BENG 186B Winter 2015 Final

Tuesday, March 17, 2015

Last Name, First Name: _____

- This final is closed book and closed notes. You may use a calculator for algebra and arithmetic.
- This final has 24 pages, including this cover sheet. Do not attach separate sheets. If you need more space, use the back of the pages.
- Circle or box your final answers and show your work on the pages provided.
- There are 10 problems. Points for each problem are given in **[brackets]**. There are 100 points total.
- You have 3 hours to complete this final.

1	/16
2	/8
3	/12
4	/10
5	/10
6	/10
7	/6
8	/12
9	/12
10	/4
Total	**/100**

You may find the following equations useful:

$$V = IR$$

$$V_o = A_d V_d + A_c V_{cm}$$

$$V_d = V_b - V_b$$

$$V_{cm} = (V_b + V_a)/2$$

$$V = \mathbf{M} \cdot \mathbf{r} = \cos\theta |\mathbf{M}||\mathbf{r}|$$

$$e = \int_0^\ell \mathbf{v} \times \mathbf{B}\, d\ell$$

$$\Delta f = \frac{v}{c}(\cos\theta_r + \cos\theta_s) f_s$$

$$V = E_{\text{glass}} - E_{\text{ref}} + E_{\text{Nernst}}$$

$$E_{\text{Nernst}} = \frac{RT}{F} \ln(10) \log_{10} \left(\frac{[\text{A}]_{\text{out}}}{[\text{A}]_{\text{in}}} \right) \text{ for some ion A}$$

$$V_m = \frac{RT}{F} \ln(10) \log_{10} \frac{P_{\text{Na}}[\text{Na}^+]_o + P_{\text{K}}[\text{K}^+]_o + P_{\text{Cl}}[\text{Cl}^-]_i}{P_{\text{Na}}[\text{Na}^+]_i + P_{\text{K}}[\text{K}^+]_i + P_{\text{Cl}}[\text{Cl}^-]_o}$$

