Chapter 1
Introduction to Electronics

Microelectronic Circuit Design

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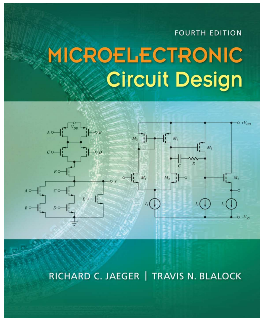
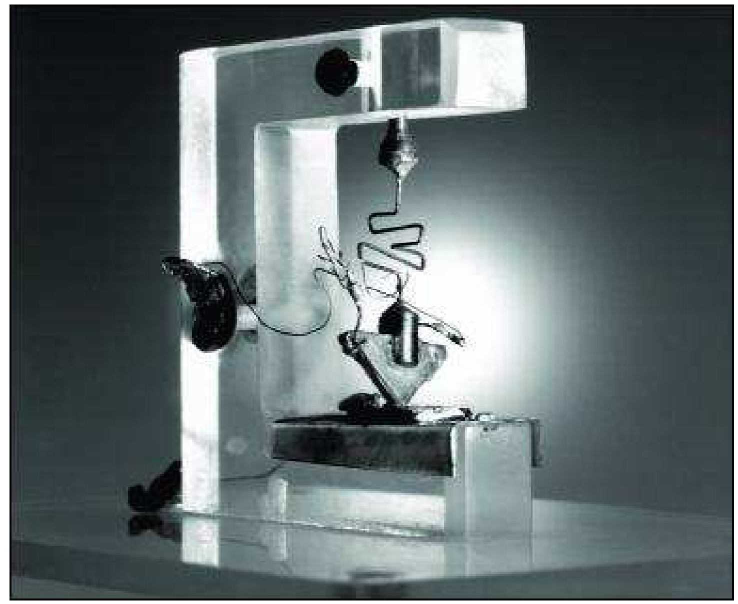


Chapter Goals

- Explore the history of electronics.
- Quantify the impact of integrated circuit technologies.
- Describe classification of electronic signals.
- Review circuit notation and theory.
- Introduce tolerance impacts and analysis.
- Describe problem solving approach

The Start of the Modern Electronics Era

Bardeen, Shockley, and Brattain at Bell Labs - Brattain and Bardeen invented the bipolar transistor in 1947.



The first germanium bipolar transistor. Roughly 50 years later, electronics account for 10% (4 trillion dollars) of the world GDP.

Electronics Milestones

1874 Braun invents the solid-state rectifier.

1906 DeForest invents triode vacuum tube.

1907-1927 First radio circuits developed from diodes and triodes.

1925 Lilienfeld field-effect device patent filed.

1947 Bardeen and Brattain at Bell Laboratories invent bipolar transistors.

1952 Commercial bipolar transistor production at Texas Instruments.

1956 Bardeen, Brattain, and Shockley receive Nobel prize.

1958 Integrated circuits developed by Kilby and Noyce

1961 First commercial IC from Fairchild Semiconductor

1963 IEEE formed from merger of IRE and AIEE

1968 First commercial IC opamp

1970 One transistor DRAM cell invented by Dennard at IBM.

1971 4004 Intel microprocessor introduced.

1978 First commercial 1-kilobit memory.

1974 8080 microprocessor introduced.

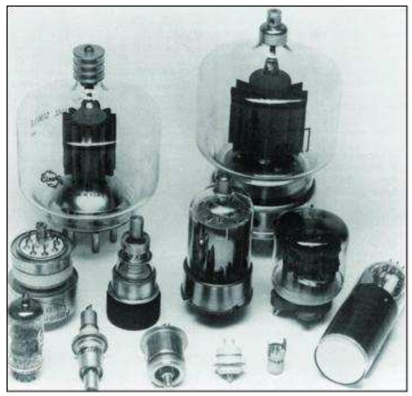
1984 Megabit memory chip introduced.

2000 Alferov, Kilby, and Kromer share Nobel prize

2009 Boyle and Smith share Nobel prize

Evolution of Electronic Devices

Vacuum Tubes



(a)

Discrete Transistors

(b)

SSI and MSI Integrated Circuits

(c)

VLSI Surface-Mount Circuits

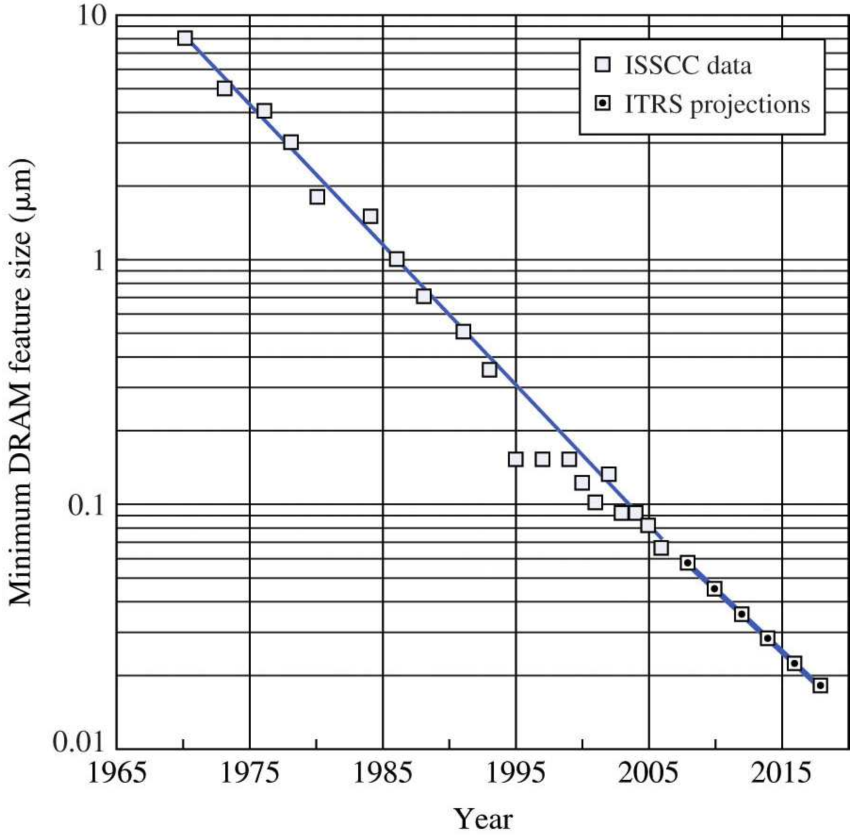
(d)

Microelectronics Proliferation

- The integrated circuit was invented in 1958.
- World transistor production has more than doubled every year for the past twenty years.
- Every year, more transistors are produced than in all previous years combined.
- Approximately 10^{18} transistors were produced in a recent year.
- Roughly 50 transistors for every ant in the world.

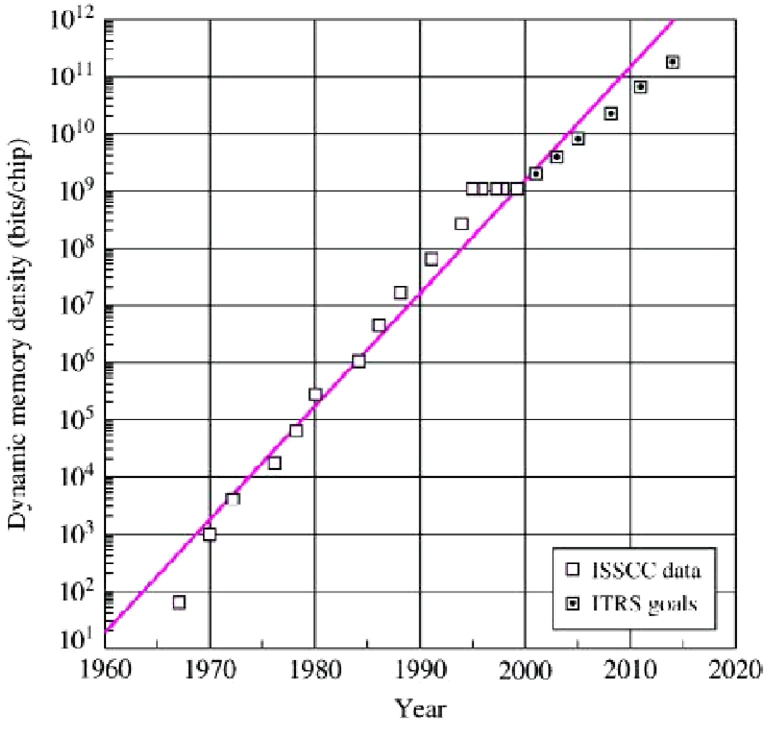
*Source: Gordon Moore's Plenary address at the 2003 International Solid-State Circuits Conference.

