Name (Last, First): ________________________________

BENG 186B Winter 2014

Final

- This exam is closed book, closed notes. Calculators are OK.
- Circle and put your final answers in the space provided; show your work only on the pages provided. Include units.
- Do not attach separate sheets. If you need more space, use the back of the pages. This exam has 25 pages, including this page.
- Points for each problem are given in [brackets], 100 points total.

1	/16
2	/08
3	/10
4	/08
5	/12
6	/10
7	/12
8	/10
9	/10
10	/4
Total	/100

Useful schematics and equations:

The Goldman-Hodgkin-Katz (GHK) equation:

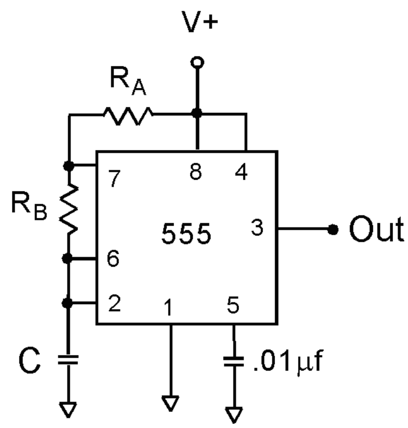
$$E = (60mV)\cdot\log_{10}\frac{P_K\left[K^+\right]_o + P_{Na}\left[Na^+\right]_o + P_{Cl}\left[Cl^-\right]_i}{P_K\left[K^+\right]_i + P_{Na}\left[Na^+\right]_i + P_{Cl}\left[Cl^-\right]_o}$$

Common mode gain and differential gain:

$$v_o = A_d\, v_d + A_c\, v_{cm}$$

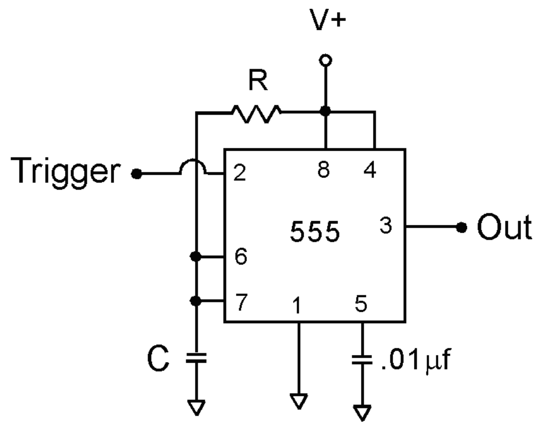
$$v_d = v_a - v_b$$

$$v_{cm} = (v_a + v_b)/2$$



Oscillator

$T_{High} = 0.7\,(R_A + R_B)\,C$; $T_{Low} = 0.7\,R_B\,C$



One-shot

$T_{Pulse} = 1.1\,R\,C$

1) **[16 pts]** Indicate whether each of the following statements is true or false.

[**TRUE / FALSE**] One of the steps in the process of analog-to-digital signal conversion is sampling.

[**TRUE / FALSE**] The minimum sampling frequency is defined by the Nyquist criterion.

[**TRUE / FALSE**] Most sensors capture digital signals, which are then converted to analog for processing.

[**TRUE / FALSE**] A voltage divider is an example of a zeroth-order system.

[**TRUE / FALSE**] The average power dissipated by capacitors and inductors in a circuit is zero.

[**TRUE / FALSE**] A diode bridge rectifier is a useful way to rectify DC voltages to AC voltages

[**TRUE / FALSE**] The Nernst equation is a special case of the Goldman-Hodgkin-Katz equation.

[**TRUE / FALSE**] The ionic concentrations of cells are passively maintained by two processes: diffusion and ionic pump activation.

[**TRUE / FALSE**] Non-polarizable electrodes are preferred for bioinstrumentation measurements.

[**TRUE / FALSE**] A common-mode rejection ratio of 10 watts/watts can be expressed as 10 dB.

[**TRUE / FALSE**] The second-order dynamics of a fluid-filled catheter are due to the inertia and diffusivity of the fluid inside the tube.

