



University of Moratuwa

Wisdom is all wealth

# Signal Conditioning: Designing an ECG Front-End

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Anton F. P. Van Putte, Electronic measurement systems, Taylor & Francis, 2<sup>nd</sup> Edition

M. M. S. Anand, Electronic instruments and Instrumentation Technology, PHI

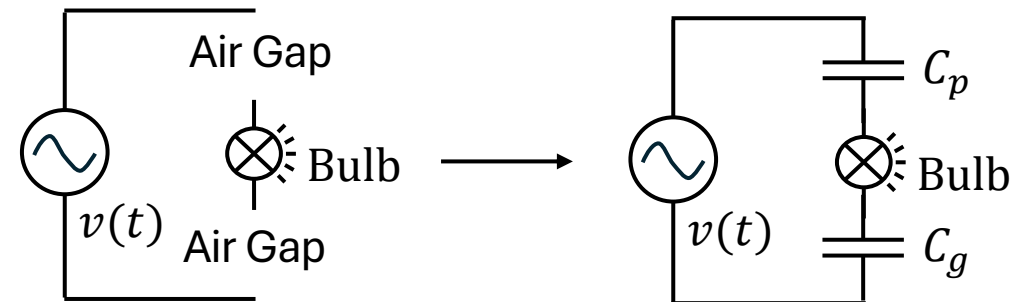
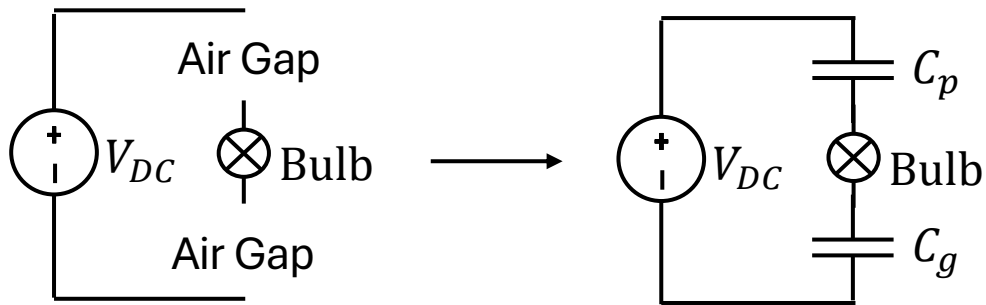
John G Webster, Medical Instrumentation- Application and Design, John Wiley & Sons, 4<sup>th</sup> Edition

R.S. Khandpur, Handbook of biomedical instrumentation, Tata McGraw-Hill, 3<sup>rd</sup> Edition

# Capacitive Coupling

## Displacement Currents

- A displacement current is the current  $i_d$  'across the gap' of a capacitance.
  - This is driven by a changing voltage  $\frac{dv}{dt}$ , and hence a changing electric field.
  - The current is given by  $i_d = C \frac{dv}{dt}$  (This is the equation for current through a capacitor).
- Although physical charge does not cross the gap between the two plates of the capacitor, a time varying signal can couple through it in the form of displacement currents.
  - In the following figure, the capacitances  $C_p$  and  $C_g$  represent the air gaps between the power wire (Live) and the bulb, and the bulb and the return wire (Neutral) respectively.
  - Assuming the bulb requires only nA of current flowing through it to light up (not practical):
    - The AC source has the potential to continuously light it up.
    - The DC source will only be able to light it up momentarily due to transients such as a switch being turned on.



# Capacitive Coupling

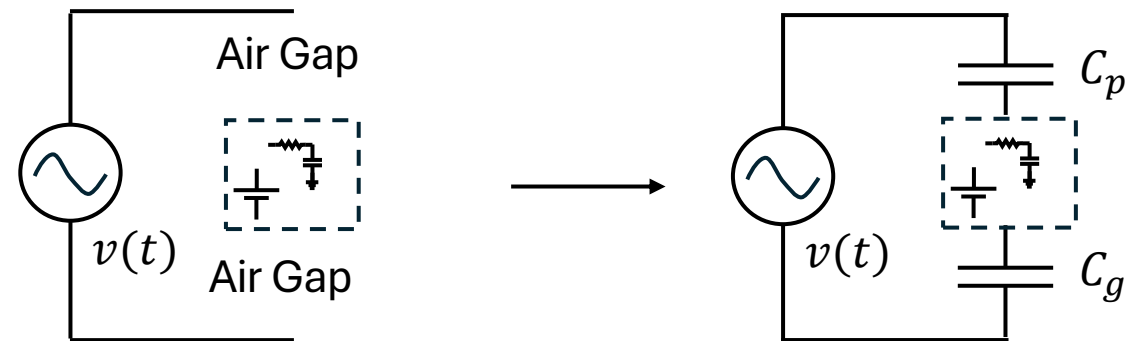
## Displacement Currents

- In practice, a 230V 40W incandescent lamp would require about  $\frac{40}{230} = 0.17$  A of current to light up.
  - However, practical impedances ( $Z = \left| \frac{1}{j\omega C} \right|$ ) created by coupling capacitances is very high (M $\Omega$  – G $\Omega$ ).
  - Let's assume  $C_p = C_g = 100$  pF (on the higher end) => Total series capacitance  $C_{tot} = \frac{C_p C_g}{C_p + C_g} = 50$  pF
  - The impedance at 50 Hz =>  $Z_{tot} = \left| \frac{1}{j \times 2\pi \times 50 \times 50 \times 10^{-12}} \right| \approx 63.6$  M $\Omega$
  - Therefore, the max displacement current that can flow through at 50 Hz is:  $\frac{230}{63.6 \times 10^6} \approx 3.6$   $\mu\text{A}_{\text{RMS}}$ .
  - This is not enough to light the incandescent bulb that requires 170 mA RMS of current.
- The maximum current that can be transferred to any system (circuit, bulb, etc.) via this capacitive coupling is limited by the highest impedance in the path (the capacitive coupling impedance).
  - i.e, whatever displacement current that flows out of a live wire must come back into the neutral wire through some path, and the highest impedance in that path will limit how much maximum current can flow through (Note other series impedances add on top of this highest impedance to limit current flow even further).

# Capacitive Coupling

## Displacement Currents and Interference Voltages

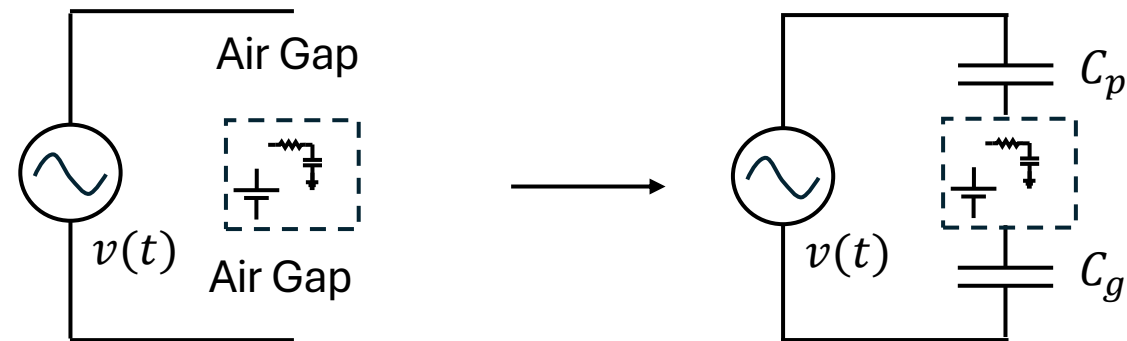
- Now consider a situation where instead of the bulb, we had some battery powered circuit that lies in the fluctuating electric field created by a time varying voltage source (ex: AC mains).



# Capacitive Coupling

## Displacement Currents and Interference Voltages

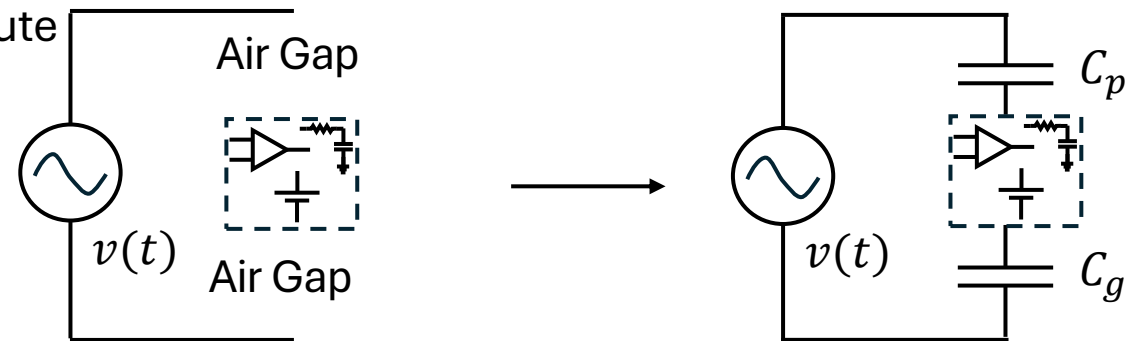
- Scenario A: All components **within** the circuit are connected together with relatively low impedances (such that current flowing through them generates negligible voltages).
  - Low impedances include PCB traces, the battery and supply rails (low internal impedance), decoupling capacitors, etc.
  - Displacement current that enters the circuit from the live travels through parallel paths along the different traces, wires, paths etc., in the circuit, out towards the neutral.
    - The magnitude of this current is limited by the highest **series** impedance in the path.
  - Because everything is coupled with low impedances, the entire circuit may be considered a single large conductor (with respect to the huge impedances at the stray capacitances).
    - Therefore, the voltage differences that can form across the circuit components as this displacement current travels through them is very small ( $i_d \times Z$ ) compared to signals in the circuit, i.e., we can consider that the entire circuit lies at the same shared voltage.
      - Therefore, these displacement currents only create negligible **differential** voltages.
  - However, this shared will fluctuate along with the fluctuation of the E-field, yielding **common-mode** voltage interference that can lead to fluctuations in the outputs due to common mode gain in amplifiers.



# Capacitive Coupling

## Displacement Currents and Interference Voltages

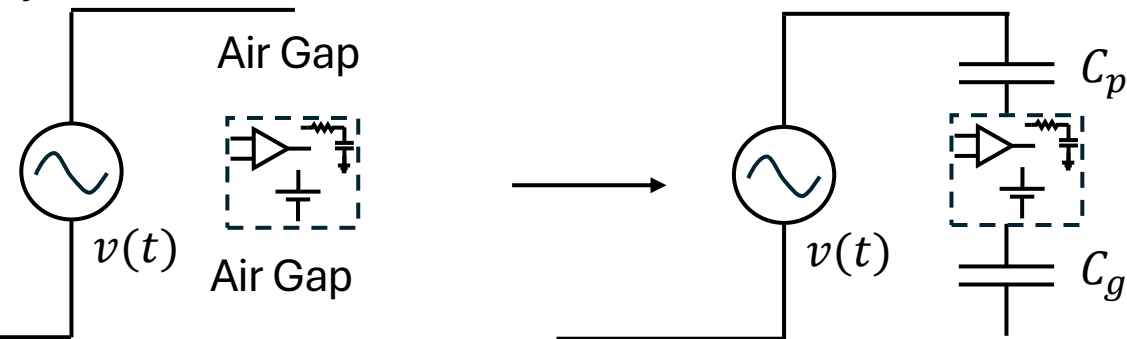
- Scenario B: We have high impedances (such that currents flowing through them generate voltages that are comparable with signals of interest) tying different components **within** the circuit.
  - This is usually the case in circuits that have voltage amplifiers and other high impedance components.
    - Voltage amplifiers have high input impedance.
  - Displacement current still enters from live and exits to neutral via the circuit as the intermediary.
    - The magnitude of this current is limited by the highest **series** impedance in the path.
  - The difference now is that the displacement current that enters the circuit takes paths with varying impedances on its way out to the neutral.
    - Currents traveling through paths with different impedances create **differential mode** voltages ( $v_{DM} = i_{d1}Z_1 - i_{d2}Z_2$ ), which are significant when they are comparable to the signal.
      - For  $\mu\text{V}$ -level biosignals, even tens of  $\text{k}\Omega$  can be enough.
    - These differential voltages can be amplified and contribute to interference.



# Capacitive Coupling

## Displacement Currents and Interference Voltages

- Scenario C: The stray capacitive coupling between the circuit and **neutral** is very weak (much larger impedance) compared to the coupling between the circuit and the **live**.
  - As an example, consider there is a 230 V 50 Hz mains live wire nearby, but the neutral wire is far away.
    - You have a battery powered circuit near the live wire, but far away from the neutral wire.
    - Irrespective of what components and impedances we have inside the circuit, the displacement current that flows from the live to neutral will now be negligibly small due to the extremely high impedance between the circuit and the neutral wire.
  - Therefore, this acts as an extreme case of scenario A, where the impedances within the circuit are inconsequential compared to the extremely high impedance from the circuit to the neutral.
    - Therefore, barely any displacement current flows.
    - Therefore, even in the presence of high impedances within the circuit, differential voltages produced are negligibly small.
    - However, common mode voltage will now couple maximally.
      - When current doesn't flow through an impedance coupled to a source, we consider both terminals of the impedance to be at the same potential as the source.
      - In this case, the potential is the 230V live that acts as the common mode voltage across the entire circuit.
        - $$v_{CM} = V_{live} \times \frac{C_p}{C_p + C_g} \rightarrow 230 \text{ V as } C_g \rightarrow 0$$



# Capacitive Coupling

## Displacement Currents and Interference Voltages

- The take homes:
  - A displacement current from **live to neutral** is **NOT** necessary for a wire to pick up interference.
    - In this case, it will just be the common mode voltage as the interference.
    - A displacement current does **NOT** have to flow from the noise source through these conductors if there is **no** closed loop for that displacement current to return to the source through.
  - The maximum displacement current that can flow through a system is limited by the highest impedance (+ other series impedances) in the path from the source's output terminal to its return terminal through the system.
  - When a displacement current flows through a system, both common-mode and differential mode interference can be observed.
    - Differential mode interference will be significant only if the impedances, and their mismatch between nodes, are large enough that  $i_{d_1}Z_1 - i_{d_2}Z_2$  is comparable to the signal being measured.
    - Nodes tied together by small impedances see only the common-mode interference.