$$\frac{RT}{F} \ln(10) = 62\,\text{mV at room temperature}$$

$$F = 96\,485\,\text{C/mol}$$

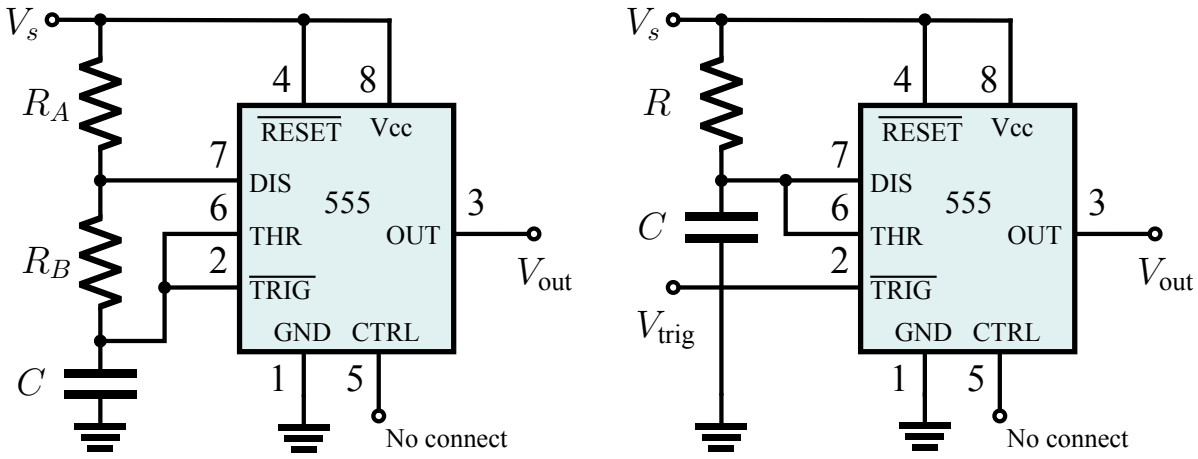
$$I = 4F[\text{O}_2]\phi$$

$$\log_{10} \text{PCO}_2 = -\text{pH} + \text{constant}$$

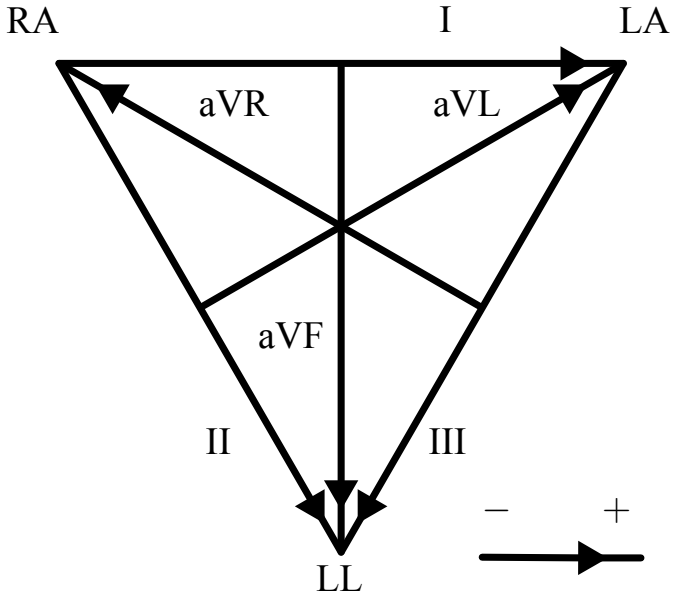
$$\text{O}_2 + 2\,\text{H}_2\text{O} + 4\,\text{e}^- \rightleftharpoons 4\,\text{OH}^-$$

$$4\,\text{Ag} + 4\,\text{Cl}^- \rightleftharpoons 4\,\text{AgCl} + 4\,\text{e}^-$$

The following diagrams may come handy as well:



$T_{\text{hi}} = 0.7(R_A + R_B)C$ $T_{\text{lo}} = 0.7R_BC$ $T = 1.1RC$



1. **[16 pts]** Circle the **best answer (only one answer per question)**:

   (a) [1 pt] You want to digitally capture voltages between 0 V to 1 V with an LSB of 0.001 V. What is the minimum number of bits the ADC needs to output?

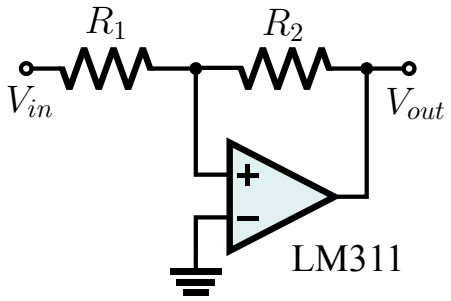
   i. 8 bits
   ii. 10 bits
   iii. 12 bits
   iv. 16 bits
   v. 24 bits

   (b) [1 pt] For a capacitive sensor, increasing the distance x between the two plates:

   i. Increases the sensitivity of capacitance to lateral displacement.
   ii. Decreases the sensitivity of capacitance to lateral displacement.
   iii. Increases the sensitivity of capacitance to transversal displacement.
   iv. Decreases the sensitivity of capacitance to transversal displacement.
   v. None of the above.

   (c) [1 pt] The circuit shown below implements what function?

   i. Inverting amplifier
   ii. Inverting comparator
   iii. Hysteretic comparator
   iv. Half-wave rectifier
   v. None of the above



   (d) [1 pt] Why is it beneficial to include hysteresis in a comparator design?

   i. Increases the response time of the comparator
   ii. Improves threshold signal detection
   iii. Increases the linear region of the op-amp
   iv. Filters out high frequency noise
   v. None of the above

(e) [1 pt] What is the approximate range of frequencies in the signals measured in EEG?

i. Less than 0.1 Hz.
ii. 0.1 Hz to 3 Hz.
iii. 3 Hz to 100 Hz.
iv. 100 Hz to 500 Hz.
v. None of the above.

(f) [1 pt] An inhibitory synapse:

i. Causes inward flow of positive ions into the postsynaptic neuron leading to a local current sink in the extracellular biopotential.
ii. Causes negative ions to flow outside of the postsynaptic neuron leading to a decrease in the membrane potential.
iii. Causes an outward current from the postsynaptic neuron generating a local current source in the extracellular biopotential.
iv. Causes a rise in the membrane potential of the postsynaptic neuron.
v. None of the above.

