Chapter 1 Design Problems

D26. In the lab you have access to a set of resistors $\frac{1}{6}$-Watt resistors that are multiples of ten of the resistor base values. The resistors have the values as given in Table ??.

<table>
<thead>
<tr>
<th>Resistance (Ω)</th>
<th>Watt (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>15</td>
<td>1.5</td>
</tr>
<tr>
<td>22</td>
<td>2.2</td>
</tr>
<tr>
<td>33</td>
<td>3.3</td>
</tr>
<tr>
<td>47</td>
<td>4.7</td>
</tr>
<tr>
<td>68</td>
<td>6.8</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>150</td>
<td>15</td>
</tr>
<tr>
<td>220</td>
<td>22</td>
</tr>
<tr>
<td>330</td>
<td>33</td>
</tr>
<tr>
<td>470</td>
<td>47</td>
</tr>
<tr>
<td>680</td>
<td>68</td>
</tr>
<tr>
<td>1 kΩ</td>
<td>10</td>
</tr>
<tr>
<td>1.5 kΩ</td>
<td>15</td>
</tr>
<tr>
<td>2.2 kΩ</td>
<td>22</td>
</tr>
<tr>
<td>3.3 kΩ</td>
<td>33</td>
</tr>
<tr>
<td>4.7 kΩ</td>
<td>47</td>
</tr>
<tr>
<td>6.8 kΩ</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 1: Resistor values for problems D1.1 and D1.2.

Watt resistor with a resistance of 5.4 $k\Omega$. Design a circuit using the given components in any combination to achieve the desired resistance and power dissipation capability.

D27. You are given the set of resistors in table ?? which are all rated at 20% tolerance. For an application, you need a 600 $\Omega$ resistor which is accurate to 10% tolerance. Design a resistor network using only resistors found in the table that will satisfy this criteria. You may use multiple resistors of the same value.

D28. An R2R ladder is an example of an infinitely-extensible circuit. Figure ?? shows a finite version of this circuit. A DC voltage source is connected between the inputs (+ and −) and the output voltage is measured at each of the points $A$, $B$, $C$ and $D$. For an input voltage of 16V, what are the measured voltages at each point?

![Figure 1](image_url)
D29. An infinitely-extendable circuit is shown in Figure ?? where the pattern of resistors continues ad infinitum. As seen between the terminals $A$ and $B$, what is the equivalent resistance of the infinite circuit?

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{circuit.png}
\caption{The circuit for problem D1.4.}
\end{figure}

D30. You have a 30V DC power supply with an output resistance of 5 $\Omega$. Design a circuit that uses the given supply and provides output voltages of 24V, 12V and 5.0V. All of the outputs must have output resistances that are no larger than 500 $\Omega$.

D31. You are asked to design a heating element which is driven by a 50V DC voltage supply. The heat is to be provided by a heating coil that has a resistance of 5 $\Omega$. You will control the heat output using a potentiometer whose resistance can vary from 1 $\Omega$ to 10 $\Omega$. Using any other resistors you need, design a heater where the power dissipated by the heating coil can vary by a factor of five over the full range of the potentiometer.

D32. Resistors can be easily purchased with power ratings (the maximum power dissipation before they burn up) of $\frac{1}{8}$W, $\frac{1}{4}$W, $\frac{1}{2}$W and 1W. The lower the power rating, the less expensive the resistor. You are asked to analyze the circuit below to specify the power ratings on each of the resistors with the goal of minimizing the cost of the circuit, but also making sure that none of the resistors will go “poof”. You are also asked to make sure that if the user accidentally reverses one of the batteries that no resistors will fail.

D33. A circuit has a Thévenin voltage of 10V and a Thévenin resistance of 100 $\Omega$. It is used to drive a 100 $\Omega$ load. Discuss the accuracy of the statement: “when the load is not connected to the circuit, the circuit dissipates no power as no current flows”.

D34. An electromagnet is made by wrapping a coil of wire around a core element. You are asked to duplicate an existing magnet and are given a spool of wire out of which the first magnet is made and a core element. Describe the steps you would take (without destroying the first magnet) to duplicate it.

D35. A copper-wire based phone system uses a DC voltage of 30V to power a phone which can be treated as a 1 kΩ load. The system is to be wired using round 20-gauge copper wire (diameter of 0.812mm). How long can the wire be if we do not want the 30V to sag by more than 0.25 V? What if we use aluminum wire?

