Summary

- An electrical signal source can be represented in either the Thévenin form (a voltage source v_s in series with a source resistance R_s) or the Norton form (a current source i_s in parallel with a source resistance R_s). The Thévenin voltage v_s is the open-circuit voltage between the source terminals; the Norton current i_s is equal to the short-circuit current between the source terminals. For the two representations to be equivalent, v_s and $R_s i_s$ must be equal.
- A signal can be represented either by its waveform versus time or as the sum of sinusoids. The latter representation is known as the frequency spectrum of the signal.
- The sine-wave signal is completely characterized by its peak value (or rms value, which is the peak/$\sqrt{2}$), its frequency (ω in rad/s or f in Hz; $\omega = 2\pi f$ and $f = 1/T$, where T is the period in seconds), and its phase with respect to an arbitrary reference time.
- Analog signals have magnitudes that can assume any value. Electronic circuits that process analog signals are called analog circuits. Sampling the magnitude of an analog signal at discrete instants of time and representing each signal sample by a number results in a digital signal. Digital signals are processed by digital circuits.
- The simplest digital signals are obtained when the binary system is used. An individual digital signal then assumes one of only two possible values: low and high (say, 0 V and +1.8 V), corresponding to logic 0 and logic 1, respectively.
- An analog-to-digital converter (ADC) provides at its output the digits of the binary number representing the analog signal sample applied to its input. The output digital signal can then be processed using digital circuits. Refer to Fig. 1.10 and Eq. (1.3).
- The transfer characteristic, v_O versus v_I, of a linear amplifier is a straight line with a slope equal to the voltage gain. Refer to Fig. 1.12.
- Amplifiers increase the signal power and thus require dc power supplies for their operation.
- The amplifier voltage gain can be expressed as a ratio A_v in V/V or in decibels, $20 \log |A_v|$, dB. Similarly, for current gain: A_i A/A or $20 \log |A_i|$, dB. For power gain: A_p W/W or $10 \log A_p$, dB.
- Depending on the signal to be amplified (voltage or current) and on the desired form of output signal (voltage or current), there are four basic amplifier types: voltage, current, transconductance, and transresistance amplifiers. For the circuit models and ideal characteristics of these four amplifier types, refer to Table 1.1. A given amplifier can be modeled by any one of the four models, in which case their parameters are related by the formulas in Eqs. (1.14) to (1.16).
- The sinusoid is the only signal whose waveform is unchanged through a linear circuit. Sinusoidal signals are used to measure the frequency response of amplifiers.
- The transfer function $T(s) \equiv V_o(s)/V_i(s)$ of a voltage amplifier can be determined from circuit analysis. Substituting $s = j\omega$ gives $T(j\omega)$, whose magnitude $|T(j\omega)|$ is the magnitude response, and whose phase $\phi(\omega)$ is the phase response, of the amplifier.
- Amplifiers are classified according to the shape of their frequency response, $|T(j\omega)|$. Refer to Fig. 1.26.
- Single-time-constant (STC) networks are those networks that are composed of, or can be reduced to, one reactive component (L or C) and one resistance (R). The time constant τ is either L/R or CR.
- STC networks can be classified into two categories: low pass (LP) and high pass (HP). LP networks pass dc and low frequencies and attenuate high frequencies. The opposite is true for HP networks.
- The gain of an LP (HP) STC circuit drops by 3 dB below the zero-frequency (infinite-frequency) value at a frequency $\omega_0 = 1/\tau$. At high frequencies (low frequencies) the gain falls off at the rate of 6 dB/octave or 20 dB/decade. Refer to Table 1.2 and Figs. 1.23 and 1.24. Further details are given in Appendices E and F.

Circuit Basics

As a review of the basics of circuit analysis and in order for the readers to gauge their preparedness for the study of electronic circuits, this section presents a number of relevant circuit analysis problems. For a summary of Thévenin's and Norton's theorems, refer to Appendix D. The problems are grouped in appropriate categories.

Resistors and Ohm's Law

1.1 Ohm's law relates V, I, and R for a resistor. For each of the situations following, find the missing item:

(a) $R = 1\ \text{k}\Omega, V = 0.5\ \text{V}$
(b) $V = 2\ \text{V}, I = 1\ \text{mA}$
(c) $R = 20\ \text{k}\Omega,\ I = 0.1\ \text{mA}$
(d) $R = 100\ \Omega, V = 5\ \text{V}$

Note: Volts, milliamps, and kilohms constitute a consistent set of units.

1.2 Measurements taken on various resistors are shown below. For each, calculate the power dissipated in the resistor and the power rating necessary for safe operation using standard components with power ratings of 1/8 W, 1/4 W, 1/2 W, 1 W, or 2 W:

(a) 1 kΩ conducting 20 mA
(b) 1 kΩ conducting 40 mA
(c) 100 kΩ conducting 1 mA
(d) 10 kΩ conducting 4 mA
(e) 1 kΩ dropping 20 V
(f) 1 kΩ dropping 11 V

1.3 Ohm's law and the power law for a resistor relate V, I, R, and P, making only two variables independent. For each pair identified below, find the other two:

(a) $R = 1\ \text{k}\Omega,\ I = 2\ \text{mA}$
(b) $V = 1\ \text{V}, I = 20\ \text{mA}$
(c) $V = 1\ \text{V}, P = 100\ \text{mW}$
(d) $I = 0.1\ \text{mA}, P = 2\ \text{mW}$
(e) $R = 1\ \text{k}\Omega,\ P = 0.1\ \text{W}$

Combining Resistors

1.4 You have available only 5-kΩ resistors, but you have as many as you would like. Using series and parallel combinations of them, realize the following resistor values: 20 kΩ, 1.67 kΩ, 12.5 kΩ, 23.75 kΩ.

1.5 In the analysis and test of electronic circuits, it is often useful to connect one resistor in parallel with another to obtain a nonstandard value, one which is smaller than the smaller of the two resistors. Often, particularly during circuit testing, one resistor is already installed, in which case the second, when connected in parallel, is said to "shunt" the first. If the original resistor is 10 kΩ, what is the value of the shunting resistor needed to reduce the combined value by 1%, 5%, 10%, and 50%? What is the result of shunting a 10-kΩ resistor by 1 MΩ? By 100 kΩ? By 10 kΩ?

