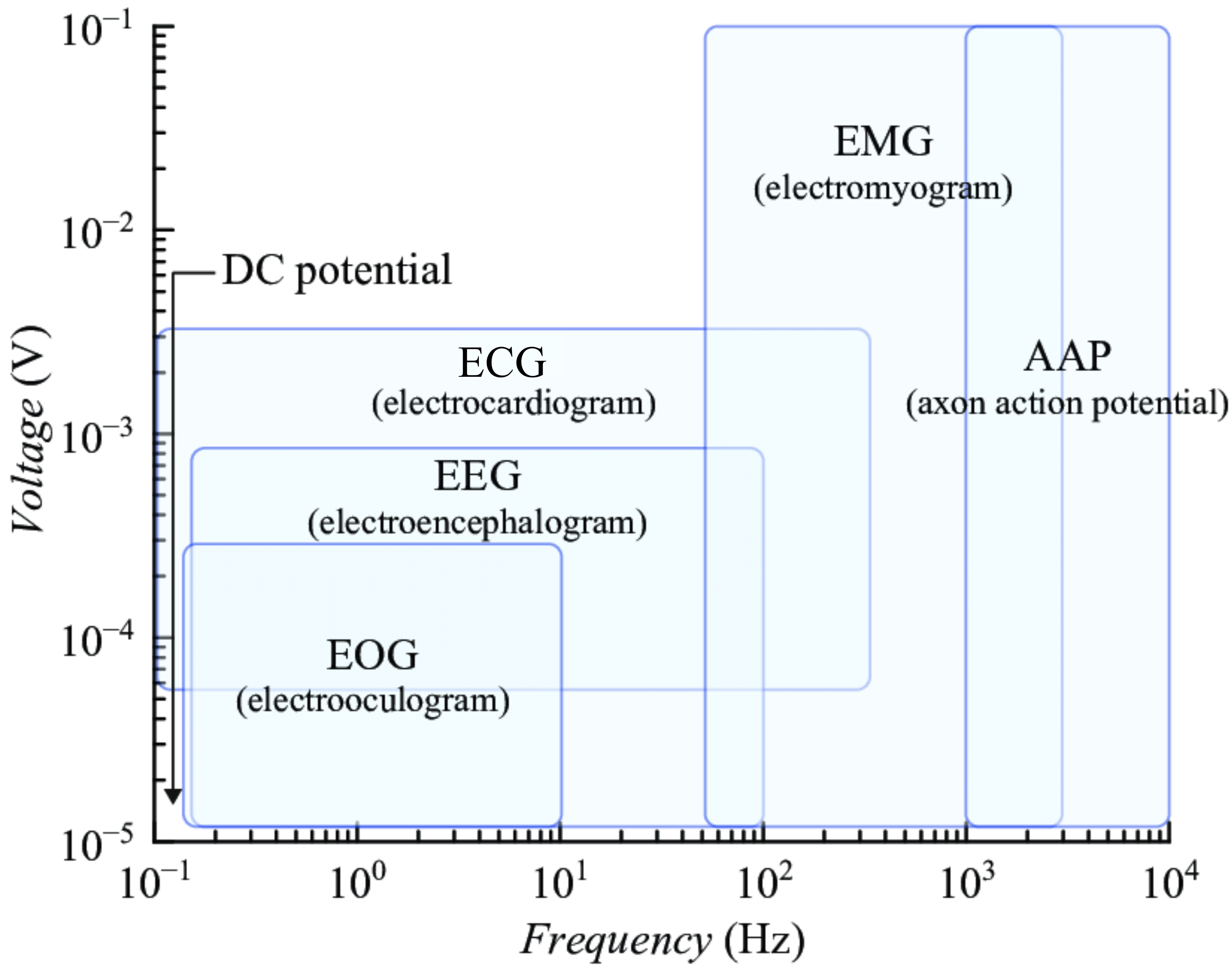
- Basic function to increase the amplitude of a weak electric signal of biological origin typically process voltages

- Typical bio-amp requirements
  - High input impedance greater than 10 MΩ
  - 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

Biopotential Amplifier

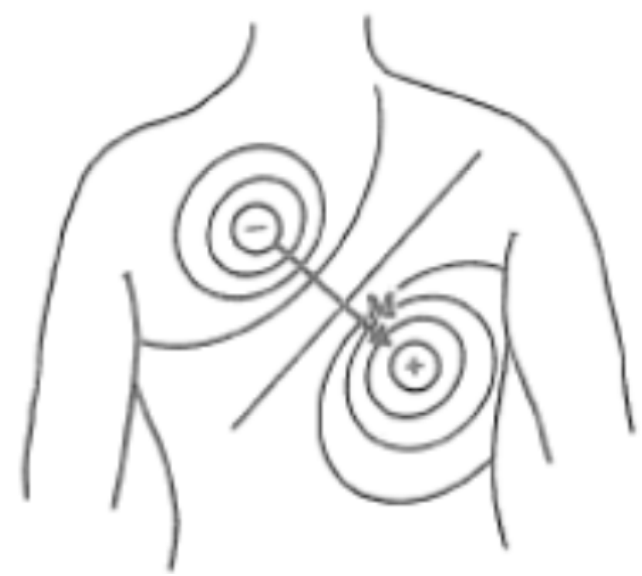
- Typical bio-amp requirements (con't)
  - Output impedance of the amplifier
    - should be low to drive any external load with minimal distortion
  - Gain greater than 1000
    - Biopotentials are typically less than a millivolt
  - Most are differential
  - High common mode rejection ratio
    - Biopotentials ride on a large offset signal
  - Rapid calibration of the amplifier in laboratory conditions
  - Adjustable gains
    - Often the change in scale is automatic

