Electrocardiogram Amplifier Design Using Basic Electronic Parts

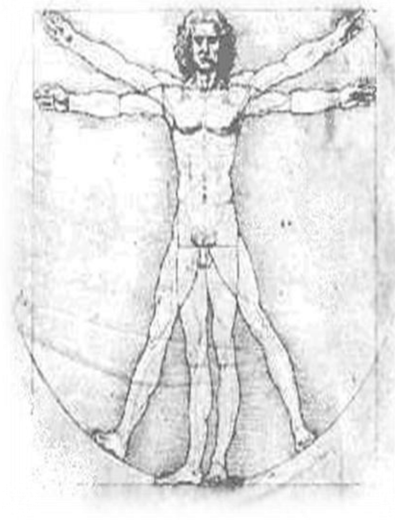
Background Lecture

Outline of Discussion

- Project scope: What are you going to do?
- Background: What is ECG?
  - Clinical relevance and importance
  - Technical challenges in measuring this signal
- Project description: How will you do the project?
  - Overview of project stages
  - Technical principles related to each stage
- Conclusion: What are the learning outcomes?

Project Scope

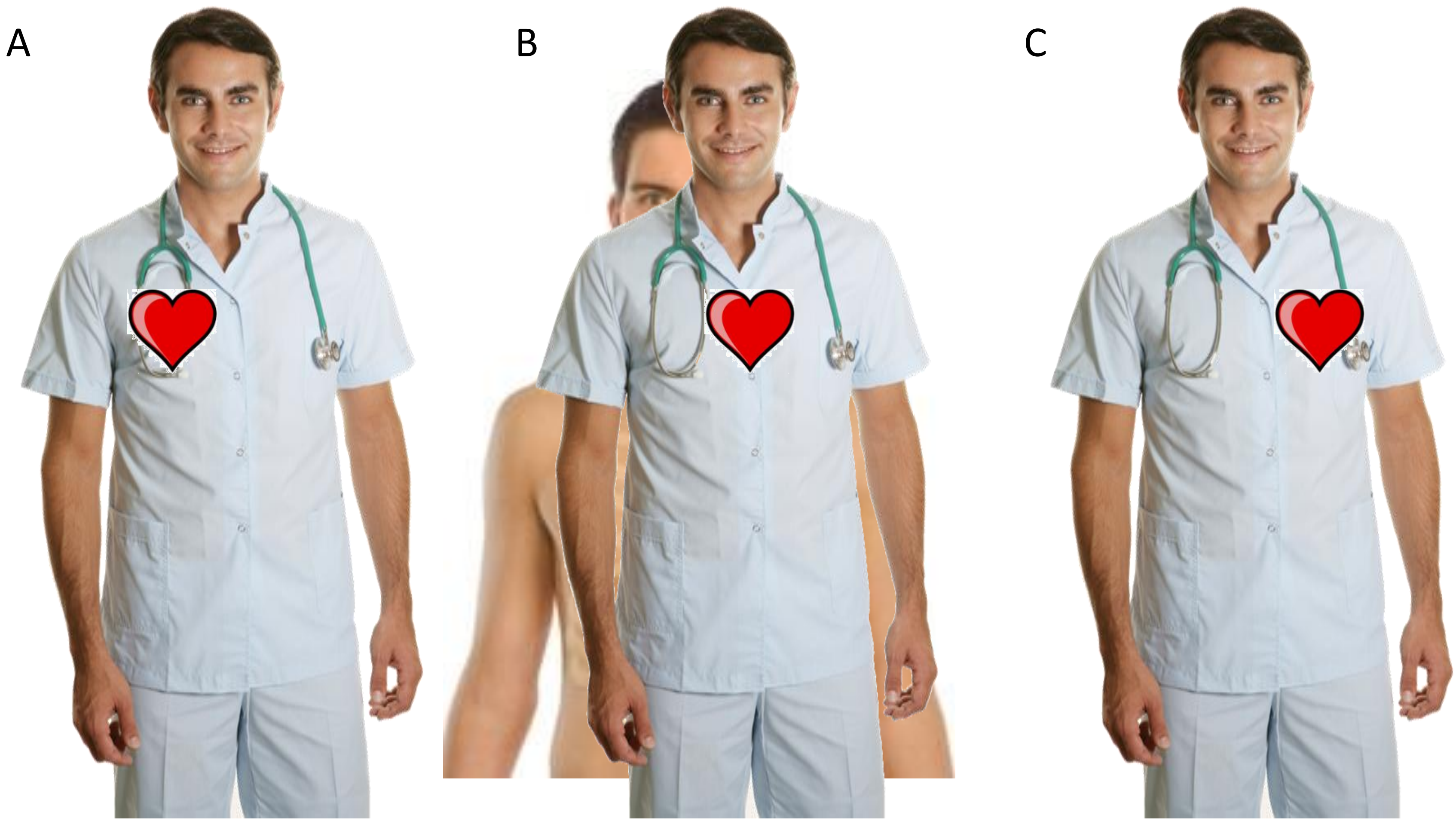
Overview of Project



- Topic: Biomedical circuits
  - Interdisciplinary in nature
  - Involve technical concepts in three areas:
    1) Electric circuits
    2) Biomedical instrumentation
    3) Human physiology
- Project aim: Develop an ECG amplifier circuit **from scratch**
  - Learn about technical details behind bio-potential measurement devices
  - Help build your interest in BME or EE!

Background Overview of ECG

Background: Where is your heart?



