BENG 186B Winter 2019

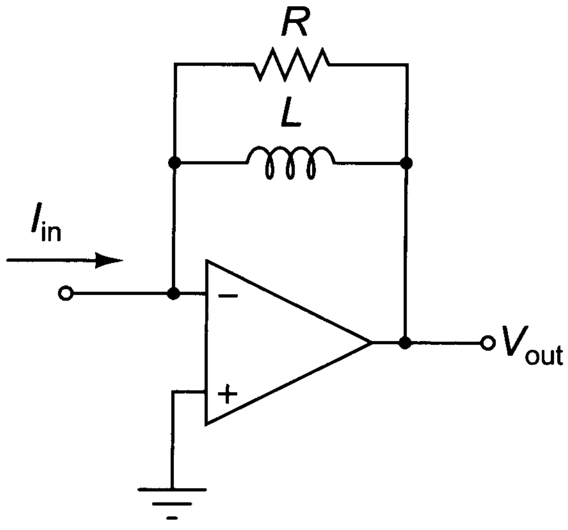
Quiz 2

Friday, February 15, 2019

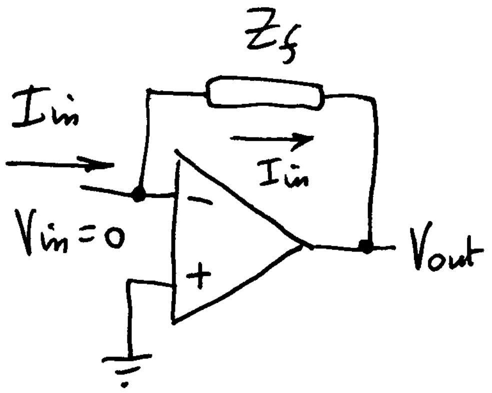
Last Name, First Name: SOLUTIONS

- This quiz is closed book and closed notes. You may use a calculator for algebra and arithmetic.
- This quiz has 9 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 4 problems. Points for each problem are given in **[brackets]**. There are 100 points total.
- You have 50 minutes to complete this quiz.

1. **[25 pts]** Consider the current-in, voltage-out active filter circuit below:



(a) [15 pts] Assume the operational amplifier is ideal and unsaturated. Derive the transfer function $H(j\omega) = V_{out}(j\omega) \,/\, I_{in}(j\omega)$. What type of filter characteristic is this? What is the cutoff frequency?



$$Z_f = R \parallel j\omega L$$

$$= \frac{R\, j\omega L}{R + j\omega L} = \frac{j\omega L}{1 + j\omega \frac{L}{R}}$$

$$H(j\omega) = \frac{V_{out}(j\omega)}{I_{in}(j\omega)} = -Z_f(j\omega) = -\frac{j\omega L}{1 + j\omega \frac{L}{R}} = -\frac{j\omega L}{1 + \frac{j\omega}{\omega_c}}$$

$\Rightarrow$ HIGHPASS with cut-off $\omega_c = \frac{R}{L}$

$$f_c = \frac{1}{2\pi} \frac{R}{L}$$

(b) [5 pts] What is the input impedance at the I_{in} node?