Voltage and Frequency Range



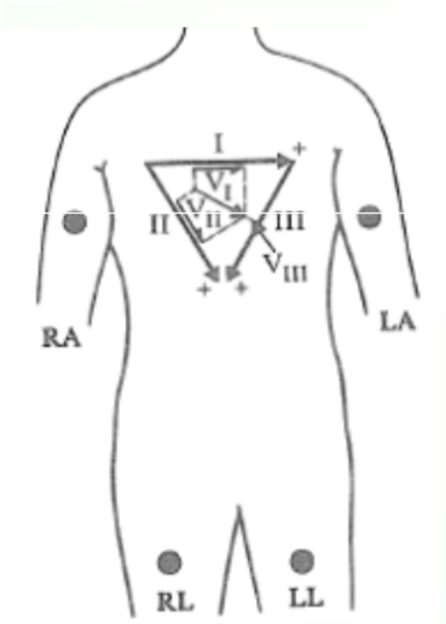
ECG Amplifiers

- 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



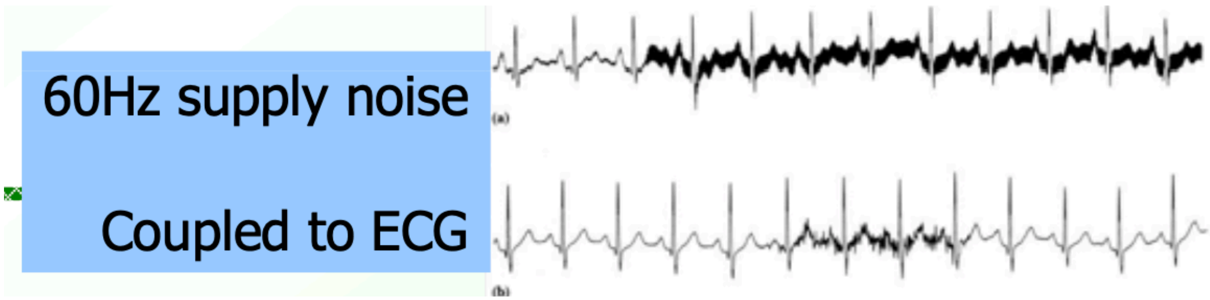
ECG Leads

- 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



Problems in ECG Measurement

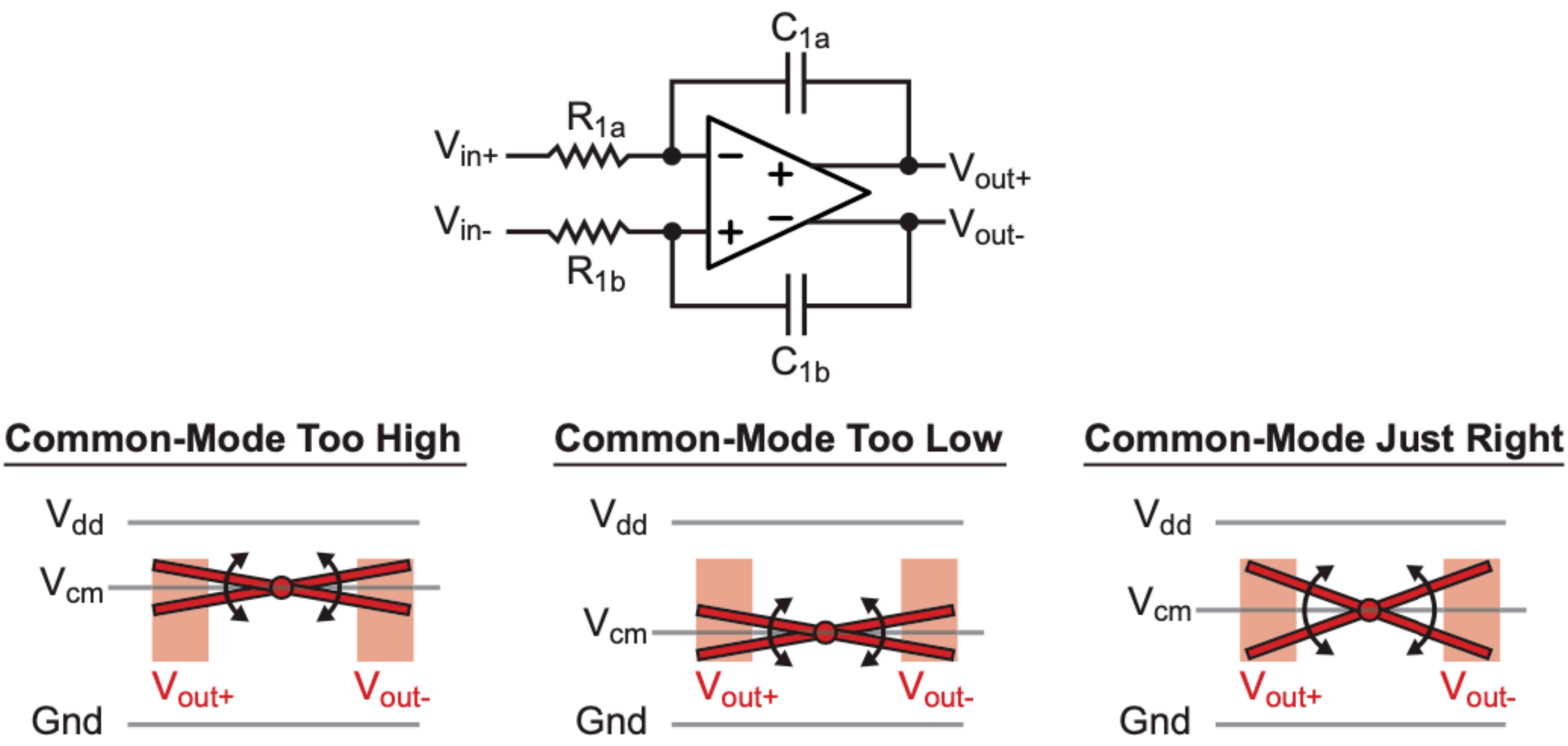
- Frequency distortion
  - If filter specification does not match the frequency content of biopotential then the results is high and low frequency distortion
- Saturation of cutoff distortion
  - High electrode offset voltage can drive the amplifier to saturation causing peaks of waveform (QRS) to be cut off
- Ground loops
  - Can cause small currents to flow through patient’s body
- Electric/magnetic field coupling
  - Open lead wires and long loops pick up EMI
- Interference from power lines (60Hz noise)



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 interference and measurement system
      - Very important for EEG measurement
    - Magnetic shield: Use high permeability materials (sheet steel)
    - Use twisted cables to reduce loops