Background: Heart Diseases

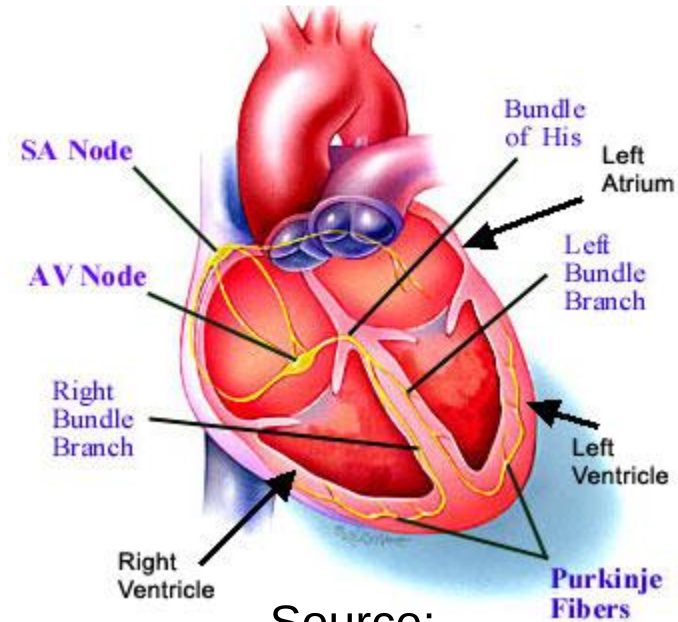
- Statistics from World Health Organization (2005)
  - Heart disease kills one person in every 5 seconds
  - 7.6 millions of death worldwide each year
- Common types of heart problems
  - Heart rhythm disorder: Irregular beats
  - Coronary heart disease: Cannot supply adequate circulation to cardiac muscle cells
  - Tachycardia: Heart beats very fast even whilst at rest

** **Electrocardiogram (ECG) Monitoring** **

One common way to help diagnose for heart diseases

Basic Principles of ECG

- Physiological origin: Sequential electrical activation of cardiac cells
  - Electrical excitation propagates from top to bottom of heart
  - Starting point: sinoatrial node (at top of heart)
  - End point: ventricular muscles

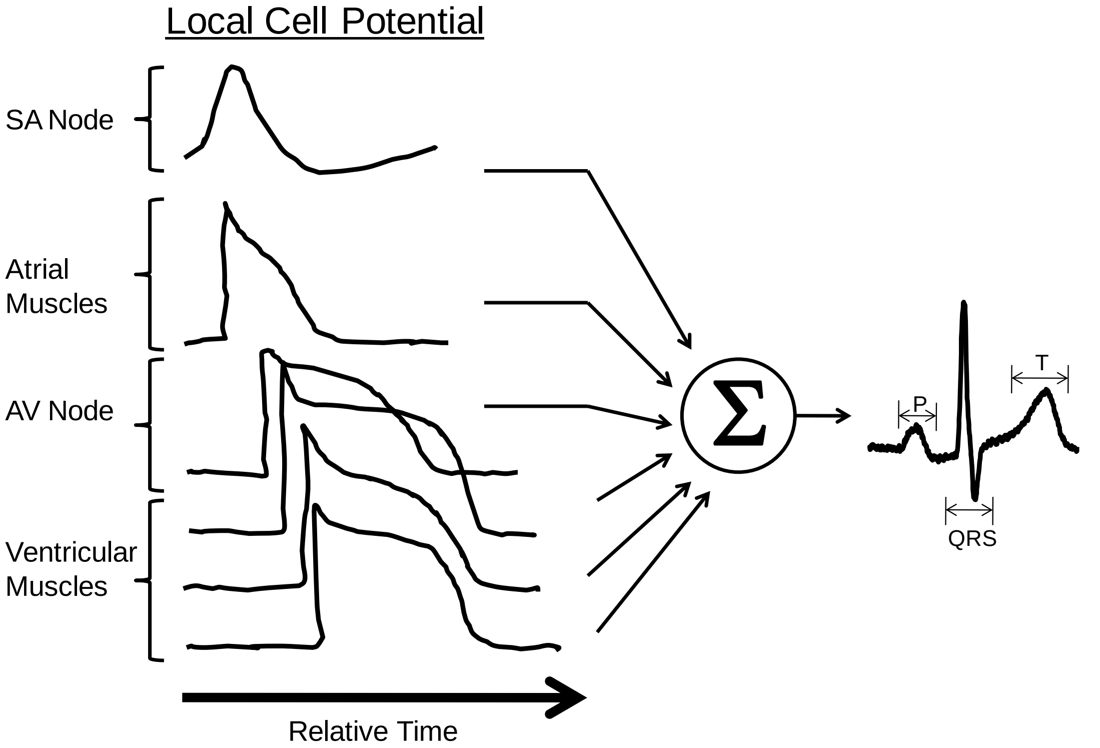


Source: www.healthsystem.virginia.edu

- Responsible for triggering cardiac contraction
  - Activation does not rely on brain signals → Heart can operate on its own

ECG: A Time-Varying Signal

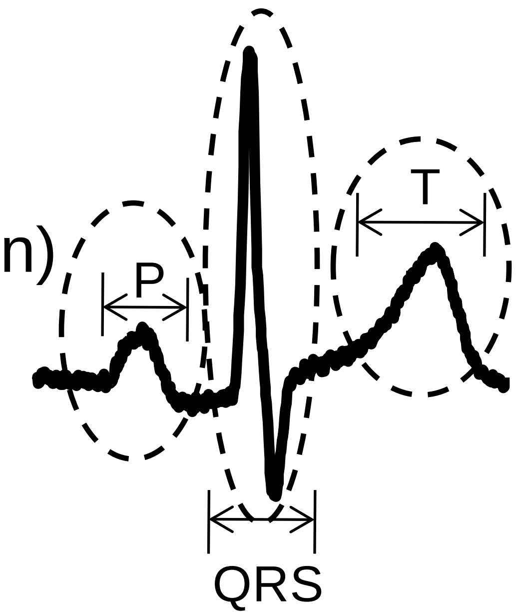
- Heart can be viewed as a time-varying voltage source
  - Net voltage amplitude = Sum of cardiac cell potentials
  - Voltage vary periodically based on cardiac cycle



ECG Waveform Characteristics

- Waveform usually contains three distinct segments

P wave
(atrial excitation)

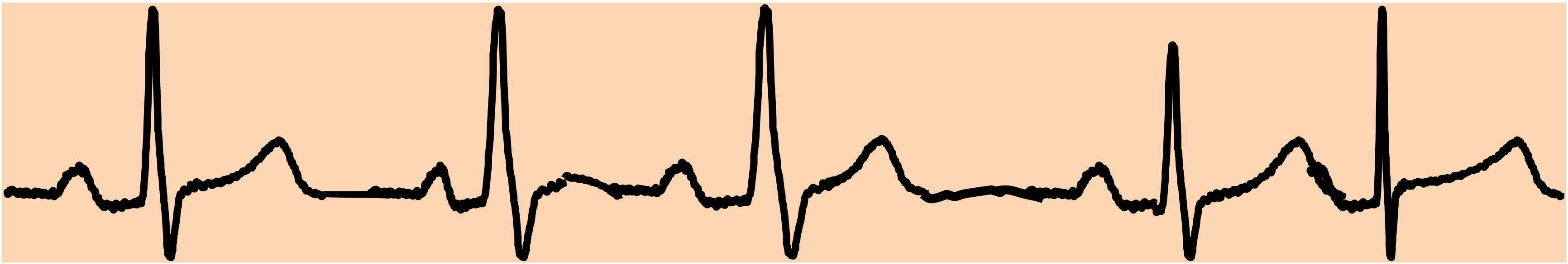


T wave
(ventricular recovery)