# Capacitive Coupling

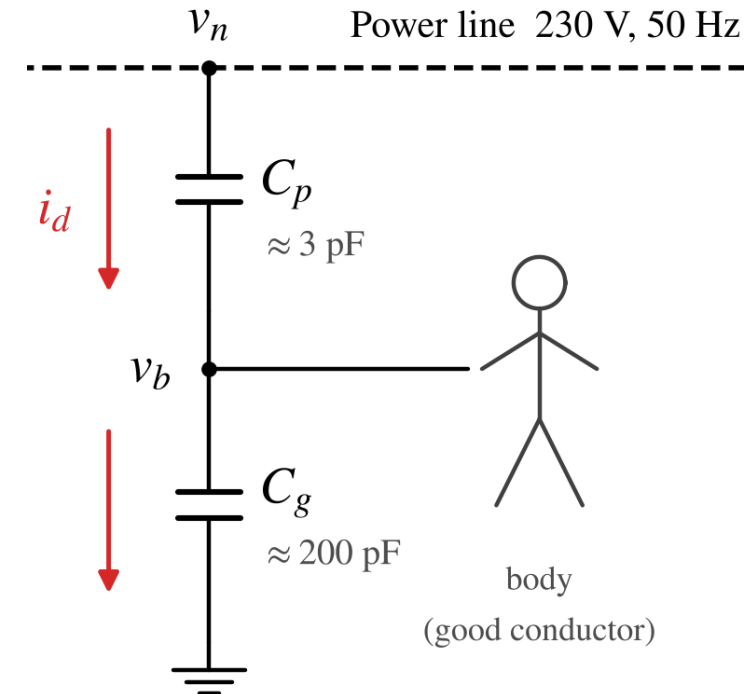
## Displacement Currents and the Earth

- What does Earth have to do with displacement currents?
  - The earth is a huge conductor (not as good as copper, but much better than the impedance of an air gap capacitance).
  - When coupled with the fact that powerlines spread over large distances, the capacitance between earth and power lines becomes significant.
  - On top of this, most commercial power grids have the neutral lines connected to earth at the distribution transformers (except isolated IT supplies, e.g. in operating theatres).
    - $\therefore$  We will always have capacitive coupling between any live wire and the neutral, as the earth is all around us.
    - This will always lead to displacement currents in circuits.
    - On top of this capacitive coupling, some devices establish a direct resistive path to earth, which closes the loop through the circuit with a much lower return impedance.
      - Ex: Class I mains-powered equipment (circuit ground tied to protective earth), a USB cable to an earthed PC, or an oscilloscope probe's ground clip.
      - Even battery powered devices may be connected to earth via a user's body: resistively if the user touches earthed metal or stands barefoot, otherwise capacitively ( $\approx 100\text{--}200\text{ pF}$  through shoes and the floor).
        - The human body can be considered an enclosed salt solution – a conductor.
    - This displacement current generally creates common mode voltages in circuits with nodes tied to each other via low impedances, but can also generate differential mode voltages if different high impedance nodes exist.

# Capacitive Coupling

## Displacement Currents in the Body

- The body is a conductor sitting in the electric field of the mains wiring.
  - The human body is essentially an enclosed ionic solution; a conductor.
  - A human touching bare earth is already directly grounded.
    - Therefore, the body is like a plate in a parallel plate capacitor that has one end connected to ground.
  - A human wearing shoes, or sitting on top of an insulator (ex: a wooden chair) acts as the midpoint of two capacitors in series:
    - The body and the power-line separated by air forms the first capacitor  $C_p$ .
    - The body and the ground forms the second capacitor  $C_g$ .
- Therefore, displacement current from mains voltage has a return path via the body.



# Capacitive Coupling

## Displacement Currents in the Body

- The voltage divider rule for impedances can be applied to calculate the voltage at the central plate (the human body) in this three-plate-capacitor.

$$v_b = v_n \times \frac{Z_{C_g}}{Z_{C_g} + Z_{C_p}} = v_n \times \frac{(1/j\omega C_g)}{(1/j\omega C_g) + (1/j\omega C_p)} = v_n \times \left( \frac{C_p}{C_p + C_g} \right)$$

- The displacement current that flows from the powerline, through the body, to ground can be calculated as:

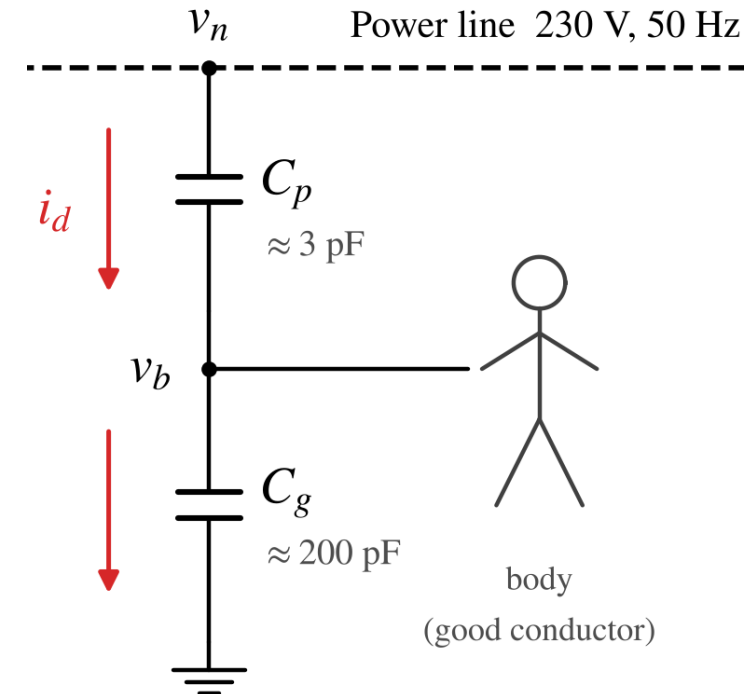
- $i_d = C \times \frac{dv_n}{dt}$  where  $C$  is the total series capacitance between the powerline and the ground.

- $C = \frac{C_p C_g}{C_p + C_g}$  (Remember, series capacitances cannot be directly added).

- Therefore,  $i_d = \frac{C_p C_g}{C_p + C_g} \times \frac{dv_n}{dt}$

- This analysis was for when the human is not in contact with ground (ex: wearing shoes/on a chair).

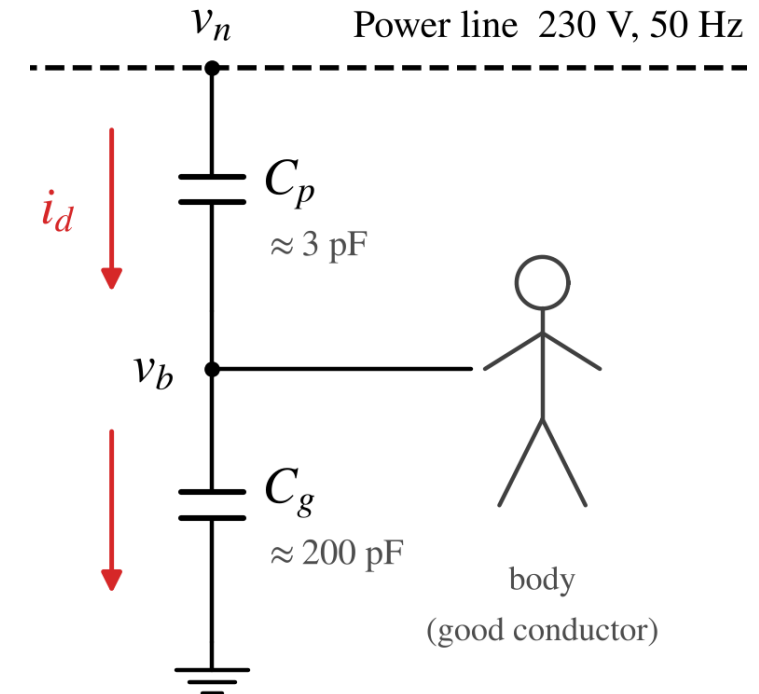
- If the human was directly in contact with ground,  $i_d = C_p \frac{dv_n}{dt}$



# Capacitive Coupling

## Displacement Currents in the Body

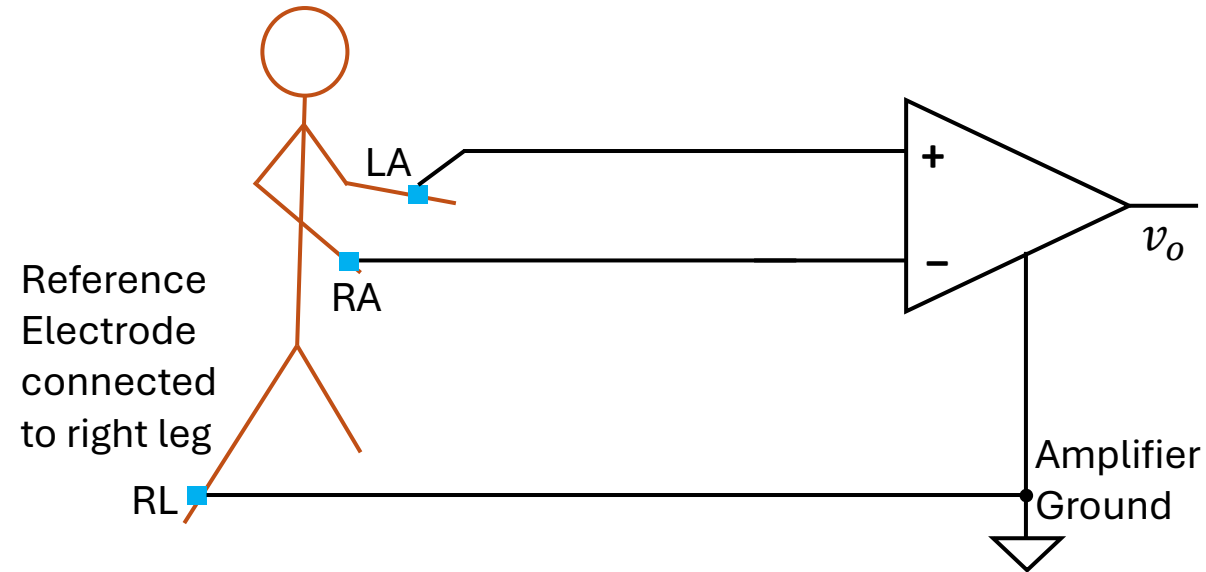
- Plugging some generic values in,  $v_n(t) = 230\sqrt{2} \times \sin(2\pi \times 50t)$ 
  - $\therefore \frac{dv_n(t)}{dt} = 230\sqrt{2} \times 2\pi \times 50 \times \cos(2\pi \times 50t)$
- Let  $C_p = 3 \text{ pF}$  and  $C_g = 200 \text{ pF}$ .
  - $V_{b_{RMS}} = V_{n_{RMS}} \times \left(\frac{C_p}{C_p + C_g}\right) = 230 \times \left(\frac{3}{3+200}\right) \approx 3.4 \text{ V}$
  - $i_d(t) = \frac{C_p C_g}{C_p + C_g} \times \frac{dv_n(t)}{dt} = \left(\frac{3 \times 200}{3+200} \times 10^{-12}\right) 230\sqrt{2} \times 2\pi \times 50 \times \cos(2\pi \times 50t)$ 
    - Note: there is a multiplication of capacitances on the numerator, hence the units must be considered (multiplication by  $10^{-12}$ ).
  - $\Rightarrow i_d(t) = 2.14 \times \sqrt{2} \times 10^{-7} \cos(2\pi \times 50t)$
  - $\therefore I_{d_{RMS}} \approx 214 \text{ nA}$
  - If the human was directly in contact with ground,  $i_d = C_p \frac{dv_n}{dt}$ 
    - $\therefore I_{d_{RMS}} = 3 \times 10^{-12} \times 230 \times 2\pi \times 50 \approx 217 \text{ nA}$
  - Note that all these values are way below the threshold of perception ( $\sim 500 \text{ }\mu\text{A}$ ).



# Capacitive Coupling

## Displacement Currents and ECG

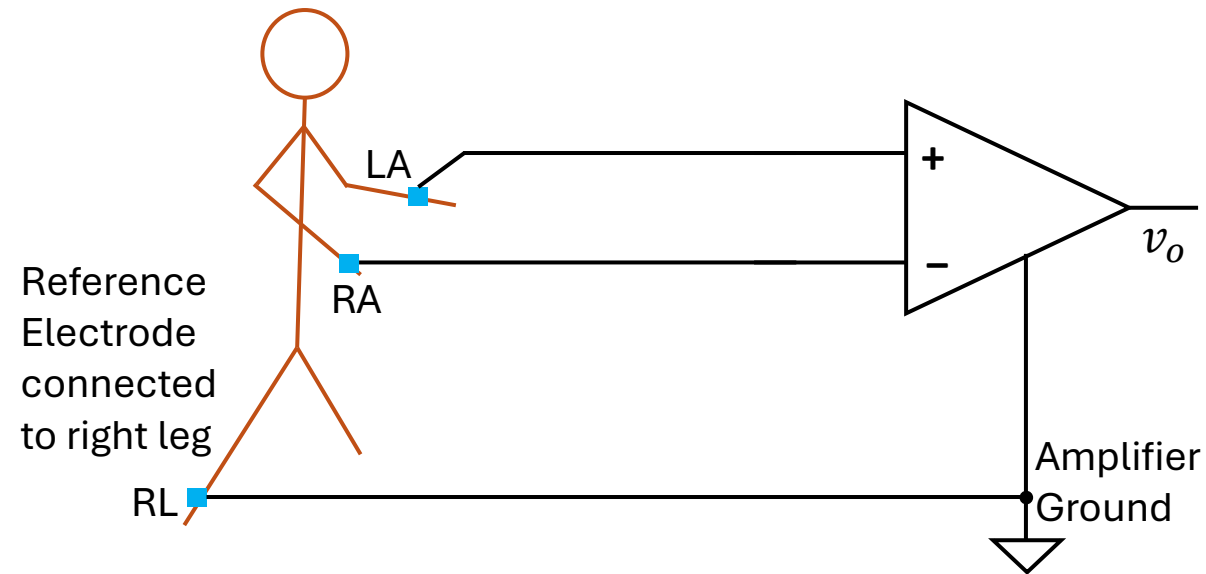
- Consider a single lead ECG system with electrodes connected to the left arm (LA), right arm (RA), and the right leg (RL) – the reference.
  - The electrodes at the left and right arms are connected to an amplifier.
  - The reference electrode defines the baseline against which all other voltages are measured.