Device Feature Size

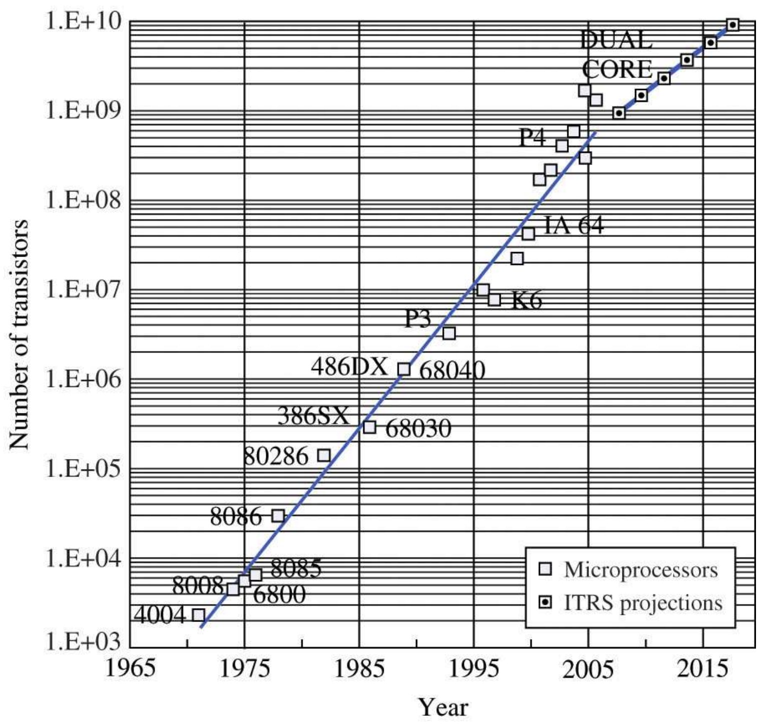


- Feature size reductions enabled by process innovations.
- Smaller features lead to more transistors per unit area and therefore higher density.

Rapid Increase in Density of Microelectronics

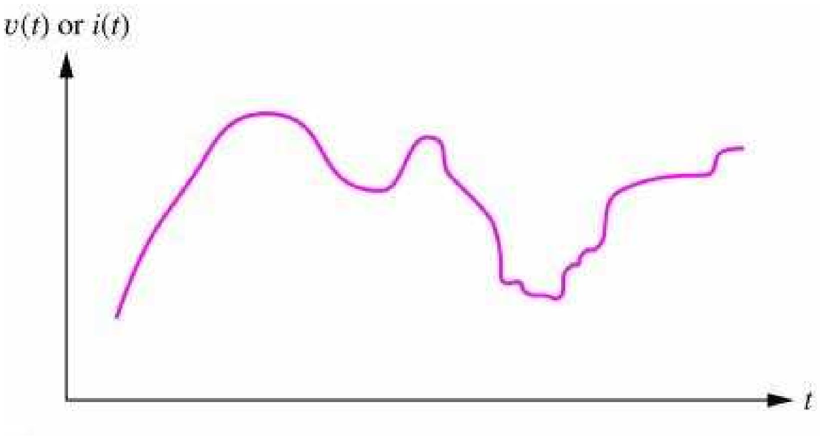


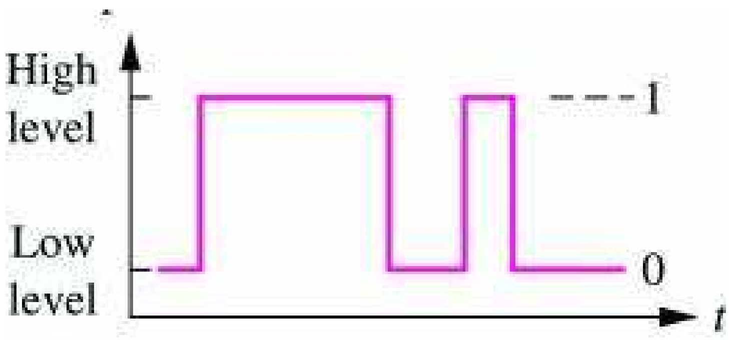
Memory chip density versus time.



Microprocessor complexity versus time.

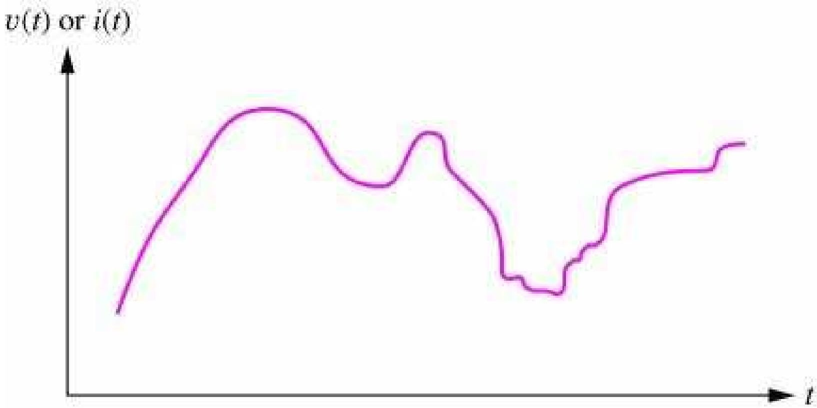
Signal Types





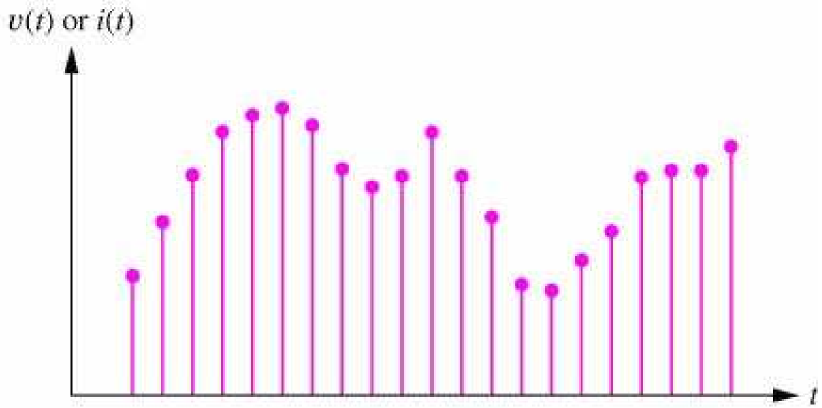
- Analog electrical signals take on continuous values - typically current or voltage.
- Digital signals appear at discrete levels. Usually we use binary signals which utilize only two levels.
- One level is referred to as logical 1 and logical 0 is assigned to the other level.

Analog and Digital Signals



(a)

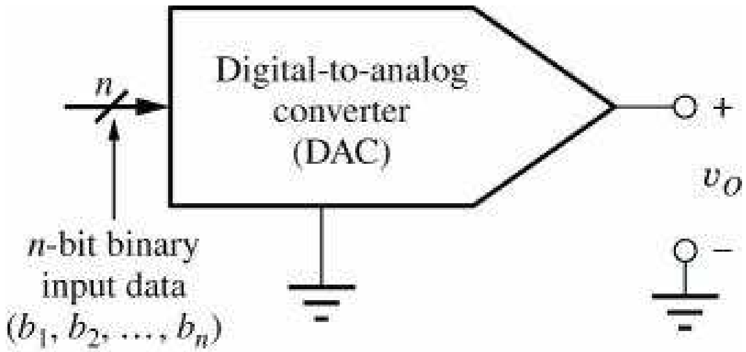
- Analog electrical signals are continuous in time - most often voltage or current. (Charge can also be utilized as a signal conveyor.)



(b)

- After digitization, the continuous analog signal becomes a set of discrete values, typically separated by fixed time intervals.

Digital-to-Analog (D/A) Conversion

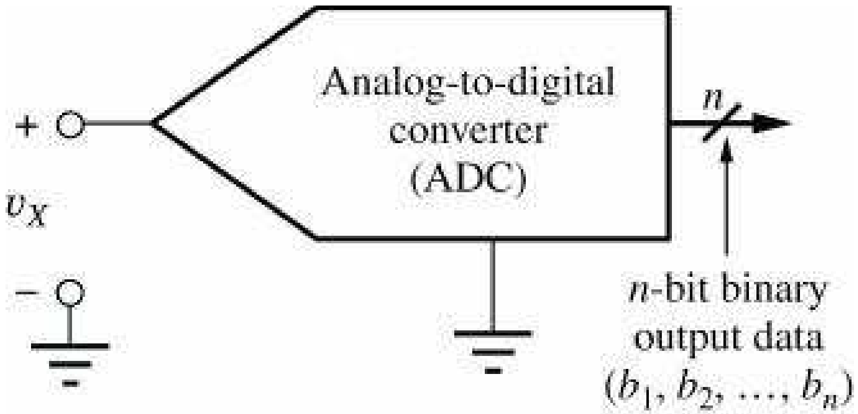


V_{FS} = Full-Scale Voltage

- For an n-bit D/A converter, the output voltage is expressed as: $$V_O = (b_1 2^{-1} + b_2 2^{-2} + ... + b_n 2^{-n})V_{FS}$$
- The smallest possible voltage change is known as the least significant bit or LSB.