(g) [1 pt] Pulse oximetry is an optical technique for determining SpO_2 in blood. It works by finding the:

i. Difference of the absorbances at 660 nm (isobestic) and 805 nm.
ii. Difference of the absorbances at 805 nm (isobestic) and 660 nm.
iii. Ratio of the absorbances at 660 nm (isobestic) and 805 nm.
iv. Ratio of the absorbances at 805 nm (isobestic) and 660 nm.
v. None of the above.

(h) [1 pt] In the event of an unexpected electrical current discharge, what is the advantage of grounded chassis vs. an ungrounded chassis?

i. In the event there is charge buildup on the device with a grounded chassis, there now exists a path to potentially discharge the charge.
ii. A grounded chassis prevents high-frequency voltage electrocution.
iii. A grounded chassis prevents low-frequency voltage electrocution.
iv. A grounded chassis caps the maximum charge accumulation on a device to ensure the maximum current is less the let-go current.
v. It prevents macroshock, but not microshock.

(i) [8 pts] Indicate for each statement below whether it is true or false:

i. **TRUE / FALSE**: Volume conduction of large numbers of current dipoles in the body leads to biopotentials that can be measured on the body surface.

ii. **TRUE / FALSE**: The P wave represents atrial repolarization.

iii. **TRUE / FALSE**: The QRS complex measures the summation of all the action potentials causing contraction uniformly across the heart.

iv. **TRUE / FALSE**: The physical basis of using a tonometer to measure blood pressure is Newton's third law of motion: to every action there is always an equal opposed reaction.

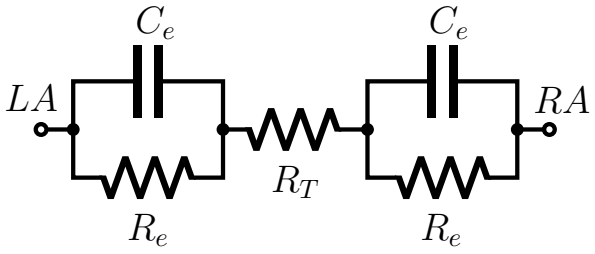
v. **TRUE / FALSE**: Without the polarizing voltage across a Clark electrode, current will flow in the direction from the Ag/AgCl electrode to the Pt electrode.

vi. **TRUE / FALSE**: A pulse oximeter measures oxygen saturation as a function of absorptivity in the red and IR wavelengths.

vii. **TRUE / FALSE**: $I_d = I_r/(1 - \exp(-d/\tau))$ signifies that when the duration of current stimulation is a significantly shorter than the time constant for the cell type, the charge delivered by the stimulation is more important.

viii. **TRUE / FALSE**: The difference between a macroshock and microshock is in the point of entry through which the current flows.

2. **[8 pts]** Some ECG machines can monitor a patient's breathing rate using a technique called *impedance pneumography*. The machine does this by measuring the impedance across the LA and RA electrodes:



Here, R_e and C_e represent the double–layer formed in the gel electrodes and R_T represents the impedance of the thoracic cavity. R_T changes as the person breathes, which can be measured.

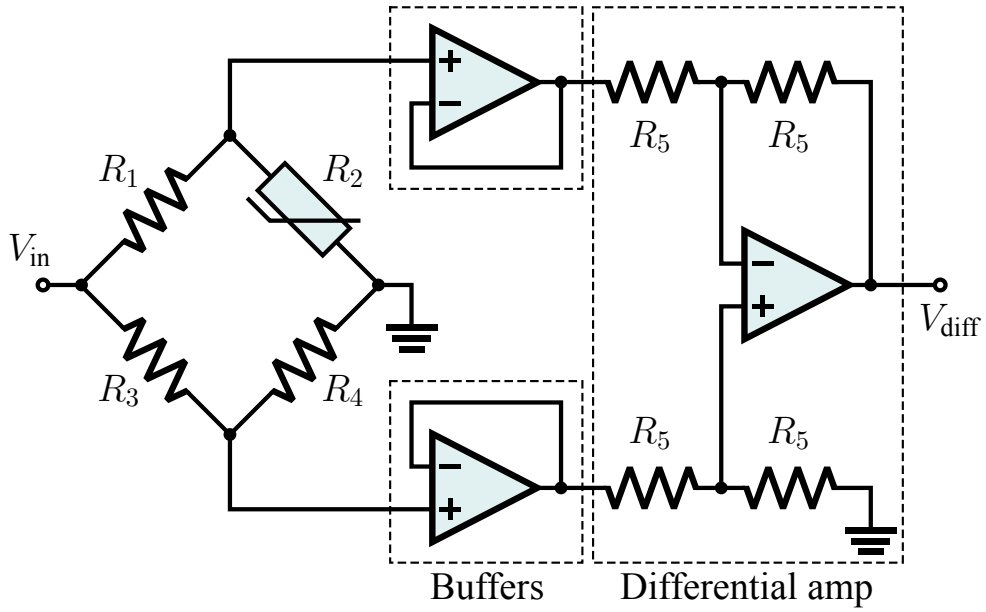
(a) [4 pts] What is the total impedance between RA and LA? Write your answer in standard form $a + jb$.