# Capacitive Coupling

## Displacement Currents and ECG

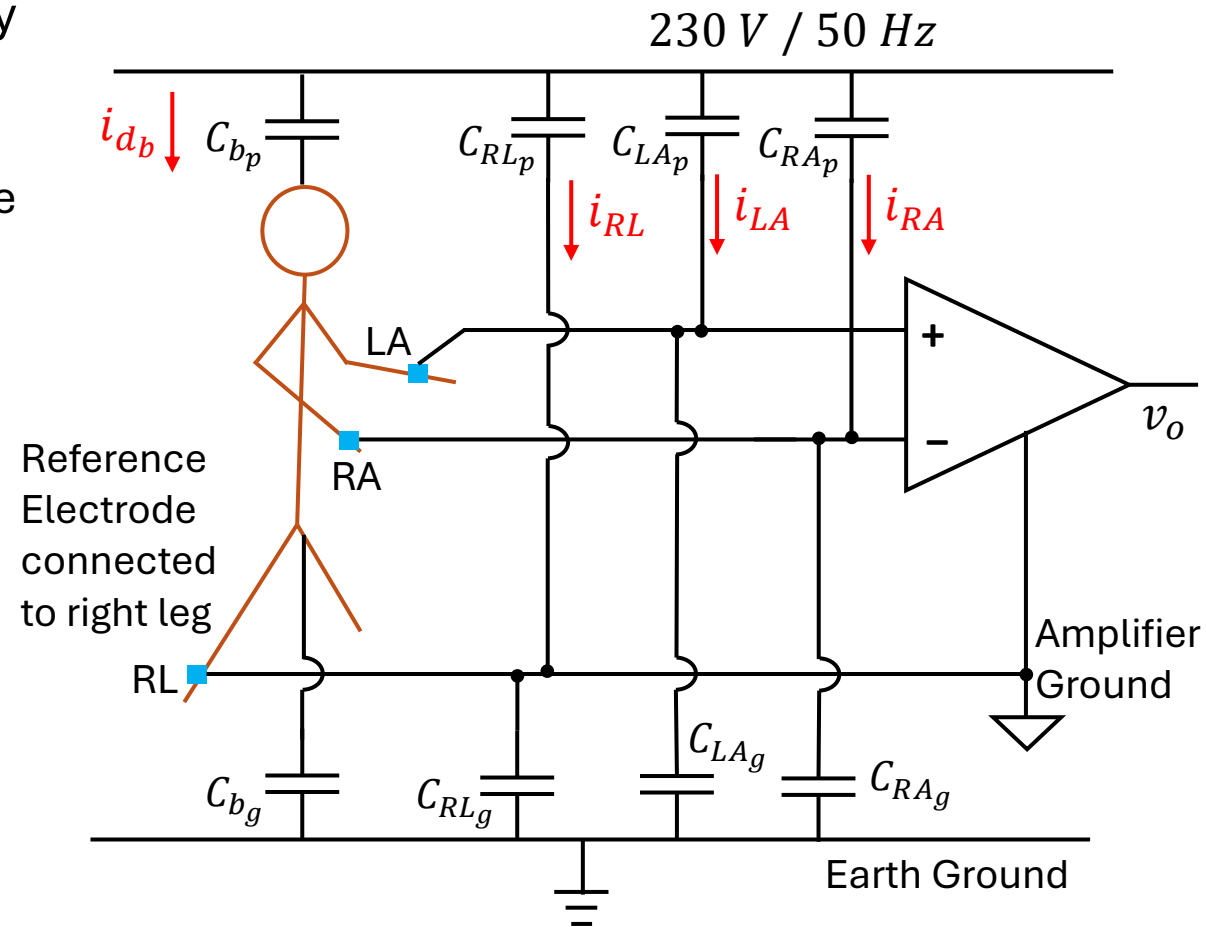
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  - The electrodes at the left and right arms are connected to an amplifier.
  - The reference electrode defines the baseline against which all other voltages are measured.
    - For now, let us tie it to the amplifier ground.



# Capacitive Coupling

## Displacement Currents and ECG

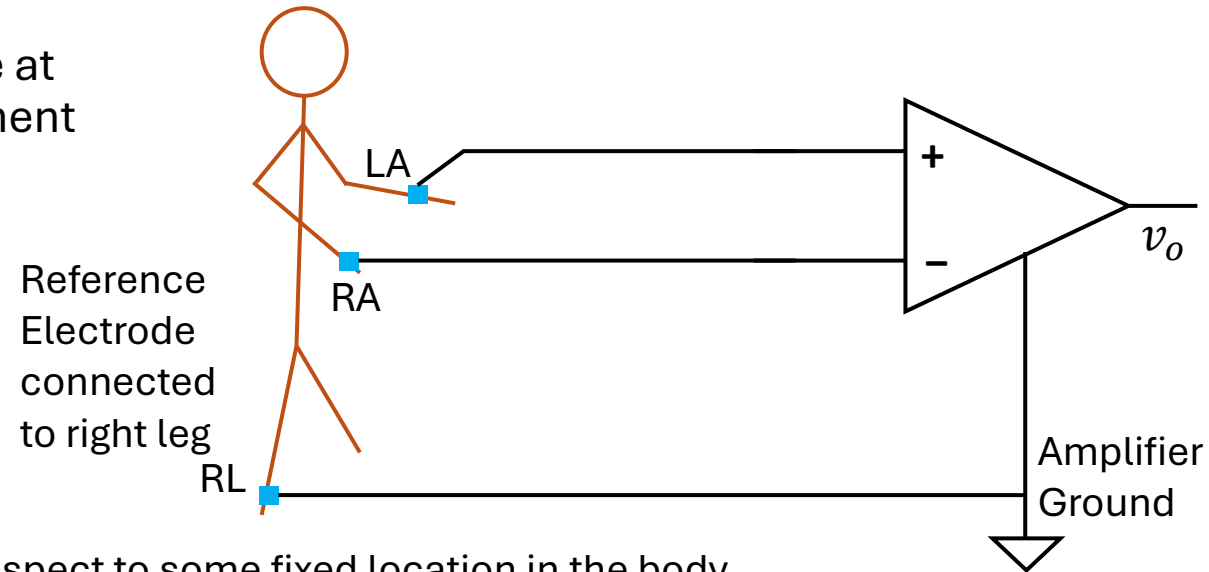
- Powerline interference from nearby mains supply couples to this circuit in many ways out of which some important ones are shown.
  - The presence of the time varying electric field nearby creates common-mode voltages in all components of the circuit including the human body.
    - We previously calculated this **common-mode** voltage to be around  $v_{cm} \approx 3.4$  V on the human body.
  - In addition, these couplings lead to displacement currents in components.
    - We previously calculated this to be  $\approx 214$  nA.
    - Given the **relatively** low impedance of the human body, these displacement currents do not generate significant differential voltages within the parts of the body.



# Capacitive Coupling

## Displacement Currents and ECG

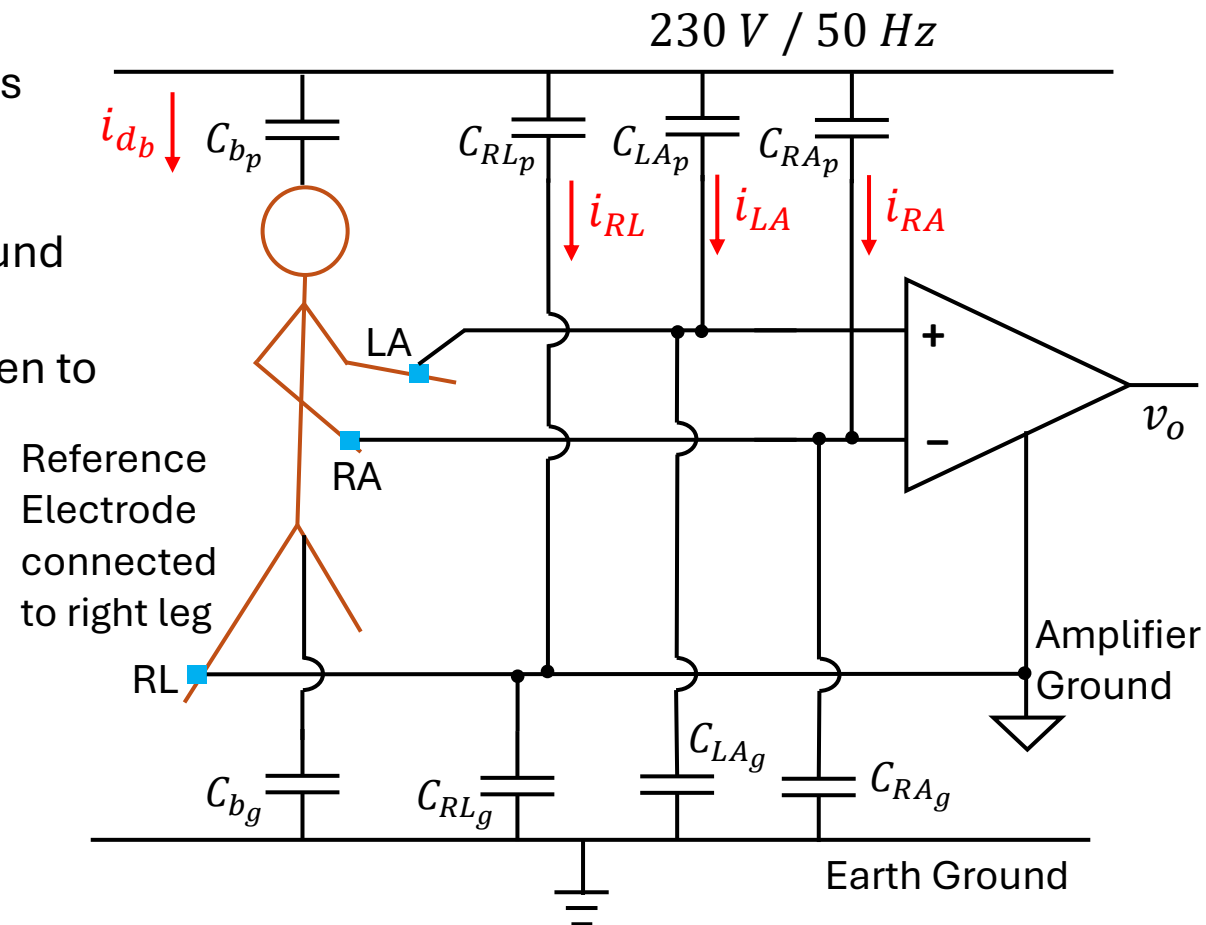
- Why did we need a reference electrode?
  - Remember, a practical op-amp amplifier amplifies not just the differential signals, but also common mode signals - Therefore, the absolute voltages the input terminals are at matter!
    - If these absolute voltages exceed the amplifier's input common-mode range, the amplifier saturates.
      - Within common-mode range, still some error is added to the amplifier output due to common mode gain.
    - We previously calculated that the human body will be at  $\approx 3.4$  V RMS common-mode voltage due to displacement current from the mains.
    - In addition, a human can be electrostatically charged to kilo-volts!
    - When they act in combination, merely connecting the left and right arm electrodes to a high gain amplifier would easily saturate it unless we offset this common-mode voltage.
      - A simple way to do this is to measure all signals with respect to some fixed location in the body.
      - This can be done by connecting the amplifier ground to a position in the human body where the ECG is least felt.
      - However, as we will see later, this does not completely eliminate common mode voltage at the inputs of the op-amp.



# Capacitive Coupling

## Displacement Currents and ECG

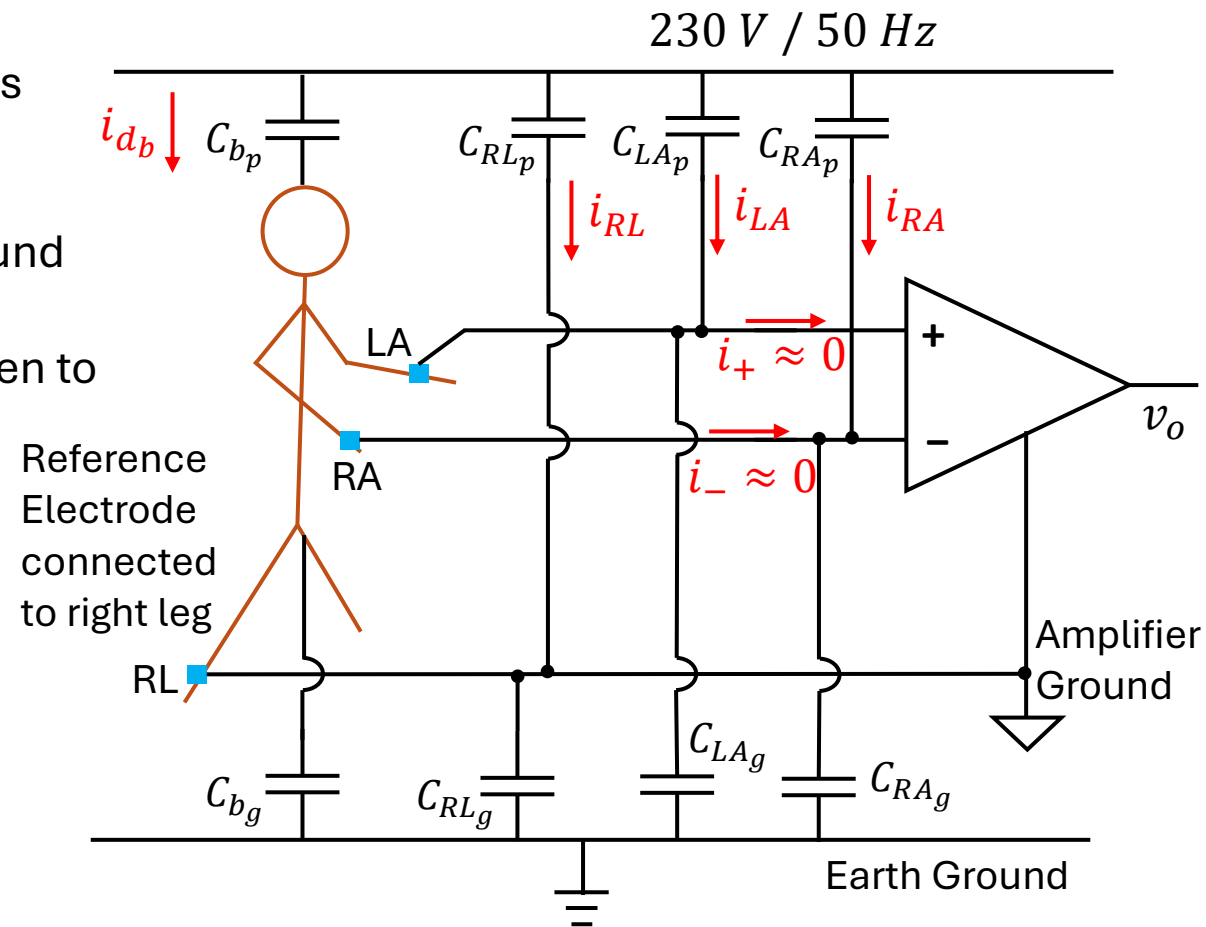
- The independent displacement currents due to capacitive coupling on the wires must form a closed loop with the mains.
  - There are three paths for this:
    - Directly through the corresponding stray capacitances to earth ground.
    - Through the amplifier inputs and then to earth via the stray capacitance (not shown) between amplifier ground and earth ground.
    - Through the human body into the RL electrode and then to ground.



