Circuits for Exercises  Use the circuits shown in figure 1 below for exercises 1 through 5.

Exercise 1  Find the equation of motion for each circuit in figure 1 in terms of the indicated variables. You may assume all input voltage and current sources and all circuit element variables are given.
Exercise 2  Write the transfer function $H(j\omega)$ in the form $\frac{(j\omega-S_{Z1})(j\omega-S_{Z2})\ldots}{(j\omega-S_{P1})(j\omega-S_{P2})\ldots}$.

(a) Find $H(j\omega)$ for circuit (a) in figure 1.
(b) Find $H(j\omega)$ for circuit (c) in figure 1.
(c) Find $H(j\omega)$ for circuit (e) in figure 1.
(d) Find $H(j\omega)$ for circuit (f) in figure 1.

Exercise 3  For each of the circuits in figure 1, assume a generic step function drive. That is, assume $v_{IN} = u(t)V_{IN}$ and $i_{IN} = u(t)I_{IN}$.

(a) List the initial current and voltage in the reactive circuit elements before and after the input step.
(b) Use your answers to part (a) to establish the requisite initial conditions to solve the differential equation.
(c) Solve for $v_{OUT}$ for circuit (a) in figure 1.
(d) Solve for $v_{OUT}$ for circuit (f) in figure 1.

Exercise 4  Assume for each circuit in figure 1 that the drive is of the form $A\cos(\omega t + \phi)$. Determine the indicated output variable.

Exercise 5  For each of the circuits in figure 1, replace the sources with impulses. That is, assume $i_{IN} = Q\delta(t)$ and $v_{IN} = \Lambda\delta(t)$. Write the expression for the indicated output variable vs time for $t > 0$. 
Problem 1 In one of the in-class demos, we showed how a long cable could contribute enough capacitance to distort and filter a waveform. Scope probes are designed to address this problem by using a capacitive voltage divider composed of the variable capacitor $C$ and the 8pF capacitor shown below in figure 2. $C_{cable}$ models the added capacitance contributed by the cable in the demo.

![Figure 2: Problem 9.1](image)

The experiment uses a 3 ft long 50Ω coax cable (Here, the 50Ω refers to the transmission line impedance. In case you are interested, that is the ratio of the amplitude of $v_{IN}$ to $i_{IN}$ when the cable is driven by high frequency sinusoidal input voltage $v_{IN}$.) However, the 50Ω impedance is not relevant for this problem. The only point of relevance is the cable parasitic capacitance, which is $30\text{pF} \cdot \text{ft}$. Thus the 3 ft long coax cable adds 90pF of capacitance in parallel with the 8pF scope capacitance.

(a) What should $C$ be such that $H(j\omega) = \frac{v_{SCOPE}(j\omega)}{v_{IN}(j\omega)}$ has no frequency dependence? What is the resulting $H(j\omega)$ with the chosen $C$?

(b) Prove that this circuit will faithfully reproduce any input waveform, $v_{IN}$ at the scope, i.e. that $v_{SCOPE}(t) = A v_{IN}(t)$ for any $v_{IN}$ and a constant $A$.

(c) You have a new kind of scope that plots current, $i_{SCOPE}$ rather than voltage, $v_{SCOPE}$, at its output port. Design a probe that will faithfully reproduce the shape of $i_{IN}(t)$ on the scope, removing the filtering influence of $C_{scope}$.

![Figure 3: Problem 1](image)
Problem 2  Consider an unknown circuit shown in figure 4, exhibiting the frequency response shown in figure 5.

(a) What is the radial resonance frequency $\omega_o$?

(b) What is the quality factor $Q$ for this filter?

(c) Assuming $v_{IN} = 3V \times \cos(2\pi \times 9kHz + 0.3)$, determine $v_{OUT}$.

(d) Assuming $v_{IN} = 3V \times (1 - u(t))$, determine the damping factor $\alpha$ and the period $T$ between zero-crossings of $v_{OUT}$ for $t > 0$. $T = \frac{2\pi}{\omega_d}$ where $\omega_d = \sqrt{\omega_0^2 - \alpha^2}$.

(e) Suggest an LRC circuit for the black box, choosing $L$, $R$, and $C$ values appropriately.

(f) For the circuit from part(e), find $v_{OUT}(0 + \varepsilon)$ and $\frac{d}{dt}v_{OUT}(0 + \varepsilon)$, the initial conditions.

(g) Using the standard form of a step response to an LRC circuit, write an analytic expression for $v_{OUT}(t)$ for $t > 0$. 