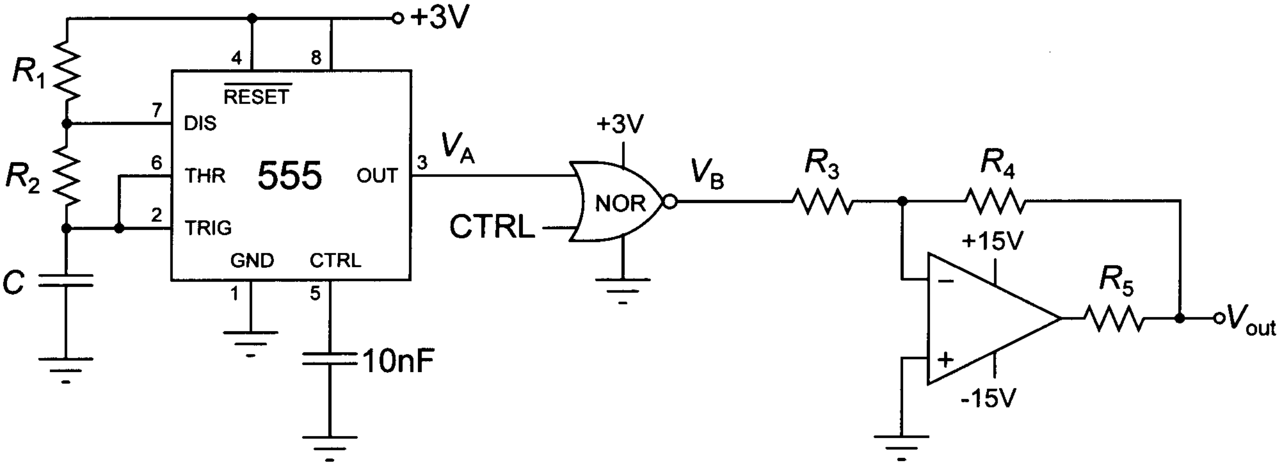
$Z_{in} = 0$ because $V_{in} = 0$ independent of I_{in}

(c) [5 pts] What is the output impedance at the V_{out} node?

$Z_{out} = 0$ because V_{out} is independent of I_{out}

2. **[35 pts]** A deep-brain stimulation (DBS) circuit is shown below. All active components are ideal. The 555 timer IC and the NOR logic gate operate from a +3V single supply, while the opamp operates from a +15V/-15V dual supply. The CTRL control input is logic low (0 V) by default. The values for the passive components are $R_1 = 572\,\text{k}\Omega$, $R_2 = 286\,\text{k}\Omega$, $R_3 = 100\,\text{k}\Omega$, $R_4 = 300\,\text{k}\Omega$, $R_5 = 0$, and $C = 10\,\text{nF}$. You may also find these equations useful for the 555 timer ($\ln(3) \approx 1.1$ and $\ln(2) \approx 0.7$):

$$T = \ln(3) \times RC \qquad T_{lo} = \ln(2) \times R_2C \qquad T_{hi} = \ln(2) \times (R_1 + R_2)C$$



(a) [25 pts] Sketch the waveforms for the voltages V_A, V_B and V_{out} on the diagrams on the next page. Ignore any initial transients, and assume that the circuit has been running forever such that the origin $t = 0$ on the time axis is arbitrary. Show your work below.