Voltage Dividers

1.6 Figure P1.6(a) shows a two-resistor voltage divider. Its function is to generate a voltage V_O (smaller than the power-supply voltage V_{DD}) at its output node X. The circuit looking back at node X is equivalent to that shown in Fig. P1.6(b). Observe that this is the Thévenin equivalent of the voltage-divider circuit. Find expressions for V_O and R_O.

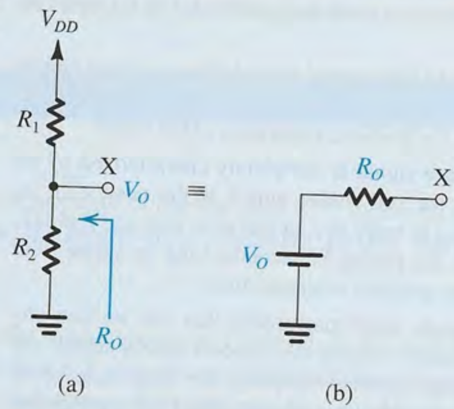

Figure P1.6

1.7 A two-resistor voltage divider employing a 2-kΩ and a 1-kΩ resistor is connected to a 3-V ground-referenced power supply to provide a 2-V voltage. Sketch the circuit. Assuming exact-valued resistors, what output voltage (measured to ground) and equivalent output resistance result? If the resistors used are not ideal but have a ±5% manufacturing tolerance, what are the extreme output voltages and resistances that can result?

problems with blue numbers are considered essential; * = difficult problem; ** = more difficult; *** = very challenging
SIM = simulation; D = design problem; ● = see related video example

D 1.8 You are given three resistors, each of 10 kΩ, and a 9-V battery whose negative terminal is connected to ground. With a voltage divider using some or all of your resistors, how many positive-voltage sources of magnitude less than 9 V can you design? List them in order, smallest first. What is the output resistance (i.e., the Thévenin resistance) of each?

D *1.9 Two resistors, with nominal values of 470 Ω and 1 kΩ, are used in a voltage divider with a +3-V supply to create a nominal +1-V output. Assuming the resistor values to be exact, what is the actual output voltage produced? Which resistor must be shunted (paralleled) by what third resistor to create a voltage-divider output of 1.00 V? If an output resistance of exactly 333 Ω is also required, what do you suggest?

Current Dividers

1.10 Figure P1.10 shows a two-resistor current divider fed with an ideal current source I. Show that

$$I_1 = \frac{R_2}{R_1 + R_2} I$$

$$I_2 = \frac{R_1}{R_1 + R_2} I$$

and find the voltage V that develops across the current divider.

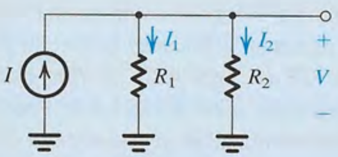

Figure P1.10

1.11 Fig. P1.11 shows a current source driving N resistors in parallel. Show that the current through the k^{th} resistor is

$$I_k = \frac{I/R_k}{\sum_{i=1}^{N} 1/R_i}$$

Show that when $N = 2$, this expression is the same as for a two-resistor current divider.

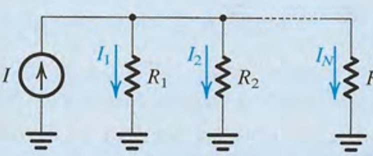

Figure P1.11

D 1.12 Design a simple current divider that will reduce the current provided to a 6-kΩ load to one-quarter of that available from the source.

D 1.13 A designer searches for a simple circuit to provide one-fifth of a signal current I to a load resistance R. Suggest a solution using one resistor. What must its value be? What is the input resistance of the resulting current divider? For a particular value R, the designer discovers that the otherwise-best-available resistor is 10% too high. Suggest two circuit topologies using one additional resistor that will solve this problem. What is the value of the resistor required in each case? What is the input resistance of the current divider in each case?

D 1.14 A current source produces a sinusoidal signal with 0.5 mA peak amplitude. However, the voltage across the source must not exceed 1 V, otherwise the signal becomes distorted. What is the maximum load resistance that may be connected to the source while respecting this limit? If a 10-kΩ load is to be connected, what additional resistor must be connected in parallel to prevent distortion? What is the resulting current signal through the 10-kΩ load?

Thévenin Equivalent Circuits

1.15 For the circuit in Fig. P1.15, find the Thévenin equivalent circuit between terminals (a) 1 and 2, (b) 2 and 3, and (c) 1 and 3.

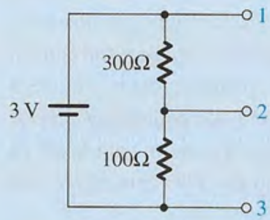

Figure P1.15

1.16 Through repeated application of Thévenin's theorem, find the Thévenin equivalent of the circuit in Fig. P1.16 between node 4 and ground, and hence find the current that flows through a load resistance of 3 kΩ connected between node 4 and ground.

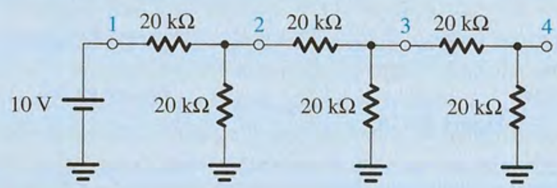

Figure P1.16

Circuit Analysis

VE 1.1 **1.17** For the circuit shown in Fig. P1.17, find the current in each of the three resistors and the voltage (with respect to ground) at their common node using two methods:

(a) Loop Equations: Define branch currents I_1 and I_2 in R_1 and R_2, respectively; write two equations; and solve them.

(b) Node Equation: Define the node voltage V at the common node; write a single equation; and solve it.

Which method do you prefer? Why?