(b) [1 pt] Write an expression for the magnitude of the total impedance.

(c) [1 pt] Write an expression for the phase of the total impedance.

(d) [2 pts] In practice, R_T changes very little between breaths, on the order of only about $\pm 1\ \Omega$. This is dwarfed by the gel electrode resistance. Without changing the electrodes themselves, how could you minimize their impedances? *Hint:* how does a capacitor behave over different frequencies?

3. **[12 pts]** You have a strain gauge R_2 and a Wheatstone bridge connected to (a variant of) an instrumentation amplifier (shown below):

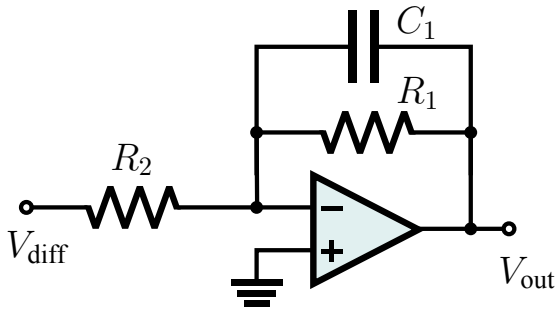


(a) [2 pts] Assume the op–amps are ideal. Write an expression for V_{diff} in terms of the resistances and V_{in}. *Hint:* What is the differential gain of the differential amplifier?

(b) [2 pts] Why are the buffers needed?

(c) [2 pts] How can you modify the above Wheatstone bridge to maximize sensitivity and provide temperature compensation?

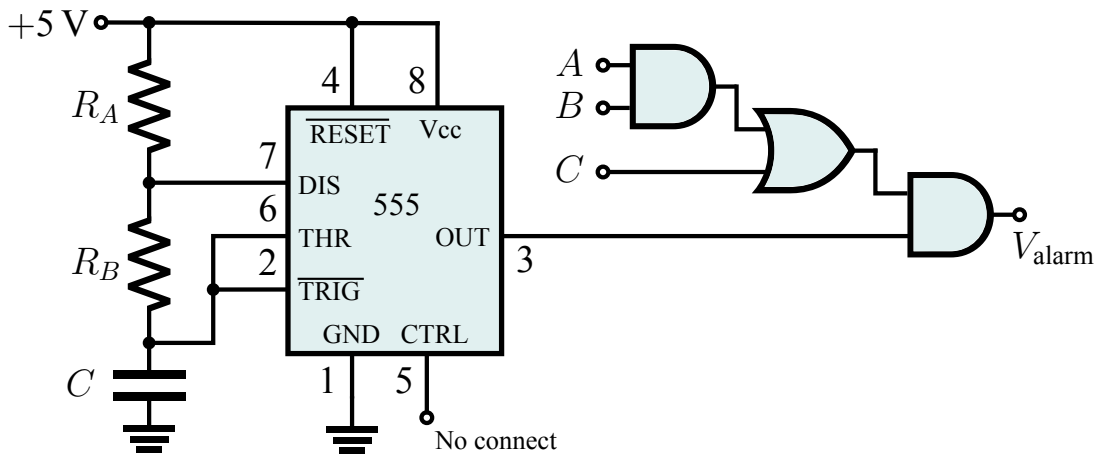
(d) [2 pts] You add the filter shown on the right to the above circuit. Derive, **from first principles**, the filter's transfer function. Assume the op–amp is ideal.