[**TRUE / FALSE**] Range-gated (pulsed) Doppler imaging operates by measuring the delays in wave propagation and the frequency difference between the emitted and reflected signals.

[**TRUE / FALSE**] The Clark electrode presents a membrane permeable to O_2, which allows it to measure the CO_2 concentration.

[**TRUE / FALSE**] A potentiostat can be used to measure the concentration of O_2 due to the linear relationship between concentration and electric current when a polarizing voltage is applied between Pt and Ag/AgCl electrodes in a salt buffer solution.

[**TRUE / FALSE**] The isosbestic wavelength defines where the maximum difference between the absorptivities of oxygenated hemoglobin and reduced hemoglobin occurs.

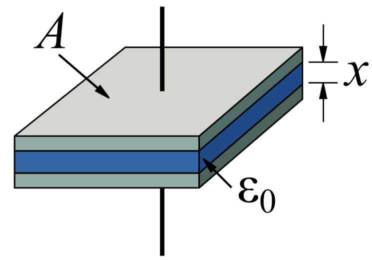
[**TRUE / FALSE**] Diodes can be an effective way of protecting your circuit from over-voltage.

2) **[8 pts]** Short answer, write your answer only in the space provided.

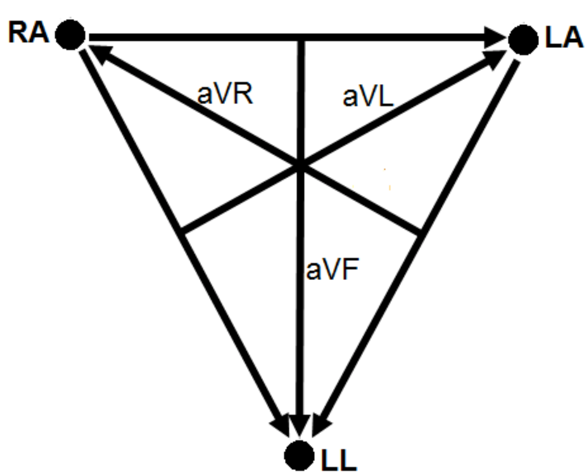
a) Draw a circuit that realizes a high-pass filter with 1 kHz cutoff frequency. Minimize the number of components, and label input and output. [2 pts]

b) For a signal with a range of 1.28 V and 4-bit representation, find the resolution of one least significant bit (1 LSB). [2 pts]

c) For a capacitive sensor of transversal displacement as shown below, derive the sensitivity of the sensor as a function of ε_0, A, and x. [2 pts]



d) Given the Einthoven's triangle, write the most simplified expression for the cardiac leads in terms of the potentials RA, LA, and LL. [2 pts]

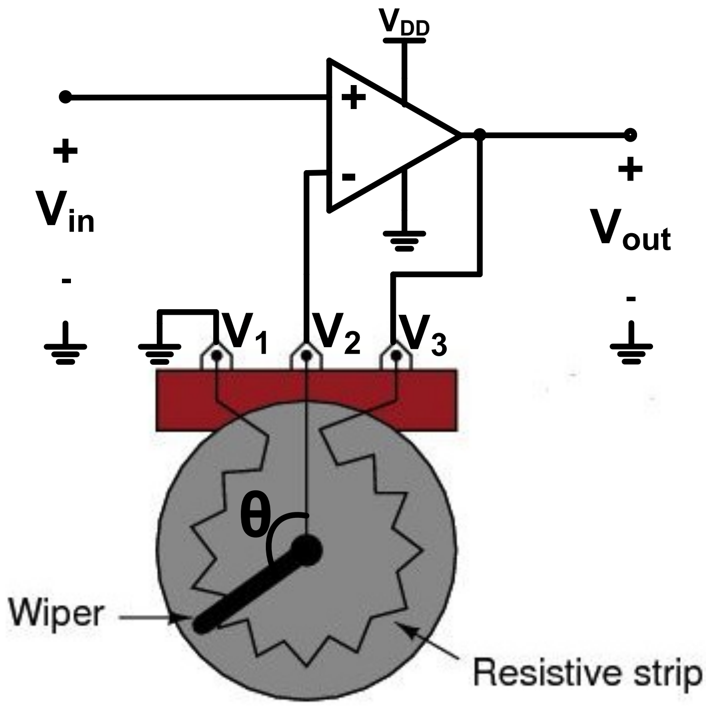


aVR = ______________________

aVL = ______________________

aVF = ______________________

3) **[10 pts]** Consider the following circuit. The potentiometer has a total resistance of 10 kΩ and its angle θ ranges from 10^{o} to 350^{o}.