QRS complex
(ventricular excitation + atrial recovery)

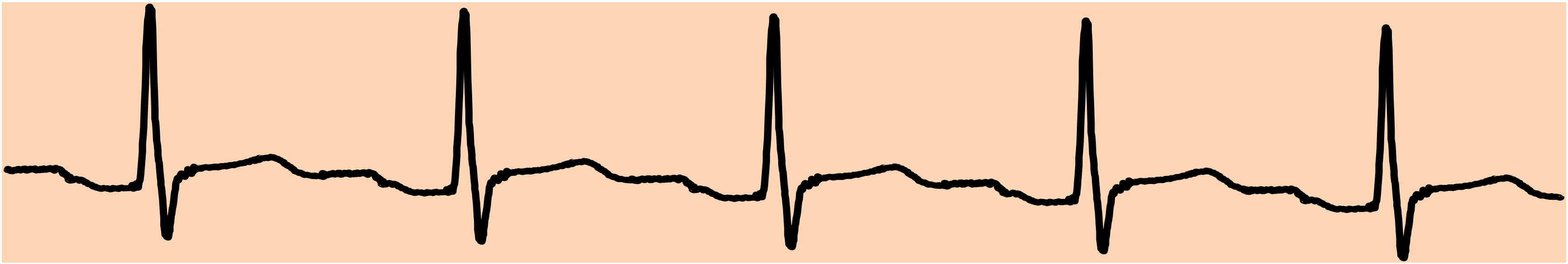
Clinical Importance of ECG

- Can provide critical insights on potential abnormalities in the subject's heart functioning
  - Commonly used as a first line of monitoring for cardiac problems
- <u>Example #1</u>: Heart rhythm disorder
  - Technically known as arrhythmia
  - Give rise to aperiodic ECG waveforms

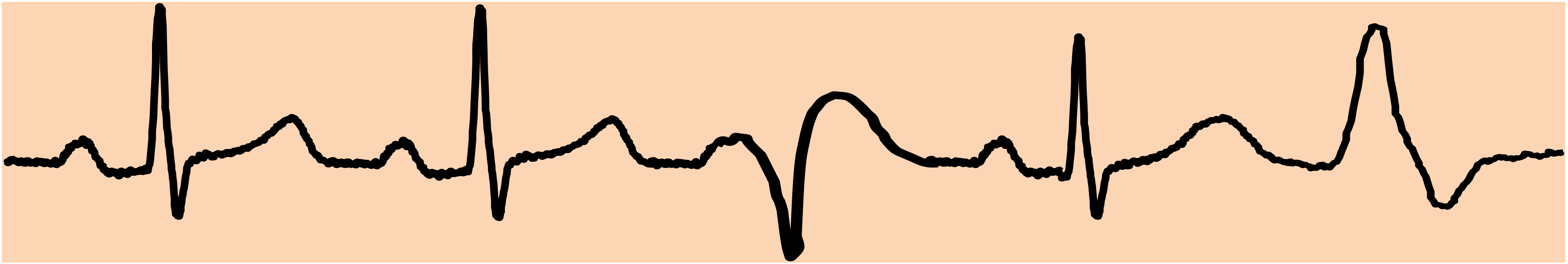


Clinical Importance of ECG

- Example #2: Atrial fibrillation
  - Missing P waves due to asynchronized excitation of atrial cardiac cells