(e) [2 pts] What are the cutoff frequencies and the DC gain of this filter?

(f) [2 pts] Sketch the Bode plot of this filter, labeling all significant features on the plot.

4. **[10 pts]** You have a patient monitoring circuit shown below:



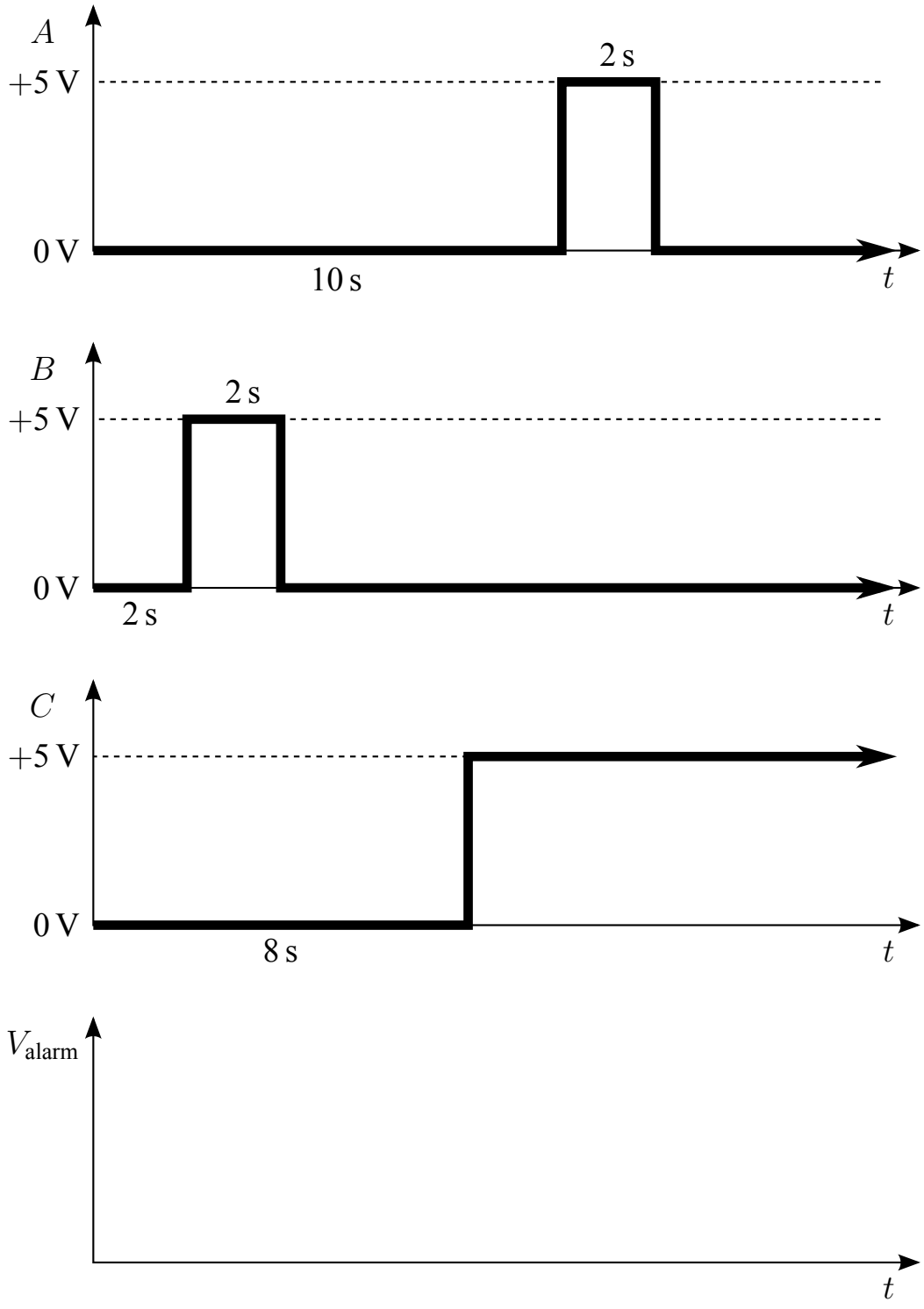
The digital outputs of three different medical instruments are connected to the inputs A, B, and C. Under certain conditions, the circuit outputs a square wave which drives an alarm speaker. This alerts medical staff of an emergency.