Illustration of Common Mode Influence



Biopotential Amplifier

- Differential amplifier

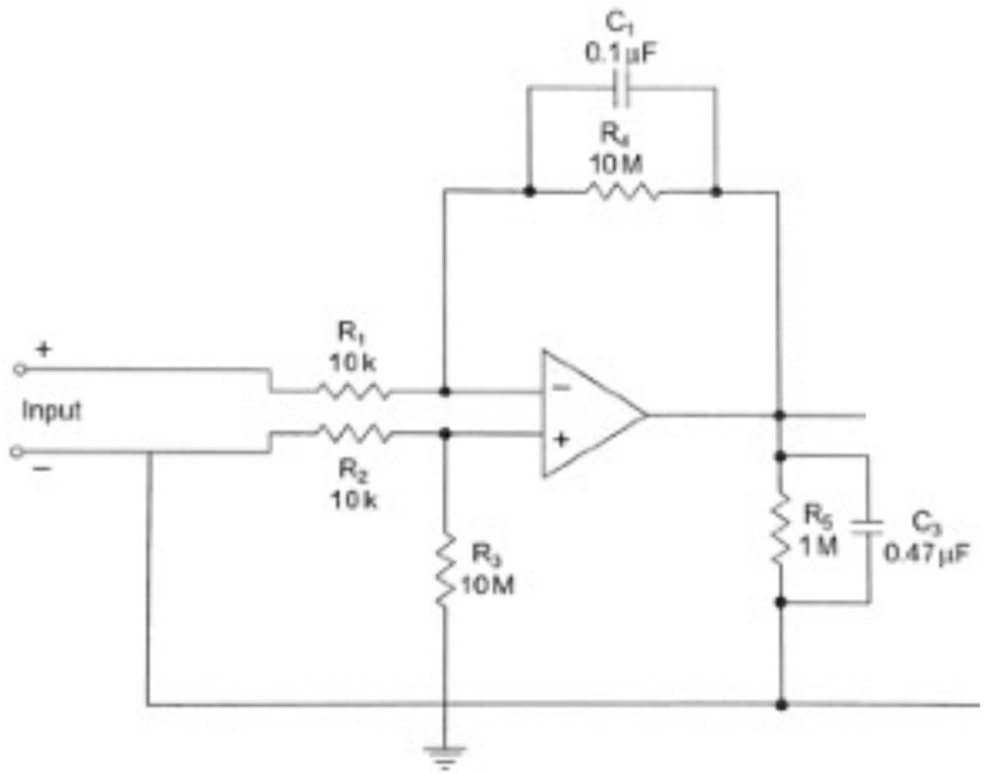
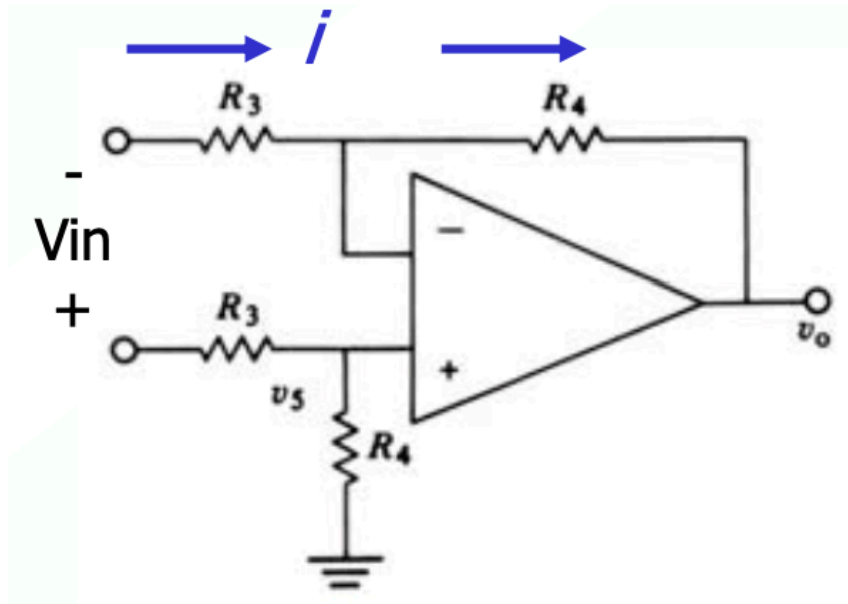


FIGURE 1.20

Differential biopotential amplifier.

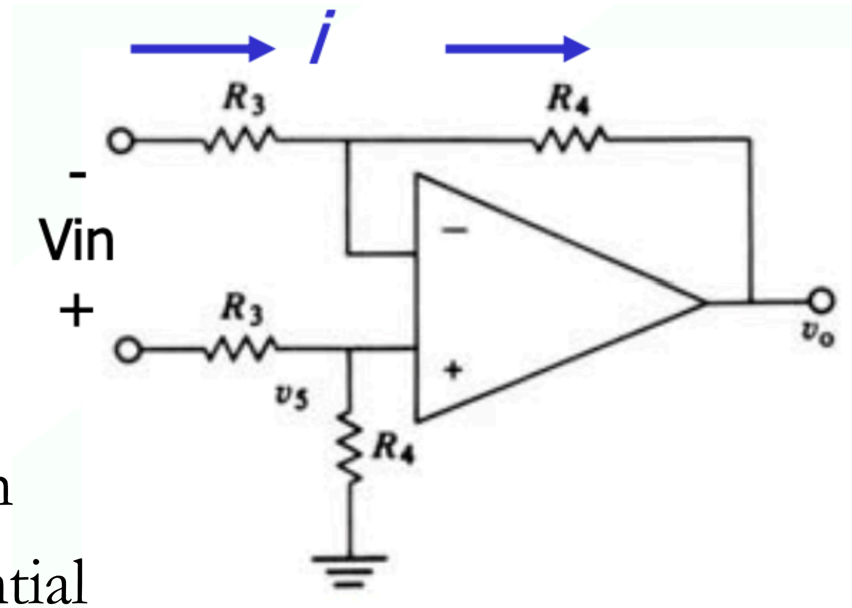
Differential Amplifier

- One-amp differential amplifier



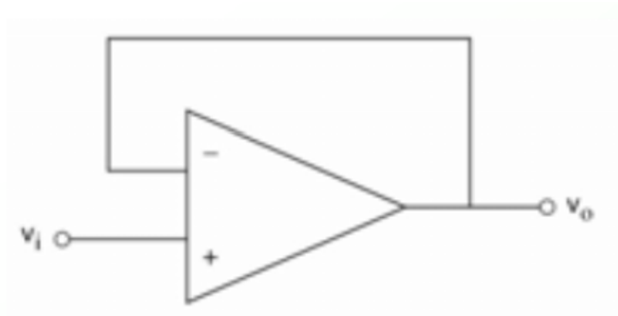
Differential Amplifier

- One-amp differential amplifier
- Differential gain:
  - $\frac{v_0}{v_i} = \frac{R_4}{R_3}$, where $R_4 \gg R_3$
- Characteristics
  - Good common mode rejection
  - Input resistance of the differential amplifier is lower than ideal op-amp
    - Not good for many biomedical applications



Differential Amplifier

- How can we fix the low input impedance?
- Option 1: Add voltage follower at each input
  - Pros and cons?