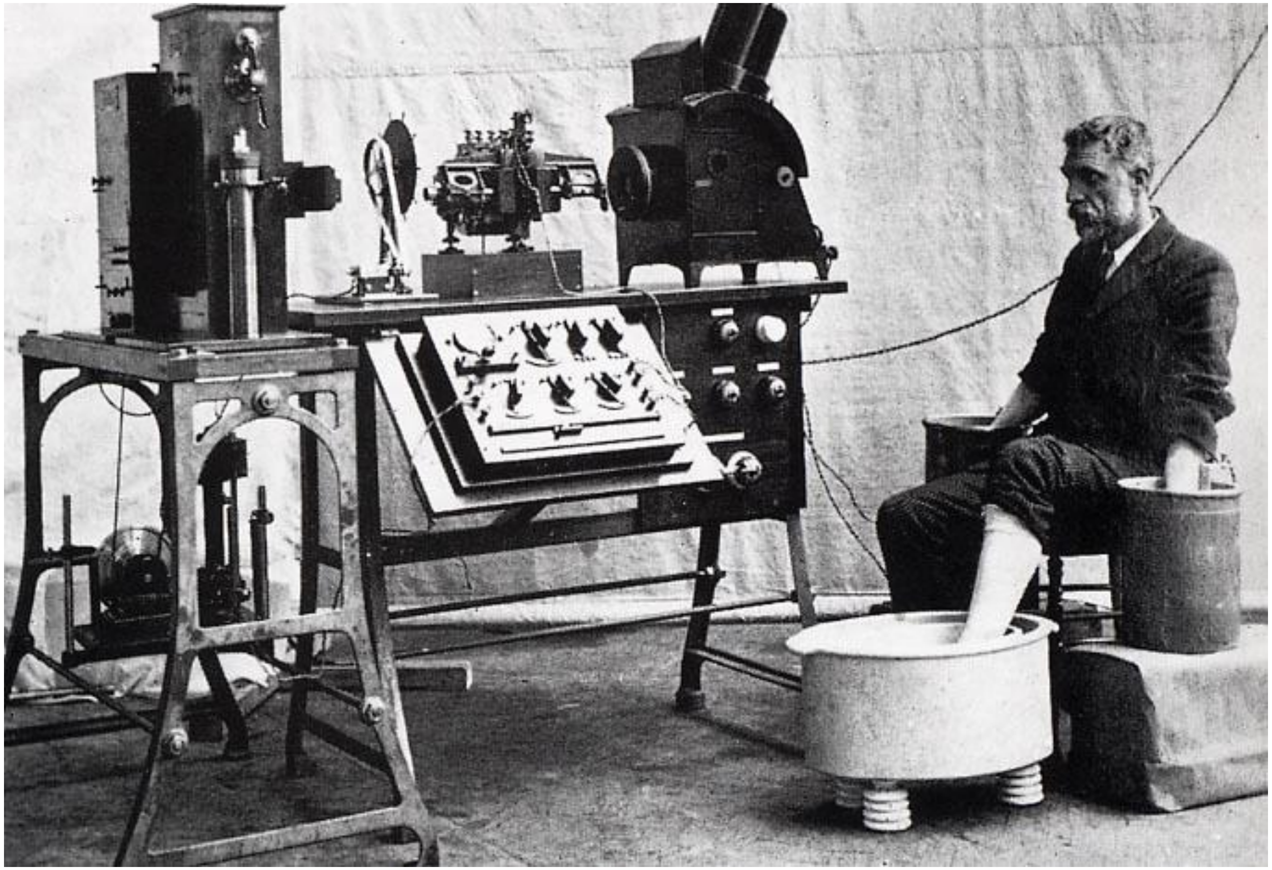


- Example #3: Premature ventricular contraction
  - Sudden broad change in the QRS complex shape



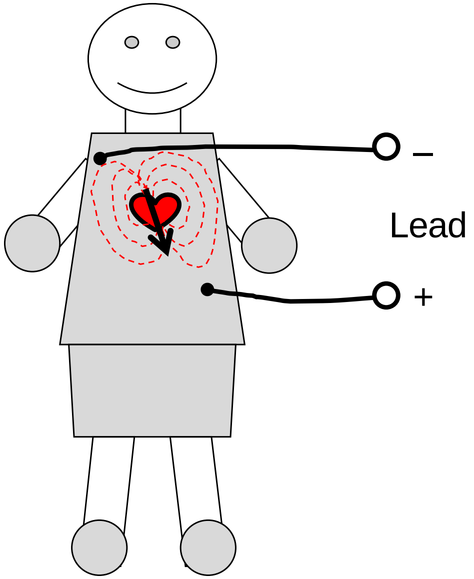
How to measure ECG?

Back in the old days…



ECG Measurements: Basic Principles

- General approach: Place electrodes at multiple places on the body surface
  - Measure potential difference across a lead (i.e. a pair of electrodes)
  - Exploit the fact that body tissue is a conductive medium that can relay cardiac potentials



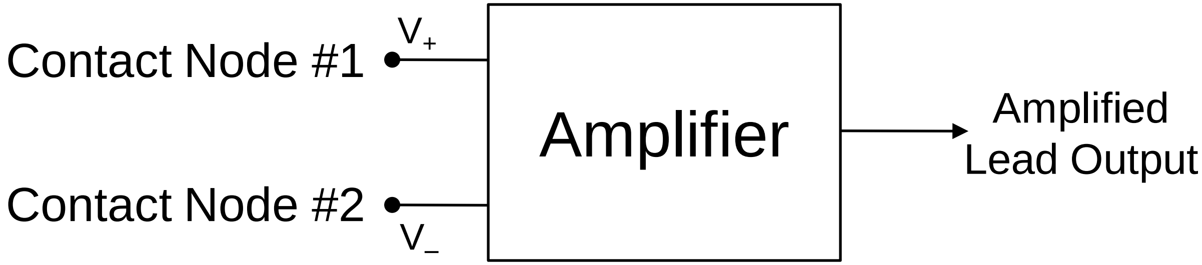
- Commonly used electrodes: Metal disk surrounded by an adhesive foam pad
  - Can self-attach to subject during operation

Project Description

Challenge in ECG Measurements

- Raw ECG signals often low in amplitude and distorted by noise sources
  - Magnitude range: 0.1 to 5 mV
  - Examples of interference sources: 1) muscle contractions, 2) power-line radiations
- Problem with having poor signal quality: Hard to obtain physiological insights
  - Low signal level → Difficult to detect
  - High noise level → May mask out useful clinical info

General Solution: Amplification Circuit



- Aim: To boost the raw ECG signal level
  - Preferably without boosting the noise at the same time
- Approach: Amplify only the potential difference across two contact points
  - Theoretically allows only AC signals to be amplified

<u>**** This is what you will do in this project!! ****</u>

What you will do in this project…

- Objective: Prototype an electronic circuit to amplify the potential difference across a lead
  - Circuit built on a breadboard
  - Use only basic circuit components like op-amp chips, resistors, and capacitors
  - Testing conducted using an ECG signal simulator (MCI-430, MediCal Instruments)
- Time required: 12-15 hours
- Work in teams of at most three people

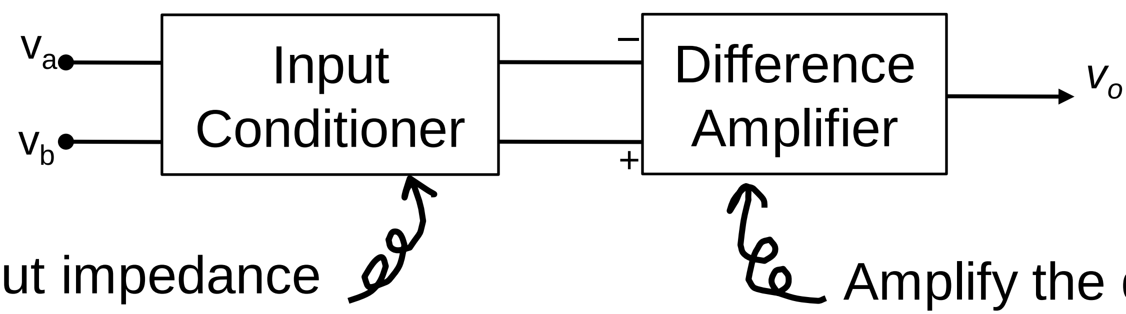
Project Structure

- Stage #1: Instrumentation amplifier design
  - Develop an amplifier with a gain large enough to boost raw ECG signals
  - Account for common-mode noise
- Stage #2: Power source reduction
  - Fine-tune ECG amplifier circuit by using only one 9V battery to drive it
  - Involve creating a virtual circuit ground
- Stage #3: Multi-lead ECG measurements
  - Use the completed amplifier to estimate direction of ECG propagation in the simulator
  - Involve measuring ECG from 12 different leads

Stage #1: Instrumentation Amplifier

Stage #1: Technical Description

- Aim: Design a circuit that only amplifies the differential voltage
  - Common-mode voltage level remains unchanged
- Method: Build an instrumentation amplifier
  - Circuit structure involves two main stages



Ensure input impedance approach infinity, and apply a gain

Amplify the difference of the conditioned input signal

Main Design Considerations

1) Amplifier gain
   – How much amplification is needed given that raw ECG signal is between 0.1 to 5 mV?
2) Circuit noise level
   – How can we reduce power-line interference?
3) Power consumption
   – Can we save power and extend the battery life?