D36. Your lab partner builds the voltage-divider circuit shown in Figure ?? out of the resistors listed in Table ???. These are all 1/8-Watt resistors which are rated with a 20% tolerance. Explain why this is a poorly designed circuit giving numerical examples of the problems.
Chapter 2 Design Problems

D28. A typical "light dimmer" used to dim the stage lights in a theater consists of a variable inductor $L$ whose inductance can take on values from close to 0 up to some maximum value, $L_{\text{max}}$. This variable inductor is connected in series with a stage light which is rated at 120V and 1000W. Power is supplied from a 120V (rms) AC supply with a frequency of 60Hz (typical household power in North America). In designing the circuit, we would like the power dissipated in the light bulb to vary by a factor of 5 from its maximum value as we vary the inductor. (a) What value of $L_{\text{max}}$ is required for this to work? (b) What is the total power dissipated in the circuit when the light is dimmed to $\frac{1}{5}$ power? (c) A dimmer circuit can also be designed using a variable resistor which has values from 0Ω up to a maximum resistance, $R_{\text{max}}$. Design a variable-resistor based circuit to accomplish the same dimming as before. (d) What is the total dissipated power with the light is dimmed using the resistor circuit?

D29. Using a 500 mH inductor and a capacitor of your choice, design a circuit that has a minimum magnitude of its impedance at a frequency of 60 Hz. What happen to this minimum impedance if we also account for the 500 Ω internal resistance of the inductor?

D30. Using a 100 mH inductor and a capacitor of your choice, design a circuit that has a maximum magnitude of impedance at a frequency of 1 kHz. What happens to the magnitude of the impedance if we account for the 200 Ω internal resistance of the inductor?

D31. A friend of yours has a large number of 0.5 F (rated at 35 V) capacitors that she recycled from old computers. Her uncle would like to use the rapid discharge (when shorted) from these capacitors to quickly (in under 30 s) cook hot dogs at his stand. Given that the resistance of 50 g hot dog is about 100Ω, discuss the feasibility of building such a cooker. You may consider the hot dog as water for heating purposes.

D32. In many situations, $RC$ circuits can be used to build clocks. In such circuits, the period is related to the time to go from $\frac{1}{3}$ maximum voltage to $\frac{2}{3}$ maximum voltage. Choose reasonable components such that the time is 1 s. How sensitive is this time on the value of the components?
D33. What is the equivalent inductance of a circuit that has two inductors, $L_1$ and $L_2$ in parallel?

D34. An $RC$ circuit can be used to buffer an output voltage so that it never falls below a given value. Consider a time dependent input voltage

$$v(t) = \begin{cases} V_0 & 0 < t < T, 2T < t < 3T, \cdots \\ 0 & T < t < 2T, 3T < t < 4T, \cdots \end{cases}$$

where the period, $T$ is 0.1 s and the voltage, $V_0 = 5$ V. Design an $RC$ circuit such that the output voltage never falls below $0.5V_0$ (after steady state has been reached).

D35. A crystal radio can be made by wrapping several hundred turns of wire around a toilet-paper roll, and then connecting with a variable capacitor to tune the circuit. This is then adjusted to match the frequency of AM radio stations (520 to 1610 kHz). Estimate the inductance of the coil that you build and then determine the range of the variable capacitor to match this.

D36. Bielectric impedance analysis is used to measure the percent of body fat in a person. The underlying idea is that the water in your body conducts electricity. Some of that water is outside the cells, and behaves as an extra-cellular resistance, $R_e$, while some of the water is inside cells. The cell membranes act as a capacitance in series with this intracellular resistance, $R_i$ and $C_i$. The total impedance of the body is then modeled as $R_e$ in parallel to the series combination of $R_i$ and $C_i$ as shown in Figure ??, Determine an expression for the equivalent impedance of the human body and determine the low-frequency and high-frequency limits of the impedance. Make a sketch the reactance versus the resistance for this impedance.