$$V_{LSB} = 2^{-n} V_{FS}$$

Analog-to-Digital (A/D) Conversion

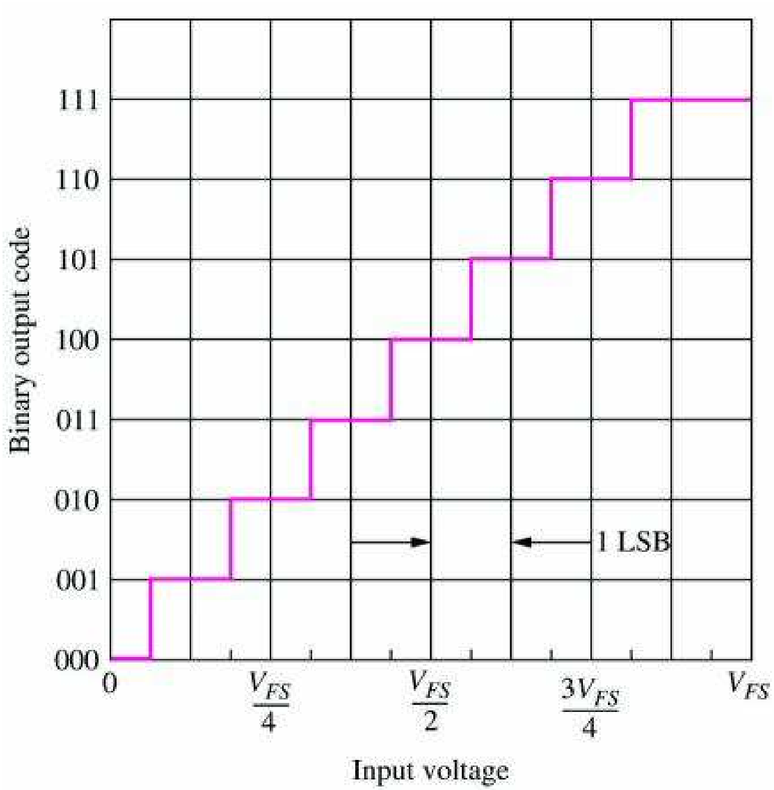


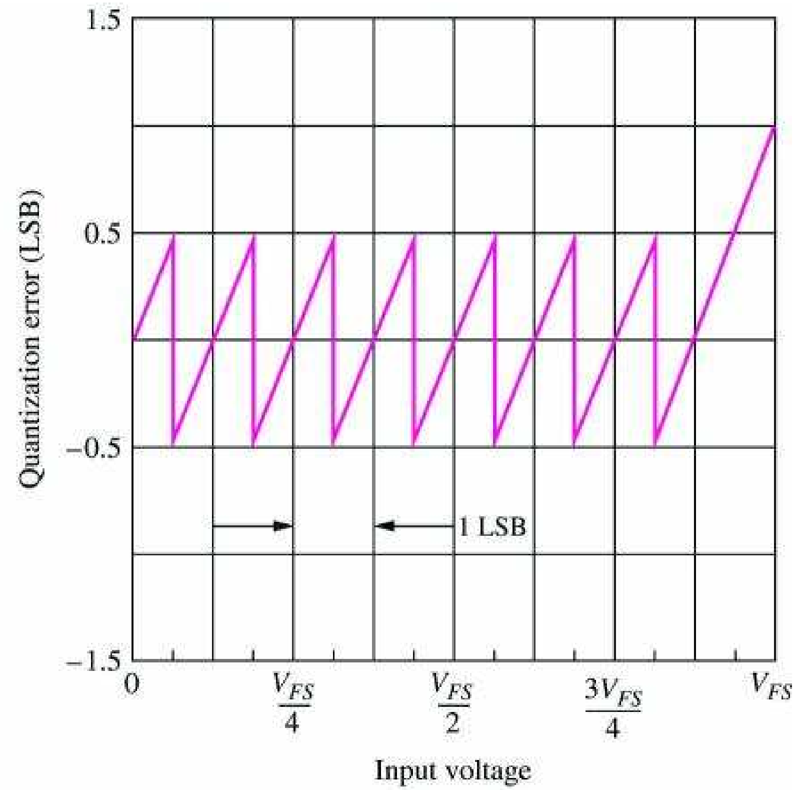
V_{FS} = Full-Scale Voltage

- Analog input voltage v_x is converted to an n-bit number.
- For a four-bit converter, v_x ranging between 0 and V_{FS} yields a digital output code between 0000 and 1111.
- The output is an approximation of the input due to the limited resolution of the n-bit output. Error is expressed as:

$$V_\varepsilon = \left| v_x - (b_1 2^{-1} + b_2 2^{-2} + \ldots + b_n 2^{-n}) V_{FS} \right|$$

A/D Converter Transfer Characteristic and Quantization Error





$$V_\varepsilon = \left| v_x - (b_1 2^{-1} + b_2 2^{-2} + \ldots + b_n 2^{-n}) V_{FS} \right|$$

Notational Conventions

- Total signal = DC bias + time varying signal

$$v_T = V_{DC} + v_{sig}$$

$$i_T = I_{DC} + i_{sig}$$

- Resistance and conductance - R and G with same subscripts will denote reciprocal quantities. The most convenient form will be used within expressions.

$$G_x = \frac{1}{R_x} \quad and \quad g_\pi = \frac{1}{r_\pi}$$

Problem-Solving Approach

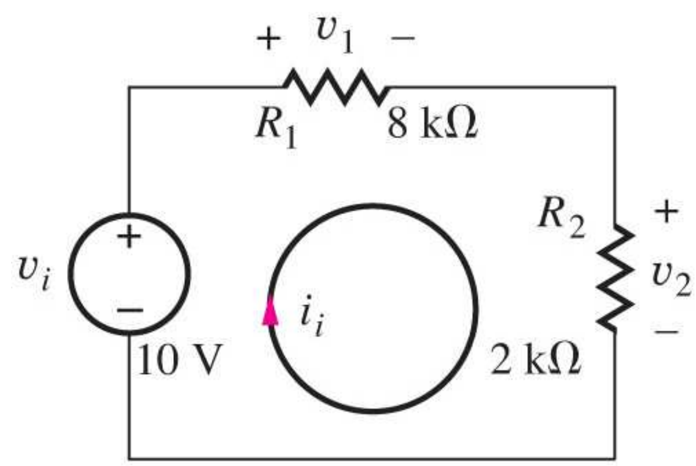
- Make a clear **problem** statement.
- List **known information and given data**.
- Define the **unknowns** required to solve the problem.
- List **assumptions**.
- Develop an **approach** to the solution.
- Perform the **analysis** based on the approach.
- **Check the results** and the assumptions.
  - Has the problem been solved?   Have all the unknowns been found?
  - Is the math correct?   Have the assumptions been satisfied?
- **Evaluate the solution**.
  - Do the results satisfy reasonableness constraints?
  - Are the values realizable?
- Use **computer-aided analysis** to verify hand analysis

What are Reasonable Numbers?

- If the power suppy is ±10 V, a calculated DC bias value of 15 V (not within the range of the power supply voltages) is unreasonable.
- Generally, our bias current levels will be between 1 microamp and a few hundred milliamps.
- A calculated bias current of 3.2 amps is probably unreasonable and should be reexamined.
- Peak-to-peak ac voltages should be within the power supply voltage range.
- A calculated component value that is unrealistic should be rechecked. For example, a resistance equal to 0.013 ohms or 10^{12} ohms
- Given the inherent variations in most electronic components, three significant digits are adequate for representation of results. Three significant digits are used throughout the text.

Circuit Theory Review: Voltage Division

$$v_1 = i_i R_1 \quad \text{and} \quad v_2 = i_i R_2$$



Applying KVL to the loop,

$$v_i = v_1 + v_2 = i_i(R_1 + R_2)$$

and $$i_i = \frac{v_i}{R_1 + R_2}$$

Combining these yields the basic voltage division formula:

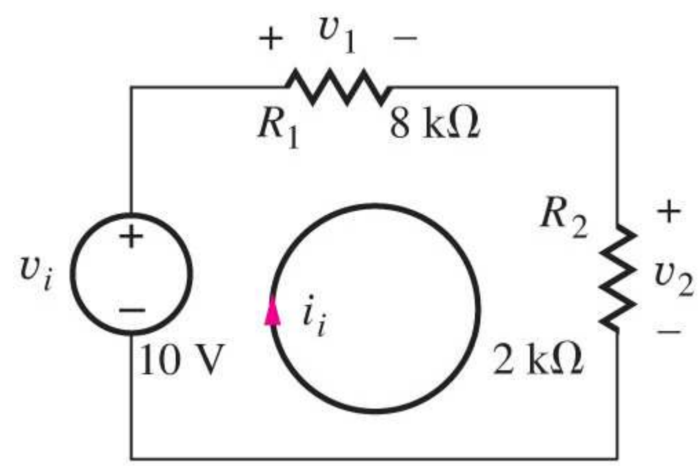
$$v_1 = v_i \frac{R_1}{R_1 + R_2} \qquad v_2 = v_i \frac{R_2}{R_1 + R_2}$$

Circuit Theory Review: Voltage Division (cont.)

Using the derived equations with the indicated values,

$$v_1 = 10\text{ V}\frac{8\text{ k}\Omega}{8\text{ k}\Omega + 2\text{ k}\Omega} = 8.00\text{ V}$$

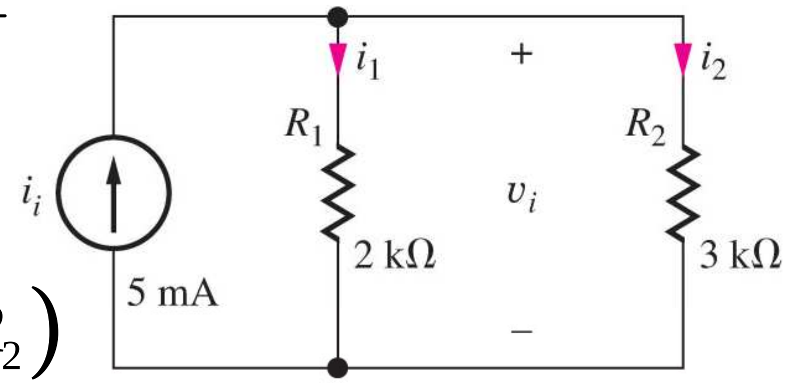
$$v_2 = 10\text{ V}\frac{2\text{ k}\Omega}{8\text{ k}\Omega + 2\text{ k}\Omega} = 2.00\text{ V}$$



Design Note: Voltage division only applies when both resistors are carrying the same current.