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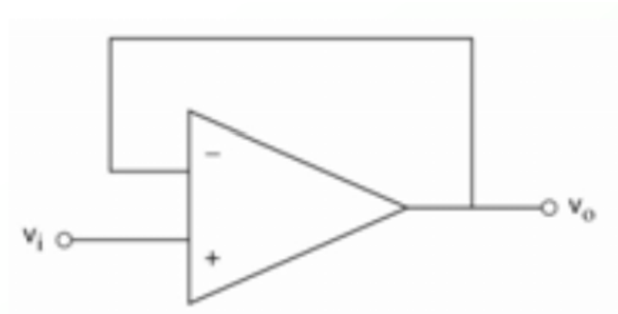
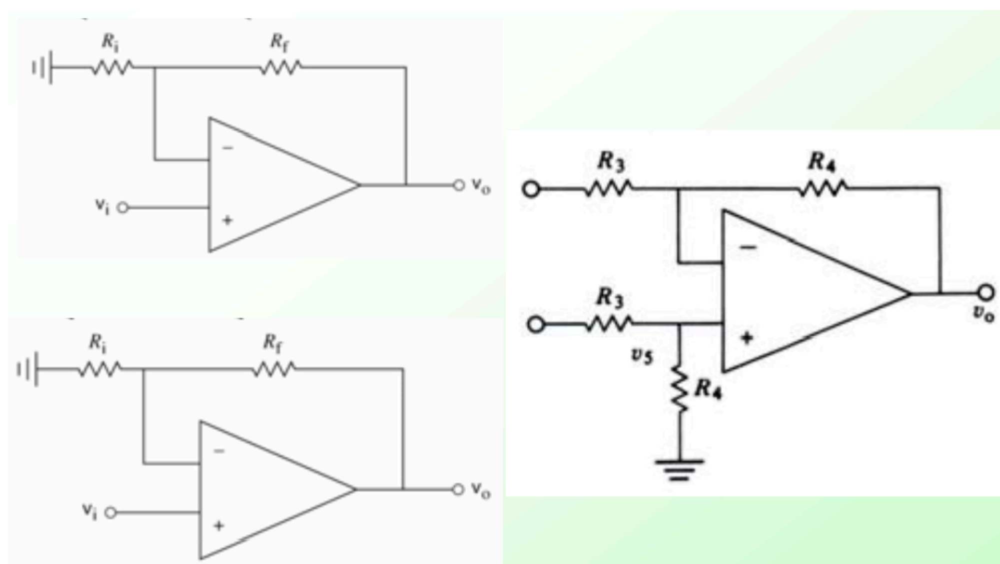
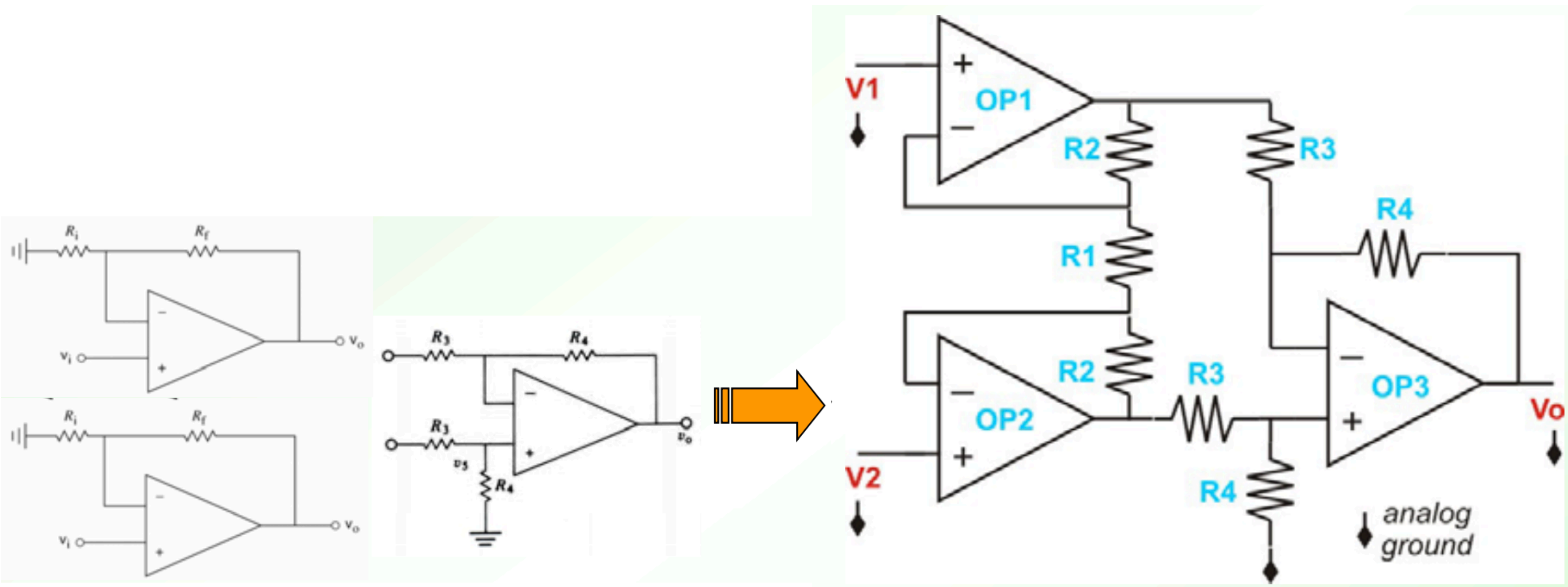


- Option 2: Add non-inverting amplifier at each input
  - Pros and cons?