![Figure 5: A model of the impedance of the human body.](image)
Chapter 3 Design Problems

D18. You have a circuit that processes signals in the $f = 5$ kHz to 10 kHz range where the typical signal size is 500 mV. It unfortunately is operating near a dirty power supply that produces a lot of noise at $f = 60$ Hz and higher harmonics. The pick-up amplitude of the 60 Hz signal is 0.5 V, and each higher harmonic is down by a factor of two, e.g. at $f = 120$ Hz, the pickup is 0.25 V, at $f = 180$ Hz, it is 0.125 V, and so on. You are asked to design an input filter that will allow the circuit to function by reducing all the noise to a level that is no more than 10% of the input signal.

D19. You need to build a low-pass filter which fully passes signals with a frequency smaller than 500 Hz. Unfortunately, the circuit needs to be used to drive a circuit whose input impedance at these frequencies is $|Z_{in}| = 1$ kΩ. Sketch the circuit and choose reasonable component values to satisfy these requirements as best you can.

D20. In this problem we will examine the input- and output-impedances for a high-pass filter. Are there any frequencies for which the two impedances are the same? Are there any frequencies for which the magnitude to the two impedances are the same? Express any frequencies In terms of $\omega RC$, what is the frequency?

D21. You are asked to build a band-pass filter for $\omega = 1$ kHz using resistors and capacitors. Choose reasonable values such that the input impedance $|Z_{in}|$ is no smaller than 1 kΩ and the output impedance is no larger than 10 kΩ. Design such a circuit and specify your component values. What will your circuit’s gain at $\omega = 1$ kHz?

D22. You are asked to build a band-pass filter using inductors and capacitors such that the gain at the pass frequency is a maximum, and equal to 1. Assume that we would like to satisfy the same criteria as described in problem D3.4. Design such a circuit and specify your component values.

D23. We looked at hooking a high-pass and a low-pass filter in series to create a band pass filter. Consider a circuit in which you place the high-pass and low-pass filter in parallel. Assume that both filters are built using the same resistor and capacitor. Discuss the behavior of the
resulting circuit. What are the high- and low- frequency behaviors? What happens at the characteristic frequency?

D24. In a audio system, one typically uses different speakers for different frequency ranges. A minimal example is the high-frequency (above $f \sim 10 \text{ kHz}$) going into a *tweeter* and the lower frequencies (below $f \sim 10 \text{ kHz}$) going into a regular speaker. The circuit that splits the signal between the speakers is known as a *cross-over* network. Design a cross-over circuit that can passively split the signal into the two ranges listed above and drive speakers. It is typical to choose the resistors in these networks to be around $10 \Omega$.

D25. Consider the LC-parallel RLC circuit shown in Figure ???. Assume that the output of the circuit is measured across the resistor. What is the gain of the circuit as a function of frequency? What happens at $\omega = 1/\sqrt{LC}$?

![Figure 6: The LC-parallel RLC circuit for problem D25.](image)

D26. A bridged T-filter is shown in Figure ???. The input comes in from the left and the output is taken from the right. (a) What is the gain of
this circuit as a function of frequency? (b) At what frequency does the gain have a minimum? (c) What is the phase difference between input and output voltages? You will find it useful to use the Kirchhoff rules to analyze this problem.

D27. A bridged T-filter is built with the two resistors a factor of $n^2$ in magnitude apart as shown in Figure 8. (a) What is the gain of this circuit as a function of frequency? (b) At what frequency does the gain have a minimum? (c) What is the phase difference between input and output voltages? You will find it useful to use the Kirchhoff rules to analyze this problem.

![Figure 8: A bridged T-filter for problem D27.](image_url)
Chapter 4 Design Problems

D12. A student sets up a circuit that looks like this, to gather data for characterizing a diode:

![Circuit Diagram](image)

Figure 9: The circuit for problem D4.12.

Measuring diode voltage and diode current in this circuit, the student generates the following table of data: You know that the behavior of a pn junction follows Shockley’s equation,

\[
I_{\text{diode}} = I_S \cdot \left[ e^{(V_{\text{diode}}/\kappa)} - 1 \right]
\]

where \( \kappa \) incorporates the thermal voltage and the constant \( m \). From your data, determine the value of \( I_S \) and \( \kappa \).

<table>
<thead>
<tr>
<th>( V_{\text{diode}} ) (V)</th>
<th>0.60</th>
<th>0.625</th>
<th>0.65</th>
<th>0.70</th>
<th>0.725</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_{\text{diode}} ) (mA)</td>
<td>1.68</td>
<td>2.88</td>
<td>5.00</td>
<td>8.68</td>
<td>14.75</td>
<td>27.25</td>
</tr>
</tbody>
</table>

Table 2: Measured data for problem D4.12.

