On all questions: **SHOW ALL WORK. BEGIN WITH FORMULAS, THEN SUBSTITUTE VALUES AND UNITS.** No credit will be given for numbers that appear without justification. Unless otherwise stated in a problem, provide 3 significant digits in your answers. Read the entire quiz before answering any questions. Also it may be easier to answer parts of questions out of order. Some questions contain reminders of these instructions, but they must be followed for the entire quiz.
24 February – Birth Date of Steve Jobs

First – two quotes from Steve Jobs:

When you’re a carpenter making a beautiful chest of drawers, you’re not going to use a piece of plywood on the back, even though it faces the wall and no one will see it. You’ll know it’s there, so you are going to use a beautiful piece of wood on the back. For you to sleep well at night, the aesthetic, the quality has to be carried all the way through.

Design is not just what it looks like and feels like. Design is how it works.

Second – a quote from Steve Wozniak:

Steve Jobs played no role at all in any of my designs of the Apple I and Apple II computer, and printer interfaces, and serial interfaces, and floppy disks and stuff that I made to enhance the computers. He did not know technology. He wanted to be important, and the important people are always the business people. So that’s what he wanted to do.

Conceptual Questions

Question V in this quiz contains some conceptual questions. The following addresses how to approach such questions, provided in the unlikely event that you have not seen such questions before.

A conceptual question is designed to help determine whether a student has an accurate working knowledge of a specific set of concepts. For example, from the background quiz you completed on the first day of class:

A 9V battery is connected across a 2kΩ resistor. If the resistor is replaced with a 10kΩ resistor, will the current from the battery

a. Increase
b. Decrease
c. Stay about the same

This question tests conceptual knowledge of Ohm’s Law. It can most rigorously be answered by recalling the relationship between voltage, current and resistance (the three parameters mentioned directly or indirectly in the question). \( I = \frac{V}{R} \). From this expression a larger \( R \) will produce a smaller \( I \) for the same voltage (9V in this case). The answer does not depend on the exact values of the two resistances, only that a resistor is replaced with one that is larger. Then the current will be smaller, so the answer is b. Decrease.
Analog Discovery Connections
### Standard Resistor Values (±5%)

<table>
<thead>
<tr>
<th>Value (Ω)</th>
<th>Value (Ω)</th>
<th>Value (Ω)</th>
<th>Value (Ω)</th>
<th>Value (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>10</td>
<td>100</td>
<td>1.0K</td>
<td>10K</td>
</tr>
<tr>
<td>1.1</td>
<td>11</td>
<td>110</td>
<td>1.1K</td>
<td>11K</td>
</tr>
<tr>
<td>1.2</td>
<td>12</td>
<td>120</td>
<td>1.2K</td>
<td>12K</td>
</tr>
<tr>
<td>1.3</td>
<td>13</td>
<td>130</td>
<td>1.3K</td>
<td>13K</td>
</tr>
<tr>
<td>1.5</td>
<td>15</td>
<td>150</td>
<td>1.5K</td>
<td>15K</td>
</tr>
<tr>
<td>1.6</td>
<td>16</td>
<td>160</td>
<td>1.6K</td>
<td>16K</td>
</tr>
<tr>
<td>1.8</td>
<td>18</td>
<td>180</td>
<td>1.8K</td>
<td>18K</td>
</tr>
<tr>
<td>2.0</td>
<td>20</td>
<td>200</td>
<td>2.0K</td>
<td>20K</td>
</tr>
<tr>
<td>2.2</td>
<td>22</td>
<td>220</td>
<td>2.2K</td>
<td>22K</td>
</tr>
<tr>
<td>2.4</td>
<td>24</td>
<td>240</td>
<td>2.4K</td>
<td>24K</td>
</tr>
<tr>
<td>2.7</td>
<td>27</td>
<td>270</td>
<td>2.7K</td>
<td>27K</td>
</tr>
<tr>
<td>3.0</td>
<td>30</td>
<td>300</td>
<td>3.0K</td>
<td>30K</td>
</tr>
<tr>
<td>3.3</td>
<td>33</td>
<td>330</td>
<td>3.3K</td>
<td>33K</td>
</tr>
<tr>
<td>3.6</td>
<td>36</td>
<td>360</td>
<td>3.6K</td>
<td>36K</td>
</tr>
<tr>
<td>3.9</td>
<td>39</td>
<td>390</td>
<td>3.9K</td>
<td>39K</td>
</tr>
<tr>
<td>4.3</td>
<td>43</td>
<td>430</td>
<td>4.3K</td>
<td>43K</td>
</tr>
<tr>
<td>4.7</td>
<td>47</td>
<td>470</td>
<td>4.7K</td>
<td>47K</td>
</tr>
<tr>
<td>5.1</td>
<td>51</td>
<td>510</td>
<td>5.1K</td>
<td>51K</td>
</tr>
<tr>
<td>5.6</td>
<td>56</td>
<td>560</td>
<td>5.6K</td>
<td>56K</td>
</tr>
<tr>
<td>6.2</td>
<td>62</td>
<td>620</td>
<td>6.2K</td>
<td>62K</td>
</tr>
<tr>
<td>6.8</td>
<td>68</td>
<td>680</td>
<td>6.8K</td>
<td>68K</td>
</tr>
<tr>
<td>7.5</td>
<td>75</td>
<td>750</td>
<td>7.5K</td>
<td>75K</td>
</tr>
<tr>
<td>8.2</td>
<td>82</td>
<td>820</td>
<td>8.2K</td>
<td>82K</td>
</tr>
<tr>
<td>9.1</td>
<td>91</td>
<td>910</td>
<td>9.1K</td>
<td>91K</td>
</tr>
</tbody>
</table>