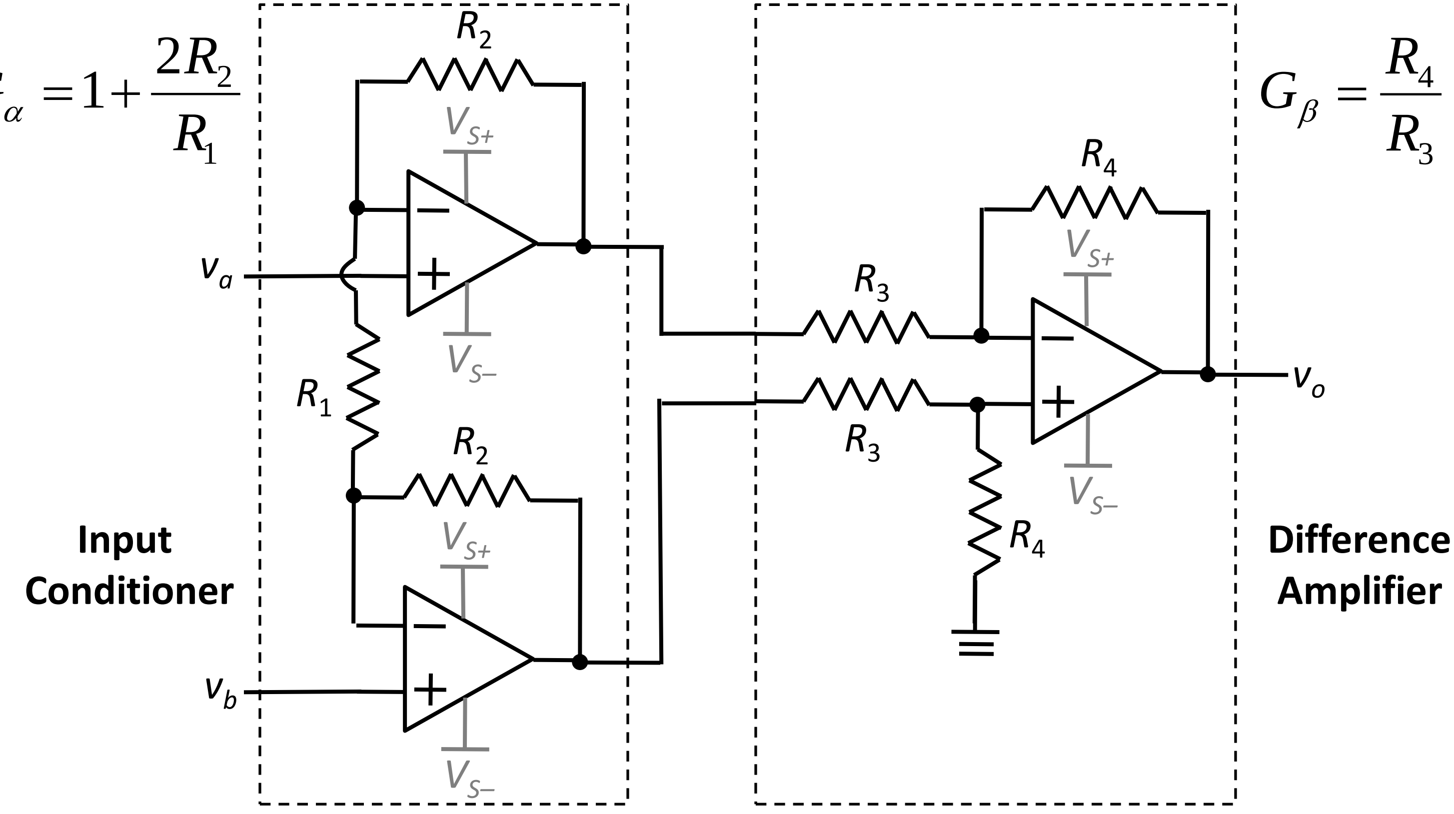
Technical Details: Instrumentation Amp.

- Overall differential gain is given by:

$$G_D = G_\alpha G_\beta = \left(1 + \frac{2R_2}{R_1}\right)\left(\frac{R_4}{R_3}\right)$$