Circuit Theory Review: Current Division

$i_i = i_1 + i_2$ where $i_1 = \dfrac{v_i}{R_1}$ and $i_2 = \dfrac{v_i}{R_2}$



Combining and solving for v_i,

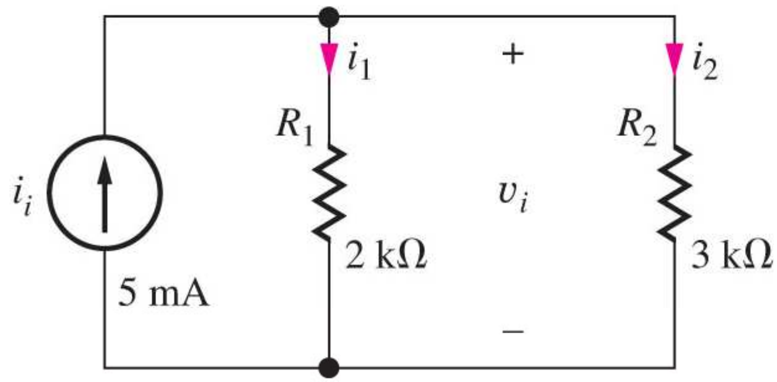
$$v_i = i_i \frac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2}} = i_i \frac{R_1 R_2}{R_1 + R_2} = i_i \left(R_1 \| R_2 \right)$$

Combining these yields the basic current division formula:

$$i_1 = i_i \frac{R_2}{R_1 + R_2} \qquad i_2 = i_i \frac{R_1}{R_1 + R_2}$$

Circuit Theory Review: Current Division (cont.)

Using the derived equations with the indicated values,

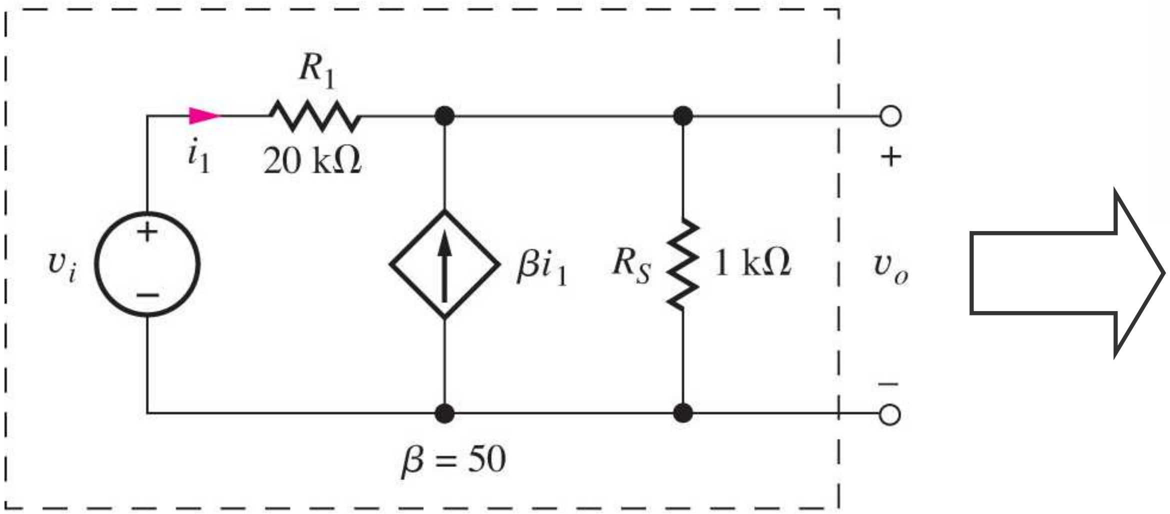


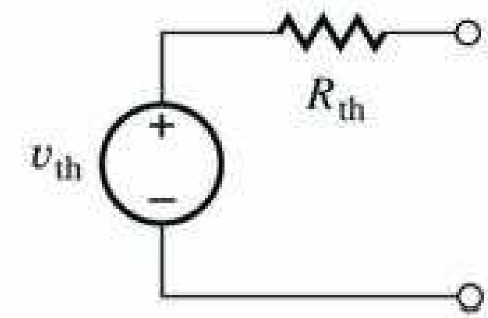
$$i_1 = 5 \text{ ma} \frac{3 \text{ k}\Omega}{2 \text{ k}\Omega + 3 \text{ k}\Omega} = 3.00 \text{ mA}$$

$$i_2 = 5 \text{ ma} \frac{2 \text{ k}\Omega}{2 \text{ k}\Omega + 3 \text{ k}\Omega} = 2.00 \text{ mA}$$

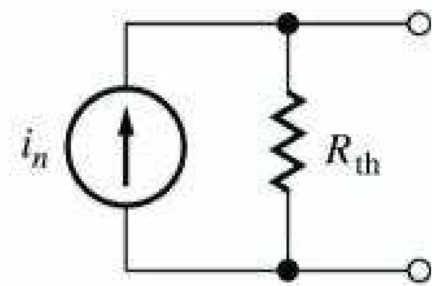
Design Note: Current division only applies when the same voltage appears across both resistors.

Circuit Theory Review: Thévenin and Norton Equivalent Circuits





Thévenin



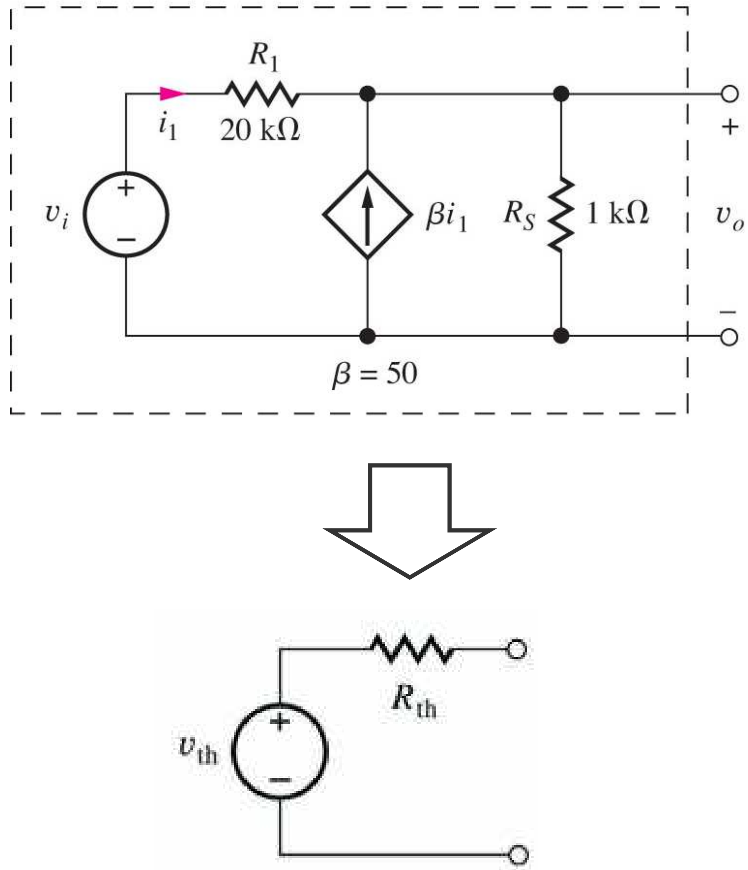
Norton

Circuit Theory Review: Find the Thévenin Equivalent Voltage

Problem: Find the Thévenin equivalent voltage at the output.

Solution:

- **Known Information and Given Data:** Circuit topology and values in figure.
- **Unknowns:** Thévenin equivalent voltage v_{th}.
- **Approach:** Voltage source v_{th} is defined as the output voltage with no load (open-circuit voltage).
- **Assumptions:** None.
- **Analysis:** Next slide…

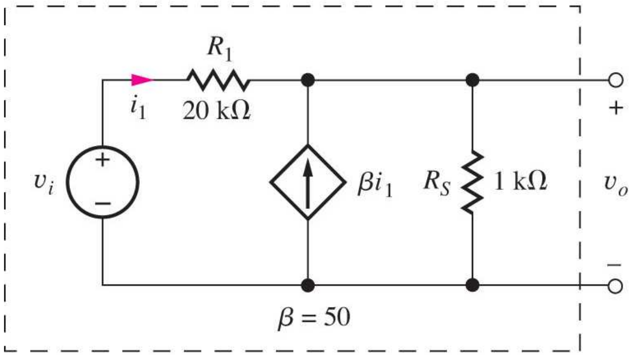


Circuit Theory Review: Find the Thévenin Equivalent Voltage

Applying KCL at the output node,

$$\beta i_1 = \frac{v_o - v_i}{R_1} + \frac{v_o}{R_S} = G_1\left(v_o - v_i\right) + G_S v_o$$

Current i_1 can be written as: $i_1 = G_1\left(v_o - v_i\right)$



Combining the previous equations

$$G_1(\beta+1)v_i = \left[G_1(\beta+1) + G_S\right]v_o$$

$$v_o = \frac{G_1(\beta+1)}{G_1(\beta+1)+G_S} v_i \times \frac{R_1 R_S}{R_1 R_S} = \frac{(\beta+1)R_S}{(\beta+1)R_S + R_1} v_i$$

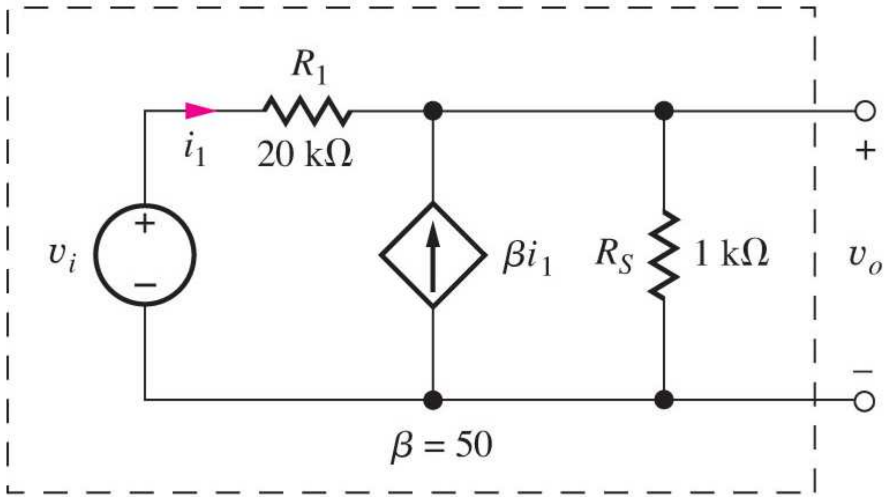
Circuit Theory Review: Find the Thévenin Equivalent Voltage (cont.)