# Capacitive Coupling

## Displacement Currents and ECG

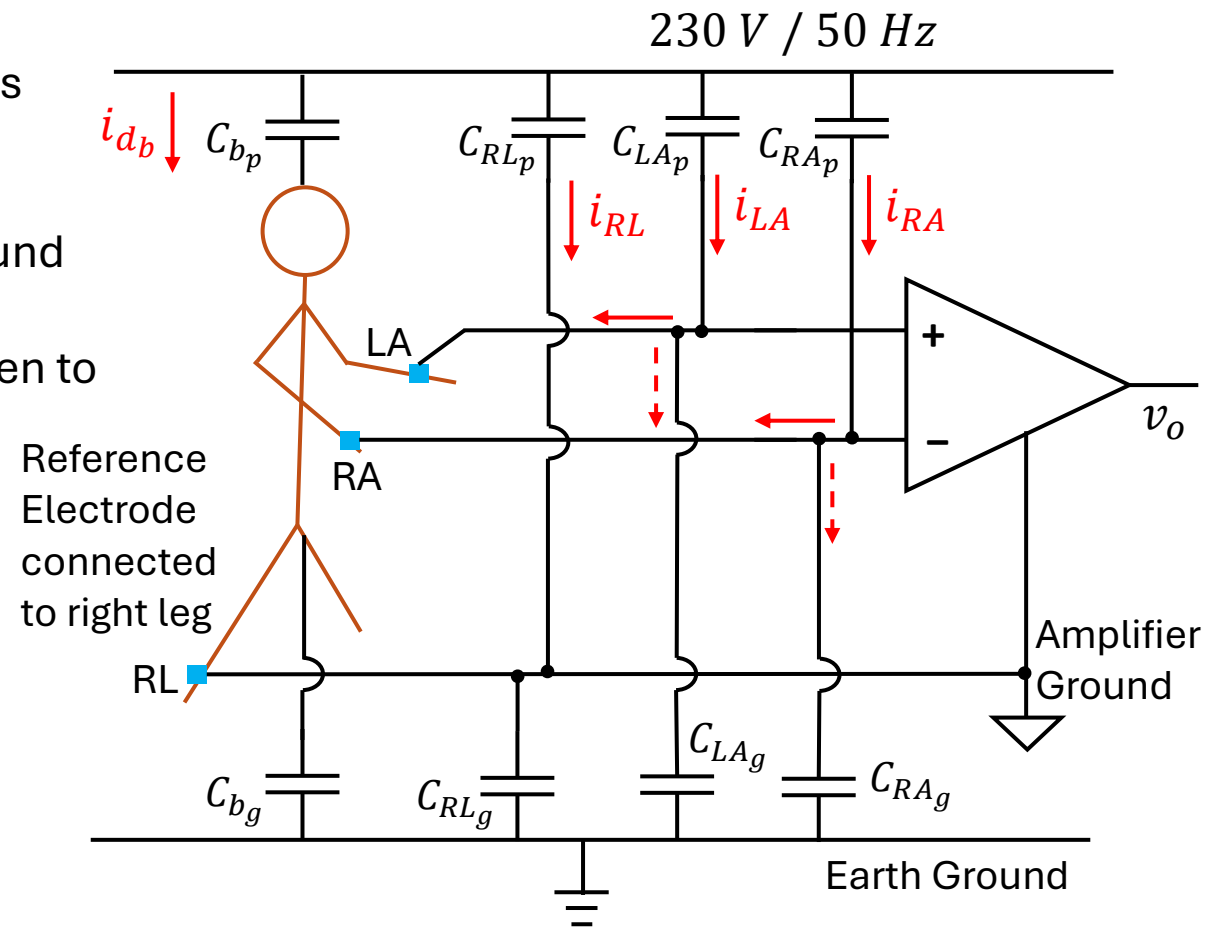
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    - Through the human body into the RL electrode and then to ground.
- Out of these, a large portion of the currents will go through the least impedance path.
  - The input impedance of the amplifier is very high.
    - Therefore, negligible current flows in that path.



# Capacitive Coupling

## Displacement Currents and ECG

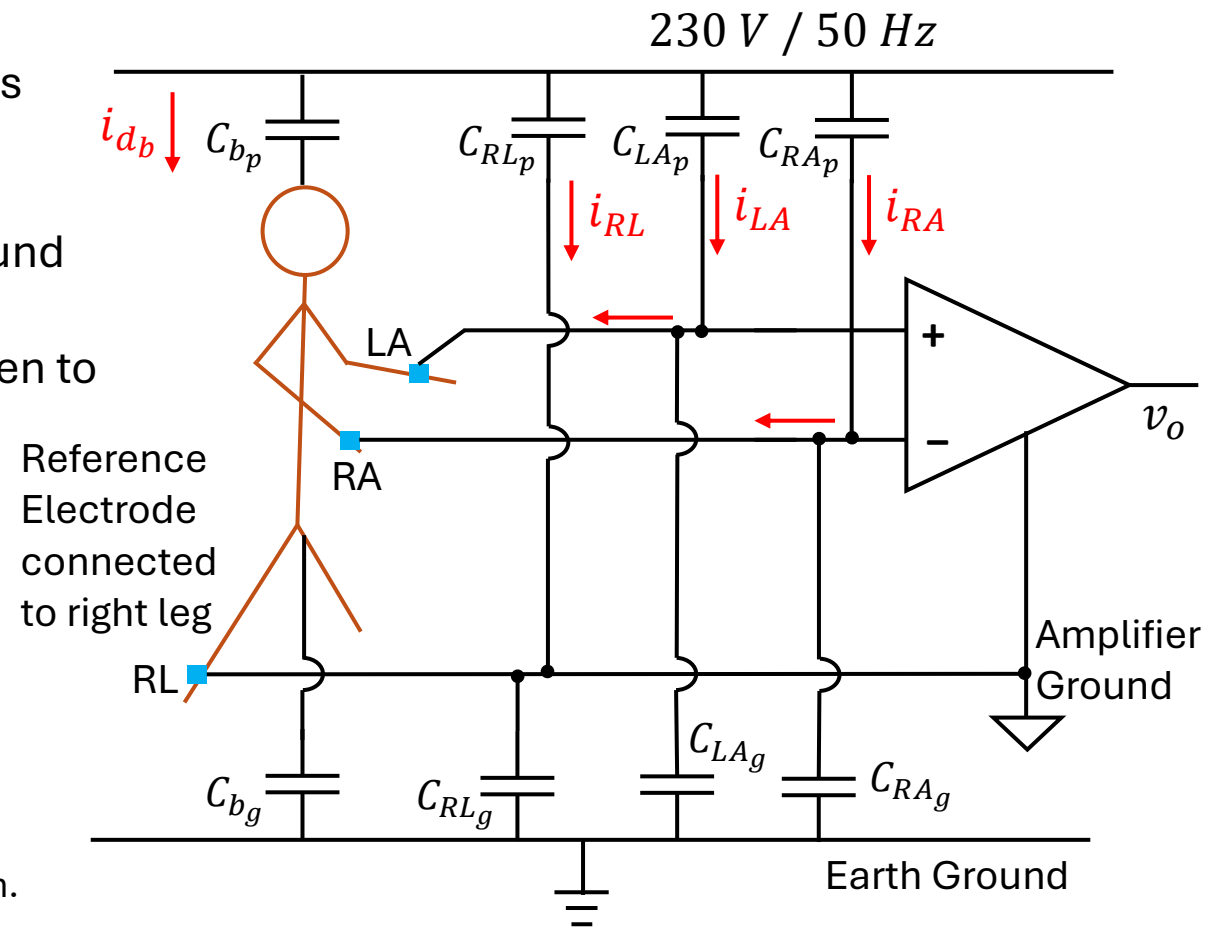
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    - The capacitance between the human body and earth is higher than the direct stray capacitances of the wires to ground=> lower impedance.



# Capacitive Coupling

## Displacement Currents and ECG

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    - Through the human body into the RL electrode and then to ground.
- Out of these, a large portion of the currents will go through the least impedance path.
  - The input impedance of the amplifier is very high.
    - Therefore, negligible current flows in that path.
    - The capacitance between the human body and earth is higher than the direct stray capacitances of the wires to ground  $\Rightarrow$  lower impedance.
      - Therefore, current mostly flows through the body to earth.

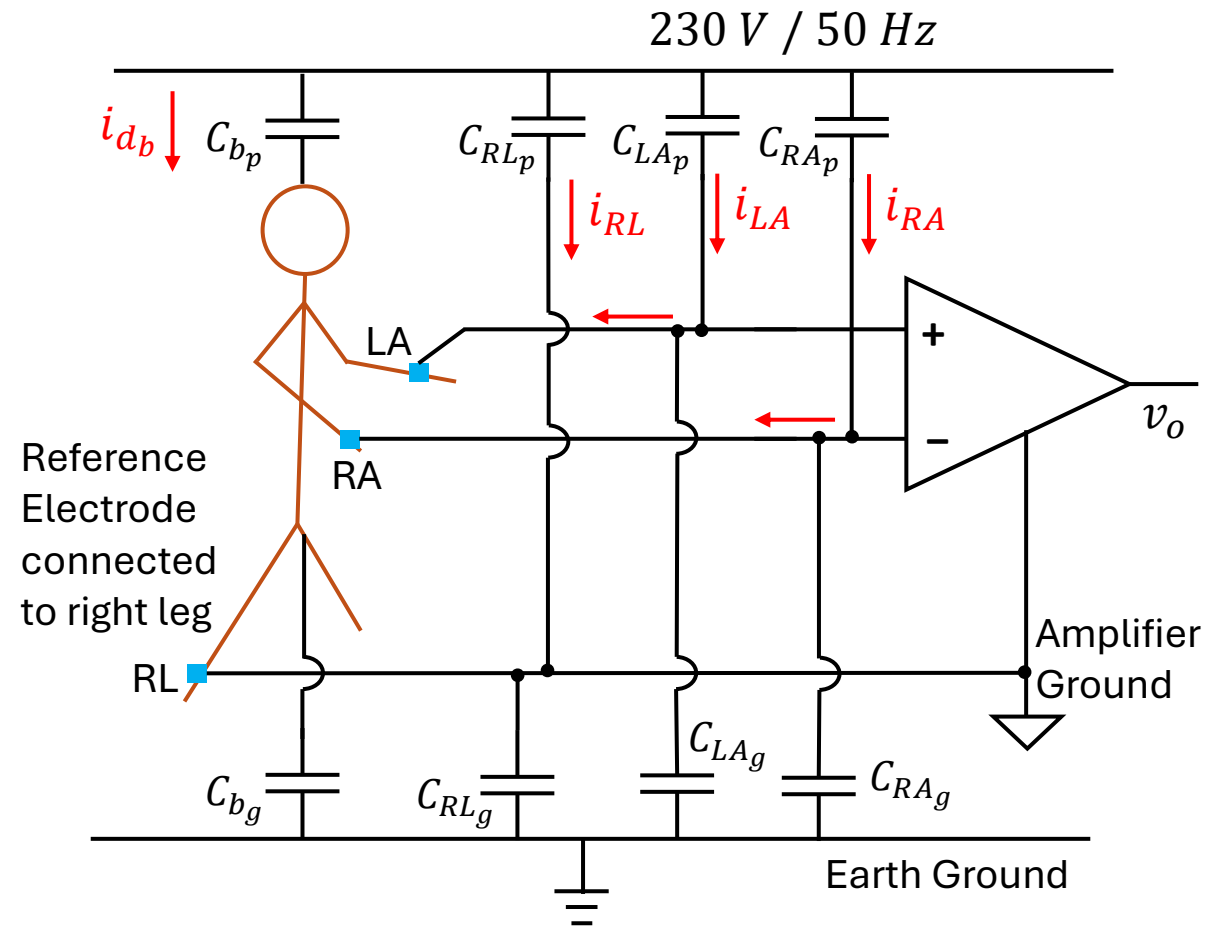


# Capacitive Coupling

## Displacement Currents and ECG

- Therefore, we can approximate that the total current through the body:

- $i_b \approx i_{db} + i_{LA} + i_{RA}$

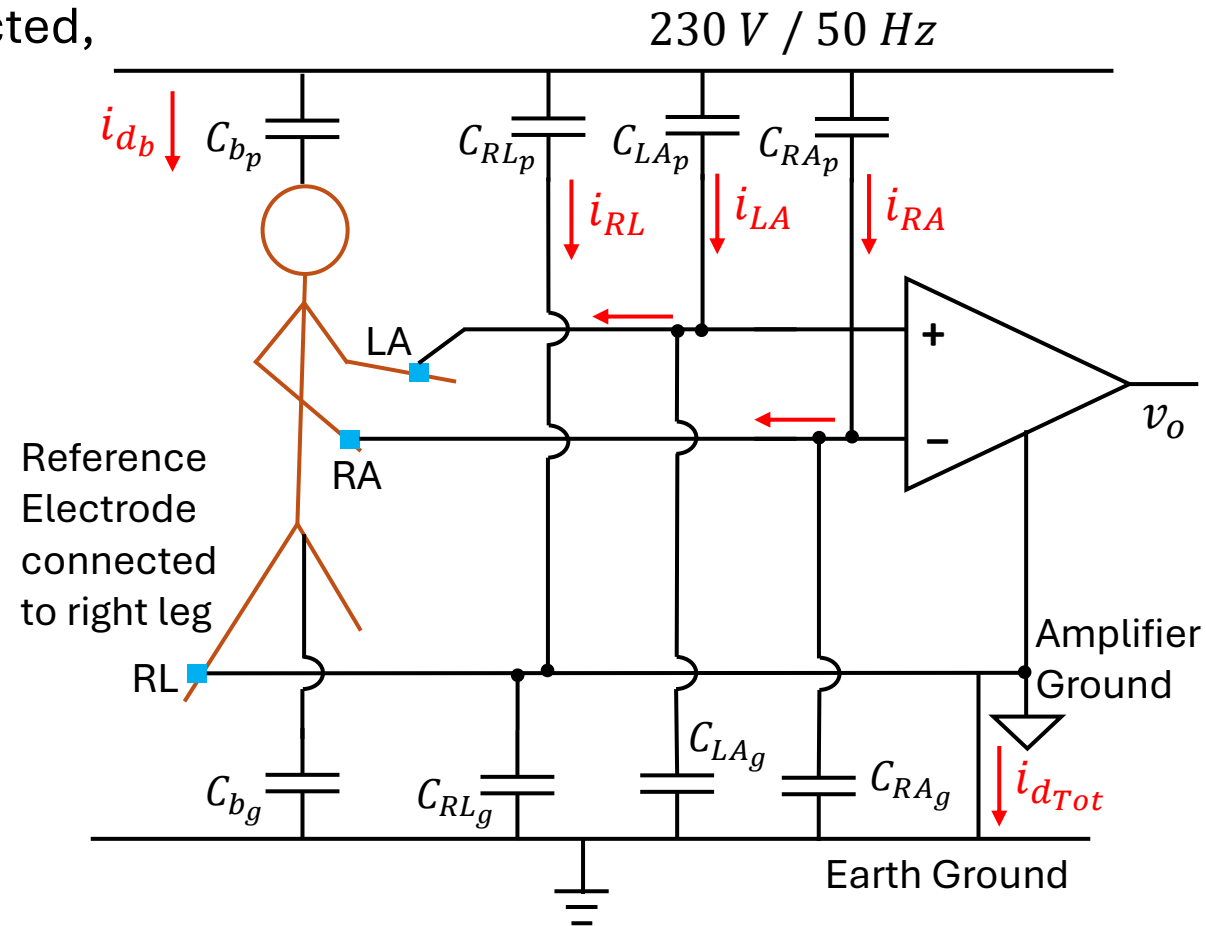


# Capacitive Coupling

## Displacement Currents and ECG

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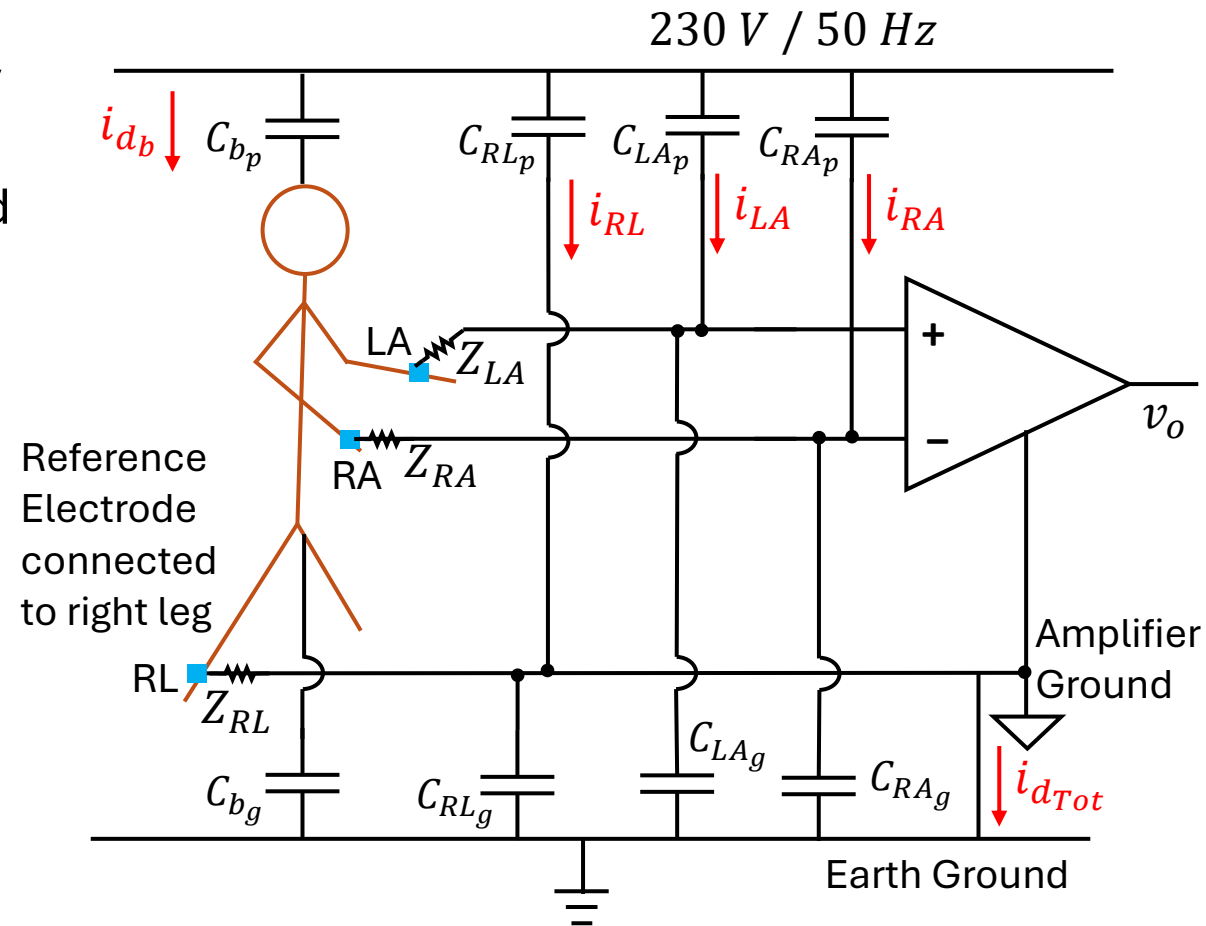
- $i_b \approx i_{db} + i_{LA} + i_{RA}$
- If the amplifier ground and earth ground was connected,
  - All this current will exit through the RL electrode into earth ground.
  - In this case,  $i_{dTot} \approx i_b + i_{RL}$



# Capacitive Coupling

## Displacement Currents and ECG

- There is however an outstanding issue: the ECG electrodes have high impedance at skin contact!
  - Displacement currents flowing through high impedances can create significant voltages.
  - If these high impedances are different in magnitude they act as differential-mode noise especially if they are in the signal path.
  - Due to imperfect contact between the electrode and the skin, the  $Z_{LA}$ ,  $Z_{RA}$ , and  $Z_{RL}$  can all take different values.

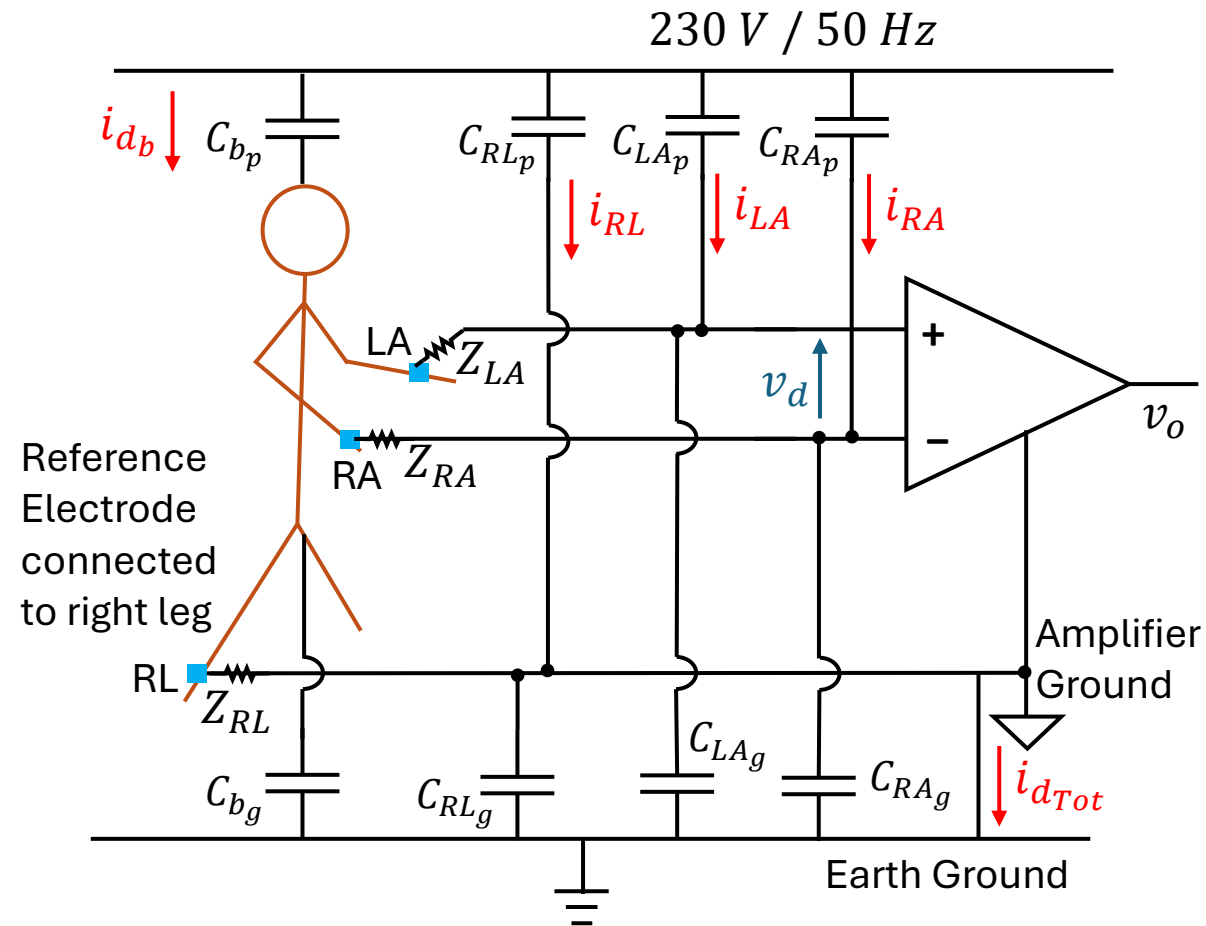


# Capacitive Coupling

## Displacement Currents and ECG

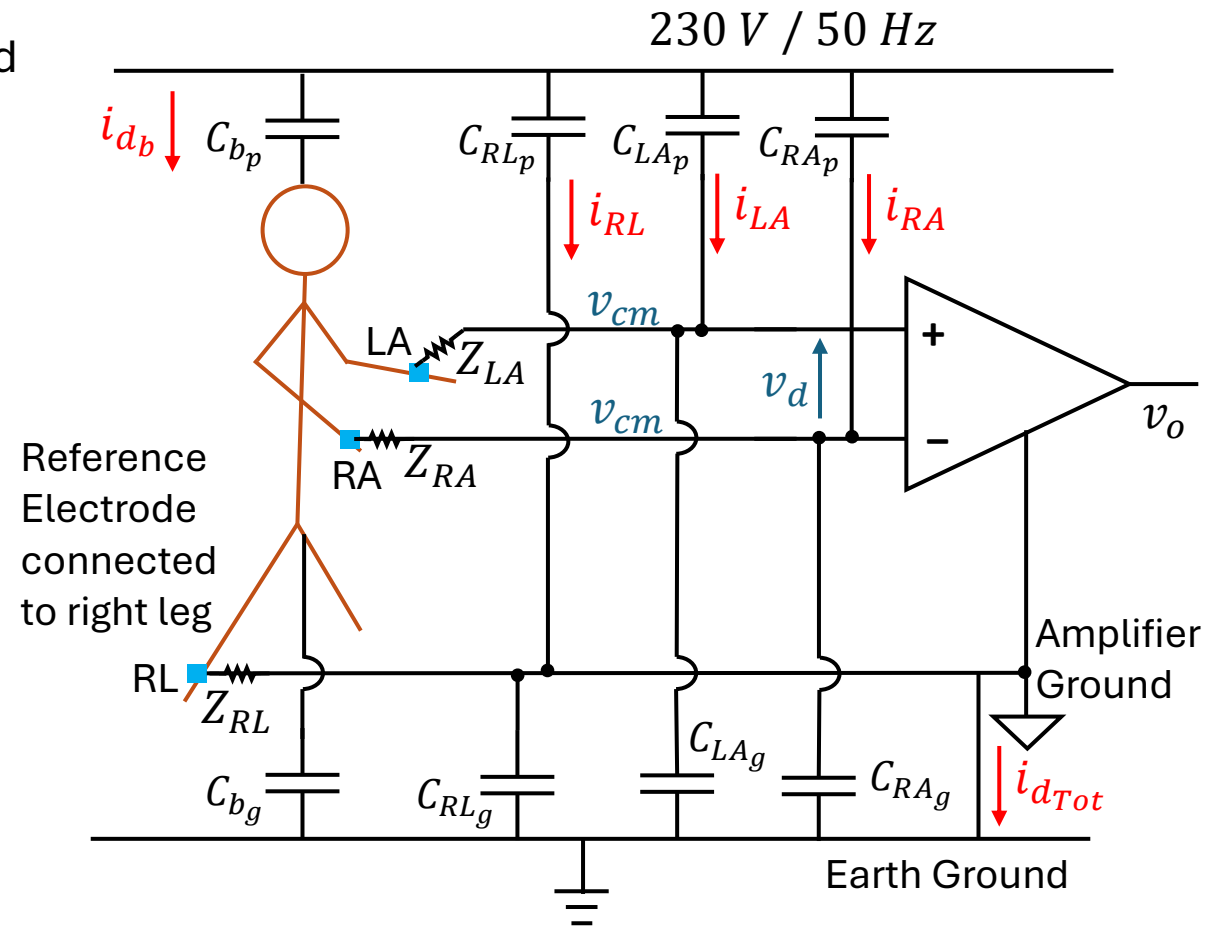
- Therefore, the displacement currents will get converted into differential mode voltages.
- Due to the displacement currents on the two input terminals going through the different electrode impedances, the amplifier will see a differential voltage of:

$$v_d = i_{LA}Z_{LA} - i_{RA}Z_{RA}$$



# Displacement Currents and ECG

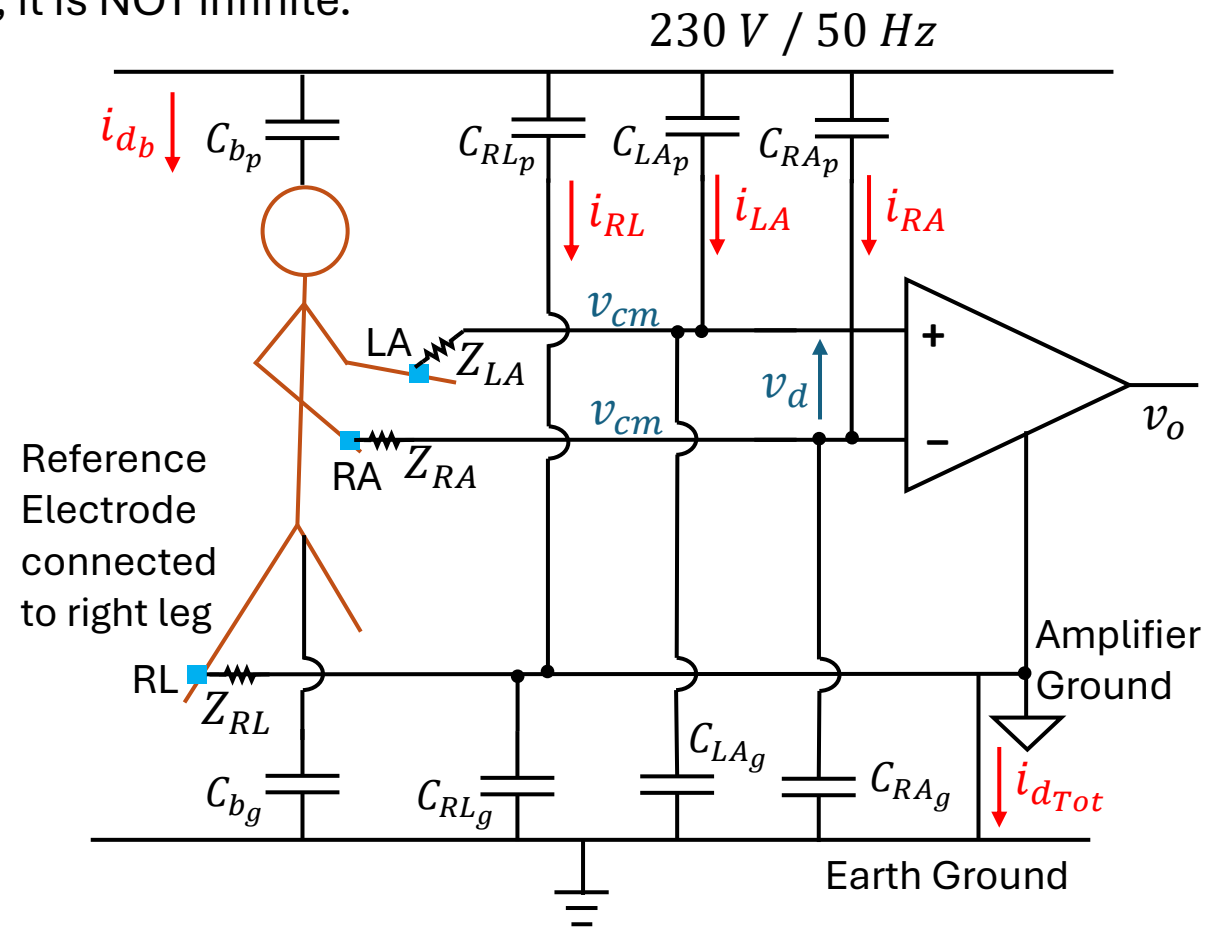
- When the amplifier ground is earthed (mains-powered ECG), nearly all of  $i_b = i_{d_b} + i_{LA} + i_{RA}$  flows through  $Z_{RL}$ .
- This acts as a common mode fluctuation on both terminals of the amplifier.
  - $v_{cm} = i_b \times Z_{RL} = (i_{d_b} + i_{LA} + i_{RA}) \times Z_{RL}$
  - Ex: With  $i_b \approx 200$  nA, and  $Z_{RL} \approx 50$  k $\Omega$ ,  $v_{cm} \approx 10$  mV
- For a battery-powered (floating) amplifier, only the current returning through the amplifier's own stray capacitance flows through  $Z_{RL}$  and the rest shunts through  $C_{b_g}$ .
  - So  $v_{cm}$  is much smaller.



# Capacitive Coupling

## Displacement Currents and ECG

- Even if we had a perfect match between the  $Z_{LA}$  and  $Z_{RA}$  electrode-skin impedances, the presence of the  $v_{cm}$  common mode voltage can induce differential voltage due to another phenomenon.
  - Although the input impedance of the amplifier is high, it is NOT infinite.
    - Therefore, there is a potential divider effect happening between the ( $Z_{RA}$  and  $Z_{in-}$ ) and another between the ( $Z_{LA}$  and  $Z_{in+}$ ).
    - Therefore, this too creates another differential voltage that the amplifier will amplify.
    - For simplicity, assume  $Z_{in+} = Z_{in-} = Z_{in}$
    - $$v_d = v_{cm} \times \left( \frac{Z_{in}}{Z_{in} + Z_{LA}} - \frac{Z_{in}}{Z_{in} + Z_{RA}} \right)$$



# The electrode offset voltage

- This is another phenomenon that adds **DC differential** voltage at the input of the amplifier.
  - At every metal-electrolyte interface, a half-cell potential forms.
    - A wet ECG electrode has electrode gel as the electrolyte.
    - Sweat could act as an electrolyte for a dry ECG electrode.
    - For Ag/AgCl electrodes, the half cell potential is  $E_{hc} \approx 220$  mV relative to the standard hydrogen electrode.
  - A differential voltage  $v_d$  forms if the two electrodes (RA and LA) have different half cell potentials.
    - $v_d = E_{hc_{RA}} - E_{hc_{LA}}$
    - If the two half cell potentials are equal, the differential voltage will be zero.
    - However, practically they are rarely equal – the mismatch comes from:
      - Different skin conditions, gel or sweat under each electrode, temperature, contact pressure, motion, etc.
    - This differential voltage adds on top of the other common mode and differential interference voltages.
- Note:
  - Although electrode offset voltage is a DC quantity, it can drift over time due to electrode movement, loosening, sweating, etc.

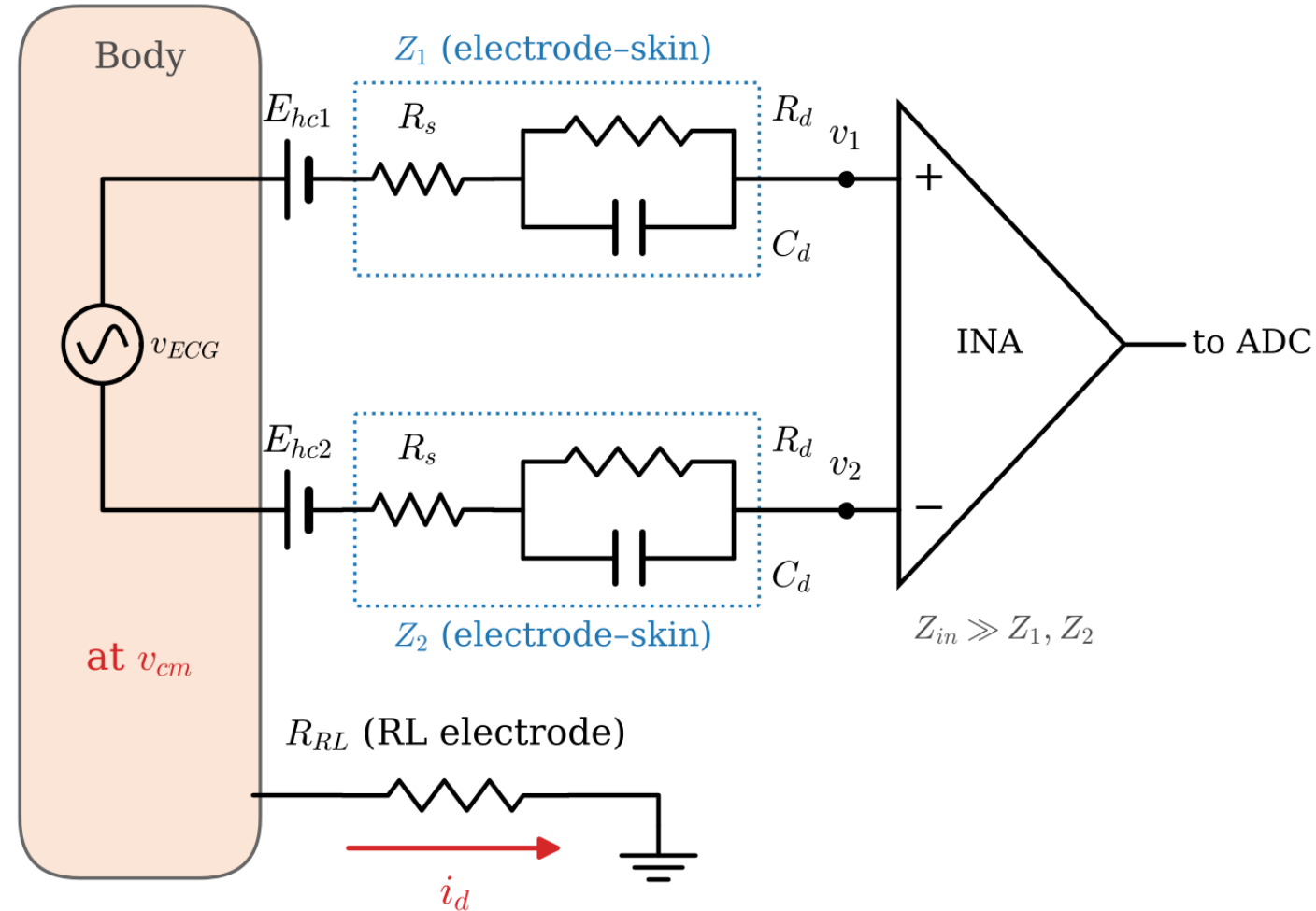
# The electrode offset voltage

- The electrode offset voltage can be as small as 1 mV for matched electrodes with well prepared skin.
  - However, with aged electrodes, drying gel, sweating, etc., it can increase to tens or even hundreds of mV.
  - ECG device standards require that the front-end be able to handle up-to  $\pm 300$  mV of offset voltage.
- How does this become a problem?
  - A DC differential voltage of the worst case 300 mV would seriously limit the gain that the front-end amplifier can have.
    - If we have a frontend amplifier running on 3.3 V power rails, the maximum gain it can have before saturating the output is  $3.3\text{V}/300\text{mV} = 11$ .
    - At 11 times gain, the tiny ECG signal of about just 1 mV would only be amplified to 11 mV!
    - Now, a 10-bit ADC supplied with  $V_{FS} = 3.3$  V will have a resolution of  $\frac{3.3}{2^{10}} = 3.2$  mV.
      - The ECG features will no longer be captured with enough fidelity!
    - This is why we tend to use higher resolution ADCs (ex: 24-bit) so that we can keep the front-end gain low while still being able to capture the ECG waveform.
    - Another approach is to send the signal amplified by the small gain through a high-pass filter so that the DC offset gets removed, and a second amplification stage amplifies just the faster-changing voltages.

# The electrode-skin interface

## Summary figure

- $i_d$  is the displacement current through the body due to powerline interference.
  - The body is at the common-mode voltage  $v_{cm} = i_d Z_{RL}$
- Each electrode adds an impedance:
  - $Z = (R_s + R_d \parallel C_d)$
  - For AC powerline interference (50Hz), the impedance can range from tens of k $\Omega$  up to the M $\Omega$  range.
  - Displacement currents flowing through give rise to differential voltages.
- Each electrode adds a half-cell potential:
  - Electrode offset voltage:  $E_{hc1} - E_{hc2} \neq 0$



# Summary of issues and mitigation strategies

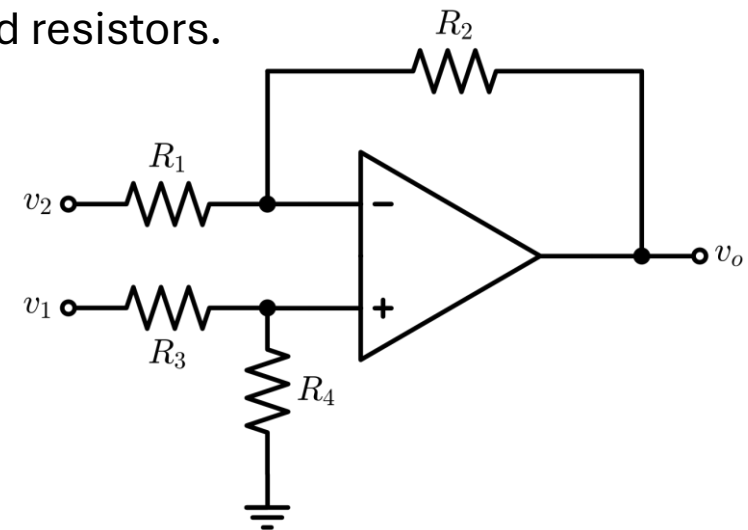
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- Differential mode voltages:
  - Displacement currents flowing through mismatched electrode impedances.
  - DC electrode offset voltage.
  - Common mode current flowing through finite input impedance and mismatched electrode impedances.
- Common mode voltages:
  - Displacement currents flowing through the body into the grounded reference electrode at the right leg.
- Mitigation strategies:
  - Displacement currents flowing through the mismatched electrode impedances can be mitigated by shielding the wires leading to the electrodes, keeping them short, etc.
  - Electrode mismatch can be reduced with better electrodes and skin preparation.
  - Saturation due to DC electrode offset voltage can be mitigated with lower front-end gain + higher resolution ADC.
  - Input impedance can be increased by multiple orders by using an instrumentation amplifier instead of a simple difference amplifier (this also improves the CMRR).
  - Magnitude of the common mode voltages can be reduced via the 'Driven Right Leg' circuit.