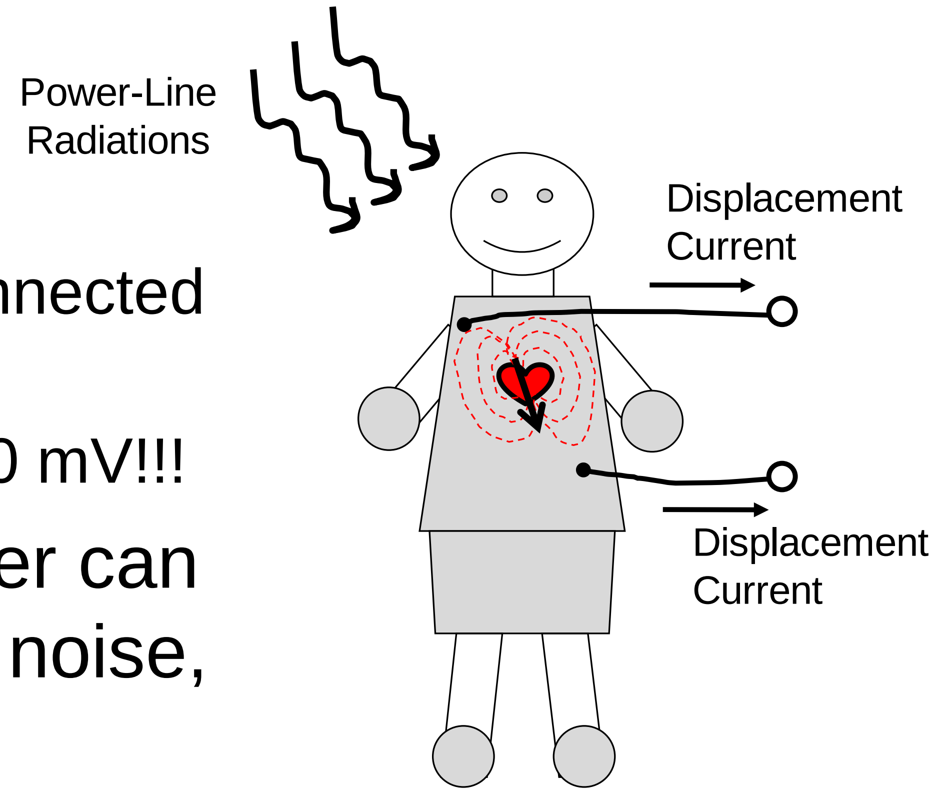
$$G_\alpha = 1 + \frac{2R_2}{R_1}$$

$$G_\beta = \frac{R_4}{R_3}$$



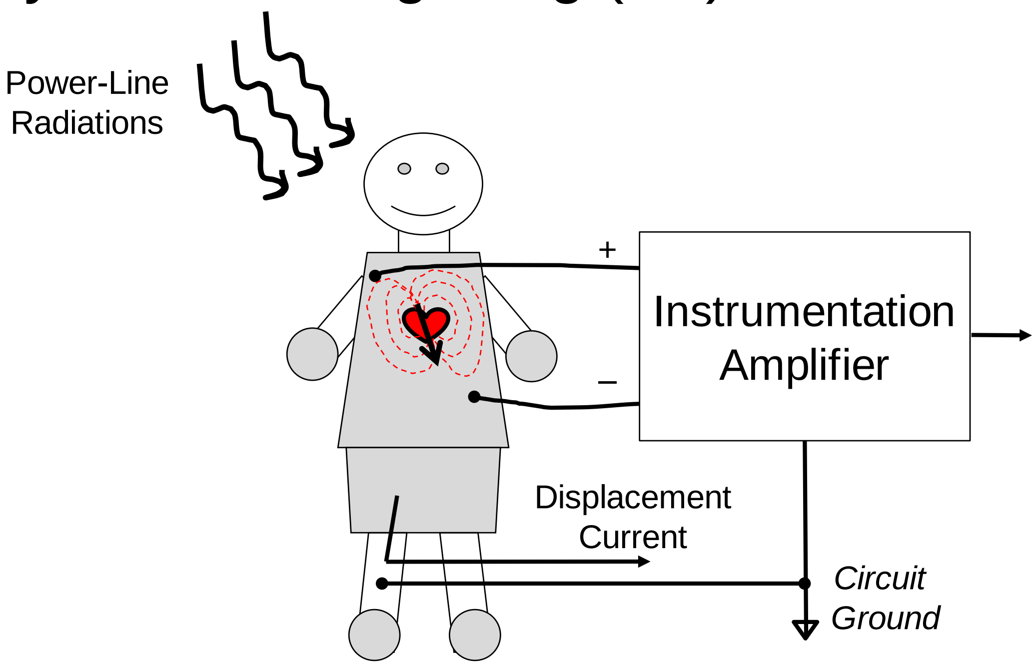
Problem: Power-Line Interference

- Origin of common-mode noise: Radiations from power lines
  - Emitted radiation induces current → Give rise to voltage when connected to circuit load
  - v_{cm} can be as high as 50 mV!!!
- Instrumentation amplifier can reduce common-mode noise, but not completely



Power-Line Noise Reduction

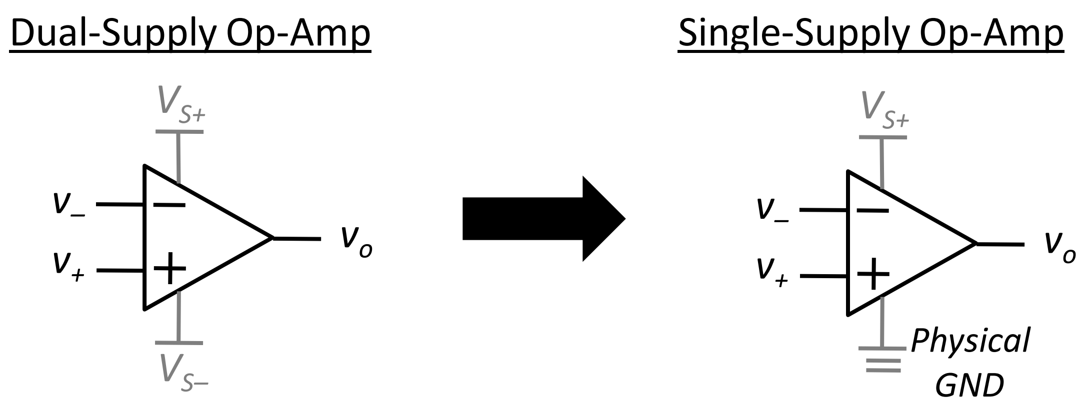
- Approach: Suppress common-mode voltage via shunting the displacement current to ground
- Implemented by adding an extra contact node with subject
  - Usually the at the right leg (RL)



Stage #2: Power Source Reduction

Stage #2: Technical Description

- Aim: Convert amplifier to a single-supply-driven circuit without affecting its operations
  - i.e. Use only one battery to power the op-amp chips



- Method: Create a virtual circuit ground via voltage divider
  - Involves creating an extra circuit block → Circuit becomes more complicated

Main Design Considerations

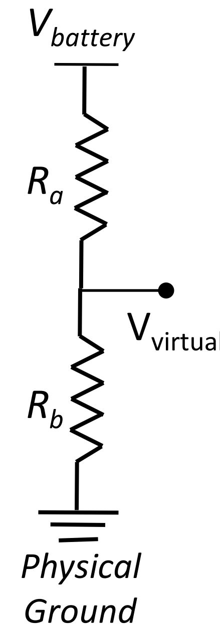
1) Impact of removing the negative battery
   – How would this affect the operation of the circuit?
2) Virtual ground voltage
   – What should the ground voltage value be to sustain normal operation of the amplifier circuit?
3) Suppression of virtual ground fluctuations
   – How can we ensure that the virtual ground voltage remains the same regardless of circuit load?