ASTABLE (Oscillator)   NOR   INVERTING AMPLIFIER

Amplitude : +3V

T_{lo} = 0.7 286 kΩ 10nF = 2 ms

T_{hi} = 0.7 858 kΩ 10nF = 6 ms

Period: 2ms + 6ms = 8 ms

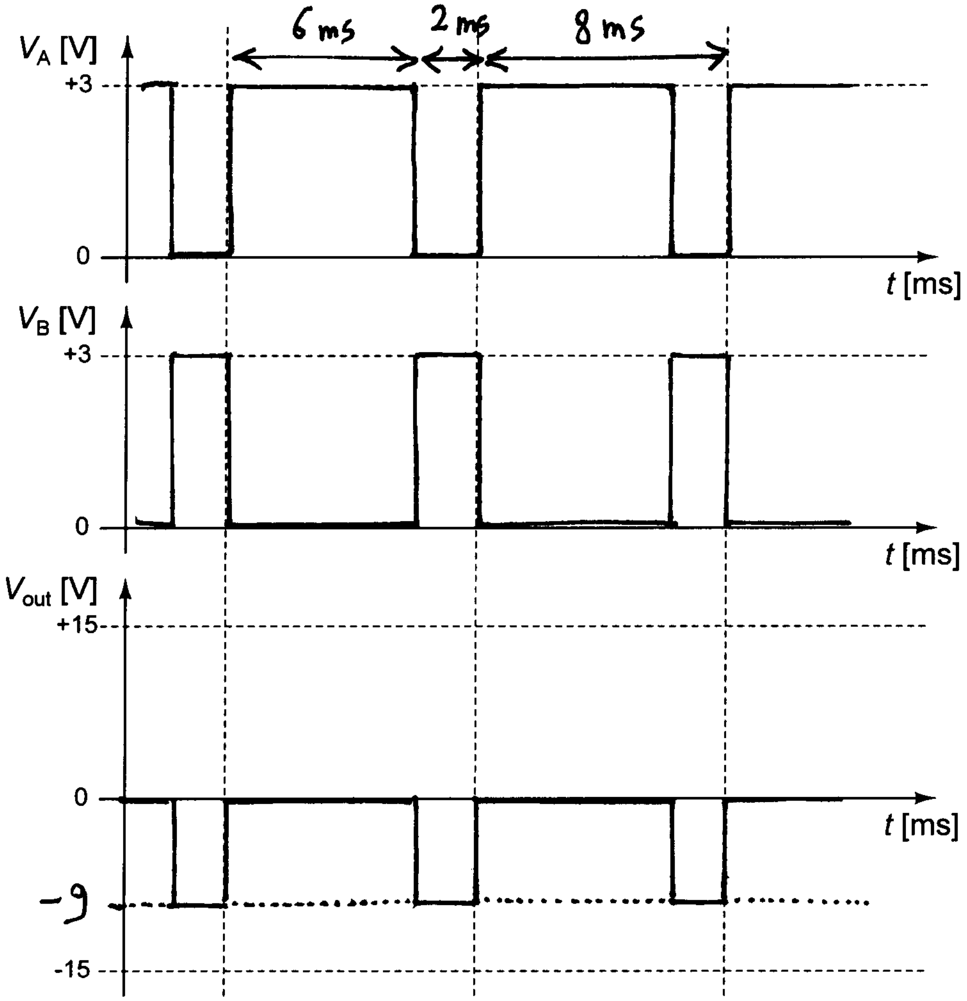
Gain:

$$A_V = -\frac{R_4}{R_3} = -3$$

$\Rightarrow$ V_A : Square wave w/ 3V amplitude, 8 ms period, 75% duty cycle

$V_B = \overline{V_A + CNTRL} = \overline{V_A}$ for $CNTRL = 0$ logic inversion

$V_{out} = -3\,V_B$



(b) [5 pts] What purpose does the control input CTRL serve in the biomedical application? Explain.

CNTRL allows to turn off the stimulator when it is not needed/wanted.

$$\begin{cases} \text{CNTRL} = 1 \Rightarrow V_B = 0, \text{ and } V_{out} = 0 & (\text{OFF}) \\ \text{CNTRL} = 0 \Rightarrow V_B = \bar{V}_A, \text{ and } V_{out} = -3\bar{V}_A & (\text{ON}) \end{cases}$$

(c) [5 pts] Does the output voltage V_{out} depend on the value of the resistance R_5? What purpose does a large R_5 serve in the biomedical application?

No, except at larger output current.

Large R_5 serves to limit the maximum current that can be drawn from the output, protecting the patient/caregiver/instrument.

3. **[20 pts]** Circle the **best answer (only one answer per question)**:

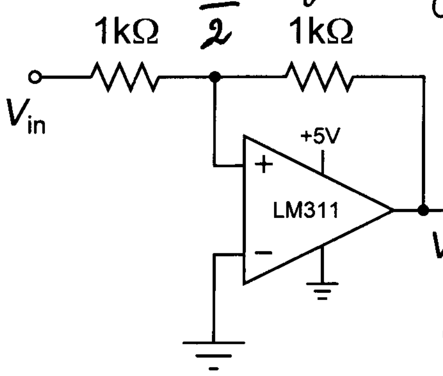
(a) [4 pts] The output V_{out} of the circuit at right (with an ideal LM311) goes high when the input V_{in} goes:

- i. below 0
- [✓ ii.] above 0
- iii. below +2.5V
- iv. above +2.5V
- v. below -5V