### 9V “1604”

<table>
<thead>
<tr>
<th>Type</th>
<th>$R_{int}$ (Ω)</th>
<th>$V_{oc}$ (V)</th>
<th>Capacity (mAh)</th>
<th>Size (in)</th>
<th>Weight (gm)</th>
<th>Connectors</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Le Clanche</td>
<td>35</td>
<td>9</td>
<td>300 1 160 10</td>
<td>0.65x1x1.9</td>
<td>35</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>Heavy Duty</td>
<td>35</td>
<td>9</td>
<td>400 1 180 10</td>
<td>*</td>
<td>40</td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>Alkaline</td>
<td>2</td>
<td>9</td>
<td>500 1 470 10</td>
<td>*</td>
<td>55</td>
<td>S</td>
<td>280mA@100mA</td>
</tr>
<tr>
<td>Lithium</td>
<td>18</td>
<td>9</td>
<td>1000 25 960 80</td>
<td>*</td>
<td>38</td>
<td>S</td>
<td>Kodak Li-MnO₂</td>
</tr>
</tbody>
</table>
I. Voltage Dividers, power, and loading (20 points) As stated on the cover page: Round answers to 3 significant digits. Show formulas first and show your work. No credit will be given for numbers that appear without justification. And remember that additional information is provided on pages 2, 3 and 4 of this exam.

a) Find the voltage $V_{out}$ in the circuit shown. $V_{in}$ is a battery. (4 pts)

$$V_{out} = (12) \left( \frac{680}{680 + 280} \right) = 8.5V$$

b) Find the current that the battery supplies. (4 pts)

$$I_{battery} = \left( \frac{8.5}{680} \right) = 12.5mA = \frac{12}{680 + 280}$$

c) Find the power provided by the battery. (2pts)

$$P = VI = (12)(12.5)mW = 150mW$$

d) Is $R_1$ a standard resistor value for 5% resistors? (1pt) NO
Is $R_2$ a standard resistor value for 5% resistors? (1pt) YES

e) Would 1/8W resistors be an appropriate choice to use for this circuit? You must justify your answer. (2pts)

$$P_{R_1} = VI = (3.5)(12.5)mW = 44mW \quad P_{R_2} = VI = (8.5)(12.5)mW = 106mW$$

Yes for both because they are smaller than 125mW. Safety factor is not very large for $R_2$. 
f) Now include non-ideal factors. The battery is non-ideal, it has a $10\Omega$ internal resistance. The Analog Discovery Board was used to measure the $V_{out}$ and it has a $1\text{Meg}\Omega$ input resistance. **Redraw the schematic** to include these real world effects and **recalculate the $V_{out}$** that would actually be measured using this battery and the Analog Discovery. (6pts)

\[
V_{out} = \left( \frac{680}{10 + 280 + 680} \right) (12) = 8.41 \text{ V}
\]
II. Resistor Combinations and more real world effects (20 points)