Using the given component values:

$$v_o = \frac{(\beta+1)R_S}{(\beta+1)R_S + R_1} v_i = \frac{(50+1)1\ \text{k}\Omega}{(50+1)1\ \text{k}\Omega + 1\ \text{k}\Omega} v_i = 0.718 v_i$$

and

$$v_{\text{th}} = 0.718 v_i$$

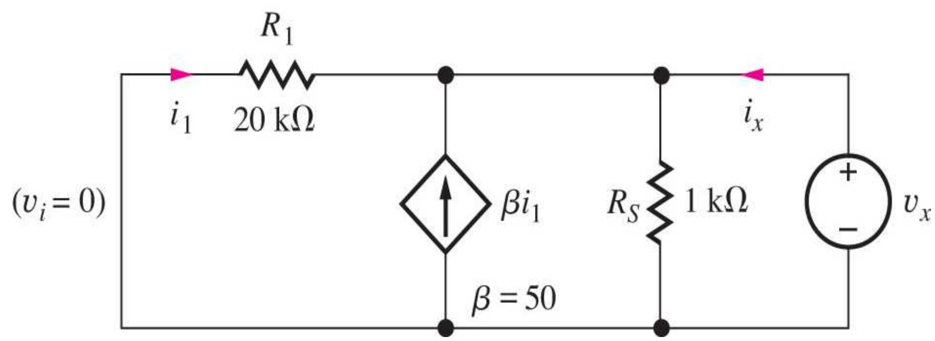


Circuit Theory Review: Find the Thévenin Equivalent Resistance

Problem: Find the Thévenin equivalent resistance.

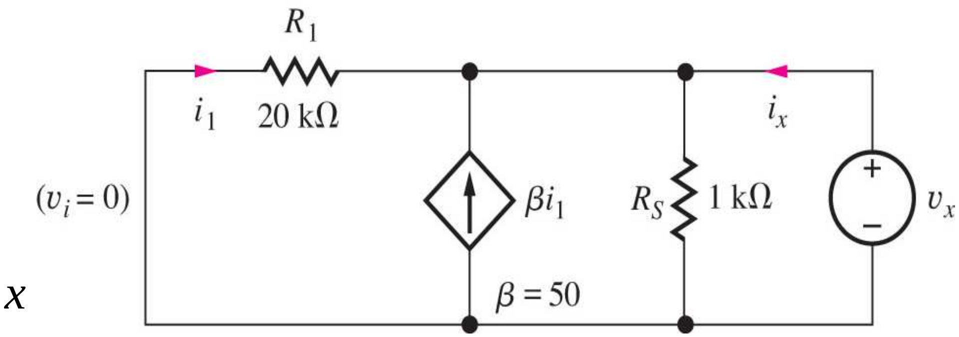
Solution:

- **Known Information and Given Data**: Circuit topology and values in figure.
- **Unknowns**: Thévenin equivalent Resistance R_{th}.
- **Approach**: Find R_{th} as the output equivalent resistance with independent sources set to zero.
- **Assumptions**: None.
- **Analysis**: Next slide…



Test voltage v_x has been added to the previous circuit. Applying v_x and solving for i_x allows us to find the Thévenin resistance as v_x/i_x.

Circuit Theory Review: Find the Thévenin Equivalent Resistance (cont.)



Applying KCL,

$$i_x = -i_1 - \beta i_1 + G_S v_x$$
$$= G_1 v_x + \beta G_1 v_x + G_S v_x$$
$$= \left[G_1(\beta+1) + G_S\right] v_x$$

$$R_{th} = \frac{v_x}{i_x} = \frac{1}{G_1(\beta+1)+G_S} = R_S \left\| \frac{R_1}{\beta+1} \right.$$

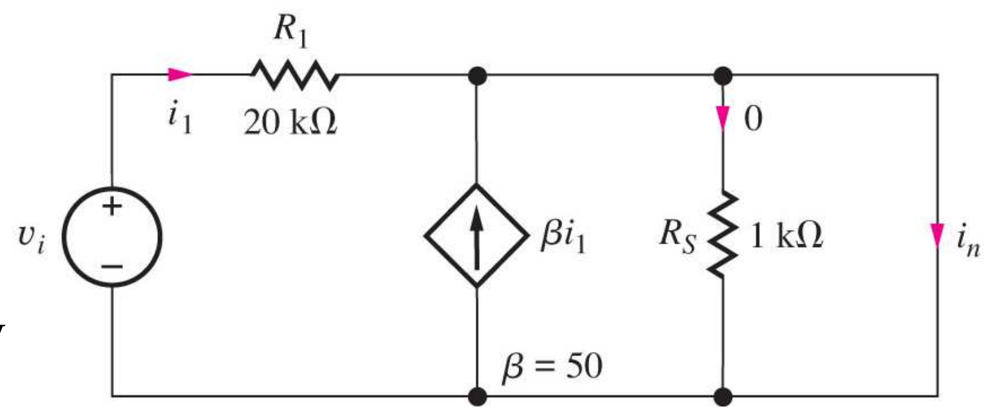
$$R_{th} = R_S \left\| \frac{R_1}{\beta+1} \right. = 1\text{ k}\Omega \left\| \frac{20\text{ k}\Omega}{50+1} \right. = 1\text{ k}\Omega \| 392\ \Omega = 282\ \Omega$$

Circuit Theory Review: Find the Norton Equivalent Circuit

Problem: Find the Norton equivalent circuit.

Solution:

- **Known Information and Given Data**: Circuit topology and values in figure.
- **Unknowns**: Norton equivalent short circuit current i_n.
- **Approach**: Evaluate current through output short circuit.
- **Assumptions**: None.
- **Analysis**: Next slide…

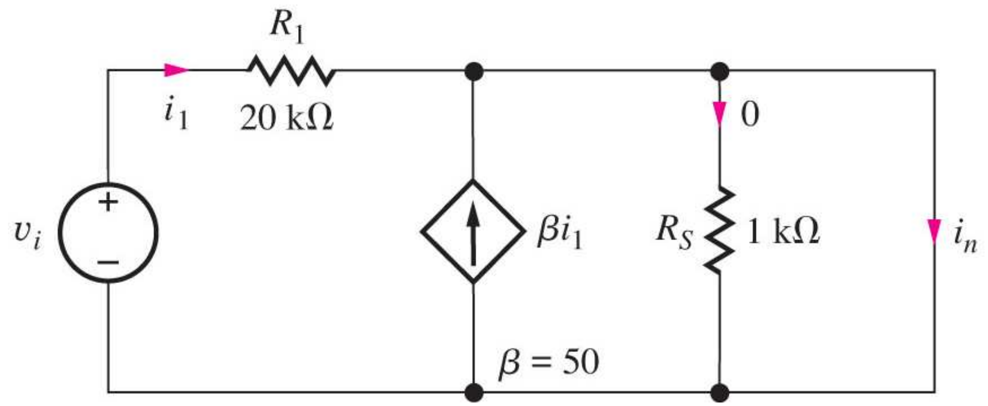


A short circuit has been applied across the output. The Norton current is the current flowing through the short circuit at the output.

Circuit Theory Review: Find the Norton Equivalent Circuit (cont.)

Applying KCL,

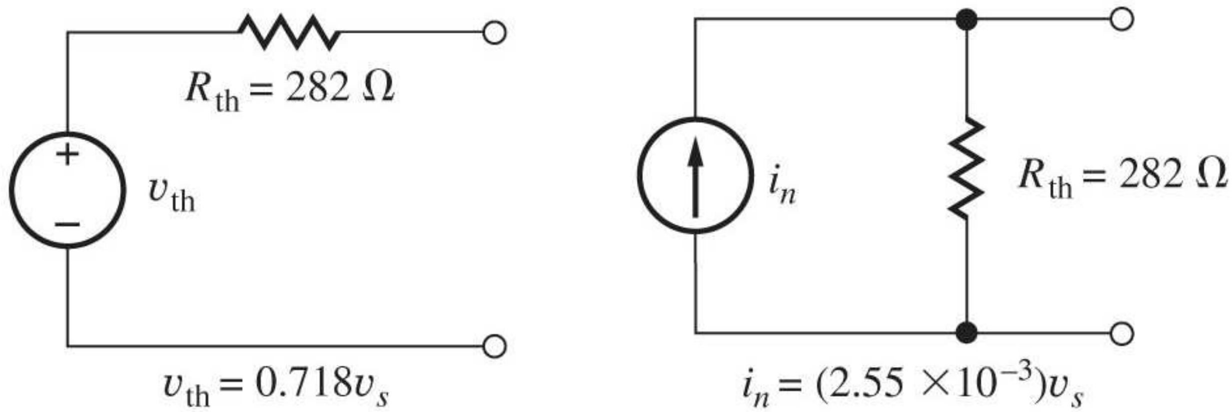
$$i_n = i_1 + \beta i_1$$
$$= G_1 v_i + \beta G_1 v_i$$
$$= G_1(\beta+1)v_i$$
$$= \frac{v_i(\beta+1)}{R_1}$$



Short circuit at the output causes zero current to flow through R_S. R_{th} is equal to R_{th} found earlier.

$$i_n = \frac{50+1}{20\ \text{k}\Omega} v_i = \frac{v_i}{392\ \Omega} = (2.55\ \text{mS})v_i$$

Final Thévenin and Norton Circuits



Check of Results: Note that $v_{th} = i_n R_{th}$ and this can be used to check the calculations: $i_n R_{th}$=(2.55 mS)v_i(282 Ω) = 0.719v_i, accurate within round-off error.