Technical Details: Virtual Ground

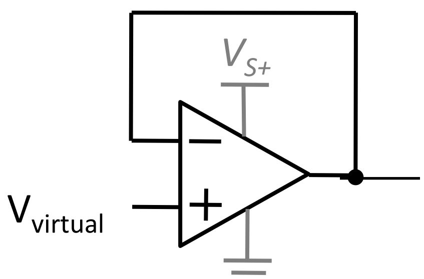
- Virtual ground voltage is given by:

$$v_{virtual} = v_{battery}\left(\frac{R_b}{R_a + R_b}\right)$$

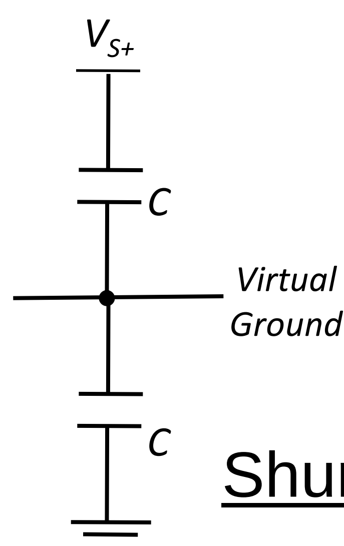
  - Can adjust it by changing R_a and R_b!!



- This voltage can be stabilized via two ways:



<u>Op-amp voltage buffer</u>

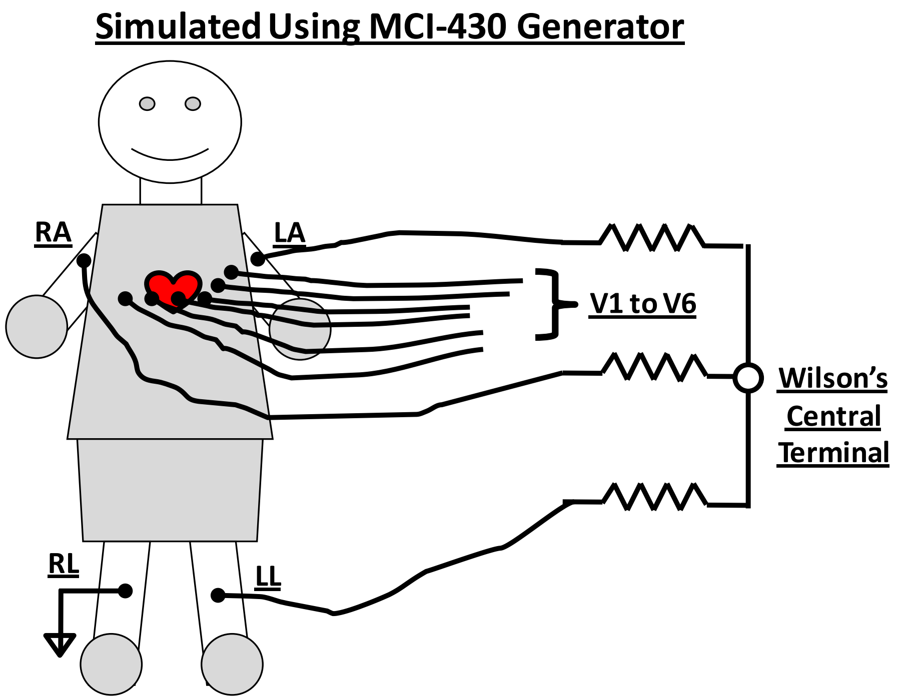


<u>Shunt capacitors</u>

Stage #3: Multi-Lead ECG Measurements

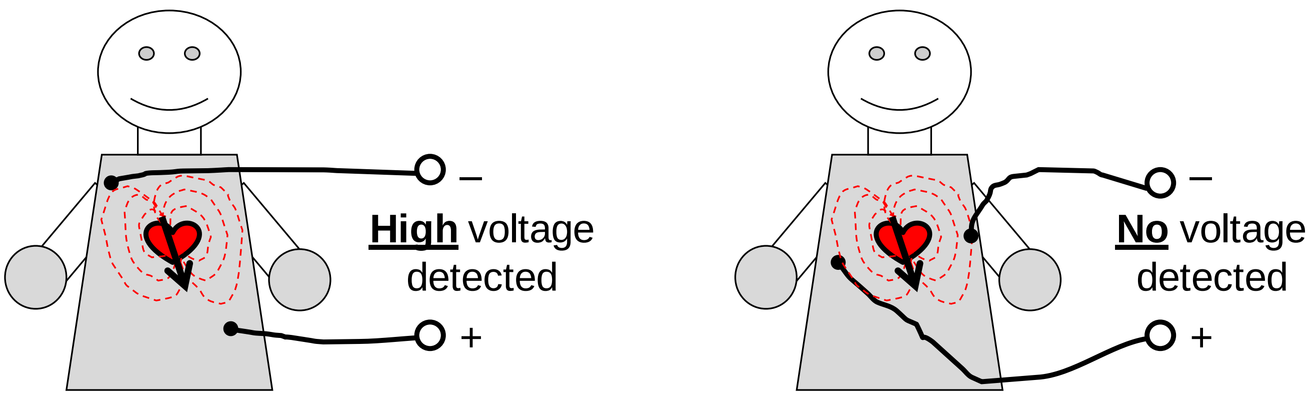
Stage #3: Technical Description

- Aim: Estimate the true direction of ECG potential propagation using your completed amplifier
- Method: Acquire ECG signal from multiple leads
  - 12 leads commonly used in clinical diagnoses



Technical Details: Lead Angle

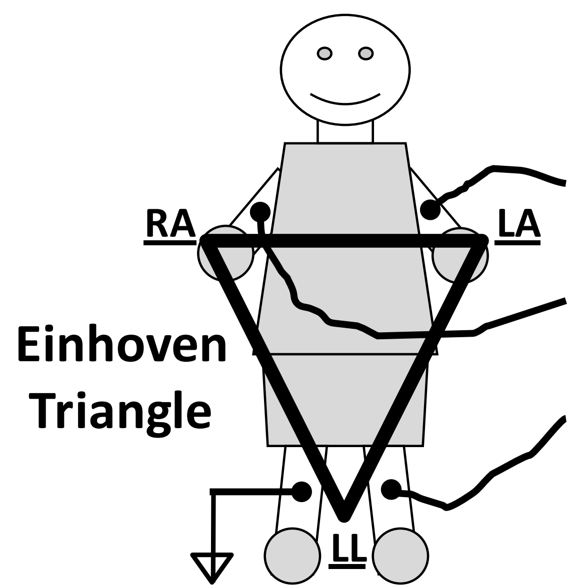
- Detected voltage affected by electrode location due to spatial dependence of cardiac electric field
  - Strongest potential when lead parallel to ECG field
  - Zero potential when at 90
  - General relationship: $|V_{detected}| = |V_{actual}| \cos \theta$



- Makes sense to measure ECG from multiple angles in practice!