Vout goes high when $\frac{V_{in}}{2}$ goes >0

⇑

$\frac{V_{in}}{2}$ (before Vout goes high)



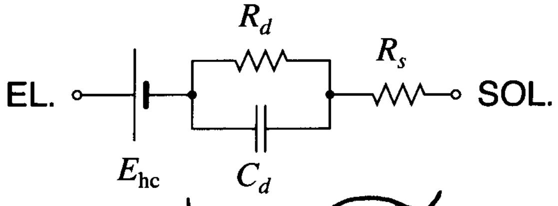
= 0 (before it goes high)

(b) [4 pts] An ideal transformer:

- i. has zero output impedance (not always; depends on input source impedance)
- ii. has infinite input impedance
- iii. converts magnetic to electrostatic energy
- [✓ iv.] shares all magnetic flux between input and output coils
- v. has mutual inductance larger than either input and output inductances

(c) [4 pts] At very low current the electrode shown on the right has:

- i. infinite impedance
- ii. zero impedance
- [✓ iii.] voltage near the half-cell potential
- iv. zero voltage
- v. zero charge



zero current ⇒ zero voltage drop across all passive components

(d) [1 pt ea.] Indicate for each statement below whether it is true or false:

i. **[✓ TRUE] FALSE**: Nernst potentials of ion types in live cells are actively maintained by ion pumps that continuously restore concentration gradients across the membrane.

ii. **[✓ TRUE] FALSE**: ECoG offers higher spatial and temporal resolution in resolving brain acitivty than EEG.

iii. **[✓ TRUE] FALSE**: EMG activity can be observed anywhere on the body.

iv. **TRUE [✓ FALSE]**: ERG is a measure of eye blink activity contaminating the EEG.

v. **[✓ TRUE] FALSE**: A dipole consists of a pair of monopoles of same magnitude and opposing polarity.

vi. **[✓ TRUE] FALSE**: The T wave of ECG indicates ventrical repolarization.

vii. **TRUE [✓ FALSE]**: At thermal equilibrium the doublelayer charge across the membrane is zero on average.

viii. **[✓ TRUE] FALSE**: Non-polarizable electrodes pass electrical current in either direction.

4. **[20 pts]** Consider two identical electrodes inserted in a Petri dish containing a biological cell culture preparation at room temperature. The cells are in a physiological saline environment of 0.15 mol/L NaCl in distilled water. Assume the cells are impermeable to K^+ and any other ion types except Na^+ and Cl^-. The GHK equation is:

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

and at room temperature $RT/F \ln(10) \approx 60$ mV.

(a) [5 pts] Assume both electrodes are in the extracellular saline environment, without penetrating any cell. What voltage do you expect to measure by a voltmeter with infinite input impedance between the electrodes, and why?

Zero, since :

1) the two half-cell potentials are identical ;

2) at zero current the voltage drop across the saline environment is zero.

(b) [15 pts] Now one of the two electrodes is inserted in one of the cells in the culture. When a pharmacological agent is introduced to block all sodium channels, the voltage measured between this electrode and the other electrode remaining in the saline environment is $V_{cell} - V_{saline} = -60$ mV. What does that tell about Nernst potentials of the cell, and ion concentrations inside the cell? Explain.

$P_K = 0$: cells are impermeable to K^+

$P_{Na} = 0$; all sodium channels are blocked

$$\Rightarrow V_{cell} - V_{saline} = 60\text{mV} \log_{10} \frac{[Cl^-]_{cell}}{[Cl^-]_{saline}}$$

$$= E_{Cl}$$

$$= -60\text{mV measured}$$

$$\Rightarrow \begin{cases} E_{Cl} = -60\text{mV} \\ [Cl^-]_{cell} = \frac{1}{10}[Cl^-]_{saline} = 0.015 \frac{\text{mol}}{L} \end{cases} \quad \text{for } Cl^-$$

Nothing can be said for the other ion types Na^+ & K^+