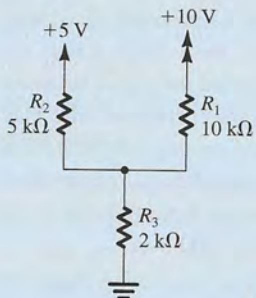

Figure P1.17

1.18 The circuit shown in Fig. P1.18 represents the equivalent circuit of an unbalanced bridge. Such equivalent circuits arise, for example, in pressure sensors where the resisances R_{1-4} vary with pressure and the output signal is observed across terminals 1 and 2. It is required to calculate the current in the detector branch (R_5) and the voltage across it. Although this can be done by using loop and node equations, a much easier approach is possible: Find the Thévenin equivalent of the circuit to the left of node 1 and the Thévenin equivalent of the circuit to the right of node 2. Then solve the resulting simplified circuit.

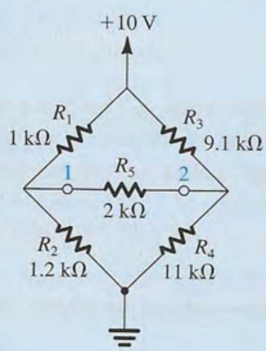

Figure P1.18

1.19 Two sources are connected as shown in Fig. P1.19 below. Use Thévenin equivalent representations to help find the voltage v_o.

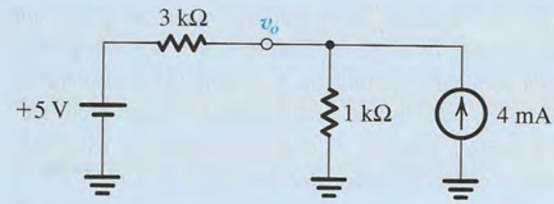

Figure P1.19

1.20 Derive an expression for v_o/v_s for the circuit shown in Fig. P1.20.

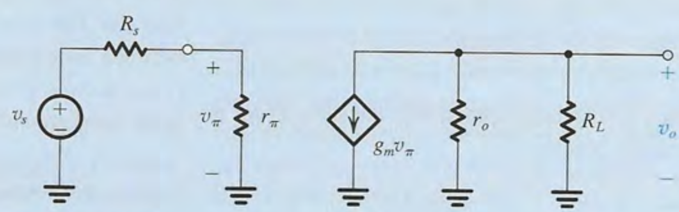

Figure P1.20

AC Circuits

1.21 The periodicity of recurrent waveforms, such as sine waves or square waves, can be completely specified using only one of three possible parameters: radian frequency, ω, in radians per second (rad/s); (conventional) frequency, f, in hertz (Hz); or period, T, in seconds (s). As well, each of the parameters can be specified numerically in one of several ways: using letter prefixes associated with the basic units, using scientific notation, or using some combination of both. Thus, for example, a particular period may be specified as 100 ns, 0.1 μs, 10^{-1} μs, 10^5 ps, or 1×10^{-7} s. (For the definition of the various prefixes used in electronics, see Appendix J.) For each of the measures listed below, express the trio of terms in scientific notation associated with the basic unit (e.g., 10^{-7} s rather than 10^{-1} μs).

problems with blue numbers are considered essential; * = difficult problem; ** = more difficult; *** = very challenging
SIM = simulation; **D** = design problem; ● = see related video example

(a) $T = 10^{-4}$ μs
(b) $f = 3$ GHz
(c) $\omega = 6.28 \times 10^4$ rad/s
(d) $T = 10^{-7}$ s
(e) $f = 60$ Hz
(f) $\omega = 100$ krad/s
(g) $f = 270$ MHz

1.22 Find the complex impedance, Z, of each of the following basic circuit elements at 60 Hz, 100 kHz, and 1 GHz:

(a) $R = 1$ kΩ
(b) $C = 10$ nF
(c) $C = 10$ pF
(d) $L = 10$ mH
(e) $L = 1$ μH

1.23 Find the complex impedance at 10 kHz of the following networks:

(a) 1 kΩ in series with 1 nF
(b) 1 kΩ in parallel with 0.01 μF
(c) 10 kΩ in parallel with 100 pF
(d) 100 kΩ in series with 10 mH

***1.24** Write an expression for the complex impedance of a parallel combination of an inductor, L, and a capacitor, C, as a function of frequency.

Find the frequency at which the magnitude of the impedance becomes infinite. What happens to the phase of the impedance at this frequency? What current will the parallel combination draw from an ideal sinusoidal voltage source at this frequency?

Section 1.1: Signals

1.25 Any given signal source provides an open-circuit voltage, v_{oc}, and a short-circuit current, i_{sc}. For the following sources, calculate the internal resistance, R_s; the Norton current, i_s; and the Thévenin voltage, v_s:

(a) $v_{oc} = 3$ V, $i_{sc} = 3$ mA
(b) $v_{oc} = 500$ mV, $i_{sc} = 50$ μA

1.26 A particular signal source produces an output of 100 μA when loaded by a 100-kΩ resistor and 500 μA when loaded by a 10-kΩ resistor. Calculate the Thévenin voltage, Norton current, and source resistance.

1.27 An audio signal source is connected to a speaker. When connected to a 16-Ω speaker, the source delivers 25% less power than when connected to a 32-Ω headphone speaker. What is the source resistance?

1.28 A temperature sensor is specified to provide 2 mV/°C. When connected to a load resistance of 10 kΩ, the output voltage was measured to change by 10 mV, corresponding to a change in temperature of 20°C. What is the source resistance of the sensor?

1.29 Refer to the Thévenin and Norton representations of the signal source (Fig. 1.1). If the current supplied by the source is denoted i_o and the voltage appearing between the source output terminals is denoted v_o, sketch and clearly label v_o versus i_o for $0 \le i_o \le i_s$.

VE 1.2

1.30 Consider voltage sources connected to loads with the values shown below. In each case, find the percentage change in V_L and I_L in response to a 10% increase in the value of R_L. In which cases is it more appropriate to use a Norton equivalent source? In those cases, find the Norton equivalent for $V_s = 1$ V.