a) Find θ for a gain (V_{out}/V_{in}) of 4. [6 pts]

b) Find the minimum and maximum achievable gain of the circuit. Show how to change the circuit to limit the maximum gain to 10. [4 pts]

4) **[8 pts]** The resting potential of a cell separated from extracellular fluid by a membrane permeable to Na^+, K^+, and Cl^- is measured at 37 °C. Refer to the table for individual ion concentrations found during the experiment.

Ion	**Intracellular concentration (mM)**	**Extracellular concentration (mM)**
Na^+	10	145
K^+	140	5
Cl^-	4	110

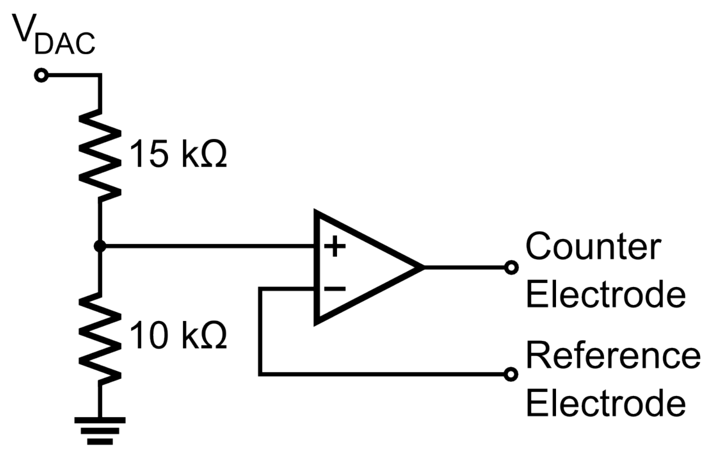
a) Find the Nernst potential for each ion type. [3 pts]

b) When we apply a pharmacological blocker that makes the membrane impermeable to K^+, the resting potential is found to be 30 mV. What is the permeability of Cl^- relative to that of Na^+? [2 pts]

c) Now assume that the cell membrane is only permeable to K^+ ions. How many K^+ ions would have to cross the membrane to lower the membrane potential by 70 mV, and in which direction? Assume the membrane capacitance of the cell to be 1 $\mu F/m^2$ and that the cell is a sphere with diameter of 10 μm. [3 pts]

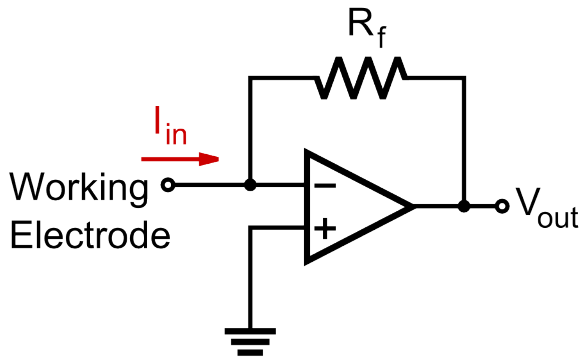
5) **[12 pts]** A crack team of bioengineers developed a glucose meter for their senior design project. You will now get to analyze their basic circuit design to see how it behaves.

a) The glucose test strip needs a bias voltage applied to its counter electrode to work. The team used the following circuit:



The op-amp is ideal, and there is a feedback path through the test strip between the counter and reference electrode. If V_{DAC} is equal to 1 V, what is the voltage at the reference electrode? (*Hint*: what can you say about the two op-amp inputs?) [2 pts]