D13. Assume that you have a diode which has a 0V drop when it is forward biased. Design a circuit using this diode and possibly other components that will allow the negative half of an AC signal to pass, but not allow the positive half to pass.

D14. Using diodes and ideal DC voltage source of the appropriate value, design a circuit that will prevent the magnitude of an AC signal from becoming larger than 10V. You may assume that the diode drop is 0.65 V.

D15. The circuit in Figure ?? is to be used with signals in the 1 kHz to 10 kHz range and is supposed to output the maximum of the input voltage.

\[
v_o = \max(v_i)
\]
Choose reasonable values for $R$ and $C$ for this to work. Based on your values, what are the limitations of this device for both the low- and high-end of the frequency range?

![Circuit Diagram]

Figure 10: The circuit for problem D4.15.

D16. AC power is typically transmitted using a so-called three-phase system, where each of the three voltages has the same amplitude, but they are all separated by 120° in phase. Based on the full-wave rectifier circuit, design such a circuit for a three-phase system.

D17. Light-emitting diodes (LED) are a type of diode that emits light when it is forward biased. They come in various colors, but a typical LED will emit light when there is about 2 V across it, and one typically wants a current through the LED of 10 to 20 mA. Design a circuit that safely lights a single LED using a 5 V DC supply.

D18. As noted in the previous problem, LEDs emit light when they are forward biased. Different colored LEDs have different forward bias voltages with a sampling given in Table ??.

<table>
<thead>
<tr>
<th>Color</th>
<th>$V_d$</th>
<th>$I_{max}$</th>
<th>$I_{typ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>2.2-2.8 V</td>
<td>30 mA</td>
<td>20 mA</td>
</tr>
<tr>
<td>Yellow</td>
<td>2.25-2.6 V</td>
<td>30 mA</td>
<td>20 mA</td>
</tr>
<tr>
<td>Green</td>
<td>3.2-3.6 V</td>
<td>30 mA</td>
<td>20 mA</td>
</tr>
<tr>
<td>Blue</td>
<td>3.2-3.5 V</td>
<td>30 mA</td>
<td>20 mA</td>
</tr>
<tr>
<td>White</td>
<td>3.6-4.0 V</td>
<td>30 mA</td>
<td>20 mA</td>
</tr>
</tbody>
</table>

Table 3: Typical performance data on different colored light-emitting diodes.

5 V battery and any other needed components that can safely light a red, yellow, green or a blue LED.
Chapter 5 Design Problems

D20. You have a 100 mV signal in the frequency range of 600 Hz to 700 Hz that you need to drive a 200 Ω load with. Unfortunately, there is a comparable amount of “line noise” at 60 Hz. You are told that the output impedance of the signal source is 300 Ω. Design a circuit that will reduce the noise to no more than 20% of the signal and be able to drive your load. You need to specify the power supply voltage and component values, but may assume that you have “reasonable” transistors.

D21. You have a 200 mV signal in the frequency range of 1 kHz to 10 kHz that comes from a source with an output impedance of 5 kΩ. You would like to be able to drive a circuit whose input impedance is 50 Ω with this signal. Using transistors whose $\beta$ is approximately 200, design a circuit that will allow you to do this. You may want to consider the use of a Darlington pair.

D22. You need a simple amplifier that can take an input signal in the frequency range of 1500 kHz to 50 kHz and maximum amplitude of 300 mV. Unfortunately, the amplifier works in a regime where there is noise of amplitude about 3 V below at 60 Hz. You would like your amplifier to produce a 3 V amplitude output signal that could be used to drive a 1 kΩ load. You would also like to make sure that the output noise is at least 10 times smaller than the signal. Design a transistor circuit to do this. You need to specify the power supply voltage and component values, but may assume that you have “reasonable” transistors.

D23. You are asked to build a times-ten amplifier using a pnp transistor where the circuit operates between ground and a negative voltage, $V_{CC}$. Sketch the needed circuit and determine if the output is inverted relative to the input.