(a) $R_s = 5$ kΩ; $R_L = 200$ kΩ
(b) $R_s = 5$ Ω; $R_L = 50$ Ω
(c) $R_s = 2$ kΩ; $R_L = 100$ Ω
(d) $R_s = 150$ Ω; $R_L = 16$ Ω

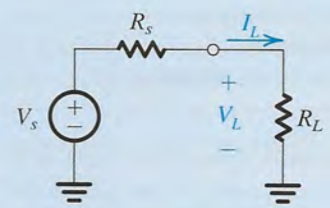

Figure P1.30

1.31 The connection of a signal source to an associated signal processor or amplifier generally involves some degree of signal loss as measured at the processor or amplifier input. Considering the two signal-source representations shown in Fig. 1.1, provide two sketches showing each signal-source representation connected to the input terminals (and corresponding input resistance) of a signal processor. What signal-processor input resistance will result in 95% of the open-circuit voltage being delivered to the processor? What input resistance will result in 95% of the short-circuit signal current entering the processor?

Section 1.2: Frequency Spectrum of Signals

1.32 To familiarize yourself with typical values of angular frequency ω, conventional frequency f, and period T, complete the entries in the following table:

Case	ω (rad/s)	f (Hz)	T (s)
a		5×10^9	
b	2×10^9		
c			1×10^{-10}
d		60	
e	6.28×10^4		
f			1×10^{-5}

1.33 For the following peak or rms values of some important sine waves, calculate the corresponding other value:

(a) 117 V rms, a household-power voltage in North America
(b) 33.9 V peak, a somewhat common voltage in rectifier circuits
(c) 220 V rms, a household-power voltage in parts of Europe
(d) 220 kV rms, a high-voltage transmission-line voltage in North America

1.34 Give expressions for the sine-wave voltage signals having:

(a) 3-V peak amplitude and 20-kHz frequency
(b) 120-V rms and 60-Hz frequency
(c) 0.2-V peak-to-peak and 10^8-rad/s frequency
(d) 100-mV peak and 1-ns period

1.35 Characterize a symmetrical square-wave wave with peak-to-peak amplitude 2V and period 0.5 ms. Sketch the waveform. What is its average value? Its lowest value? Its highest value? Its frequency? Write an expression for it in terms of its sinusoidal components.

1.36 Measurements taken of a square-wave signal using a frequency-selective voltmeter (called a spectrum analyzer) show its spectrum to contain adjacent components (spectral lines) at 98 kHz and 126 kHz of amplitudes 63 mV and 49 mV, respectively. What would direct measurement of the fundamental show its frequency and amplitude to be? What is the rms value of the fundamental? What are the peak-to-peak amplitude and period of the originating square wave?

1.37 A symmetrical square wave with peak amplitude $\hat{V}$ and zero average is to be approximated by its first five (lowest frequency) sinusoidal components. Compare the rms value of the square wave to that of its approximation. What is the percentage difference?

1.38 Find the amplitude of a symmetrical square wave of period T that provides the same power as a sine wave of peak amplitude $\hat{V}$ and the same frequency. Does this result depend on equality of the frequencies of the two waveforms?

Section 1.3: Analog and Digital Signals

1.39 Give the binary representation of the following decimal numbers: 0, 5, 13, 32, and 63.

1.40 Consider a 4-bit digital word $b_3b_2b_1b_0$ in a format called signed-magnitude, in which the most significant bit, b_3, is interpreted as a sign bit—0 for positive and 1 for negative values. List the values that can be represented by this scheme. What is peculiar about the representation of zero? For a particular analog-to-digital converter (ADC), each change in b_0 corresponds to a 0.5-V change in the analog input. What is the full range of the analog signal that can be represented? What signed-magnitude digital code results for an input of +2.5 V? For −3.0 V? For +2.7 V? For −2.8 V?

1.41 Consider an N-bit DAC whose output varies from 0 to V_{FS} (where the subscript FS denotes "full-scale").

(a) Show that a change in the least significant bit (LSB) induces a change of $V_{FS}/(2^N - 1)$ in the output. This is the resolution of the converter.
(b) Convince yourself that the DAC can produce any desired output voltage between 0 and V_{FS} with at most $V_{FS}/2(2^N - 1)$ error (i.e., one-half the resolution). This is called the quantization error of the converter.
(c) For $V_{FS} = 5$ V, how many bits are required to obtain a resolution of 2 mV or better? What is the actual resolution obtained? What is the resulting quantization error?

1.42 Figure P1.42 shows the circuit of an N-bit DAC. Each of the N bits of the digital word to be converted controls one of the switches. When the bit is 0, the switch is in the position labeled 0; when the bit is 1, the switch is in the position labeled 1. The analog output is the current i_O. V_{ref} is a constant reference voltage.

problems with blue numbers are considered essential; * = difficult problem; ** = more difficult; *** = very challenging
SIM = simulation; **D** = design problem; ● = see related video example

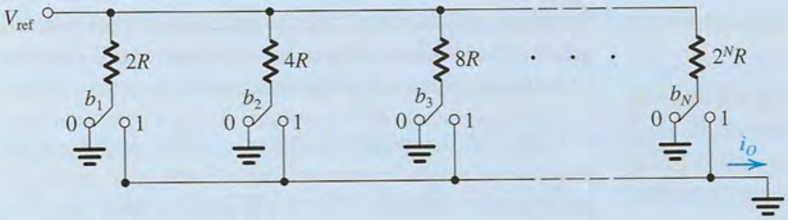

Figure P1.42

(a) Show that

$$i_O = \frac{V_{ref}}{R}\left(\frac{b_1}{2^1} + \frac{b_2}{2^2} + \cdots + \frac{b_N}{2^N}\right)$$

(b) Which bit is the LSB? Which is the MSB?

(c) For $V_{ref} = 10$ V, $R = 10$ kΩ, and $N = 8$, find the maximum value of i_O obtained. What is the change in i_O resulting from the LSB changing from 0 to 1?

1.43 An audio signal is sampled at 44.1 kHz. Each sample is represented by 16 bits. What is the speed of this system in bits per second?

1.44 Each pixel in a 10-megapixel image is represented by 8 bits for the intensity of red, 8 bits for green, and 8 bits for blue. How many such images can be stored in 16 Gbits of memory?