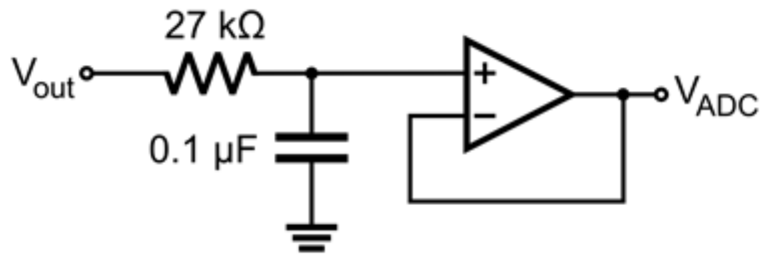
b) When the bias voltage and a glucose sample are applied to the test strip, it produces a small amount of current through its working electrode. The transimpedance amplifier shown below converts this current to a voltage:



The op-amp is ideal. **Derive from first principles** the transfer function V_{out}/I_{in} for the above circuit. [2 pts]

c) Why is this circuit better than a simple resistor? [2 pts]

d) The team also used the following circuit to filter the output of the transimpedance amplifier before it is read by the ADC:



The op-amp is ideal. **Derive from first principles** the transfer function for the above circuit. What kind of filter is this and what is the cutoff frequency? [4 pts]

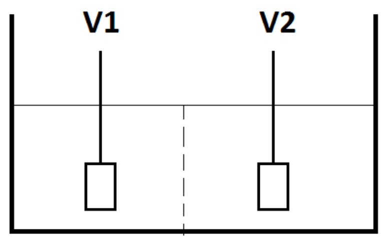
e) **[BONUS 4 pts]** Show how to implement this function without this additional circuit by modifying the transimpedance amplifier.

f) The team calibrated their circuit against standard glucose solutions to obtain the following transfer function:

$$B_{\text{ADC}} = -53.05 \, \frac{\text{L}}{\text{mmol}} \times [\text{Glucose}] - 47.5$$

[Glucose] is the glucose concentration in mmol/L, while B_{ADC} is the output reading in arbitrary units. What is the sensitivity of the device? [2 pts]

6) **[10 pts]** The following set up is used to sense pH. The membrane separating chamber 1 and 2 is only permeable to H^+. Both chambers have Ag/AgCl electrodes with E_{hc}= 0.223 V, series resistance of 1 kΩ, double layer resistance of 100 kΩ, and double layer capacitance of 10 pF. The resistance of the H^+-permeable membrane is 2 MΩ.



a) What is the polarity of the voltage V1-V2 measured by a voltmeter of infinite impedance when chamber 1 contains a strong acid and chamber 2 contains a weak base. [1 pt]

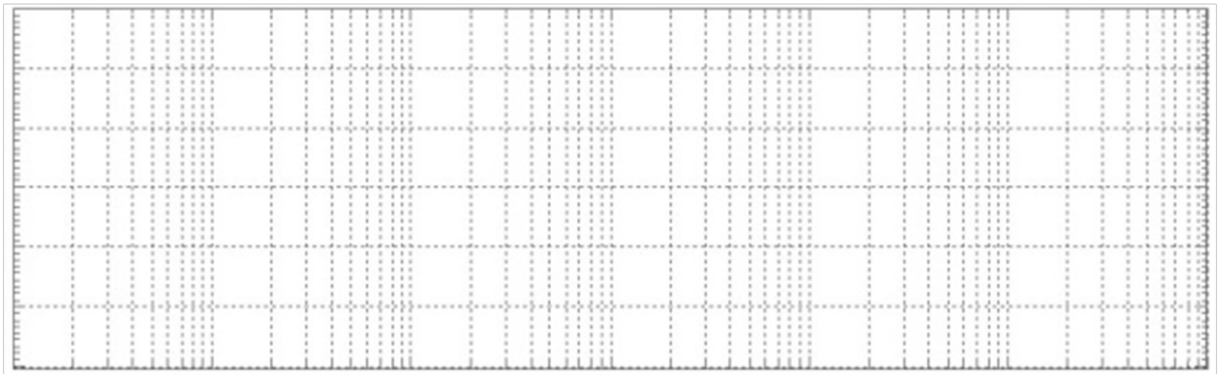
b) What is the expected V1-V2 when chamber 1 contains 10 mmol/L KCl solution and chamber 2 contains 1 mmol/L HCl solution? [2 pts]

c) You now find out from the manufacturer of the electrodes that the two electrodes used are not identical and produce an open circuit voltage V1-V2 of 0.02 V when immersed in the same solution. How does this affect the expected voltage in part (b)? [1 pt]