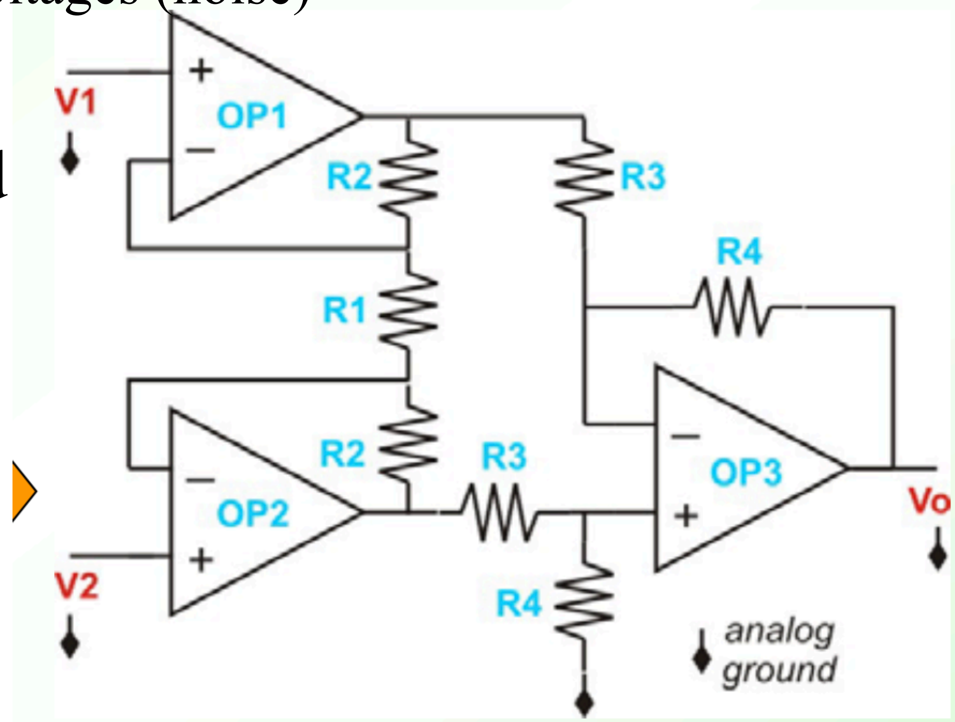
Instrumentation Amplifier

- Better option
  - Share R in input amps and eliminate ground connection

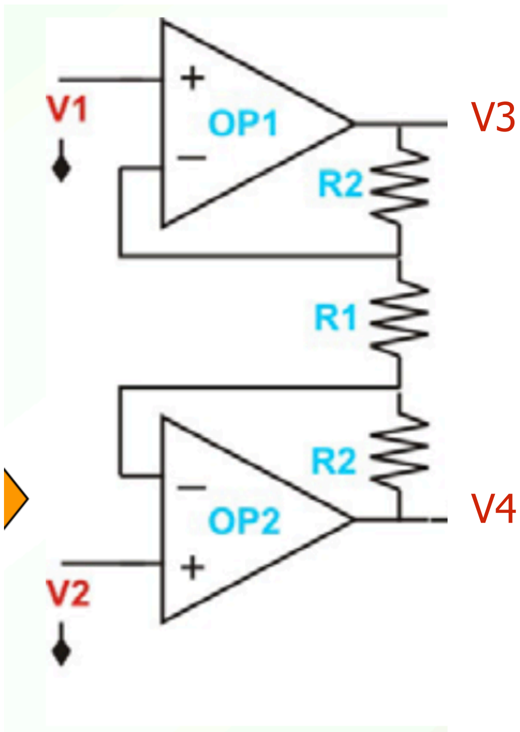


Instrumentation Amplifier

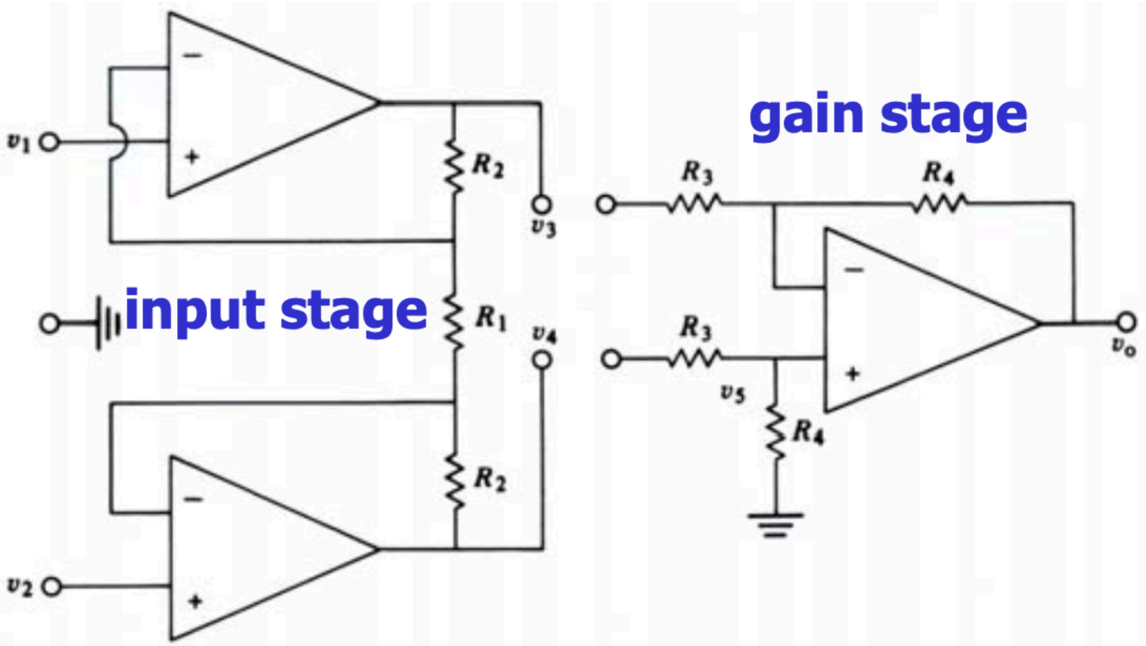
- This 3-op-amp circuit is called an **instrumentation amplifier**
- Input stage characteristics
  - low common-mode gain
    - -rejects common mode voltages (noise)
  - high input impedance
  - Input stage gain adjusted



Instrumentation Amplifier



Instrumentation Amplifier

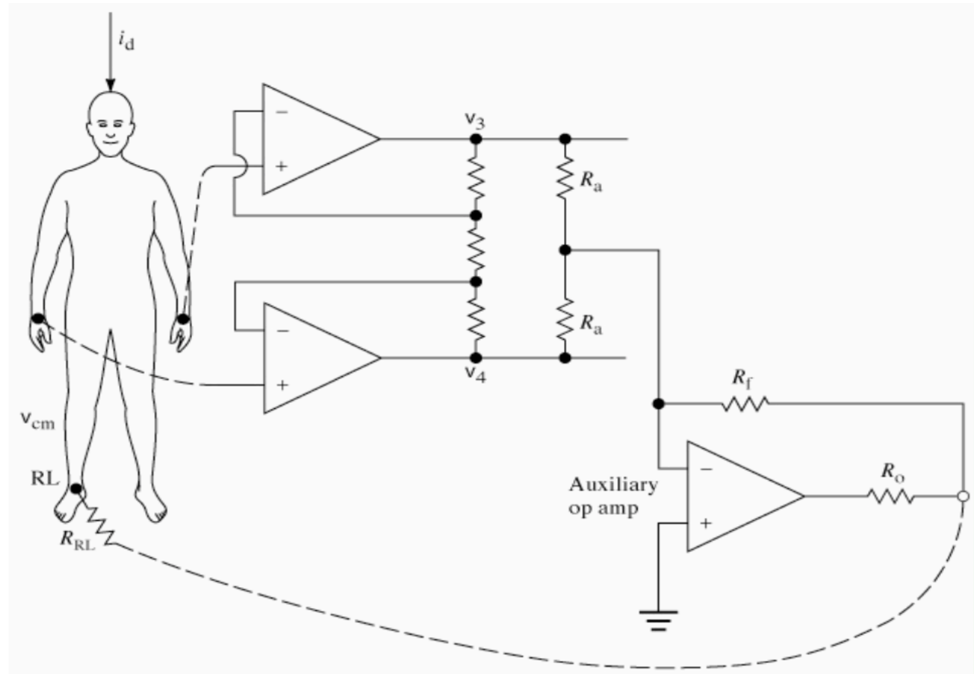


$$\frac{v_0}{v_i} = \left(\frac{2R_2 + R_1}{R_1}\right)\frac{R_4}{R_3}$$

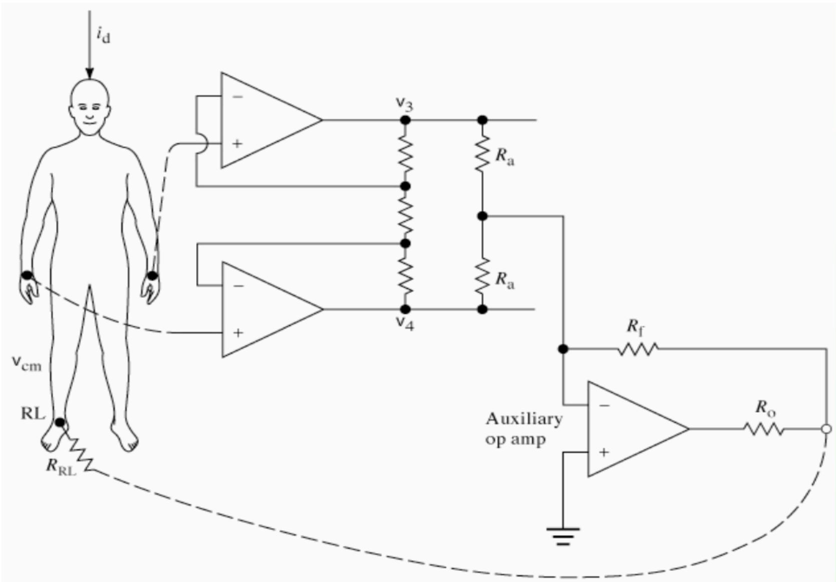
- Overall amplifier
  - Amplifies only the differential component
    - High common mode rejection ratio
  - High input impedance suitable for biopotential electrodes