Section 1.4: Amplifiers

1.45 Various amplifier and load combinations are measured as listed below using rms values. For each, find the voltage, current, and power gains (A_v, A_i, and A_p, respectively) both as ratios and in dB:

(a) $v_I = 100$ mV, $i_I = 100$ µA, $v_O = 10$ V, $R_L = 100$ Ω
(b) $v_I = 10$ µV, $i_I = 100$ nA, $v_O = 1$ V, $R_L = 10$ kΩ
(c) $v_I = 1$ V, $i_I = 1$ mA, $v_O = 5$ V, $R_L = 10$ Ω

1.46 An amplifier operating from ±3-V supplies provides a 2.2-V peak sine wave across a 100-Ω load when provided with a 0.2-V peak input from which 1.0 mA peak is drawn. Find the voltage gain, current gain, and power gain expressed as ratios and in decibels. If the amplifier efficiency is 10%, find the supply power, supply current, and amplifier dissipation.

1.47 An amplifier using balanced power supplies is known to saturate for signals extending within 1.0 V of either supply. For linear operation, its gain is 200 V/V. What is the rms value of the largest undistorted sine-wave output available, and input needed, with ±5-V supplies? With ±10-V supplies? With ±15-V supplies?

Section 1.5: Circuit Models for Amplifiers

1.48 Consider the voltage-amplifier circuit model shown in Fig. 1.16(b), in which $A_{vo} = 100$ V/V under the following conditions:

(a) $R_i = 10R_s$, $R_L = 10R_o$
(b) $R_i = R_s$, $R_L = R_o$
(c) $R_i = R_s/10$, $R_L = R_o/10$

Calculate the overall voltage gain v_o/v_s in each case, expressed both directly and in decibels.

1.49 An amplifier with 40 dB of small-signal, open-circuit voltage gain, an input resistance of 1 MΩ, and an output resistance of 100 Ω, drives a load of 500 Ω. What voltage and power gains (expressed in dB) would you expect with the load connected? If the amplifier has a peak output-current limitation of 20 mA, what is the rms value of the largest sine-wave input for which an undistorted output is possible? What is the corresponding output power available?

VE 1.3

1.50 A 10-mV signal source having an internal resistance of 5 kΩ is connected to an amplifier for which the input resistance is 1 kΩ, the open-circuit voltage gain is 100 V/V, and the output resistance is 200 Ω. The amplifier is connected in turn to a 100-Ω load.

(a) What overall voltage gain results as measured from the source internal voltage to the load? Where did all the gain go? What would the gain be if the source was connected directly to the load? What is the ratio of these two gains? This ratio is a useful measure of the benefit the amplifier brings.

(b) Now instead, replace the source by its Norton equivalent and the amplifier with the equivalent current amplifier from Table 1.1. What is the current gain, i_o/i_s? Show that it is the same as would be computed using the voltage amplifier model.

1.51 A buffer amplifier with a gain of 1 V/V has an input resistance of 1 MΩ and an output resistance of 20 Ω. It is connected between a 1-V, 200-kΩ source and a 100-Ω load. What load voltage results? What are the corresponding voltage, current, and power gains (in dB)?

1.52 Consider the cascade amplifier of Example 1.3. Find the overall voltage gain v_o/v_s obtained when the first and second stages are interchanged. Compare this value with the result in Example 1.3, and comment.

1.53 You are given two amplifiers, A and B, to connect in cascade between a 10-mV, 100-kΩ source and a 100-Ω load. The amplifiers have voltage gain, input resistance, and output resistance as follows: for A, 100 V/V, 100 kΩ, 10 kΩ, respectively; for B, 10 V/V, 10 kΩ, 1 kΩ, respectively. Your problem is to decide how the amplifiers should be connected. To proceed, evaluate the two possible connections between source S and load L, namely, SABL and SBAL. Find the voltage gain for each both as a ratio and in decibels. Which amplifier arrangement is best?

D *1.54 A designer has available voltage amplifiers with an input resistance of 100 kΩ, an output resistance of 1 kΩ, and an open-circuit voltage gain of 15. The signal source has a 50-kΩ resistance and provides a 5-mV rms signal, and it is required to provide a signal of at least 3 V rms to a 200-Ω load. How many amplifier stages are required? What is the output voltage actually obtained?

D *1.55 Design an amplifier that provides 0.5 W of signal power to a 100-Ω load resistance. The signal source provides a 30-mV rms signal and has a resistance of 0.5 MΩ. Three types of voltage-amplifier stages are available:

(a) A high-input-resistance type with $R_i = 1$ MΩ, $A_{vo} = 10$, and $R_o = 10$ kΩ
(b) A high-gain type with $R_i = 10$ kΩ, $A_{vo} = 100$, and $R_o = 1$ kΩ
(c) A low-output-resistance type with $R_i = 10$ kΩ, $A_{vo} = 1$, and $R_o = 20$ Ω

Design a suitable amplifier using a combination of these stages. Your design should utilize the minimum number of stages and should ensure that the signal level is not reduced below 10 mV at any point in the amplifier chain. Find the load voltage and power output realized.

D *1.56 You are required to design a voltage amplifier to be driven from a signal source having a 5-mV peak amplitude and a source resistance of 10 kΩ to supply a peak output of 2 V across a 1-kΩ load.

(a) What is the required voltage gain from the source to the load?
(b) If the peak current available from the source is 0.1 μA, what is the smallest input resistance allowed? For the design with this value of R_i, find the overall current gain and power gain.
(c) If the amplifier power supply limits the peak value of the output open-circuit voltage to 3 V, what is the largest output resistance allowed?
(d) For the design with R_i as in (b) and R_o as in (c), what is the required value of open-circuit voltage gain, i.e., $\left.\frac{v_o}{v_i}\right|_{R_L=\infty}$, of the amplifier?
(e) If, as a possible design option, you are able to increase R_i to the nearest value of the form 1×10^n Ω and to decrease R_o to the nearest value of the form 1×10^m Ω, find (i) the input resistance achievable; (ii) the output resistance achievable; and (iii) the open-circuit voltage gain now required to meet the specifications.