(a) [2 pts] Fill in the following truth table for all possible combinations of A, B, and C:

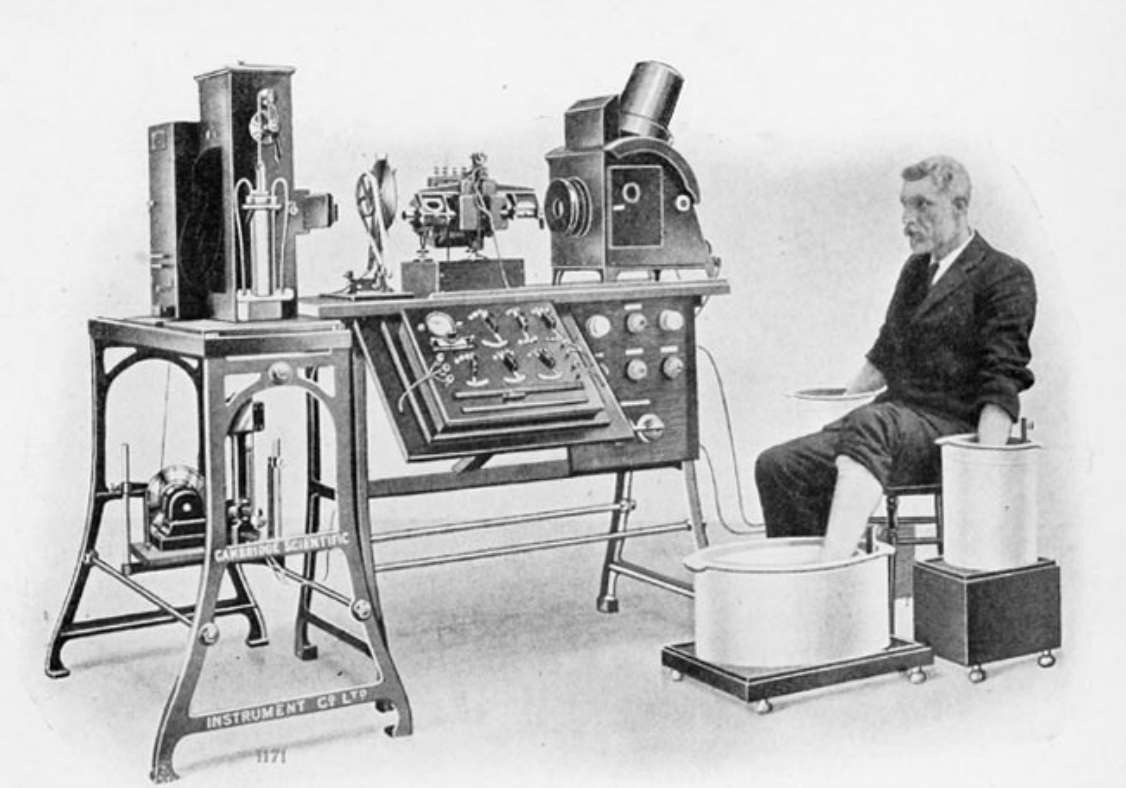
A	B	C	Alarm (yes/no)

(b) [4 pts] Suppose $R_A = 1\,\text{k}\Omega$. What values for R_B, and C could you use to generate a 680 Hz output with a duty cycle of 53% for the alarm speaker?

(c) [4 pts] Using the same quantities from part (b) (680 Hz output with a duty cycle of 53%), sketch and fully label the V_{alarm} waveform given the following input waveforms.



5. **[10 pts]** Electrocardiograms as known today have been measured as early as the turn of the 19th century. Consider the 1911 setup shown below:



PHOTOGRAPH OF A COMPLETE ELECTROCARDIOGRAPH, SHOWING THE MANNER IN WHICH THE ELECTRODES ARE ATTACHED TO THE PATIENT, IN THIS CASE THE HANDS AND ONE FOOT BEING IMMERSED IN JARS OF SALT SOLUTION

(a) [3 pts] Which leads of the electrocardiogram can be obtained with this setup? Specify how to obtain each of these leads from the electrical potentials of the three basins connected to the respective limbs.