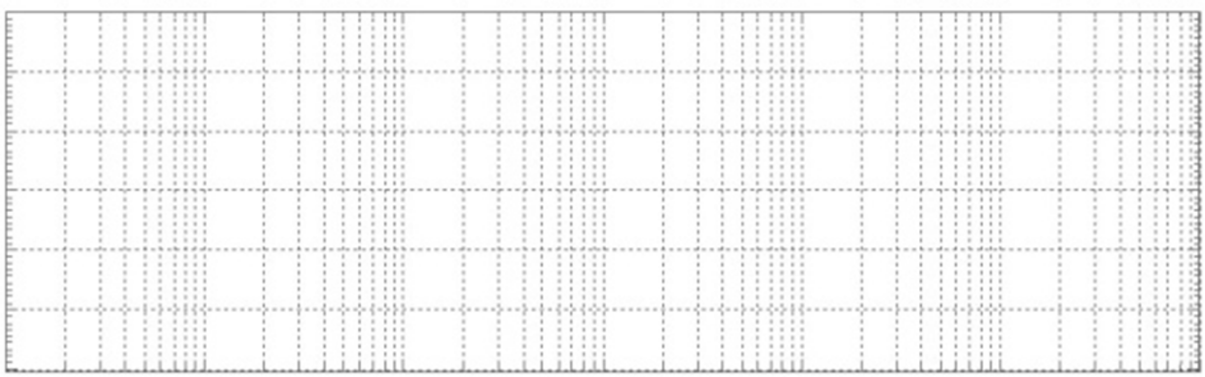
d) Write the equivalent impedance between the electrodes as a function of radial frequency ω. [3 pts]

e) Plot the magnitude (in dB) and the phase (in degrees) of the impedance as a function of frequency *f* (in Hz) and specify the corner frequencies. [3 pts]