Figure 4: Problem 2

Figure 5: Problem 2
Problem 3  The network shown below models an oscilloscope probe that provides a 10:1 voltage attenuation. Resistor $R_1$ is a fixed resistor in the probe, resistor $R_2$ models the input resistance of the oscilloscope, capacitor $C_1$ is a variable capacitor in the probe, and capacitor $C_2$ models the combined input capacitance of the oscilloscope and the cable between the probe and the oscilloscope. What relations are required between $R_1$, $R_2$, $C_1$ and $C_2$ so that $v_{\text{OUT}}(t) = 0.1v_{\text{IN}}(t)$ for all $\omega$? That is, what relations are required so that $V_{\text{out}} = 0.1V_{\text{in}}$ and $\phi = 0$ for all $\omega$? (Note that the value of $C_2$ is difficult to guarantee in practice due to variations in cable length and oscilloscope input capacitance, so $C_1$ is made manually adjustable in the probe.)
Problem 4 This problem focuses on the (greatly simplified) design of crossover networks for audio speaker systems driven by a single amplifier. The purpose of these networks is to direct low-frequency signals to a low frequency (LF) speaker, mid-range signals to a mid-range (MR) speaker, and high-frequency signals to a high-frequency (HF) speaker. The interconnection of the amplifier, modeled here as a cosinusoidal voltage source, the three speakers, each modeled here as a resistor, and the three cross-over networks is shown below. Note that this was once a final exam problem.

The three cross-over networks $N_{\text{LF}}$, $N_{\text{MR}}$, and $N_{\text{HF}}$ may each be a single capacitor, a single inductor, a series capacitor and inductor, or a parallel capacitor and inductor. The topology of each network, and the values of the components in each network, are to be designed to provide the three voltage responses shown below as functions of frequency. Note that $\omega_L$ and $\omega_H$ are the frequencies at which $|v_{\text{LF}}|$, $|v_{\text{MR}}|$ and $|v_{\text{HF}}|$ fall to the value of $V_a/\sqrt{2}$. They are related by $\omega_L \ll \omega_H$ in this problem.

(a) Consider the network $N_{\text{LF}}$ for the low-frequency speaker. What type of network should be used for $N_{\text{LF}}$: a single capacitor, a single inductor, a series capacitor and inductor, or a parallel capacitor and inductor?

(b) Determine the values of the corresponding capacitance $C_{\text{LF}}$, if used, and inductance $L_{\text{LF}}$, if used, in terms of $R_{\text{LF}}$, $R_{\text{MR}}$, $R_{\text{HF}}$, $\omega_L$ and $\omega_H$. 
(c) Consider the network $N_{MR}$ for the mid-range speaker. What type of network should be used for $N_{MR}$, a single capacitor, a single inductor, a series capacitor and inductor, or a parallel capacitor and inductor?

(d) Determine the values of the corresponding capacitance $C_{MR}$, if used, and inductance $L_{MR}$, if used, in terms of $R_{LF}$, $R_{MR}$, $R_{HF}$, $\omega_L$ and $\omega_H$.

(e) Consider the network $N_{HF}$ for the high-frequency speaker. What type of network should be used for $N_{HF}$, a single capacitor, a single inductor, a series capacitor and inductor, or a parallel capacitor and inductor?

(f) Determine the values of the corresponding capacitance $C_{HF}$, if used, and inductance $L_{HF}$, if used, in terms of $R_{LF}$, $R_{MR}$, $R_{HF}$, $\omega_L$ and $\omega_H$. 
Problem 5  In this problem, a low-voltage sinusoidal source is coupled to a resistive load through an inductor-capacitor network as shown below. The role of the network is to boost the voltage at the load.

(a) Derive a second-order differential equation that describes the evolution of $v_{\text{OUT}}$ as driven by $v_{\text{IN}}$. You need not solve the differential equation.

(b) Assume that the circuit operates in the sinusoidal steady state with $v_{\text{IN}}(t) = V_{\text{in}} \cos(\omega t)$. Correspondingly, let $v_{\text{OUT}}(t)$ take the form $v_{\text{OUT}} = V_{\text{out}} \cos(\omega t + \phi)$. Determine $\phi$, and the voltage gain $G$ defined by $G \equiv V_{\text{out}}/V_{\text{in}}$.

(c) For a given $R$, $L$ and $\omega$, determine the value of $C$ that maximizes $G$, and for this value of $C$, determine $G$.

(d) Suppose that $v_{\text{IN}}(t)$ is abruptly set to zero in an attempt to remove the voltage at the load. In this case, the amplitude of the load voltage will decay in proportion to $e^{t/\tau}$. Assuming that $C$ is chosen to maximize $G$ following the result from Part (c), determine $\tau$ in terms of $G$ and $\omega$. Hint: can you get the time constant (as a function of $C$, $L$ and $R$) from the differential equation found in Part (a)?