(b) [2 pts] Explain why this setup works without a driven right leg.

(c) [2 pts] Does the setup shown above give information on components of the cardiac vector in the transversal plane? Why or why not?

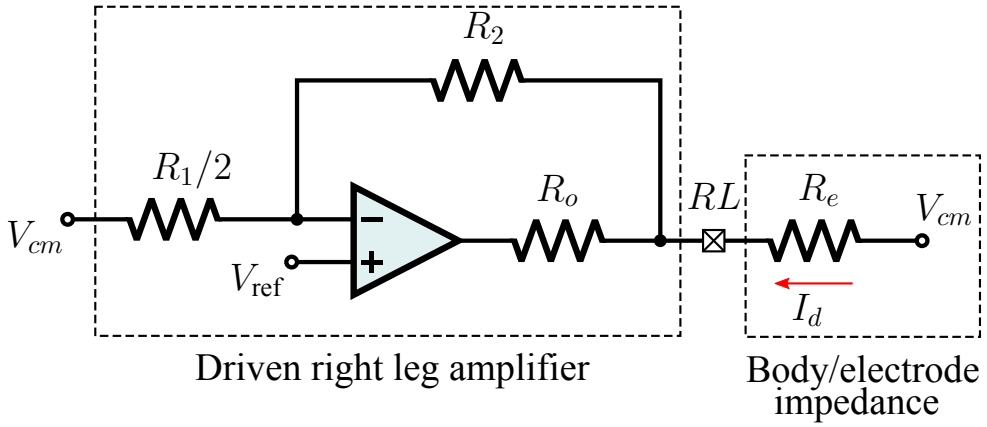
(d) [3 pts] Suppose the cardiac vector points in the opposite direction of aVR and has a magnitude of $2\sqrt{3} \approx 3.46\,\text{mV/m}$. If the bipolar lead vectors are 1 m in magnitude, what is the voltage magnitude of each of the bipolar leads?

i. lead I:

ii. lead II:

iii. lead III:

6. **[10 pts]** Battery–powered ECG amplifiers often do not have dual positive and negative voltage supplies available, and hence cannot handle signals centered around zero ground potential. As a workaround, you can connect a "ground reference" voltage V_{ref} to the driven right leg (DRL) amplifier in the following way:



(a) [4 pts] Assume that the op–amp is ideal. Derive, **from first principles**, an expression for the voltage on RL.

(b) [2 pts] Derive an expression for V_{cm} in terms of displacement current I_d into the body, ground reference V_{ref}, and the resistances.

(c) [2 pts] Let $R_2 = 50\,\text{k}\Omega$. What value of R_1 should you use to reduce the common–mode noise by 101 times?

(d) [2 pts] The ECG amplifier has a differential gain of 1000 and has a common–mode rejection ratio (CMRR) of 80 dB. Without DRL the SNR at the output of the ECG amplifier is 40 dB. What is the output SNR with the DRL setup from part (c)?

7. **[6 pts]** The table on the right shows ion concentrations found in typical mammalian cells.

Ionic species	Concentration (mM)	
	Intracellular	Extracellular
K^+	400	20
Na^+	50	400
Cl^-	40	550

(a) [2 pts] Determine the Nernst potentials for each of the ionic species.

(b) [2 pts] The conductances for each of the ionic species are:

$$G_{\mathrm{K}} = 3.4 \times 10^{-4}\,\Omega^{-1} \quad G_{\mathrm{Na}} = 3.3 \times 10^{-5}\,\Omega^{-1} \quad G_{\mathrm{Cl}} = 3.0 \times 10^{-4}\,\Omega^{-1}$$

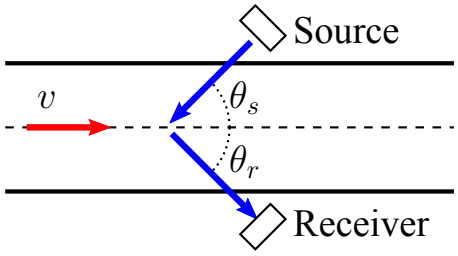
What is the ionic current for each species? Specify if it is going in or out of the cell.