D 1.57 A voltage amplifier with an input resistance of 40 kΩ, an output resistance of 100 Ω, and a gain of 300 V/V is connected between a 10-kΩ source with an open-circuit voltage of 10 mV and a 100-Ω load. For this situation:

(a) What output voltage results?
(b) What is the voltage gain from source to load?
(c) What is the voltage gain from the amplifier input to the load?
(d) If the output voltage across the load is twice that needed and there are signs of amplifier saturation, suggest the location and value of a single resistor that would produce the desired output. Choose an arrangement that would cause minimum disruption to an operating circuit. (*Hint:* Use parallel rather than series connections.)

1.58 A current amplifier supplies 1 mA to a load resistance of 1 kΩ. When the load resistance is increased to 12 kΩ, the output current decreases to 0.5 mA. What are the values of the short-circuit output current and the output resistance of the amplifier?

1.59 A transresistance amplifier for which $R_i = 100\ \Omega$, $R_o = 10\ \Omega$, and $R_m = 5\ \text{k}\Omega$ is to be connected between a 100-mV source with a resistance of 1 kΩ and a load of 1 kΩ. What are the values of current gain i_o/i_i, of voltage gain v_o/v_s, and of power gain expressed directly and in decibels?

1.60 A transconductance amplifier with $R_i = 2\ \text{k}\Omega$, $G_m = 20$ mA/V, and $R_o = 5\ \text{k}\Omega$ is fed with a voltage source having a source resistance of 500 Ω and is loaded with a 1-kΩ resistance. Find the voltage gain realized.

D **1.61 A designer is required to provide, across a 10-kΩ load, the weighted sum, $v_O = 10v_1 + 20v_2$, of input signals v_1 and v_2, each having a source resistance of 10 kΩ. She has a number of transconductance amplifiers for which the input and output resistances are both 10 kΩ and $G_m = 20$ mA/V, together with a selection of suitable resistors. Sketch an appropriate amplifier topology with additional resistors selected to provide the desired result. Your design should use the minimum number of amplifiers and resistors. (*Hint*: In your design, arrange to add currents.)

1.62 Figure P1.62 shows a transconductance amplifier whose output is *fed back* to its input.

(a) Find the input resistance R_{in} of the resulting one-port network. (*Hint*: Apply a test voltage v_x between the two input terminals, and find the current i_x drawn from the source. Then, $R_{in} \equiv v_x/i_x$.)

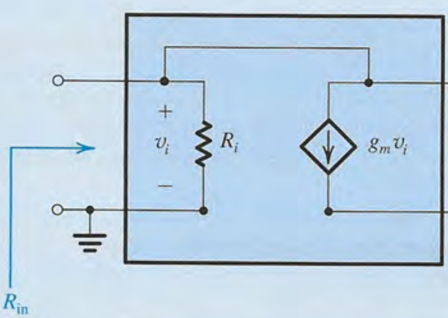

Figure P1.62

(b) Show that when driven by a voltage source, v_s, having source resistance $R_s = R_{in}$, the voltage gain $v_o/v_s = 0.5 \cdot v_o/v_i$ (This is another method for finding the input resistance.)

D 1.63 You are required to design an amplifier to sense the open-circuit output voltage of a transducer and to provide a proportional voltage across a load resistor. The equivalent source resistance of the transducer is specified to vary in the range of 1 kΩ to 10 kΩ. Also, the load resistance varies in the range of 1 kΩ to 10 kΩ. The change in load voltage corresponding to the specified change in R_s should be 10% at most. Similarly, the change in load voltage corresponding to the specified change in R_L should be limited to 10%. Also, corresponding to a 10-mV transducer open-circuit output voltage, the amplifier should provide a minimum of 1 V across the load. What type of amplifier is required? Sketch its circuit model, and specify the values of its parameters. Specify appropriate values for R_i and R_o of the form $1 \times 10^m\ \Omega$.

D 1.64 You are required to design an amplifier to sense the short-circuit output current of a light sensor and to provide a proportional voltage across a load resistor. The equivalent source resistance of the transducer is specified to vary in the range of 1 kΩ to 10 kΩ. Similarly, the load resistance is known to vary in the range of 1 kΩ to 10 kΩ. The change in load voltage corresponding to the specified change in R_s should be 10% at most. Similarly, the change in load voltage corresponding to the specified change in R_L is to be limited to 10%. Also, for a nominal transducer short-circuit output current of 10 μA, the amplifier is required to provide a minimum voltage across the load of 1 V. What type of amplifier is required? Sketch its circuit model, and specify the values of the model parameters. For R_i and R_o, specify appropriate values in the form $1 \times 10^m\ \Omega$.

1.65 For the circuit in Fig. P1.65, show that

$$\frac{v_c}{v_b} = \frac{-\beta R_L}{r_\pi + (\beta+1)R_E}$$

and

$$\frac{v_e}{v_b} = \frac{R_E}{R_E + [r_\pi/(\beta+1)]}$$

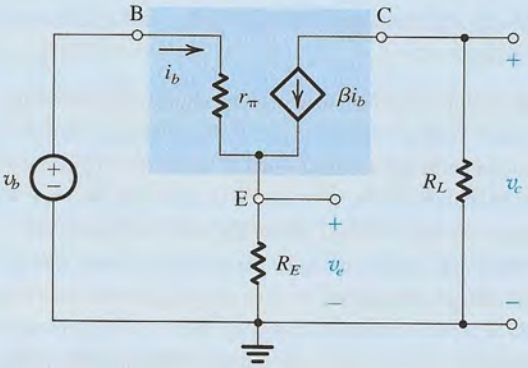

Figure P1.65

1.66 An amplifier with an input resistance of 5 kΩ, when driven by a current source of 1 μA and a source resistance of 200 kΩ, has a short-circuit output current of 5 mA. When the amplifier is used to drive a 2-kΩ load, an output voltage of 5 V is observed. When connected to a 1-kΩ load, give the values of the voltage gain, current gain, and power gain expressed as ratios and in decibels.