# Difference Amplifier input impedance and CMRR

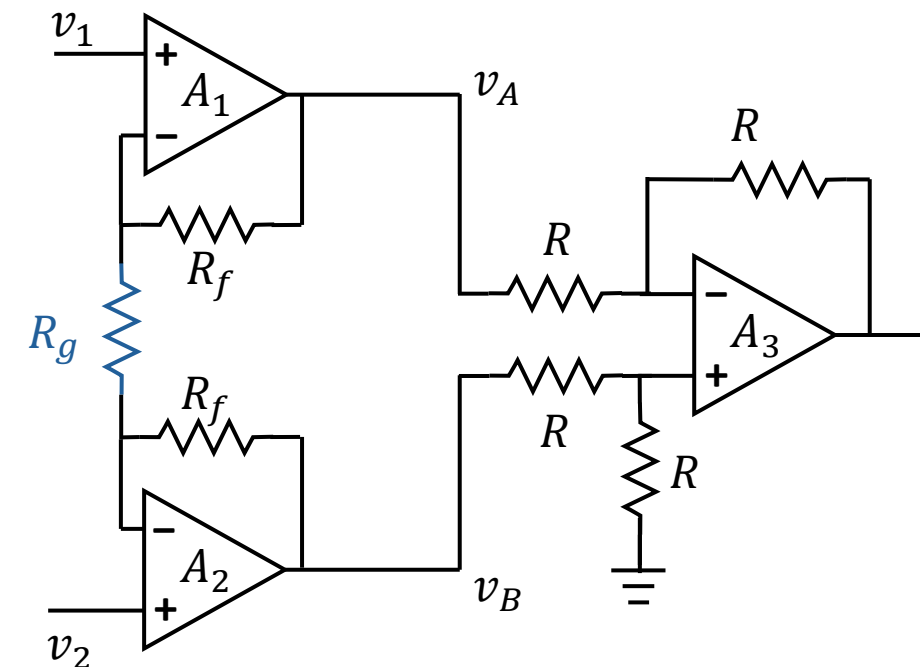
- The difference amplifier theoretically has an infinite CMRR with matched resistors  $\left(\frac{R_4}{R_3} = \frac{R_2}{R_1}\right)$ .
  - However, we also observed how this is practically difficult to achieve due to resistor tolerances, and the presence of source impedances that may be variable.
  - This is exactly the case with the ECG.
    - The source impedances on each electrode can vary!
- The input impedance of a difference amplifier has two different values at the two different inputs.
  - For the inverting input, the input impedance is  $(R_1 + R_2)$  for common mode voltages.
    - $\because v_o = 0$  for common mode inputs for a differential amplifier with matched resistors.
  - For the non-inverting input, the input impedance is  $(R_3 + R_4)$ 
    - $\because$  No current flows into the input of the amplifier.

$$v_o = v_1 \left( \frac{R_4}{R_3 + R_4} \right) \left( \frac{R_1 + R_2}{R_1} \right) - v_2 \left( \frac{R_2}{R_1} \right)$$



# Instrumentation Amplifier input impedance and CMRR

- The INA is a difference amplifier with signals fed via two non-inverting gain stages at each input.
  - Since the input stages are non-inverting, their input impedance becomes extremely high.
  - In an INA IC, you only have to externally set the gain resistor  $R_g$ , so no resistor matching required.
- Since the second differential amplifier stage doesn't see the electrode impedances at all, it is easier to maintain the ideal CMRR by matching the resistor tolerances.
  - Source (electrode) impedances cannot upset the resistor ratios.
- Since there are two series stages, the total  $CMRR_{total}$  is the of the second stage  $CMRR_2$  amplified by the differential mode gain  $G_1$  of the first stage.
  - $CMRR_{total} = G_1 \times CMRR_2$
- The first stage has a common-mode gain of 1.
  - i.e., the second stage receives the differential mode signals amplified by  $G_1$  but common mode signals remain the same.
  - The output of the first stage can be used to sample the common-mode voltage without loading the electrodes.



# Instrumentation Amplifier Benefits

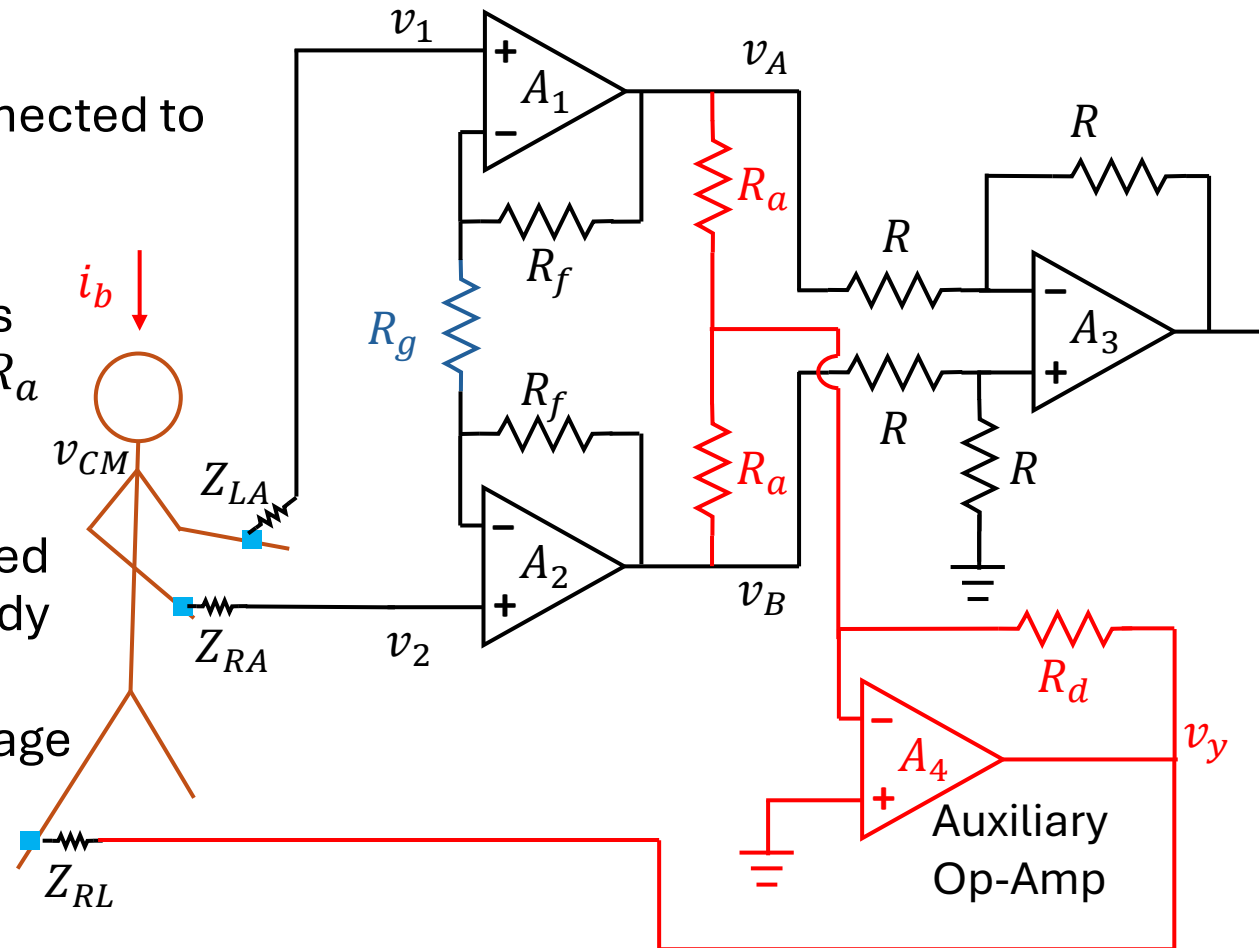
## Summary

- The INA allows:
  - Higher input impedance:
    - Hence the **common mode voltage** will not turn into a significant differential voltage due to the electrode impedance mismatches.
      - Note: The **displacement currents** flowing through the electrode mismatch will still create a differential voltage.
    - Prevents signal loading (dropping of the signal across the electrode impedances due to non-zero current flowing into the amplifier due to inadequate input impedance).
  - Matched input impedance:
    - Unlike a difference amplifier, the input impedance of the inverting and non-inverting inputs of an instrumentation amplifier are not different.
  - Higher CMRR, hence reduces the transfer of the common-mode fluctuations to the output side.
  - Allows the tapping into the common mode voltage that can be used as an input to the **driven right leg** circuit.
  - Only need to set the gain resistor externally, hence the amplifier characteristics like CMRR does not require tuning.

# Common-mode voltage mitigation

## The Driven Right Leg

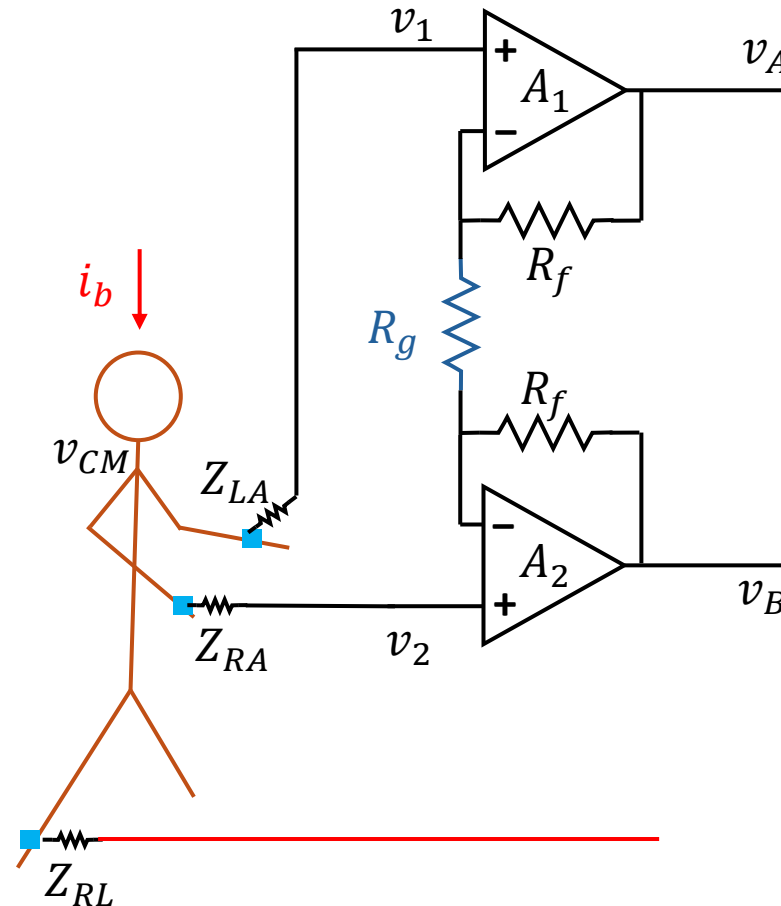
- In most modern ECG systems the patient is not grounded.
  - Instead, active common-mode compensation is used.
  - This is often referred to as driven-right-leg (DRL)
  - Note: The DRL electrode does not have to be connected to the right leg.
- DRL principle of operation:
  - First, the common mode signal on the body  $v_{CM}$  is sensed – This is done via two averaging resistors  $R_a$  tapped into the output of the first amplification stage of the INA.
  - This common mode signal is inverted and amplified via the auxiliary op-amp, and fed back into the body via the DRL electrode.
  - Negative feedback drives the common mode voltage  $v_{CM}$  towards zero, hence the amplifier has less common mode noise/signal to reject.