a) The circuit on the right above is intended to be a simpler equivalent version of the circuit on the left. Find $R_e$ and $R_f$ as functions of $R_a$, $R_b$, $R_c$, and $R_d$ so that $V_{out}$ will be the same for both circuits given that $V_{in}$ is also the same for both. (4pts)

\[ R_e = R_a + R_b \]

\[ R_f = \frac{(R_c)(R_d)}{(R_c + R_d)} \text{ or } \frac{1}{R_c} + \frac{1}{R_d} \]

b) Now write an equation for $V_{out}$ in terms of $V_{in}$, $R_a$, $R_b$, $R_c$, and $R_d$. It might help to first write the equation of $V_{out}$ in terms for $V_{in}$, $R_e$, and $R_f$. And then substitute in the equations from part a). (4pts)

\[ V_{out} = V_{in} \frac{R_f}{R_e + R_f} = V_{in} \frac{\frac{R_cR_d}{R_c + R_d}}{\frac{R_aR_b + \frac{R_cR_d}{R_c + R_d}}{R_c + R_d}} = V_{in} \frac{\frac{R_cR_d}{R_aR_b + \frac{R_cR_d}{R_c + R_d} + R_cR_d}}{(R_a + R_b)(R_c + R_d) + R_cR_d} \]

Does not have to be simplified
c) Find Vout in Volts for the circuit below. You must show your work to receive credit. (6pts)

Becomes simple voltage divider with $R_1 = 6k$ and $R_2 = 2.4k$

$$V_{out} = \frac{10 \times 2.4}{2.4 + 6} = 2.86V$$

d) Another non-ideal factor is that the resistors we use in EI have a 5% tolerance. A 100k resistor could have a value between 95k and 105k, but this range includes temperature and aging effects. This site looked into this issue:

http://www.kerrywong.com/2013/02/01/100k-5-carbon-film-resistor-value-distribution/

The plot below showing measured values for 100kΩ resistors is from this site. The x axis is in kΩ, the y axis is the number of resistors that fit into bins that are 250Ω wide. Note that the distribution is much closer to 100kΩ than a 5% tolerance would imply.

Also complicating precise calculations is that for the resistors used for the plot have a temperature effect. The resistance will drop by a factor between 0 and 850pmm/°C. This may or may not explain the shift to lower values.
Part 1) Based on the plot, what is the approximate tolerance range for this set of resistors. It clearly isn’t symmetric around 100k so your answer shouldn’t be either. Express your answer as R ± X% (2pts)

Range 98 to 100.5
Answer: 99.3 ± 1.3%

Part 2) For the circuit shown below, calculate the expected Vout range using the extremes of the ±5% tolerance range. Give Vout(max) and Vout(min). (2pts)

max is R1 = 95Ω and R2 = 105Ω
So 5.25V
min is R2 = 95Ω and R1 = 105Ω
So 4.75V

Part 3) Now do the same as Part 2) but use the tolerance range from Part 1). (2pts)

max is R1 = 98Ω and R2 = 100.5Ω
So 5.06V
min is R2 = 98Ω and R1 = 100.5Ω
So 4.94V
III. Filters & Transfer Functions (20 points)

Shown above are the four basic, two-element, passive filter configurations made with RL and RC combinations. In this problem, we will consider the bottom two configurations that can be constructed by adding either an inductor or capacitor to a resistive load. Assume that the circuits are made with ideal components, unless specifically told otherwise.

a) Determine the general complex transfer function for circuits C and D in terms of R, L, C and frequency $\omega$, by modeling each as a voltage divider. (2 pts)

C) LR:
$$\frac{V_{OUT}}{V_{IN}} = \frac{V_{34}}{V_{12}} = \frac{R}{R + j\omega L}$$

D) CR:
$$\frac{V_{OUT}}{V_{IN}} = \frac{V_{34}}{V_{12}} = \frac{R}{R + \frac{1}{j\omega C}} = \frac{j\omega RC}{1 + j\omega RC}$$

Either form is OK

b) Simplify the two expressions at low (not zero) frequencies. That is, assume $\omega$ is small. (2 pts)

C) LR:
$$\frac{V_{OUT}}{V_{IN}} = \frac{V_{34}}{V_{12}} \approx \frac{R}{R} = 1$$

D) CR:
$$\frac{V_{OUT}}{V_{IN}} = \frac{V_{34}}{V_{12}} \approx \frac{j\omega RC}{1} = j\omega RC$$
c) Simplify the two expressions at high (not infinite) frequencies. That is, assume $\omega$ is large. (2 pts)