While the two circuits are identical in terms of voltages and currents at the output terminals, there is one difference between the two circuits. With no load connected, the Norton circuit still dissipates power!

Frequency Spectrum of Electronic Signals

- Non repetitive signals have continuous spectra often occupying a broad range of frequencies
- Fourier theory tells us that repetitive signals are composed of a set of sinusoidal signals with distinct amplitude, frequency, and phase.
- The set of sinusoidal signals is known as a **Fourier series**.
- The frequency spectrum of a signal represents the amplitude and phase components of the signal versus frequency.

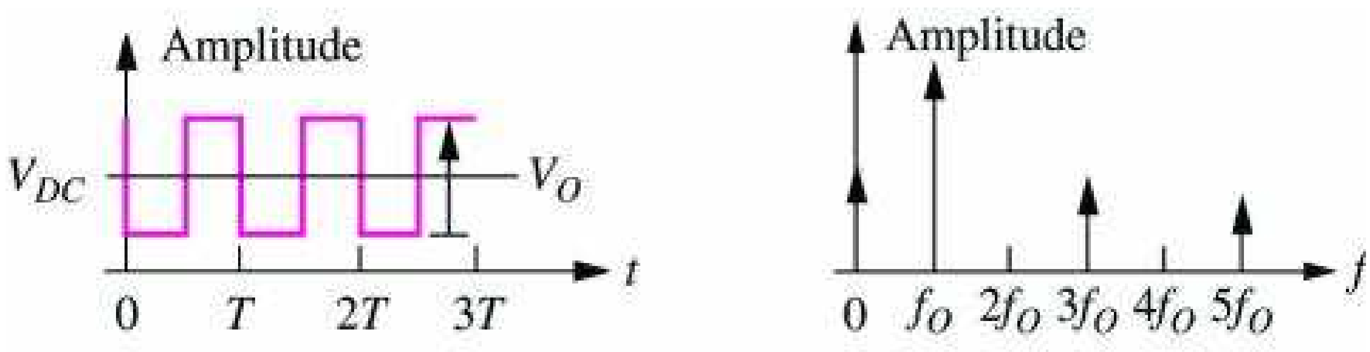
Frequencies of Some Common Signals

• Audible sounds	20 Hz - 20 KHz
• Baseband TV	0 - 4.5 MHz
• FM Radio	88 - 108 MHz
• Television (Channels 2-6)	54 - 88 MHz
• Television (Channels 7-13)	174 - 216 MHz
• Maritime and Govt. Comm.	216 - 450 MHz
• Cell phones and other wireless	0.8 - 3 GHz
• Satellite TV	3.7 - 4.2 GHz
• Wireless Devices	5.0 - 5.5 GHz

Fourier Series

- A periodic signal contains spectral components only at discrete frequencies related to the period of the original signal.
- A square wave is represented by the following Fourier series:

$$v(t) = V_{DC} + \frac{2V_O}{\pi}\left(\sin\omega_0 t + \frac{1}{3}\sin 3\omega_0 t + \frac{1}{5}\sin 5\omega_0 t + ...\right)$$



$\omega_0 = 2\pi/T$ (rad/s) is the fundamental radian frequency, and $f_0 = 1/T$ (Hz) is the fundamental frequency of the signal. $2f_0$, $3f_0$, and $4f_0$ are known as the second, third, and fourth harmonic frequencies.

Amplifier Basics

- Analog signals are typically manipulated with linear amplifiers.
- Although signals may be comprised of several different components, linearity permits us to use the **superposition principle**.
- Superposition allows us to calculate the effect of each of the different components of a signal individually and then add the individual contributions to create the total resulting signal.

Amplifier Linearity

Given an input sinusoid:

$$v_i = V_i \sin(\omega_i t + \phi)$$

For a linear amplifier, the output is at the same frequency, but different amplitude and phase.

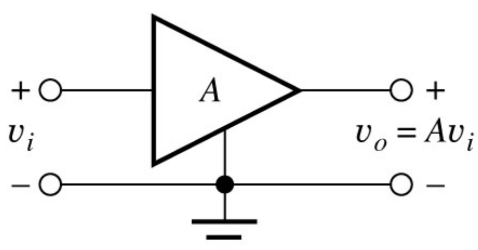
$$v_o = V_o \sin(\omega_i t + \phi + \theta)$$

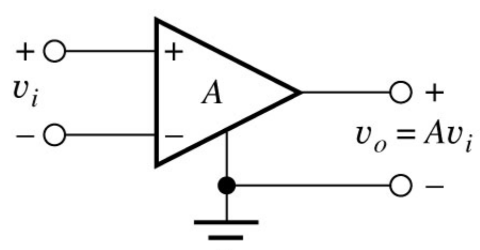
In phasor notation:

$$\mathbf{v}_i = V_i \angle \phi \qquad \mathbf{v_o} = V_o \angle (\phi + \theta)$$

Amplifier gain is:

$$A = \frac{\mathbf{v_o}}{\mathbf{v_i}} = \frac{V_o \angle (\phi + \theta)}{V_i \angle \phi} = \frac{V_o}{V_i} \angle \theta$$



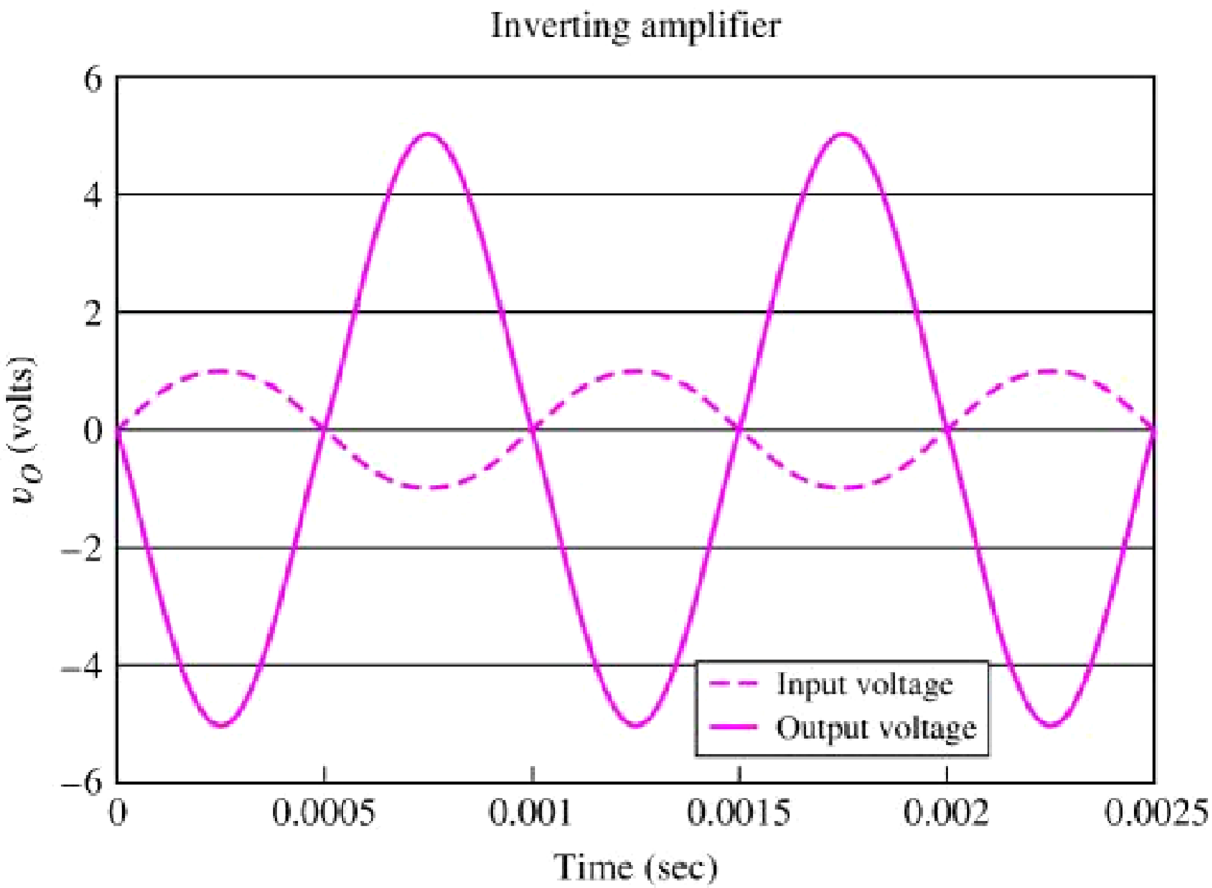


Amplifier Input/Output Response

$v_i = \sin 2000\pi t$ V

$A_v = -5$

Note: negative gain is equivalent to 180 degrees of phase shift.