(e) In view of the results of Parts (c) and (d), what is the disadvantage of using an inductor-capacitor network to boost the voltage which excites the load?
Problem 2: Op-Amps – 20%

Assume that the op-amps in this problem are ideal. For Parts (2A) and (2B), consider the circuit shown below.

\[ v_{IN}(t) = V u(t) \text{ where } u(t) \text{ is the unit step function.} \]

\[ v_{OUT}(t) = \]

(A) Assume that the inductor and capacitor are initially at rest. At \( t = 0 \) the voltage source steps to \( V \) such that \( v_{IN}(t) = V u(t) \). Determine \( v_{OUT}(t) \) for \( t \geq 0 \).
(B) Let $v_{\text{IN}}(t) = V \cos(\omega t)$. Further, assume that $v_{\text{OUT}}$ has a zero-valued time average. Determine $v_{\text{OUT}}$ in the sinusoidal steady state.

$v_{\text{OUT}}(t) =$
For Part (2C), consider the circuit shown below.

(C) Determine the output voltage $v_{\text{OUT}}$.

$$v_{\text{OUT}} =$$
Problem 3: Second-Order Network Transients – 20%

This problem concerns the second-order network shown below. To begin, the current source delivers a current impulse with area $Q$, the total charge delivered, such that $I(t) = Q\delta(t)$. A graph of the subsequent capacitor voltage $v$ in volts and inductor current $i$ in milliamps is also shown below as a function of time in microseconds. Use the graphical waveforms to answer the following questions.

![Second-Order Network Diagram]

![Capacitor Voltage & Inductor Current Graph]
(A) What is the *approximate* value of the inductance $L$? *A numerical answer with proper units is expected.*

$L =$

(B) What is the *approximate* value of the capacitance $C$? *A numerical answer with proper units is expected.*

$C =$
(C) What is the approximate value of the resistance $R$? Hint: $e^{-0.5} \approx 0.6$. A numerical answer with proper units is expected.

\[ R = \]

(D) What is the approximate value of the impulse charge $Q$? A numerical answer with proper units is expected.

Charge $Q =$
(E) What is the approximate value of the quality factor of the network? A numerical answer with proper units is expected.

Quality Factor =
(F) Complete each sentence in the chart below by circling the phrase that correctly replaces the question marks. In completing the last two sentences, assume that the impulse charge $Q$ remains fixed.

<table>
<thead>
<tr>
<th></th>
<th>increases</th>
<th>decreases</th>
<th>stays fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>The oscillation frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with increasing $L$</td>
<td>increases</td>
<td>decreases</td>
<td>stays fixed</td>
</tr>
<tr>
<td>The oscillation frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with increasing $C$</td>
<td>increases</td>
<td>decreases</td>
<td>stays fixed</td>
</tr>
<tr>
<td>The decay rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with increasing $L$</td>
<td>increases</td>
<td>decreases</td>
<td>stays fixed</td>
</tr>
<tr>
<td>The decay rate</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>with increasing $C$</td>
<td>increases</td>
<td>decreases</td>
<td>stays fixed</td>
</tr>
<tr>
<td>The decay rate</td>
<td></td>
<td></td>
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<tr>
<td>with increasing $R$</td>
<td>increases</td>
<td>decreases</td>
<td>stays fixed</td>
</tr>
<tr>
<td>The current amplitude</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with increasing $L$</td>
<td>increases</td>
<td>decreases</td>
<td>stays fixed</td>
</tr>
<tr>
<td>The voltage amplitude</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with increasing $L$</td>
<td>increases</td>
<td>decreases</td>
<td>stays fixed</td>
</tr>
</tbody>
</table>
Finally, suppose that the current source is a sinusoid taking the form $I(t) = I_0 \cos(\omega t)$, and that values of $R$, $C$, and $L$ are unchanged. In this case, answer the following questions assuming that the network operates in the sinusoidal steady state.

(G) For a given value of $I_0$, approximately what value for the frequency $\omega$ will yield the largest amplitude for the voltage $v$? A numerical answer with proper units is expected.

$$\omega =$$
(H) Assume that $\omega$ is set to be that frequency found in Part (3G) and that $I_0 = 1$ mA. What will be the approximate maximized amplitude of $v$? A numerical answer with proper units is expected.