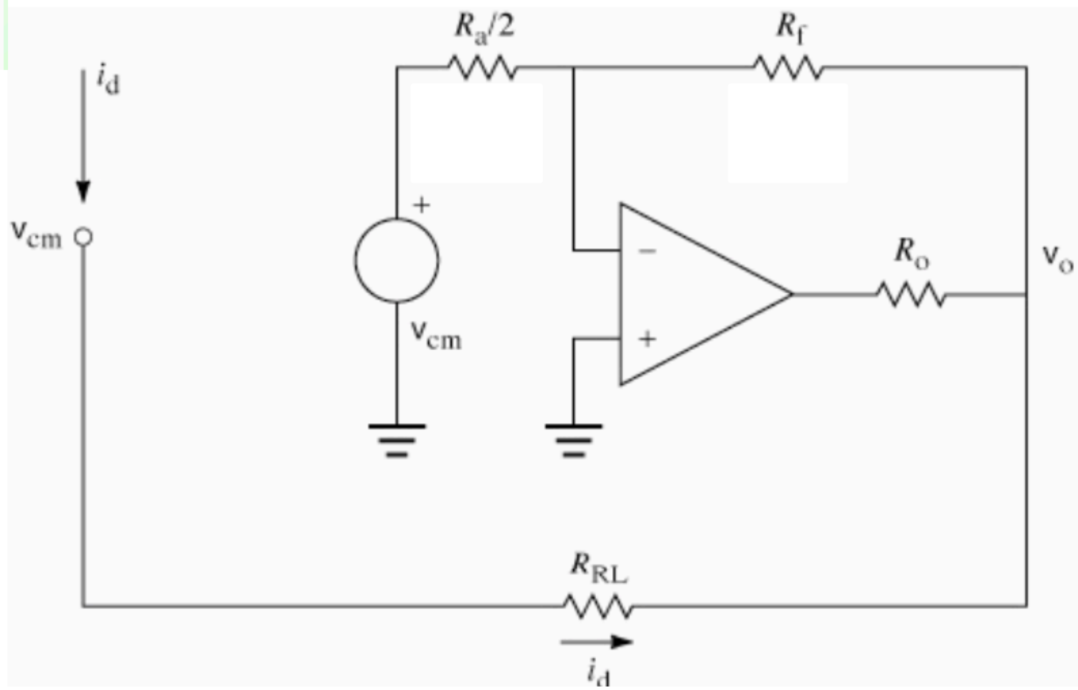
Driven Right Leg System

- 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



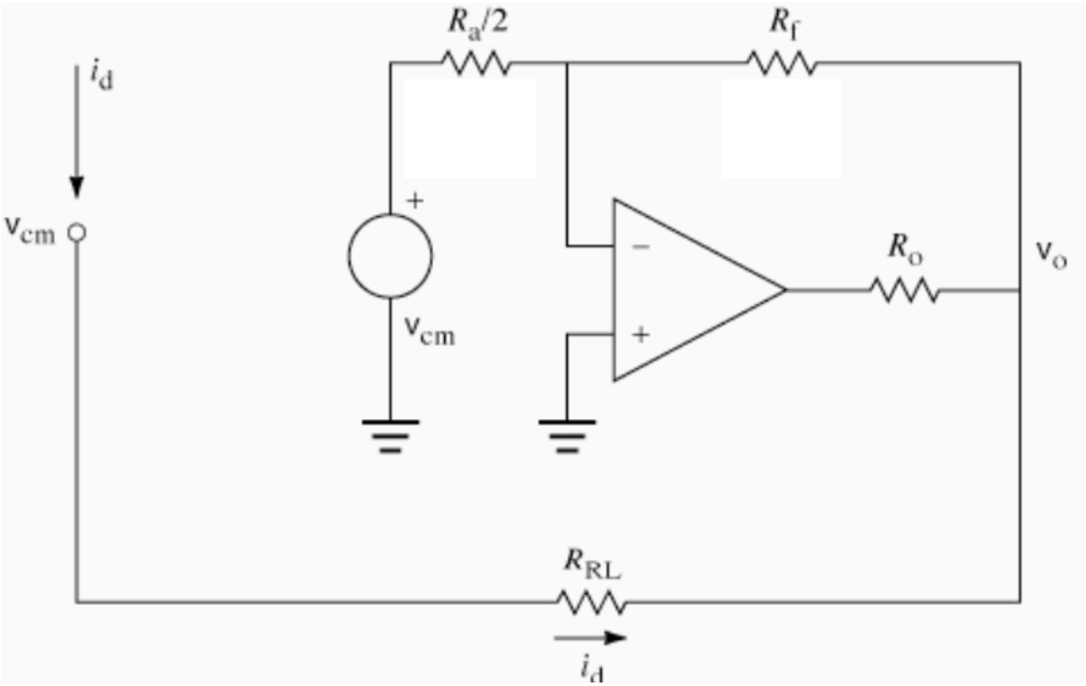
Driven Right Leg System Example





Driven Right Leg System Example

- **Problem**: Determine the common-mode voltage v_{cm} on the patient in the driven-right-leg circuit 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. With a worst-case electrode resistance of 100k**Ω**, what is the v_{cm} when $i_d = 0.2uA$?



Big Ideas

- Amplification
  - Use operational amplifier with differential signaling
- Biopotential Amplifier
  - Designed to amplify and filter sensor outputs for data acquisition or driving
- Instrumental Amplifier
  - Designed specifically for biopotential signals to compensate for non-idealities
  - Common-mode voltages responsible for much of the interference in biopotential amplifiers

Admin

- Finish Lab 2 and submit deliverables in Canvas by next lab day at midnight
- Lab 3 on Monday