1.67 Figure P1.67(a) shows two transconductance amplifiers connected in a special configuration. Find v_o in terms of v_1 and v_2. Let $g_m = 100$ mA/V and $R = 5$ kΩ. If $v_1 = 1$ V and $v_2 = 1$ V, find the value of v_o. Also, find v_o for the case $v_1 = 1.01$ V and $v_2 = 0.99$ V. (*Note*: This circuit is called a **differential amplifier** and is given the symbol shown in Fig. P1.67(b). A particular type of differential amplifier known as an **operational amplifier** will be studied in Chapter 2.)

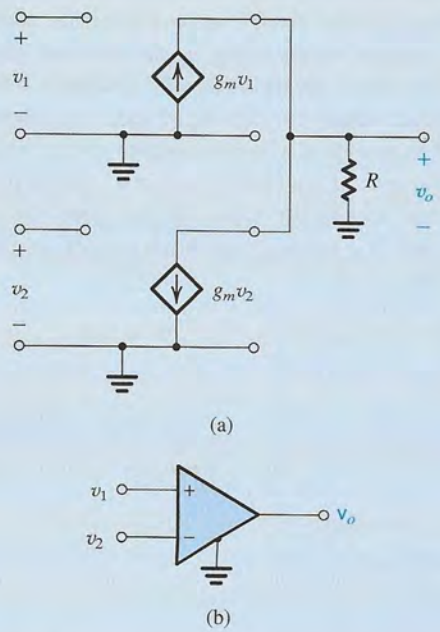

Figure P1.67

1.68 Any linear two-port network including linear amplifiers can be represented by one of four possible parameter sets, given in Appendix C. For the voltage amplifier, the most convenient representation is in terms of the g parameters. If the amplifier input port is labeled as port 1 and the output port as port 2, its g-parameter representation is described by the two equations:

$$I_1 = g_{11}V_1 + g_{12}I_2$$

$$V_2 = g_{21}V_1 + g_{22}I_2$$

Figure P1.68 shows an equivalent circuit representation of these two equations. By comparing this equivalent circuit to that of the voltage amplifier in Fig. 1.16(a), identify corresponding currents and voltages as well as the correspondence between the parameters of the amplifier equivalent circuit and the g parameters. Hence give the g parameter that corresponds to each of R_i, A_{vo}, and R_o. Notice that there is an additional g parameter with no correspondence in the amplifier equivalent circuit. Which one? What does it signify? What assumption did we make about the amplifier that resulted in the absence of this particular g parameter from the equivalent circuit in Fig. 1.16(a)?

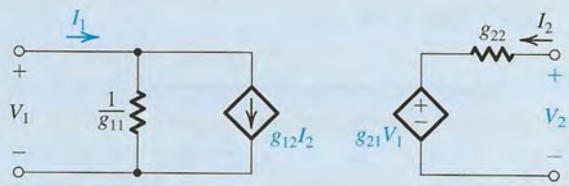

Figure P1.68

Section 1.6: Frequency Response of Amplifiers

1.69 Use the voltage-divider rule to derive the transfer functions $T(s) \equiv V_o(s)/V_i(s)$ of the circuits shown in Fig. 1.22, and show that the transfer functions are of the form given at the top of Table 1.2.

VE 1.4 **1.70** Figure VE 1.4 shows a signal source connected to the input of an amplifier. Here R_s is the source resistance, and R_i and C_i are the input resistance and input capacitance, respectively, of the amplifier. Derive an expression for $V_i(s)/V_s(s)$, and show that it is of the low-pass STC type. Find the 3-dB frequency and dc gain for the case $R_s = 10\text{ k}\Omega$, $R_i = 40\text{ k}\Omega$, and $C_i = 5\text{ pF}$.

1.71 For the circuit shown in Fig. P1.71, find the transfer function $T(s) = V_o(s)/V_i(s)$, and arrange it in the appropriate standard form from Table 1.2. Is this a high-pass or a low-pass network? What is its transmission at very high frequencies? [Estimate this directly, as well as by letting $s \to \infty$ in your expression for $T(s)$.] What is the corner frequency ω_0? For $R_1 = 20\text{ k}\Omega$, $R_2 = 100\text{ k}\Omega$, and $C = 0.1\ \mu\text{F}$, find f_0. What is the value of $|T(j\omega_0)|$?

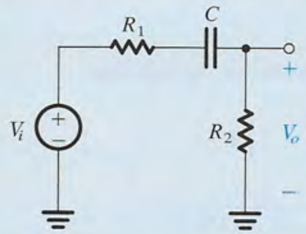

Figure P1.71

D 1.72 It is required to couple a voltage source V_s with a resistance R_s to a load R_L via a capacitor C. Derive an expression for the transfer function from source to load (i.e., V_l/V_s), and show that it is of the high-pass STC type. For $R_s = 4\text{ k}\Omega$ and $R_L = 10\text{ k}\Omega$, find the smallest coupling capacitor that will result in a 3-dB frequency no greater than 200 Hz.

1.73 Measurement of the frequency response of an amplifier yields the data in the following table:

f (Hz)	$\lvert T\rvert$ (dB)	$\angle T$ (°)
0	60	0
100	60	
1000		−45
10^4	40	
10^5	20	
	0	

Provide plausible approximate values for the missing entries. Also, sketch and clearly label the magnitude frequency response (i.e., provide a Bode plot) for this amplifier.

1.74 Measurement of the frequency response of an amplifier yields the data in the following table:

f (Hz)		1	10^2	10^3	10^4	10^5	10^6	10^7	
$\lvert T\rvert$ (dB)	0	40	77	80		77	60	40	0

Provide approximate plausible values for the missing table entries. Also, sketch and clearly label the magnitude frequency response (Bode plot) of this amplifier.

1.75 The unity-gain voltage amplifiers in Fig. P1.75 have infinite input resistances and zero output resistances and thus function as perfect buffers. Assuming that their gain is frequency independent, convince yourself that the overall gain V_o/V_i will drop by 3 dB below the value at dc at the frequency for which the gain of each RC circuit is 1.0 dB down. What is that frequency in terms of CR?