$|v| =$
Problem 4: Sinusoidal Steady State – 20%

The circuits shown below are driven by sinusoidal voltage sources, and operate in the sinusoidal steady state with transfer function $H(\omega) \equiv V_{\text{out}}/V_{\text{in}}$ where $V_{\text{in}}$ and $V_{\text{out}}$ are complex voltage magnitudes. For each circuit below, circle the letter that corresponds to the plot of its transfer function magnitude (A-F), and to the plot of its transfer function phase (G-L); the plots are shown on the following page. The magnitude plots have log-log scales, and the phase plots have log-linear scales. These plots are sketches, and so you should choose one with a correct approximate shape. Further, the horizontal axes of the log-magnitude plots do not necessarily intersect the vertical axes at $\log |H| = 1$. The op-amp in the last circuit below is ideal.
Problem 2 – 35%

The circuit shown below models the electrical interaction between a digital processor, its power supply, and the connection between the two. Specifically, the current source ($i_P$) models the processor, the voltage source ($v_S$) models the supply, the resistor ($R$) and inductor ($L$) model the parasitics introduced by the interconnect wiring, and the capacitor ($C$) helps filter the processor voltage ($v_P$).

Both $i_P$ and $v_S$ can be functions of time. For example, the current drawn by the processor will depend on the number of its sections that are active, and the speed at which they operate, all of which can vary dynamically. Similarly, the supply voltage can vary due to external disturbances. Variations in $i_P$ and $v_S$ will in turn cause variations in $v_P$, which are important to understand because the processor will not operate properly if the variations in $v_P$ are too large.
(2A) (5%) Derive a second-order differential equation that relates $v_P$ to $v_S$ and $i_P$.

Diff Eqn:
(2B)  (10%) Assume that the supply voltage \( v_S \) and the processor current \( i_P \) have both been constant for a long time at the values \( V_S \) and \( I_{P1} \), respectively. Then, at \( t = 0 \), \( i_P \) takes a step such that \( i_P(t) = I_{P1} + I_{P2}u(t) \). In response, for \( t \geq 0 \), \( v_P \) takes the form \( v_P(t) = V_{P1} + V_{P2}e^{-\alpha t} \cos(\omega t + \phi) \). Determine the constants \( V_{P1}, V_{P2}, \alpha, \omega \) and \( \phi \) in terms of \( R, L, C \) and the source parameters; you may also express \( V_{P1}, V_{P2}, \alpha, \omega \) and \( \phi \) in terms of each other as long as only simple back substitution is required to ultimately express them in terms of \( R, L, C \) and the source parameters.

\[
\begin{align*}
V_{P1} &= \quad V_{P2} = \\
\alpha &= \quad \omega = \\
\phi &= 
\end{align*}
\]
(2C) (10%) Assume that the supply voltage $v_S$ and the processor current $i_P$ have both been constant for a long time at the values $V_S$ and $I_P$, respectively. Then, at $t = 0$, a noise spike occurs in $v_S$ such that $v_S = V_S + \Lambda \delta(t)$, where $\Lambda$ is a constant. Determine the values of $v_P$ and $dv_P/dt$ just after the noise spike in terms of $R$, $L$, $C$ and the source parameters.

\[ v_P(0^+) = \quad dv_P/dt(0^+) = \]
A cyclic program is written for the processor that results in \( i_P = I_P + I_C \cos(\omega t) \), while \( v_S = V_S \), where \( I_P, I_C \) and \( V_S \) are all constants. The steady-state response to the cyclic processor current takes the form \( v_P = V_P + V_C \cos(\omega t + \phi) \). Determine the constants \( V_P, V_C \) and \( \phi \) in terms of \( R, L, C, \omega \) and the source parameters.