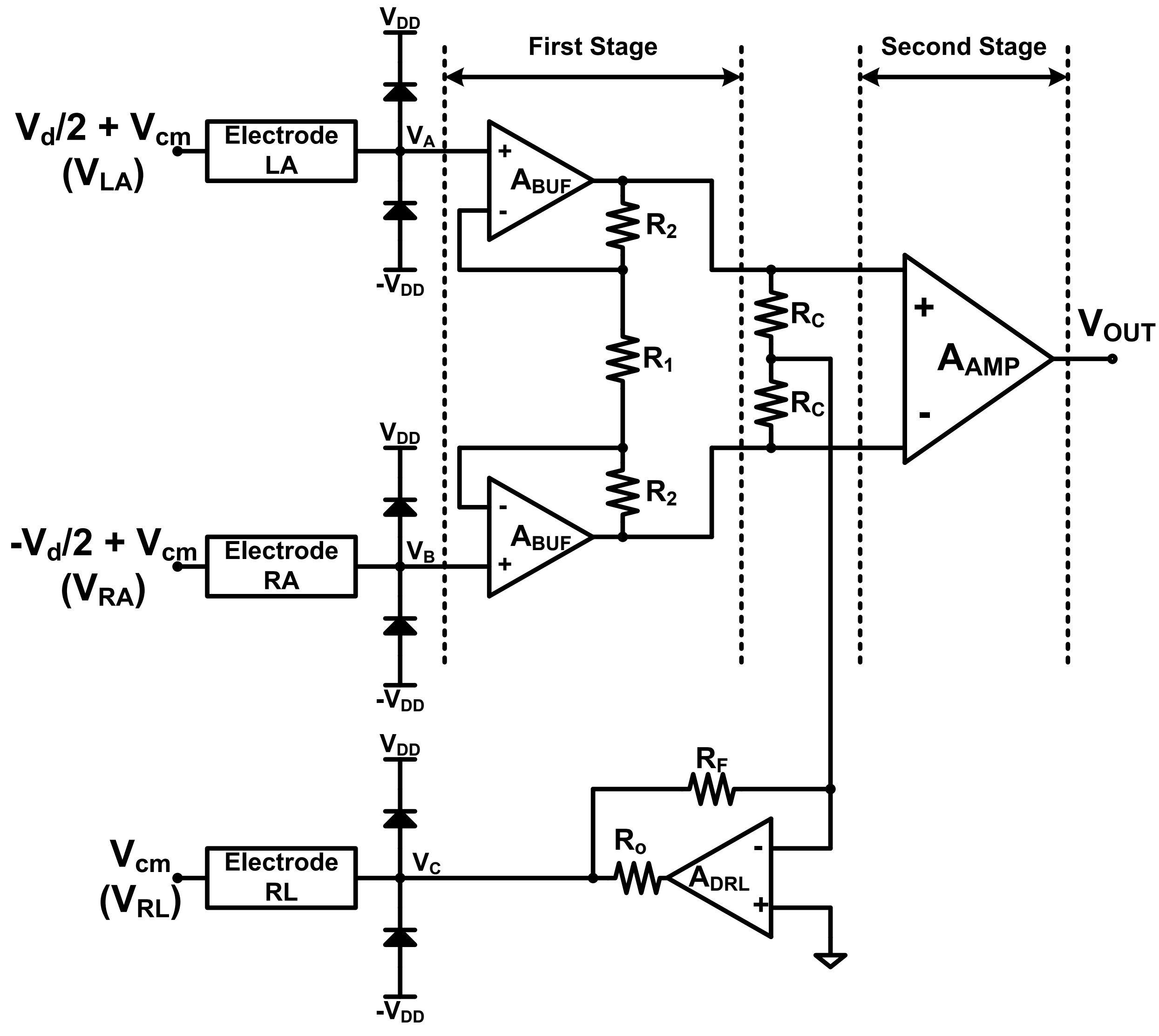
Magnitude



Phase



7) **[12 pts]** An instrumentation amplifier (IA) with driven right leg active grounding common-mode suppression is shown below. The IA has resistances R_1 = 10 kΩ, R_2 = 500 kΩ, R_C = 20 kΩ, R_F = 1 MΩ, and R_O = 1 MΩ. The IA second stage A_{AMP} has differential gain of 100 V/V and common-mode gain of 0 V/V. Assume the amplifiers A_{BUF} are ideal.



a) Assume the protection diodes are ideal with turn-on voltage of 0.7 V. Find the resulting voltage range at V_A, V_B, and V_C. [2pts]