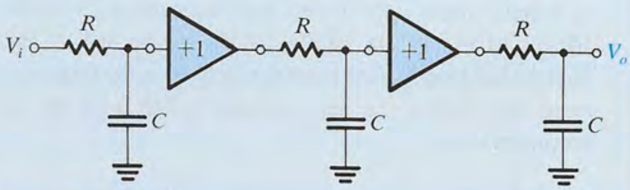

Figure P1.75

1.76 When a high-frequency transconductance amplifier whose output resistance is 100 kΩ is connected to a load capacitor, the measured 3-dB bandwidth of the amplifier is reduced from 5 MHz to 100 kHz. Estimate the value of the load capacitor. If the original cutoff frequency can be attributed to a small parasitic capacitor at the output node (i.e., between the output and ground), what would you estimate it to be?

D *1.77 A designer wishing to lower the overall upper 3-dB frequency of a three-stage amplifier to 5 kHz considers shunting one of two nodes to ground with a capacitor: Node A, at the output of the first stage, or Node B, at the output of the second stage. While measuring the overall frequency response of the amplifier, she connects a capacitor of 1 nF, first to node A and then to node B, lowering the 3-dB frequency from 3 MHz to 200 kHz and 40 kHz, respectively.

If she knows that each amplifier stage has an input resistance of 100 kΩ, what output resistance must the driving stage have at node A? At node B? What capacitor value should she connect to which node to solve her design problem most economically?

D 1.78 An amplifier with an input resistance of 100 kΩ and an output resistance of 1 kΩ is to be capacitively coupled to a 10-kΩ source and a 1-kΩ load. Available capacitors have values only of the form 1×10^{-n} F. What are the values of the smallest capacitors needed to ensure that the corner frequency associated with each is less than 100 Hz? What actual corner frequencies result? For the situation in which the basic amplifier has an open-circuit voltage gain (A_{vo}) of 100 V/V, find an expression for $T(s) = V_o(s)/V_s(s)$.

***1.79** A voltage amplifier has the transfer function

$$A_v = \frac{1000}{\left(1 + j\frac{f}{10^5}\right)\left(1 + \frac{10^2}{jf}\right)}$$

Using the Bode plots for low-pass and high-pass STC networks (Figs. 1.23 and 1.24), sketch a Bode plot for $|A_v|$. Give approximate values for the gain magnitude at $f = 10$ Hz, 10^2 Hz, 10^3 Hz, 10^4 Hz, 10^5 Hz, 10^6 Hz, 10^7 Hz, and 10^8 Hz. Find the bandwidth of the amplifier (defined as the frequency range over which the gain remains within 3 dB of the maximum value).

***1.80** For the circuit shown in Fig. P1.80, first evaluate $T_i(s) = V_i(s)/V_s(s)$ and the corresponding cutoff (corner) frequency. Second, evaluate $T_o(s) = V_o(s)/V_i(s)$ and the corresponding cutoff frequency. Put each of the transfer functions in the standard form (see Table 1.2), and combine them to form the overall transfer function, $T(s) = T_i(s) \times T_o(s)$. Provide a Bode plot for $|T(j\omega)|$. What is the bandwidth between 3-dB cutoff points?

D **1.81 A transconductance amplifier having the equivalent circuit shown in Table 1.1 is fed with a voltage source V_s having a source resistance R_s, and its output is connected to a load consisting of a resistance R_L in parallel with a capacitance C_L. For given values of R_s, R_L, and C_L, it is required to specify the values of the amplifier parameters R_i, G_m, and R_o to meet the following design constraints:

(a) At most, x% of the input signal is lost in coupling the signal source to the amplifier (i.e., $V_i \geq [1 - (x/100)]V_s$).
(b) The 3-dB frequency of the amplifier is equal to or greater than a specified value f_{3dB}.
(c) The dc gain V_o/V_s is equal to or greater than a specified value A_0.

Show that these constraints can be met by selecting

$$R_i \geq \left(\frac{100}{x} - 1\right)R_s$$

$$R_o \leq \frac{1}{2\pi f_{3dB} C_L - (1/R_L)}$$

$$G_m \geq \frac{A_0/[1 - (x/100)]}{(R_L \| R_o)}$$

Find R_i, R_o, and G_m for $R_s = 10$ kΩ, $x = 10\%$, $A_0 = 100$ V/V, $R_L = 10$ kΩ, $C_L = 20$ pF, and $f_{3dB} = 2$ MHz.

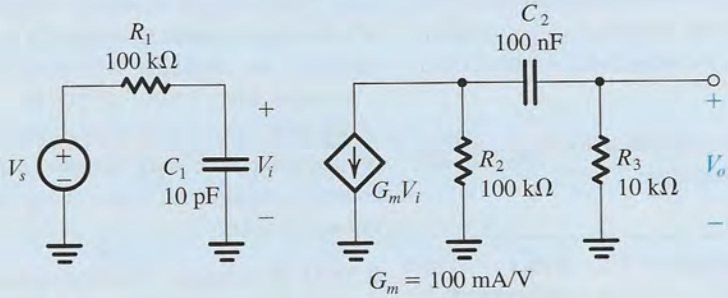

Figure P1.80

***1.82** Consider the circuit in Fig P1.82. It is desired to make the transfer function independent of frequency. Show this is achieved by selecting C_1 with a value $C_2(R_2/R_1)$. Under this condition the circuit is called a **compensated attenuator** and is frequently employed in the design of oscilloscope probes. Find the transmission of the compensated attenuator in terms of R_1 and R_2.

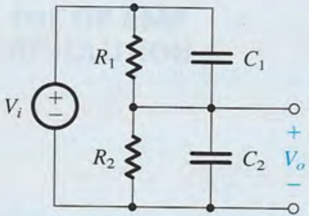

Figure P1.82

***1.83** An amplifier with a frequency response of the type shown in Fig. 1.21 is specified to have a phase shift of magnitude no greater than 5.7° over the amplifier bandwidth, which extends from 100 Hz to 1 kHz. You learn that the gain falloff at the low-frequency end is determined by the response of a high-pass STC circuit and that at the high-frequency end it is determined by a low-pass STC circuit. What do you expect the time constants of these two STC circuits to be? What is the drop in gain in decibels (relative to the maximum gain) at the two frequencies that define the amplifier bandwidth? What are the frequencies at which the drop in gain is 3 dB? (*Hint*: Refer to Figs. 1.23 and 1.24.)