(c) [2 pts] Use the GHK equation to calculate the membrane potential. *Hint:* the conductances are directly proportional to permeability.

8. **[12 pts]** Cardiovascular disease is a leading cause of preventable death worldwide. Knowing this, a doctor (who happens to have a degree in bioengineering) is doing tests on patients to assess their cardiovascular health.

   (a) [2 pts] One way of determining cardiac output is use the Hall effect on a blood vessel. Suppose you applied a 0.5 T magnetic field across the vessel diameter (1.6 cm). As a result, a voltage potential of 30 mV forms across the vessel diameter, perpendicular to the magnetic field. What is the patient's volumetric flow rate through the vessel?

   (b) [2 pts] A doctor uses a much less invasive method involving a 1 MHz ultrasonic transceiver on a patient's vessel, put together as shown on the right.



   With $\theta_r = \theta_s = 30°$, the doctor detects a frequency shift of 1200 Hz. Assume that the speed of sound in blood is 1500 m/s and the vessel cross-sectional area is 2 cm^2. What is the patient's volumetric flow rate through the vessel?

(c) [2 pts] The doctor submerges a pH electrode into the patient's blood sample, which has a pH of 6.9. Both electrodes are almost identical except that the glass electrode containing 10 mM HCl has a half-cell potential of 0.021 V and the reference electrode in the sample has a half-cell potential of 0.036 V. What voltage does the doctor read?

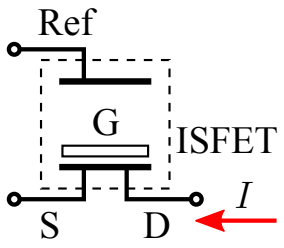
(d) [2 pts] The carbon dioxide electrode is calibrated to 40 mmHg at pH 7.4. What is the partial pressure of carbon dioxide in the patient's blood?

(e) [2 pts] Using a potentiotat with an effective resistance of 100 MΩ, the doctor applies 0.7 V across an oxygen probe, which produces a current. What voltage signal will the doctor measure if the silver electrode is degrading at a rate of 0.3 mmol/s?

(f) [2 pts] Blood pressure is measured (automatically or manually) by listening for Korotkoff sounds. Explain the origin of Korotkoff sounds and how a doctor can determine systole and diastole blood pressure based on those sounds. You may use diagrams in your explanation.

9. **[12 pts] Design problem:** You have an ISFET–based biosensor you would like to interface to a microcontroller. The biosensor can measure immunoglobulin A (IgA) concentration up to 200 nM and has three terminals.

For proper operation, the reference (Ref) terminal needs to be 0.5 V higher than the source terminal (S). In turn, the source terminal needs to be 0.1 V lower than the drain terminal (D). When driven in this way, the ISFET produces a current that is directly proportional to IgA concentration:



$$I = (5 \times 10^{-9}\,\text{A/nM}) \times [\text{IgA}]$$

In addition to the biosensor, you have a ± 5 V supply, a microcontroller, an ADC, and any number of op–amps with any needed resistors and capacitors.

Design a circuit so a microcontroller can read the ISFET. It must:

- Drive the ISFET with the correct voltages mentioned previously.
- Provide a voltage output covering a range of 0 V to 5 V, which is low–pass filtered ($f_c = 100$ Hz) and fed to an ADC digitizing the output.
- Provide a minimum resolution of 0.1 nM in the digital output.

Be sure to specify numerical values for all components, including resistors, capacitors, and the number of bits for the ADC.

(Design problem continued)

10. **[4 pts] Guest lectures**

(a) *Dry ECG and EEG systems*

i. [1 pt] How does contact impedance of a non-contact (capacitive) electrode depend on distance away from the body surface?

ii. [1 pt] What is the challenge of measuring EEG through hair with dry electrodes, and how can it be overcome?

(b) *Global and wireless health*

i. [1 pt] What is cardiotocography, and what does it do to protect the baby in the womb?

ii. [1 pt] How does life expectancy depend on GDP? In particular, what is the trend for countries with GDPs below and above $10,000?