\[
V_P = \\
V_C = \\
\phi = 
\]
Problem 2 – 25%

This problem studies the op-amp circuit shown below. Note that its output voltage is the voltage $v_{OUT}$. Assume that the op-amp is ideal. Also, assume that the circuit is stable. That is, assume that all voltages are finite for a finite input voltage $v_{IN}$.
Determine the Thevenin-equivalent resistance of the op-amp circuit at its output port as a function of the circuit parameters. Note that the output port is the port at which $v_{OUT}$ is defined.
(2B) Determine the Thevenin-equivalent voltage and the Norton-equivalent current of the op-amp circuit at its output port as a function of the circuit parameters.
(2C) The op-amp circuit is connected to a load resistor at its output port as shown below. Assume that \( R_1 = R_2 = R \). Determine the current \( i_L \) into the load as a function of \( v_{IN} \), \( R \) and \( R_L \).
(2D) Assume that the op-amp output voltage $v_{AMP}$ must satisfy $|v_{AMP}| < V_S$ for the op-amp to operate properly. Still assuming that the op-amp circuit is connected to a load resistor as shown in Part 2C, and still assuming that $R_1 = R_2 = R$, determine the allowable range of $R_L$ that ensures proper operation of the circuit. Do so in terms of $v_{IN}$, $R$ and $V_S$. 
The load resistor in Part 2C is replaced by a load capacitor having capacitance $C$. Assume that $v_{\text{IN}}$ is constant, and that $v_{\text{OUT}}(t = 0) = 0$. Still assuming $R_1 = R_2 = R$, determine $v_{\text{OUT}}(t)$ for $t > 0$ as a function of $v_{\text{IN}}$, $R$ and $C$. 
The load resistor in Part 2C is replaced by a load inductor having inductance $L$. Assume that $v_{IN}$ has been zero for all time prior to $t = 0$, and that $v_{IN} = Kt$ thereafter. Still assuming $R_1 = R_2 = R$, determine $v_{OUT}(t)$ for $t > 0$ as a function of $v_{IN}$, $R$, $L$ and the constant $K$. 
The circuit shown below is initially at rest such that $v_C(0^-) = 0$ and $i_L(0^-) = 0$. At $t = 0$, the current source steps up to produce 1 A. The figures shown below plot four waveforms within the circuit following the current step. Their horizontal axes all show time measured in seconds [s]. Their vertical axes show either voltage measured in Volts [V] or current measured in Amperes [A], as appropriate. Note that the initial slopes of the waveforms in Figures 1 and 3 are positive, while the initial slopes of the waveforms in Figures 2 and 4 are zero.
For each variable listed below, identify the corresponding figure by circling the figure number. *Briefly explain your reasoning in the space below.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_C$</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>$i_C$</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>$i_L$</td>
<td>1 2 3 4</td>
</tr>
</tbody>
</table>
(3B) Estimate the value of $R$. A *numerical answer with appropriate units is expected.*

(3C) Estimate the value of $C$. A *numerical answer with appropriate units is expected.*
(3D) Estimate the value of $L$. A numerical answer with appropriate units is expected.

(3E) Estimate the Q of the circuit. A numerical answer is expected.
For each statement below, circle the correct completion. *Briefly explain your reasoning in the space below.*

- If the resistance $R$ is increased, the quality factor $Q$ will
  - ... increase.  
  - ... decrease.  
  - ... remain unchanged.

- If the capacitance $C$ is increased, the quality factor $Q$ will
  - ... increase.  
  - ... decrease.  
  - ... remain unchanged.

- If the inductance $L$ is increased, the quality factor $Q$ will
  - ... increase.  
  - ... decrease.  
  - ... remain unchanged.
After a long time $T$, the current source steps down to turn off. For each statement below concerning the subsequent decay of stored energy, circle the correct completion. Briefly explain your reasoning in the space below.

- If the resistance $R$ is increased, the time at which the stored energy falls to half its value at time $T$ will · · ·

  · · · increase. · · · decrease. · · · remain unchanged.

- If the capacitance $C$ is increased, the time at which the stored energy falls to half its value at time $T$ will · · ·

  · · · increase. · · · decrease. · · · remain unchanged.

- If the inductance $L$ is increased, the time at which the stored energy falls to half its value at time $T$ will · · ·

  · · · increase. · · · decrease. · · · remain unchanged.
Problem 3: Integrator – 25%

Consider the circuit shown above with switch S1 *initially open* and the source is a constant 5V. Assume that the Op-Amp is ideal.

(3A) 6 pts Find $v_{\text{OUT}}(t)$.

$$v_{\text{OUT}}(t)=$$
(3B) 6 pts Suppose at $t = 0$, switch S1 is moved from an open to a closed position. Assume that the capacitor voltage $v_C(0) = 0$ (i.e. there is no initial charge). Find the time constant $\tau$ of the system after this event, i.e. for $t > 0$.

$\tau =$
(3C) 7 pts Solve for $v_{\text{OUT}}(t)$ in the situation described in problem (3B) for $t > 0$. Leave $\tau$ as a symbol, rather than substituting your answer from (3B).

For $t > 0$, $v_{\text{OUT}}(t) =$
(3D) **6 pts** At \( t = \tau \), assume the switch is switched *back to being open*. Solve for \( v_{\text{OUT}}(t) \) for \( t > \tau \).

For \( t > \tau \), \( v_{\text{OUT}}(t) = \)
Problem 17: 4 points

![Circuit Diagram]

Figure 16.

Derive an expression for $v_o(t)$ in terms of $v_1(t)$ and $v_2(t)$.

$v_o(t) =$