C) LR: $$V_{out} \approx \frac{V_{34}}{V_{12}} \approx \frac{R}{j\omega L}$$

D) CR: $$V_{out} \approx \frac{V_{34}}{V_{12}} \approx \frac{j\omega RC}{j\omega RC} = 1$$

d) In engineering, when we say something is large or small, we make such a statement by comparing it to a specific quantity. If you have answered the previous two questions correctly, you have used an expression like either $\omega \gg \omega_{\text{REFERENCE}}$ or $\omega \ll \omega_{\text{REFERENCE}}$ so that you can neglect terms in the general complex transfer functions. What is $\omega_{\text{REFERENCE}}$ for the two circuits? (2 pts) The reference is the corner frequency

C) LR: $\omega_{\text{REFERENCE}} = \frac{R}{L}$

D) CR: $\omega_{\text{REFERENCE}} = \frac{1}{RC}$

e) Assume the circuits are made with ideal components. Identify which are high pass filters and which are low pass filters by circling the high pass and underlining the low pass in the following list (2 pts): CR LR

The figure below shows what is called a crossover network for audio speakers. Since very good speakers do not work well over the entire audio frequency range, audio signals from music, speech, etc. are separated into more limited frequency bands (typically low, midrange, and high frequencies) and then directed to speakers designed for each band. High frequency speakers are called tweeters and low frequency speakers are called woofers. In the middle range of frequencies, speakers are called midranges, so it seems that audio people ran out of fun names. Of course, there are many different versions of each type, with the best known probably the subwoofer, which is designed for 20 – 60 Hz and is more felt than heard. In the crossover circuit diagram below, the speakers are modeled as 8Ω resistors for simplicity. Also, practical crossover networks have more components to balance the power to each range. However, the components shown are the most important in the design and allow us to understand how crossovers work. Note that the circuit consists of three sub-circuits: a, b, and c as indicated by the subscripts on the components and nodes. Note also that you have just analyzed two types of circuits used as sub-circuits in the crossover.
f) In this course, we address four general types of filters: low-pass, high-pass, band-pass and band-reject. Identify the type of filter for each sub-circuit. (3 pts)

Circuit a) HP Circuit b: BP Circuit c) LP

g) Determine the corner or resonant frequency for each sub-circuit. Express your answer as an angular frequency \( \omega \), not as \( f \). (3 pts)

Circuit a) Circuit b: Circuit c)

\[
\frac{1}{RC} = \frac{1}{8 \times 15 \times 10^{-6}} = \frac{10^6}{120} = 8333.3 = 8330 \quad \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{150 \times 10^{-9}}} = 2581.99 = 2580
\]

\[
\frac{R}{L} = 800
\]
h) Good speaker systems incorporate all of the individual speakers and the crossover network in the same box. Thus, when an amplifier is connected to the input to the box, it sees the combination of crossover and speakers, not individual speakers. Assume that you have a speaker system configured as shown in the circuit diagram and that you connect your multi-meter to the input to measure the DC resistance. What value resistance will be indicated on your meter? Explain your answer. (2 pts)

At DC, C is open circuit and L is short circuit. Thus, the measured resistance is 8Ω.

i) The figure above shows the output from PSpice simulation of the crossover. Four voltages are shown as a function of frequency. The horizontal axis is labeled at 10Hz, 30Hz, 100Hz, 1kHz, 3kHz, and 10kHz. The vertical axis is labeled at 0V, 10V, 20V and 30V. The voltages are labeled V1, V2, V3, and V4. Identify which is Vin, Va, Vb, and Vc. Identify the voltages by drawing lines between the voltages in the two columns.
IV – Signals, Transformers and Inductors (20 points)

Given the circuit above, assume an ideal transformer with full coupling. In your answers to the following questions, use all available and useful information.

a) For the given information, write out the expressions for the ratios $V_{out}/V_{in}$, $I_{out}/I_{in}$ and the transformer input impedance $R_{IN}$. (6 pts)

\[
\frac{V_{OUT}}{V_{IN}} = \frac{I_{IN}}{I_{OUT}} = \sqrt{\frac{L_2}{L_1}} = 10 \quad Z_{IN} = \frac{R_2}{L_2/L_1} = \frac{55.55}{100} = .5555\Omega = .556\Omega
\]

b) Draw the circuit diagram for the voltage divider consisting of the transformer input impedance $R_{IN}$ and the resistance $R_1$. Then solve for $V_{IN}$, the voltage across the input terminals of the ideal transformer. (4 pts)