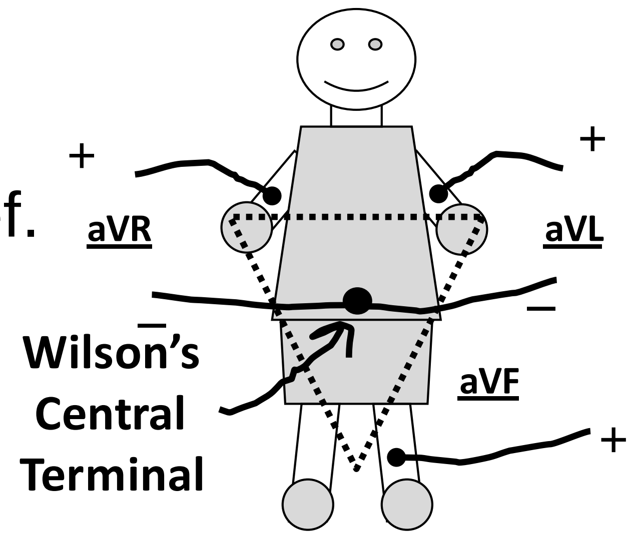
Clinical Practice: Frontal ECG

- Useful for examining cardiac electric field along front side of human body
  - Often regarded as the traditional form of ECG recording
- Three basic electrode points placed at the limbs
  - Locations: 1) Right arm (RA), 2) Left arm (LA), 3) left leg (LL)
  - Forms three leads with pointing directions at ~60 against each other → Forms a triangle known as <u>Einhoven triangle</u>



Clinical Practice: Frontal ECG

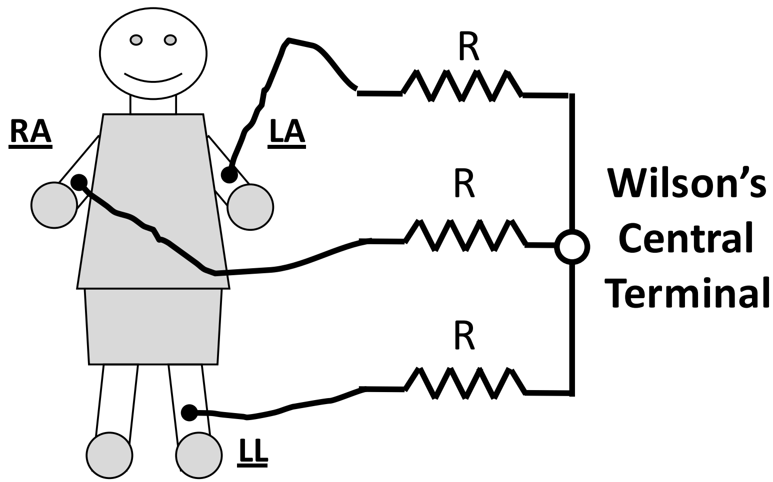
- Three additional leads sometimes included in clinical ECG systems
  - Formed from connecting RA, LA, and LL electrodes with a central ref. node (Wilson's central terminal)
  - Naming: 1) aVR (right arm); 2) aVL (left arm); 3) aVF (foot)



- Total frontal ECG leads = 6
  - 3 basic + 3 augmented
  - Helps to more accurately identify the instantaneous cardiac cycle phase during operation

Technical Details: Central Terminal

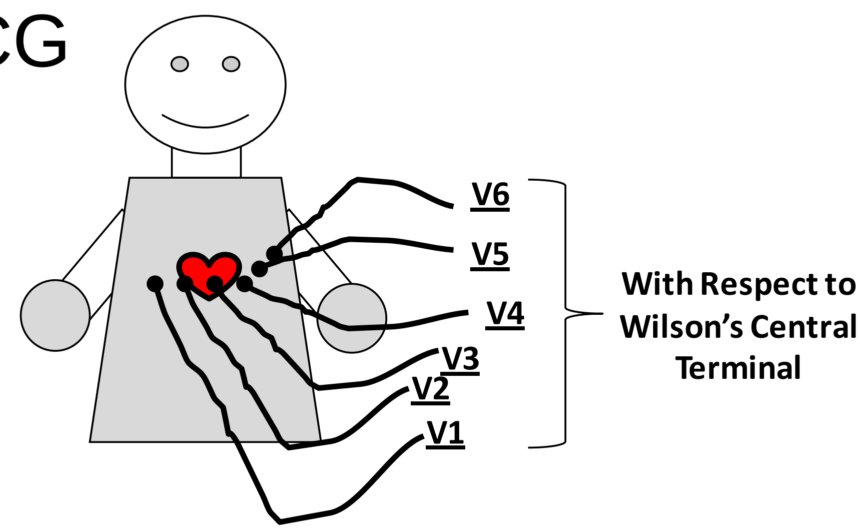
- General approach: Voltage summing circuit
  - Need the resistor R in each branch to avoid short circuit



- Connect the RA, LA, and LL nodes to this summing circuit to get Wilson's central terminal
  - This node is positioned at center of Einhoven triangle

Clinical Practice: Transverse ECG

- Useful for examining cardiac electric field over a cross-section around the heart
- Six electrode points placed below chest
  - Forms six leads with pointing directions at ~30 against each other
- Clinical systems usually perform frontal and transverse ECG simultaneously
  - Involve 12 leads in total (6 frontal + 6 transverse)



Concluding Remarks

Conclusion: Learning Outcomes

1) Explain biopotential amplifier circuits to others
   - Their practical importance and technical details
   - How they can be used for ECG potential measurements
2) Develop an ECG amplifier
   - Implemented on a breadboard
   - Use only basic parts like op-amp chips, resistors, & capacitors
3) Address the power-line interference problem
   - Why they appear as common-mode noise in ECG signals
   - How to reduce them
4) Describe the issue of measurement lead angle
   - Why the detected ECG magnitude depends on the angle between a lead and the actual ECG potential direction