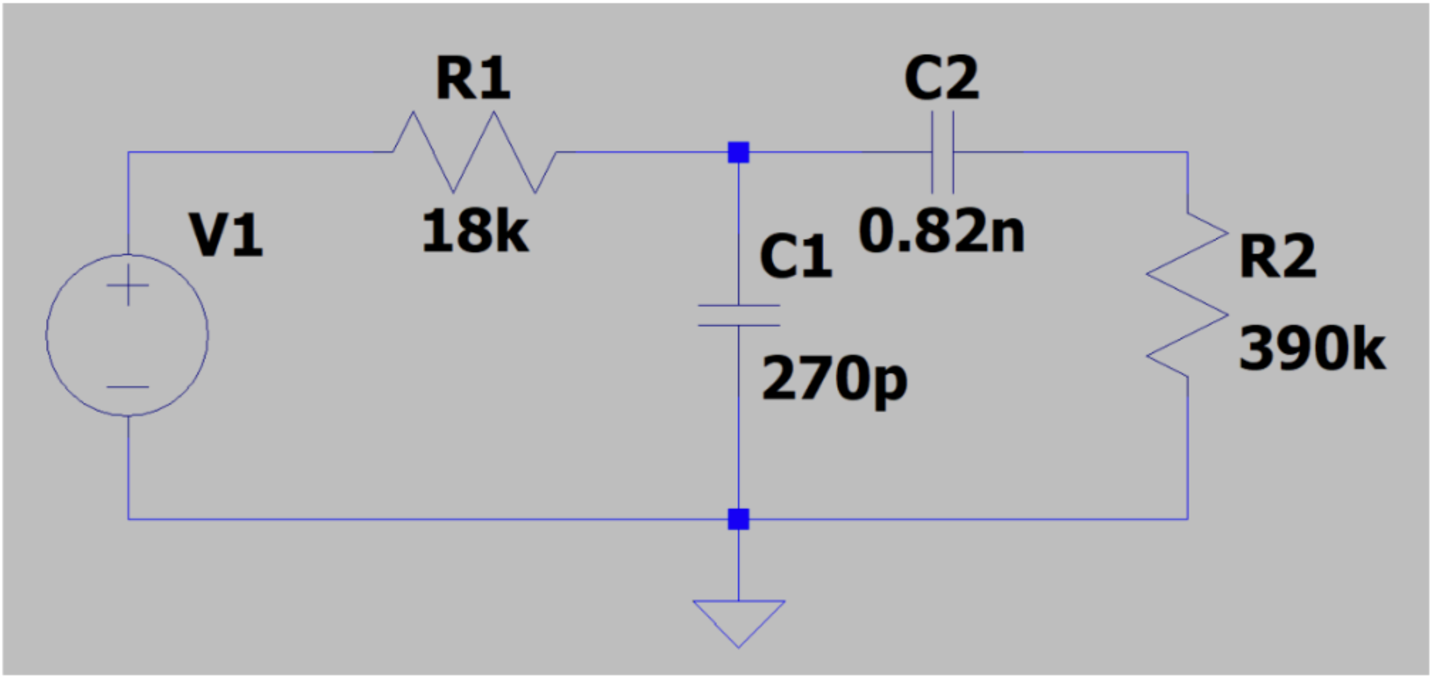
Lab 3

- LT Spice
- Simulate the signal conditioning specific to our ECG design

LT Spice

- Circuit Simulator
  - LTspice is high performance SPICE simulator software, including a graphical schematic capture interface. Schematics can be probed to produce simulation results—easily explored through LTspice's built-in waveform viewer.

LT Spice BP Filter Example



Lab 3

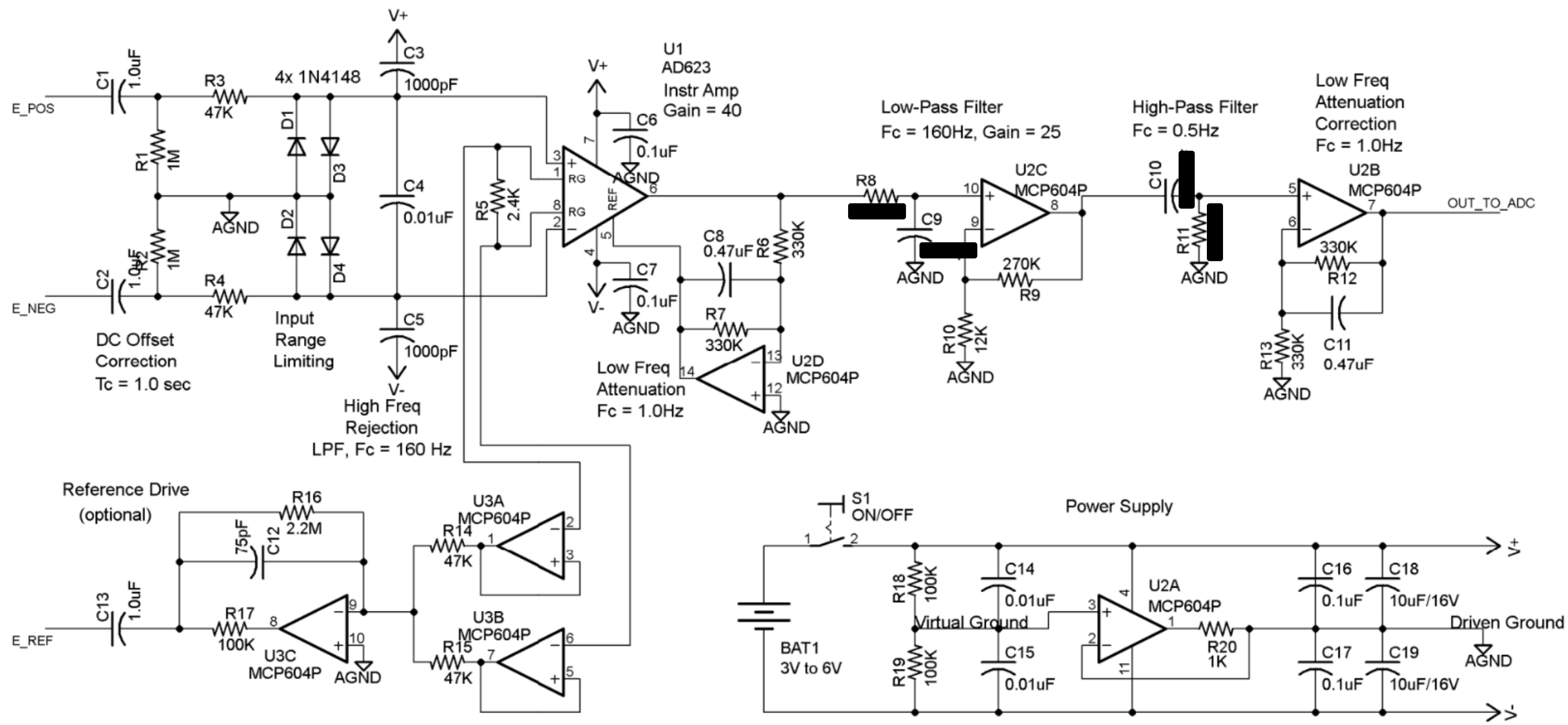
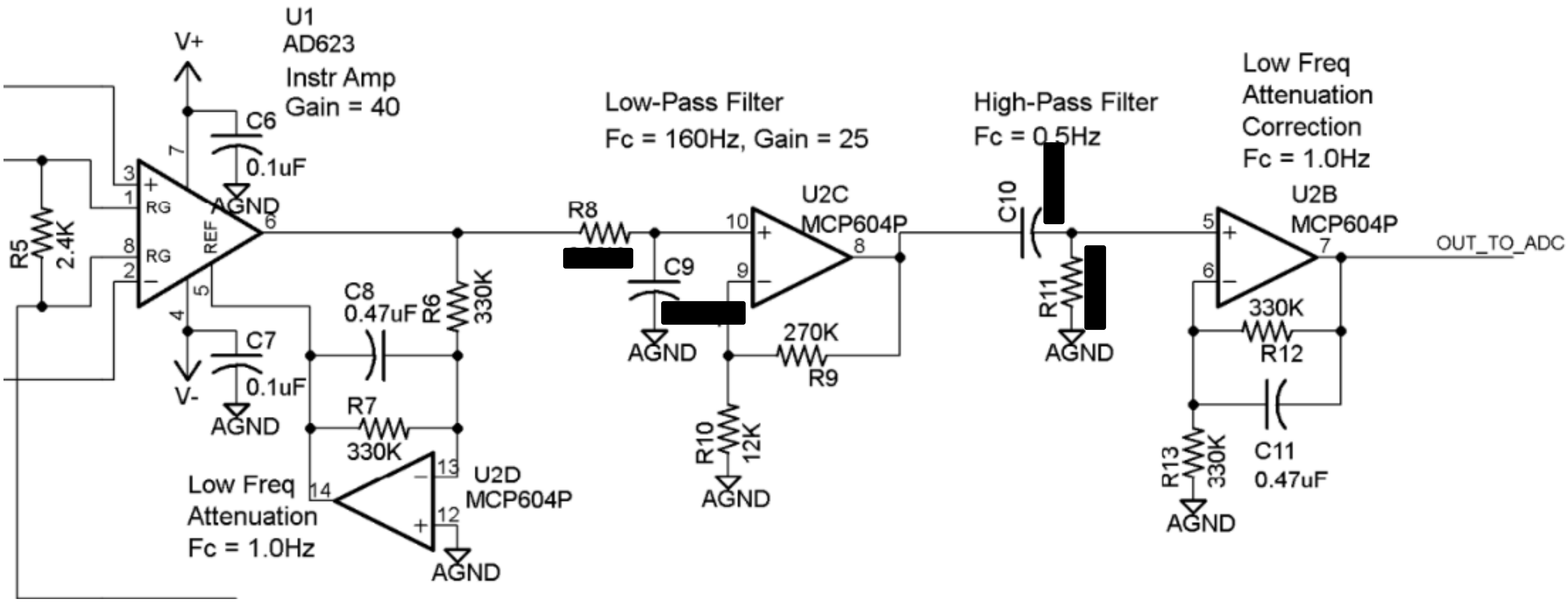