# Driven-Right-Leg

## Webster, example 6.4

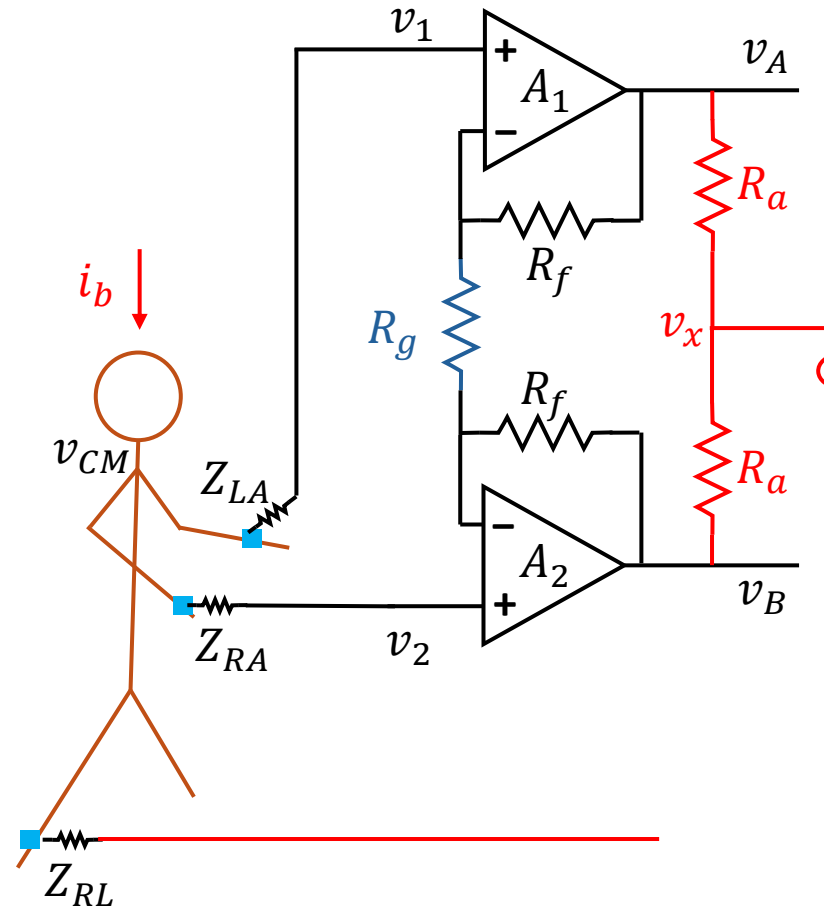
- Assume a displacement current  $i_b$  flows from the powerlines into the RL electrode through the patient's body.
  - This leads to a common-mode voltage  $v_{cm}$  throughout the patient's body.
  - The differential mode signals like the ECG itself, and differential interference and noise voltages all appear on top of this  $v_{CM}$ .
- Assuming the input voltages at each input of the INA to be  $v_1$  and  $v_2$ , we have
  - $v_A = v_1 + \frac{R_f}{R_g}(v_1 - v_2)$  and
  - $v_B = v_2 - \frac{R_f}{R_g}(v_1 - v_2)$



# Driven-Right-Leg

## Webster, example 6.4

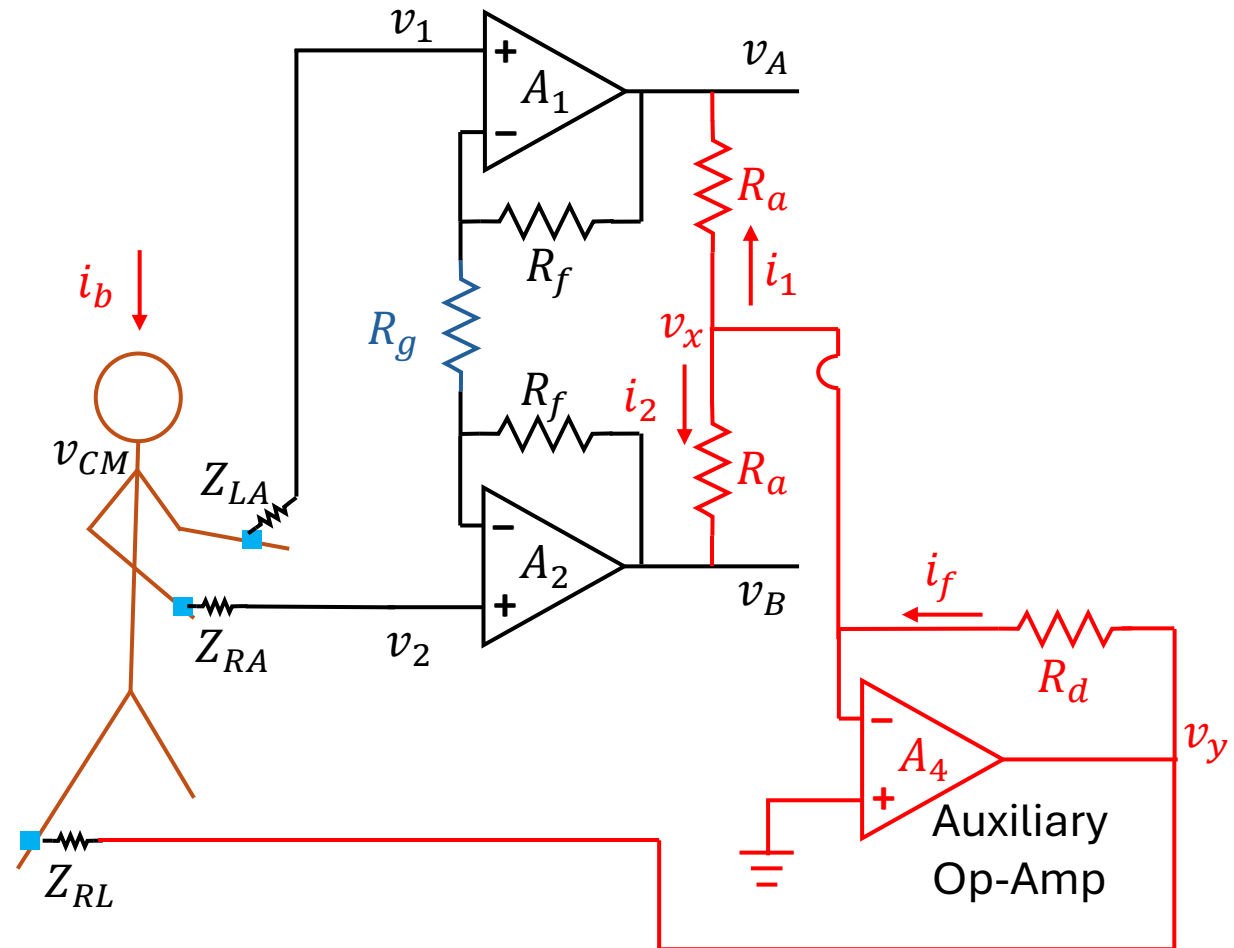
- We can segregate  $v_1$  and  $v_2$  into common mode and differential mode components:
  - $v_1 = v_{CM} + \frac{v_{DM}}{2}$  and  $v_2 = v_{CM} - \frac{v_{DM}}{2}$
  - Now,
    - $v_A = v_1 + \frac{R_f}{R_g}(v_1 - v_2) = v_{CM} + \left(\frac{R_f}{R_g} + \frac{1}{2}\right)v_{DM}$
    - $v_B = v_2 - \frac{R_f}{R_g}(v_1 - v_2) = v_{CM} - \left(\frac{R_f}{R_g} + \frac{1}{2}\right)v_{DM}$
  - Now, if we calculate the voltage  $v_X$  at the center of the two  $R_a$  resistors,
    - $v_X = v_B + (v_A - v_B) \times \frac{1}{2} = \frac{v_A + v_B}{2} = v_{CM}$
    - Therefore,  $v_X$  acts as a good location to sample the common-mode voltage without loading the electrodes!
    - However, note that  $v_X = v_{CM}$  is ONLY valid as long as there is nothing drawing current out of that center point.



# Driven-Right-Leg

## Webster, example 6.4

- Next, we connect the auxiliary op-amp inverting amplifier with feedback resistor  $R_d$ .
  - The two  $R_a$  resistors act as the input resistors for the signals from  $v_A$  and  $v_B$ .
  - Now, a current will flow along the  $R_a$  resistors.
    - Since the auxiliary amplifier is in negative feedback, its two input terminals will be virtual short, and because the non-inverting input is grounded, the inverting input will also be pulled to ground, hence  $v_x = 0$ .
  - The current flowing through the feedback branch  $i_f$  is therefore:
    - $$i_f = i_1 + i_2 = \frac{0 - v_A}{R_a} + \frac{0 - v_B}{R_a} = -\frac{v_A + v_B}{R_a} = -\frac{2v_{CM}}{R_a}$$
  - Therefore, the output voltage  $v_y$  is:
    - $$(v_y - 0) = R_d \times i_f \Rightarrow v_y = -\frac{2v_{CM}R_d}{R_a}$$



# Driven-Right-Leg

## Webster, example 6.4

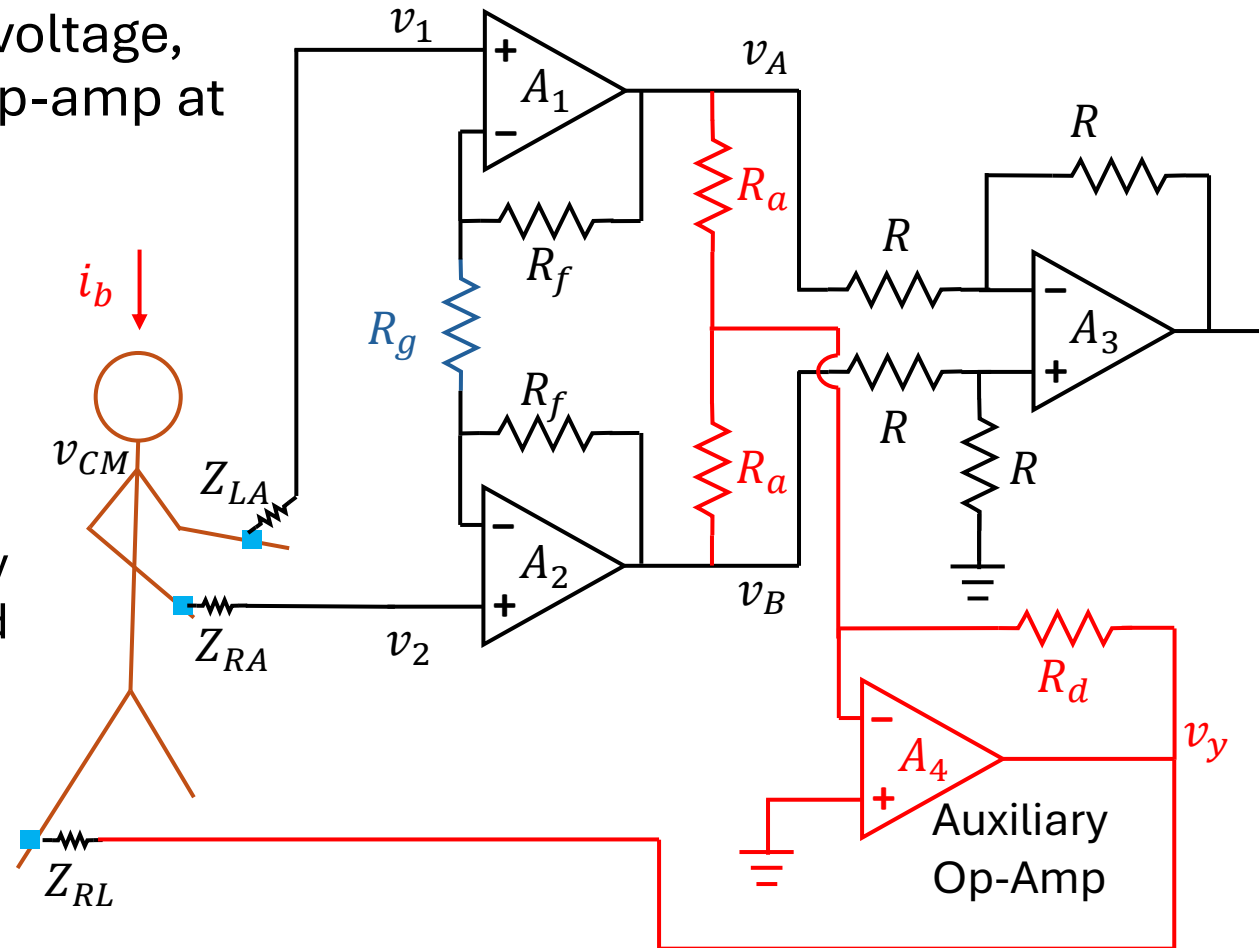
- The displacement current  $i_b$  from the powerline coupling flows through  $Z_{RL}$  electrode impedance where one side of this impedance is connected to the body at  $v_{CM}$  voltage, and the other side to the output of the auxiliary op-amp at  $v_y$  voltage.

- Therefore, from Ohm's law across  $Z_{RL}$ :

$$i_b = \frac{v_{CM} - v_y}{Z_{RL}} = \frac{v_{CM} + \frac{2v_{CM}R_d}{R_a}}{Z_{RL}} = v_{CM} \times \frac{1 + \frac{2R_d}{R_a}}{Z_{RL}}$$

$$\therefore v_{CM} = i_b \times \left( \frac{Z_{RL}}{1 + \frac{2R_d}{R_a}} \right)$$

- Compare this to the  $v_{CM} = i_b \times Z_{RL}$  we previously had when the RL electrode was simply connected to ground.
  - It appears that connecting the DRL has effectively shrunk the common-mode voltage on the body by a factor of  $1 + 2R_d/R_a$



# Driven-Right-Leg

## Webster, example 6.4

- In a different perspective, we can say that the RL electrode impedance  $Z_{RL}$  had shrunk by this same factor effectively.
  - Hence,  $Z_{RL_{Eff}} = \frac{Z_{RL}}{1 + \frac{2R_d}{R_a}}$
  - Therefore, via negative feedback, the DRL reduces the common-mode voltage on the body, thereby mitigating the downstream effects of this common-mode voltage such as amplifier saturation and differential voltage generation.
- We would like the effective impedance  $Z_{RL_{Eff}}$  to be as low as possible during normal operation.
  - This ensures that the  $v_{CM} = i_b Z_{RL_{Eff}}$  remains low!
  - Therefore, large values are chosen for  $R_d$  and small values for  $R_a$  so that  $R_d/R_a$  remains large.
  - Typical values of  $R_a = 20 \text{ k}\Omega$  and  $R_d = 5 \text{ M}\Omega$  may be used.
  - Assuming  $i_b = 200 \text{ nA}$ , and  $Z_{RL} = 50 \text{ k}\Omega$ ,
    - For the scenario where a DRL is NOT used,  $v_{CM} = 10 \text{ mV}$ .
    - When DRL is used,  $v_{CM} \approx 20 \text{ }\mu\text{V}$ , hence a reduction by a factor of 400 for the chosen resistance values!

# Driven-Right-Leg

## Webster, example 6.4

- The DRL introduces a safety risk to a patient.
  - If the auxiliary op-amp gets saturated for some reason (ex: high transient  $v_{CM}$ ), a low impedance path to ground may be formed through the output terminal of the op-amp.
  - To limit the current that could flow through the body below the regulatory values, a large resistance  $R_O \approx 5 \text{ M}\Omega$  is added in series with the output.
  - Now, the maximum current that can flow through the op-amp will be limited to approximately  $R_O || R_f = 5 \text{ M}\Omega || 5 \text{ M}\Omega = 2.5 \text{ M}\Omega$  when the op-amp saturates.
  - Thus large ( $> 1 \text{ M}\Omega$ ) values of  $R_f$  and  $R_O$  are used to limit the current to the body below regulatory values (electrical safety).