Ideal Operational Amplifier (Op Amp)

Ideal op amps are assumed to have
infinite voltage gain, and
infinite input resistance.

These conditions lead to two assumptions useful in analyzing ideal op-amp circuits:

1. The voltage difference across the input terminals is zero.
2. The input currents are zero.

Ideal Op Amp Example

Find the voltage gain of an op amp with resistive feedback

Writing a loop equation:

$$v_i - i_i R_1 - i_2 R_2 - v_o = 0$$

From assumption 2, we know that $i_- = 0$.

$$i_i = i_2 = \frac{v_i - v_-}{R_1}$$

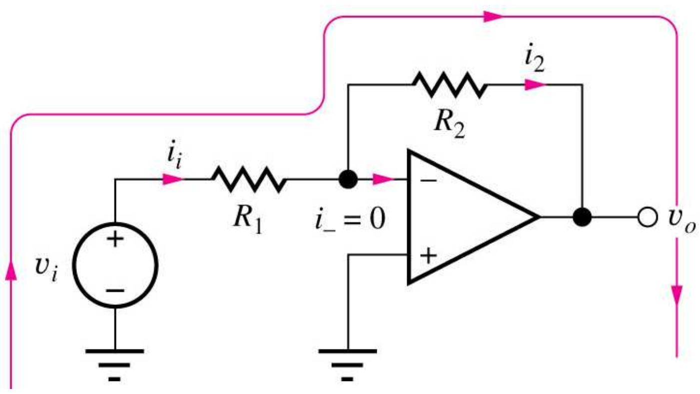
Assumption 1 requires $v_- = v_+ = 0$.

$$i_i = \frac{v_i}{R_1}$$

Combining these equations yields:

$$A_v = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

Assumption 1 requiring $v_- = v_+ = 0$ creates what is known as a **virtual ground** at the inverting input of the amplifier.



Ideal Op Amp Example (Alternative Approach)

From Assumption 2, $i_2 = i_i$:

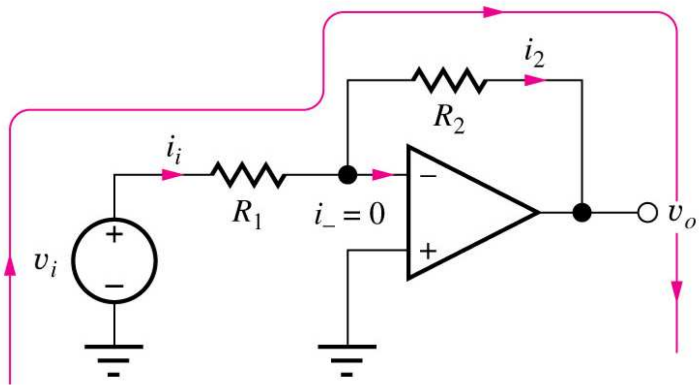
$$i_i = \frac{v_i}{R_1} \quad \text{and} \quad i_2 = \frac{v_- - v_o}{R_2} = \frac{-v_o}{R_2}$$

$$i_2 = i_i \quad \text{gives} \quad \frac{v_i}{R_1} = \frac{-v_o}{R_2}$$

Yielding:

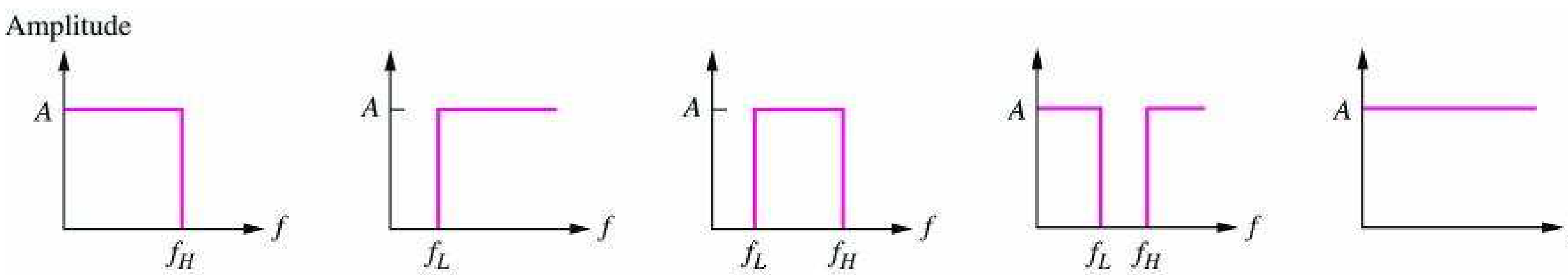
$$A_v = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

Design Note: The virtual ground is *not* an actual ground. Do not short the inverting input to ground to simplify analysis.



Amplifier Frequency Response

Amplifiers can be designed to selectively amplify specific ranges of frequencies. Such an amplifier is known as a filter. Several filter types are shown below:



Low Pass High Pass Band Pass Band Reject All Pass

Circuit Element Variations

- All electronic components have manufacturing tolerances.
  - Resistors can be purchased with $\pm$ 10%, $\pm$ 5%, and $\pm$ 1% tolerance. (IC resistors are often $\pm$ 10%.)
  - Capacitors can have asymmetrical tolerances such as +20%/-50%.
  - Power supply voltages typically vary from 1% to 10%.
- Device parameters will also vary with temperature and age.
- Circuits must be designed to accommodate these variations.
- We will use worst-case and Monte Carlo (statistical) analysis to examine the effects of component parameter variations.

Tolerance Modeling

- For symmetrical parameter variations

$$P_{nom}(1 - \varepsilon) \leq P \leq P_{nom}(1 + \varepsilon)$$

- For example, a 10 kΩ resistor with ±5% percent tolerance could take on the following range of values:

$$10k\Omega(1 - 0.05) \leq R \leq 10k\Omega(1 + 0.05)$$

$$9500\ \Omega \leq R \leq 10500\ \Omega$$

Circuit Analysis with Tolerances

- Worst-case analysis
  - Parameters are manipulated to produce the worst-case min and max values of desired quantities.
  - This can lead to over design since the worst-case combination of parameters is rare.
  - It may be less expensive to discard a rare failure than to design for 100% yield.
- Monte-Carlo analysis
  - Parameters are randomly varied to generate a set of statistics for desired outputs.
  - The design can be optimized so that failures due to parameter variation are less frequent than failures due to other mechanisms.
  - In this way, the design difficulty is better managed than a worst-case approach.

Worst Case Analysis Example

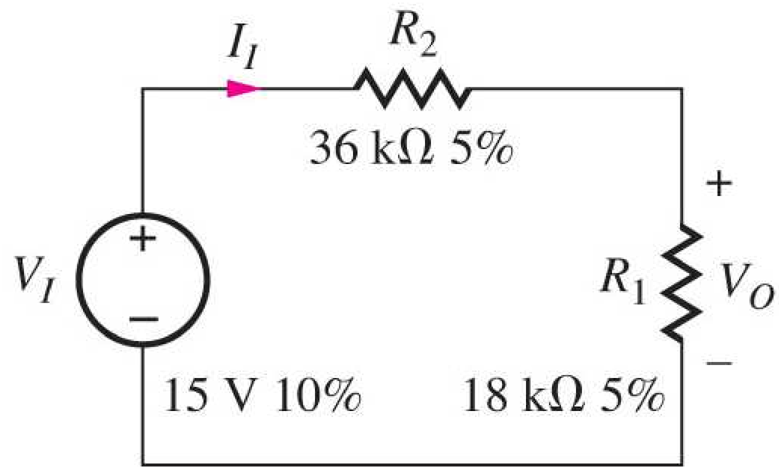
Problem: Find the nominal and worst-case values for output voltage and source current.

Solution:

- **Known Information and Given Data**: Circuit topology and values in figure.
- **Unknowns**:

$$V_O^{nom},\ V_O^{\min},\ V_O^{\max},\ I_I^{nom},\ I_I^{\min},\ I_I^{\max}$$

- **Approach**: Find nominal values and then select R_1, R_2, and V_I values to generate extreme cases of the unknowns.
- **Assumptions**: None.
- **Analysis**: Next slides…

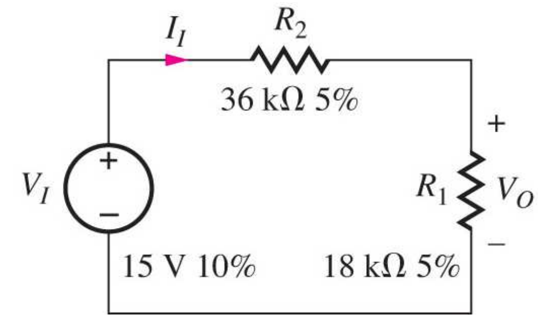


Nominal voltage solution:

$$V_O^{nom} = V_I^{nom} \frac{R_1^{nom}}{R_1^{nom} + R_2^{nom}}$$

$$= 15V \frac{18k\Omega}{18k\Omega + 36k\Omega} = 5V$$

Worst-Case Analysis Example (cont.)