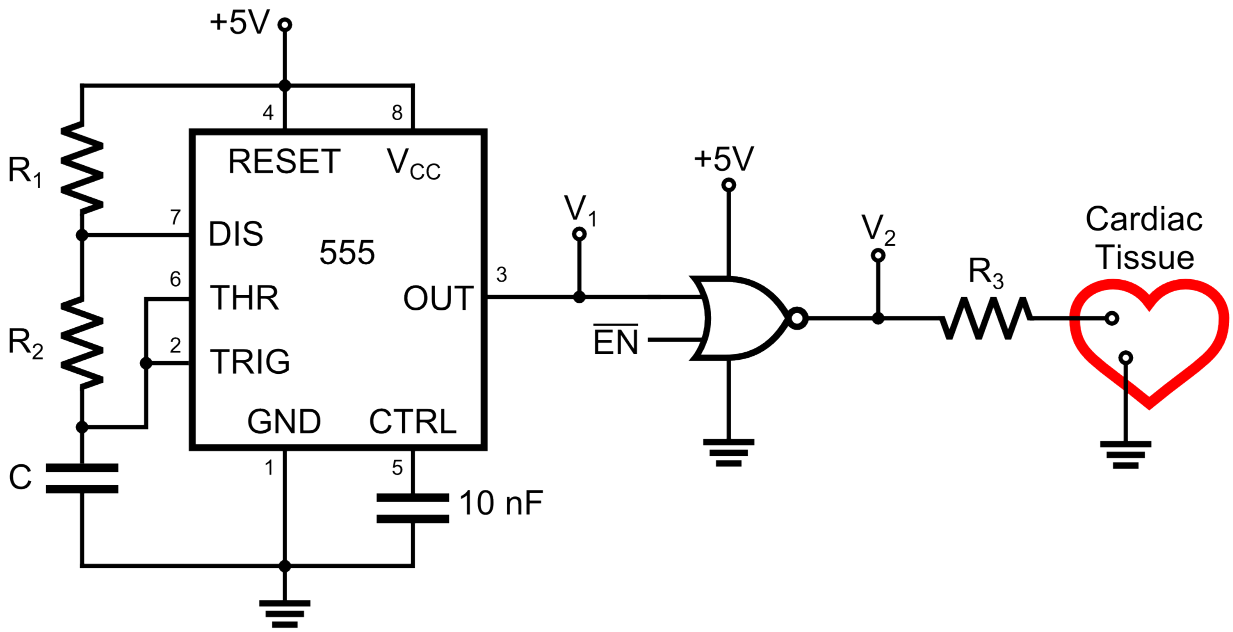
b) The body couples to a 60 Hz, 110 Vrms outlet with 1 pF capacitance. Find the rms amplitude of the displacement current entering the body. (*Hint*: for this part, you may assume the body is practically at ground potential) [2 pts]

c) Electrode RL connects to the body with an impedance of 100 kΩ. For a 2 mVrms differential input V_d, find the signal-to-noise ratio SNR_{IN} in dB at each of the input nodes V_A and V_B for the displacement current found in part (b). [2 pts]

d) Assume the electrode-body impedances of LA and RA are 90 kΩ and 110 kΩ, respectively. Find the common-mode rejection ratio CMRR and output signal-to-noise ratio SNR_{OUT} in dB. [2 pts]

e) Each protection diode has a parallel resistance of 400 MΩ. Now find the resulting CMRR and SNR_{OUT} in dB. [4 pts]

8) **[10 pts]** The circuit below is used to generate a pacemaker drive signal. It is powered by a +5V battery, and has an "enable" input labeled $\overline{EN}$. The output of the circuit connects through an electrode to cardiac tissue. The values of the components are $R_1 =$ 200 kΩ, $R_2 =$ 500 kΩ, $R_3 =$ 10 kΩ, and C = 1 μF.



a) Plot the waveform seen at V_1. [4 pts]

b) What is V_2 when $\overline{\mathrm{EN}} = 1$? [2 pts]

c) What is V_2 when $\overline{\mathrm{EN}} = 0$? [2 pts]

d) What is the maximum current entering the body? [2 pt]

9) **[10 pts]** Congratulations! You just landed an internship at a major bioinstrumentation company. Your first assignment is to design an infant ECG device with the following specifications:

- Band-pass filtering between 0.1 Hz and 1 kHz corner frequencies.
- Amplification of the 1 mVpp ECG differential signal by 60 dB.
- Level-crossing detection with 20 mV hysteresis to produce a square wave output signal at the heartbeat frequency.

You have two electrodes, a single 2.5 V battery, ideal op-amps, and any required resistors and capacitors. Be sure to label all components, inputs, outputs, and needed values.

10) **[4 pts]** Questions from guest lectures. Please write your answer only in the space provided.

<u>Wireless non-contact ECG and EEG</u>

a. Name two characteristics of the circuit that are compromised due to the extremely high impedance of the non-contact sensors. [1 pt]

b. What kind of artifacts is still the major challenge for this type of electrode? [1 pt]

<u>Wireless medical technology in global health</u>

a. Name two applications of wireless technology in health care. [1 pt]

b. Which developed country presents the highest health expenditure per capita? [1 pt]