$R_1=5$, $R_2=.5555$

$V_{IN}=200(.5555/5.5555)=20V$
c) Find $V_{out}$ from your value for $V_{in}$. (4 pts)

$$V_{OUT} = 200V$$

d) Determine both the primary and secondary currents ($I_1$ and $I_2$). (4 pts)

$$I_1 = \frac{200}{5.5555} = 36A \quad I_2 = \frac{200}{55.55} = 3.6A$$

e) Determine the power delivered to the load $R_2$. (4 pts)

$$200 \times 3.6 = 720 \text{ W} \text{ (also correct divided by 2, either answer is OK)}$$
V – Misc & Conceptual Questions (20 points)

The following questions all come from or are inspired by the daily videos. The answers for all questions are worth (1 pt) each, except where noted. Remember to briefly explain your answers.

a) Is the image shown at the right

1. a short circuit?
2. an open circuit?

b) Is the image shown at the right

1. a short circuit?
2. an open circuit?

(c) In the standard voltage divider configuration shown at the right, resistor $R_1$ is much larger than resistor $R_2$. Is the power dissipated in $R_1$

1. Much greater than the power dissipated in $R_2$
2. Much less than the power dissipated in $R_2$
3. About the same as the power dissipated in $R_2$

d) In the circuit at the right, two resistors ($R_1$ much larger than $R_2$) are connected in parallel across a voltage source $V$. Is the power dissipated in $R_1$

1. Much greater than the power dissipated in $R_2$
2. Much less than the power dissipated in $R_2$
3. About the same as the power dissipated in $R_2$
e) Assume that you have a broad-band recorded audio signal containing frequencies from 50Hz to nearly 10kHz, like the combination of a typical singer and a typical orchestra shown above. If this signal is passed through a high-pass or low pass RC filter, some of the signal will pass through the filter and some will not. Where does the signal go that does not make it through the filter?

1. It is stored in the capacitor C.
2. It is turned into heat by the resistor R.
3. It is reflected back to the source.

f) The signal shown above consists of two sinusoidal voltage waves with different frequencies. What are the two frequencies? The vertical scale is 100mV/Div and the horizontal scale is 3ms/Div. Circle the correct answers. (2 pts)

- 500Hz
- 2kHz
- 5kHz
- 1kHz
- 2.5kHz
- 10kHz
- 25kHz
g) A student gets into the tinkering spirit and decides to see what happens if a voltage divider is connected backwards. That is, the input voltage \( V_{IN} \) is connected where the output is usually measured and the output is measured where the input voltage is usually connected, as shown in the figure. If \( V_{IN} = 4 \text{Volts} \), \( R_1 = 3k\Omega \) and \( R_2 = 1k\Omega \), what voltage will be measured? Circle the correct answer.

- 0V
- 1V
- 2V
- 4V
- 6V
- 8V
- 12V
- 16V

h) What are the colors & names of the two wires for ‘Scope Ch2?

- 2+ and 2- blue and blue/white

i) What are the colors & names of the two wires for Arbitrary Waveform Generator (AWG) 1?

- W1 and Ground (down arrow), Yellow and Black

j) Is it always necessary to measure both the input and output voltage or current for every circuit studied?

Yes!

k) What are the magnitude and phase of the transfer function for this RL circuit at high (not infinite) frequencies? (2 pts)

\[
\frac{i\omega L}{R + j\omega L} \approx \frac{j\omega L}{j\omega L} = 1\text{ so the phase is zero}
\]
1) In the CR circuit at the right, is the current in R relatively large or small when the frequency is high?

High because the capacitor is a short circuit

m) What could you do to improve the coupling of your transformer so that it will work equally well in both step up and step down modes?

Make the primary and secondary the same length.

n) What is the color code for a 10kΩ resistor? (2 pts)

Brown  Black  Orange

o) Whose birthday is it today?

Steve Jobs

p) Which of the following images might be shown when searching online for ‘filters’?

All of them

q) What is a typical internal resistance for a 9V Lithium battery?

From page 4, $R_{\text{int}}$ is 18Ω