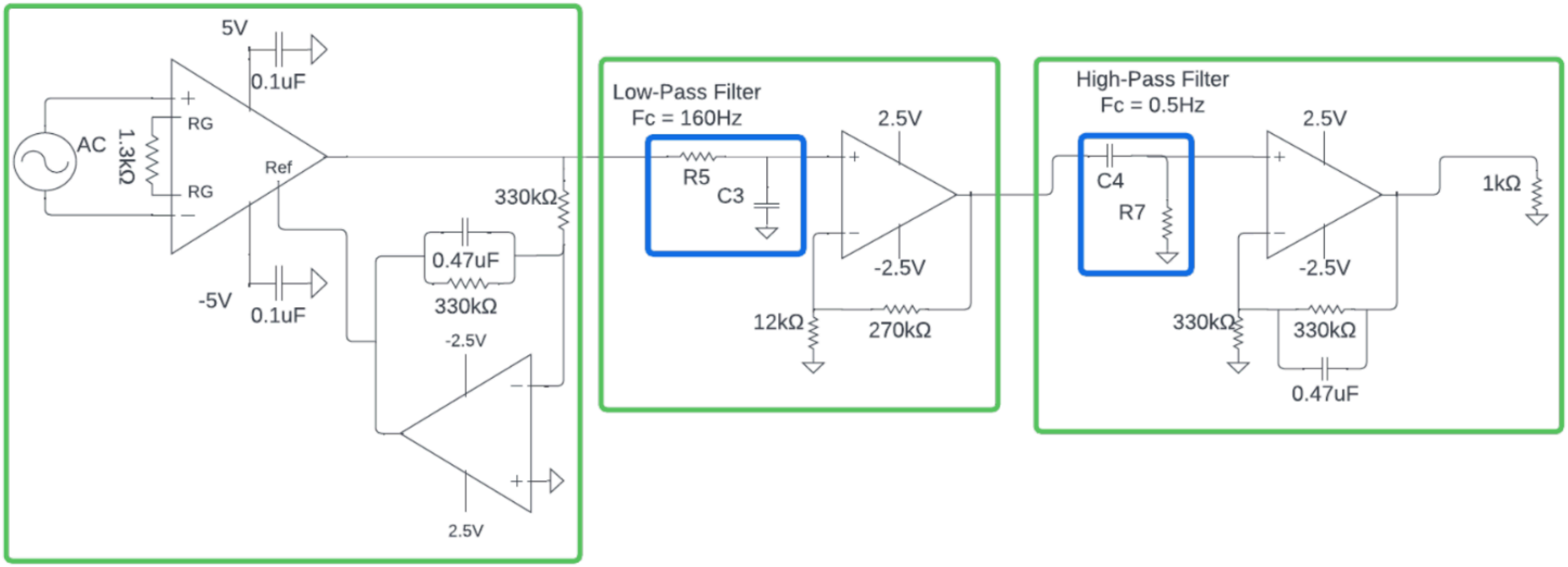
Figure 2: Schematic of 2-Electrode ECG Amplifier with Optional Driven Reference Electrode

Lab 3



U1
AD623
Instr Amp
Gain = 40
V+
C6
0.1uF
AGND
R5
2.4K
RG
RG
REF
C7
0.1uF
V-
AGND
C8
0.47uF
R6
330K
R7
330K
U2D
MCP604P
Low Freq
Attenuation
Fc = 1.0Hz
AGND
Low-Pass Filter
Fc = 160Hz, Gain = 25
R8
C9
AGND
U2C
MCP604P
270K
R9
R10
12K
AGND
High-Pass Filter
Fc = 0.5Hz
C10
R11
AGND
Low Freq
Attenuation
Correction
Fc = 1.0Hz
U2B
MCP604P
OUT_TO_ADC
330K
R12
C11
0.47uF
R13
330K
AGND

Lab 3



5V
0.1uF
AC
1.3kΩ
RG
RG
Ref
-5V
0.1uF
330kΩ
0.47uF
330kΩ
-2.5V
2.5V
Low-Pass Filter
Fc = 160Hz
R5
C3
2.5V
-2.5V
12kΩ
270kΩ
High-Pass Filter
Fc = 0.5Hz
C4
R7
2.5V
-2.5V
1kΩ
330kΩ
330kΩ
0.47uF