D24. Consider the modified differential amplifier circuit shown in Figure ???. Assume that the input voltage is a DC voltage, $V_B$ plus an input AC voltage, $v_{in}$. The output voltage is similarly a DC component, $V_C$ and a time-dependent part, $v_{out}$. What is the gain of the circuit ($v_{out}/v_{in}$) assuming that both transistors are in their nominal operating range?
D25. A light-dependent resistor (LDR) is a device whose resistance decreases as the amount of light it is exposed to increases. These devices are based on CdS and in darkness, they have a resistance on the order of $R_{LDR} \approx 1\, M\Omega$, while in bright light, $R_{LDR} \approx 1\, k\Omega$. As an example, the NSL-4960 Photo Cell from Silonex is most sensitive to 515 nm wavelength light. In the bright light (100 ftc), it has a resistance of 0.5$\, k\Omega$, while in the dark, it has a resistance of 1$\, M\Omega$.

An LDR can be used to build a circuit that turns a light on when it is dark outside. In our case, we can have it turn on a light-emitting diode (LED) when it is dark. A typical white LED has a voltage drop of about 3.4 V and draws about 20 mA when it is on. Design a circuit using an npn transistor, and NORPS-13 LDR, a white LED and appropriate resistors such that the LED will turn on when it is dark outside. Use a 9 V battery to power your circuit.

D26. A light-dependent resistor (LDR) is a device whose resistance decreases as the amount of light it is exposed to increases. These devices are based on CdS and in darkness, they have a resistance on the order of $R_{LDR} \approx 1\, M\Omega$, while in bright light, $R_{LDR} \approx 1\, k\Omega$. As an example, the NSL-4960 Photo Cell from Silonex is most sensitive to 515 nm wavelength light. In the bright light (100 ftc), it has a resistance of 0.5$\, k\Omega$, while in the dark, it has a resistance of 1$\, M\Omega$.

You are asked to build a circuit that can sense if a light was left on in a nominally dark attic space. Your circuit should be based on a 6 V DC power supply and have a red-light indicator. A red LED is on if the
light has been left on in the attic. Design your circuit using the LDR sensor described about and npn and or pnp transistors as switches to control the LED. A red LED has a nominal voltage drop of $1.7\, \text{V}$ and a maximum current of $30\, \text{mA}$.

D27. A *thermistor* is a device whose resistance has a strong temperature dependence. Depending on the device, the resistance can either increase or decrease with temperature. These devices can be effectively used in circuits where we want to turn something on or off when a certain temperature is reached. In Table 4 are given a number of values of resistance for different temperatures for the ICT 151-237 thermistor.

<table>
<thead>
<tr>
<th>$T, (\text{C})$</th>
<th>$-50$</th>
<th>$-20$</th>
<th>$-10$</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R, (\Omega)$</td>
<td>670k</td>
<td>97k</td>
<td>55k</td>
<td>32k</td>
<td>19k</td>
<td>12.5k</td>
<td>8.0k</td>
<td>5.2k</td>
<td>3.6k</td>
</tr>
<tr>
<td>$T, (\text{C})$</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
<td>140</td>
</tr>
<tr>
<td>$R, (\Omega)$</td>
<td>2.5k</td>
<td>1.7k</td>
<td>1.26k</td>
<td>915</td>
<td>678</td>
<td>510</td>
<td>389</td>
<td>301</td>
<td>235</td>
</tr>
</tbody>
</table>

Table 4: Data on the ICT 151-237 thermistor.

Design a circuit using a 4.5 V DC voltage source that will switch off a yellow LED when a pot of water has started to boil. A yellow LED has a 2.1 V drop across it when it is on and it can draw a maximum of $30\, \text{mA}$ of current. You will probably want to design your circuit using a potentiometer so that you can adjust the performance of the device.

D28. A *thermistor* is a device whose resistance has a strong temperature dependence. Depending on the device, the resistance can either increase or decrease with temperature. These devices can be effectively used in circuits where we want to turn something on or off when a certain temperature is reached. In Table 4 are given a number of values of resistance for different temperatures for the ICT 151-237 thermistor.

Design a circuit using a 9 V battery that will switch on a blue LED when the outside temperature get close to freezing. A blue LED has a 4.5 V drop across it when it is on and it can draw a maximum of $30\, \text{mA}$ of current. You will probably want to design your circuit using a potentiometer so that you can adjust the performance of the device.