Nominal Source current:

$$I_I^{nom} = \frac{V_I^{nom}}{R_1^{nom} + R_2^{nom}} = \frac{15V}{18k\Omega + 36k\Omega} = 278\mu A$$

Rewrite V_O to help us determine how to find the worst-case values.

$$V_O = V_I \frac{R_1}{R_1 + R_2} = \frac{V_I}{1 + \dfrac{R_2}{R_1}}$$

V_O is maximized for max V_I, R_1 and min R_2.

V_O is minimized for min V_I, R_1, and max R_2.

$$V_O^{\max} = \frac{15V(1.1)}{1 + \dfrac{36K(0.95)}{18K(1.05)}} = 5.87V \qquad V_O^{\min} = \frac{15V(0.95)}{1 + \dfrac{36K(1.05)}{18K(0.95)}} = 4.20V$$

Worst-Case Analysis Example (cont.)

Worst-case source currents:

$$I_I^{\max} = \frac{V_I^{\max}}{R_1^{\min} + R_2^{\min}} = \frac{15V(1.1)}{18k\Omega(0.95) + 36k\Omega(0.95)} = 322\mu A$$

$$I_I^{\min} = \frac{V_I^{\min}}{R_1^{\max} + R_2^{\max}} = \frac{15V(0.9)}{18k\Omega(1.05) + 36k\Omega(1.05)} = 238\mu A$$

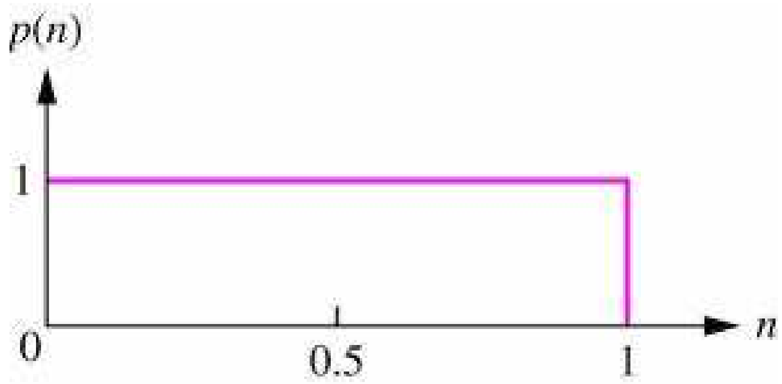
Check of Results: The worst-case values range from 14-17 percent above and below the nominal values. The sum of the three element tolerances is 20 percent, so our calculated values appear to be reasonable.

Monte Carlo Analysis

- Parameters are varied randomly and output statistics are gathered.
- We use programs like MATLAB, Mathcad, SPICE, or a spreadsheet to complete a statistically significant set of calculations.
- For example, with Excel®, a resistor with a nominal value R_{nom} and tolerance ε can be expressed as:

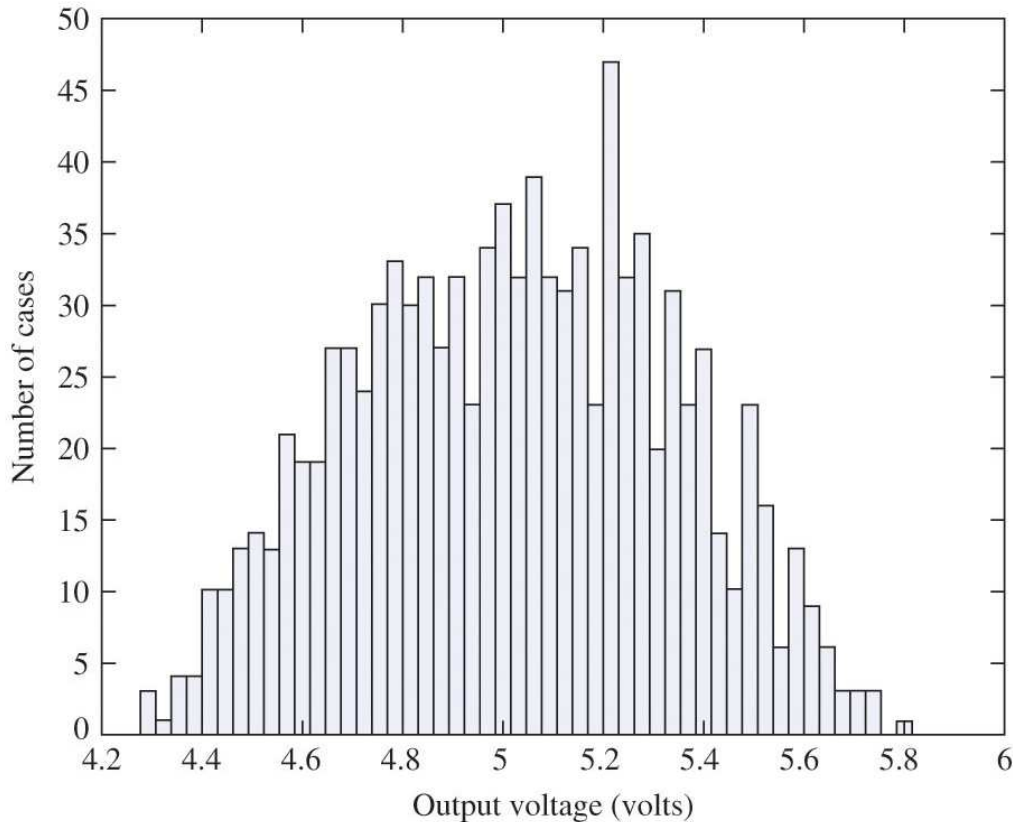
$$R = R_{nom}(1 + 2\varepsilon(RAND() - 0.5))$$

The RAND() function returns random numbers uniformly distributed between 0 and 1.



Monte Carlo Analysis Results

V_O (V)	
Average	4.96
Nominal	5.00
Standard Deviation	0.30
Maximum	5.70
W/C Maximum	5.87
Minimum	4.37
W/C Minimum	4.20



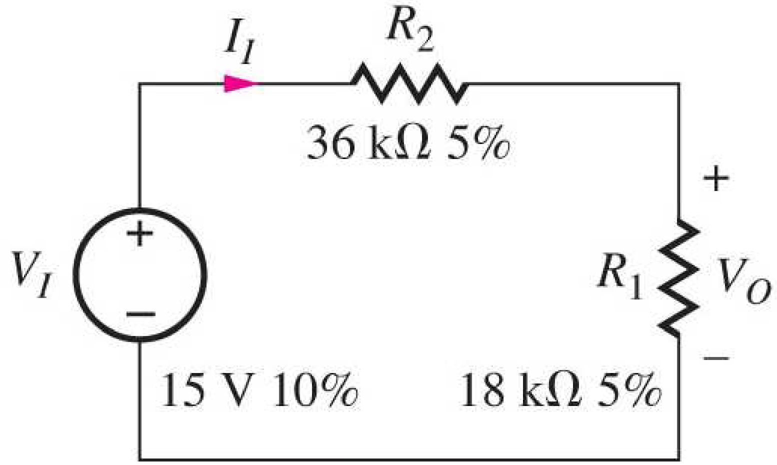
Histogram of output voltage from 1000 case Monte Carlo simulation.

Monte Carlo Analysis Example

Problem: Perform a Monte Carlo analysis and find the mean, standard deviation, min, and max for V_O, I_I, and power delivered from the source.

Solution:

- **Known Information and Given Data**: Circuit topology and values in figure.
- **Unknowns**: The mean, standard deviation, min, and max for V_O, I_I, and P_I.
- **Approach**: Use a spreadsheet to evaluate the circuit equations with random parameters.
- **Assumptions**: None.
- **Analysis**: Next slides…



Monte Carlo parameter definitions:

$$V_I = 15(1 + 0.2(RAND() - 0.5))$$

$$R_1 = 18{,}000(1 + 0.1(RAND() - 0.5))$$

$$R_2 = 36{,}000(1 + 0.1(RAND() - 0.5))$$

Monte Carlo Analysis Example (cont.)

Monte Carlo parameter definitions:

$$V_I = 15(1 + 0.2(RAND() - 0.5))$$

$$R_1 = 18{,}000(1 + 0.1(RAND() - 0.5))$$

$$R_2 = 36{,}000(1 + 0.1(RAND() - 0.5))$$

Circuit equations based on Monte Carlo parameters:

$$V_O = V_I \frac{R_1}{R_1 + R_2} \qquad I_I = \frac{V_I}{R_1 + R_2} \qquad P_I = V_I I_I$$

Results:

	Avg	Nom.	Stdev	Max	WC-max	Min	WC-Min
V_o (V)	4.96	5.00	0.30	5.70	5.87	4.37	4.20
I_I (mA)	0.276	0.278	0.0173	0.310	0.322	0.242	0.238
P (mW)	4.12	4.17	0.490	5.04	--	3.29	--

Temperature Coefficients

- Most circuit parameters are temperature sensitive.

  $P = P_{nom}(1+\alpha_1 \Delta T + \alpha_2 \Delta T^2)$ where $\Delta T = T - T_{nom}$

  P_{nom} is defined at T_{nom}
- Most versions of SPICE allow for the specification of TNOM, T, TC1(α_1), TC2(α_2).
- SPICE temperature model for resistor:

  $R(T) = R(TNOM)*[1+TC1*(T-TNOM)+TC2*(T-TNOM)^2]$
- Many other components have similar models.

Numeric Precision

- Most circuit parameters vary from less than ± 1 % to greater than ± 50%.
- As a consequence, more than three significant digits is meaningless.
- Results in the text will be represented with three significant digits: 2.03 mA, 5.72 V, 0.0436 μA, and so on.
- However, extra guard digits are normally retained during calculations.

End of Chapter 1