ECE321 Electronics I: Lecture 1

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

- Review circuit notation and theory.
- Introduce tolerance impacts and analysis.
- Describe problem solving approach

Notational Conventions

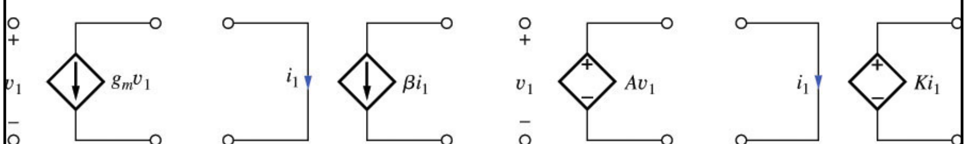
- Total signal = DC bias + time varying signal

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

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

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

Figure 1.10 Controlled Sources



(a) VCCS (b) CCCS (c) VCVS (d) CCVS

Problem-Solving Approach

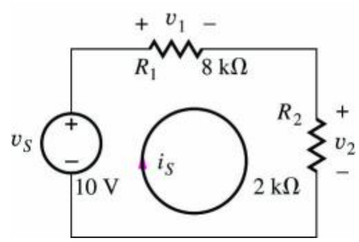
- Make a clear **problem** statement.
- List **known information and given data**.
- Define the **unknowns** required to solve the problem.
- List **assumptions**.
- Develop an **approach** to the solution.
- Perform the **analysis** based on the approach.
- **Check the results** and the assumptions.
  - 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 supply 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 μA 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.
- 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

$v_1 = i_s R_1$ and $v_2 = i_s R_2$



Applying KVL to the loop,

$$v_s = v_1 + v_2 = i_s(R_1 + R_2)$$

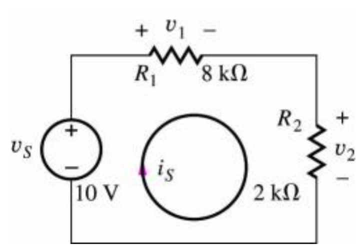
and $$i_s = \frac{v_s}{R_1 + R_2}$$

Combining these yields the basic voltage division formula:

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

Circuit Theory Review: Voltage Division (cont.)

Using the derived equations with the indicated values,



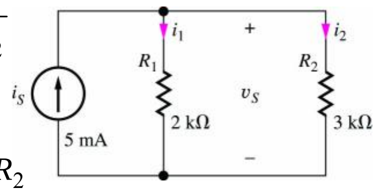
$$v_1 = 10\text{ V}\frac{8\text{ k}\Omega}{8\text{ k}\Omega + 2\text{ k}\Omega} = 8.00\text{ V}$$

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

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

Circuit Theory Review: Current Division

$i_s = i_1 + i_2$ where $i_1 = \dfrac{v_s}{R_1}$ and $i_2 = \dfrac{v_s}{R_2}$



Combining and solving for v_s,

$$v_s = i_s \frac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2}} = i_s \frac{R_1 R_2}{R_1 + R_2} = i_s R_1 \parallel R_2$$

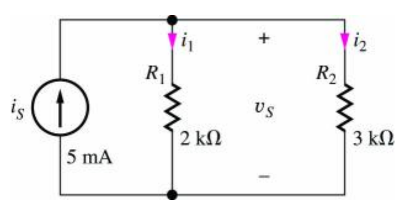
Combining these yields the basic current division formula:

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

and

Circuit Theory Review: Current Division (cont.)

Using the derived equations
with the indicated values,

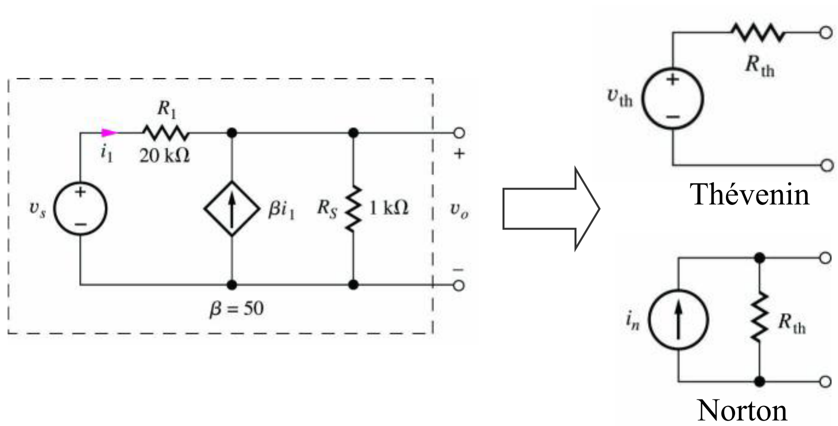


$$i_1 = 5 \text{ ma} \frac{3 \text{ k}\Omega}{2 \text{ k}\Omega + 3 \text{ k}\Omega} = 3.00 \text{ mA}$$

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

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

Circuit Theory Review: Thévenin and Norton Equivalent Circuits

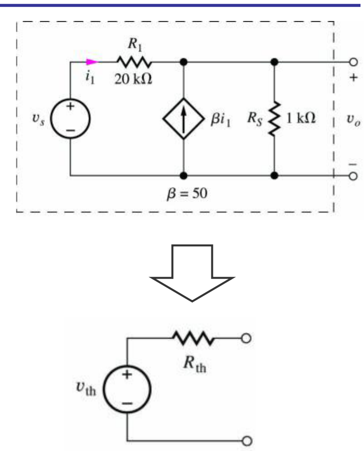


Circuit Theory Review: Find the Thévenin Equivalent Voltage

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.
- **Assumptions:** None.
- **Analysis:** Next slide…

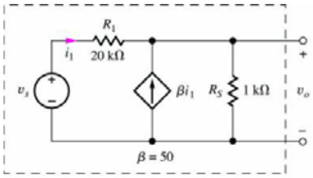


Circuit Theory Review: Find the Thévenin Equivalent Voltage

Applying KCL at the output node,

$$\beta i_1 = \frac{v_O - v_S}{R_1} + \frac{v_O}{R_S} = G_1(v_O - v_S) + G_S v_O$$

Current i_1 can be written as: $i_1 = G_1(v_O - v_S)$



Combining the previous equations

$$G_1(\beta+1)v_S = [G_1(\beta+1) + G_S]v_O$$

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

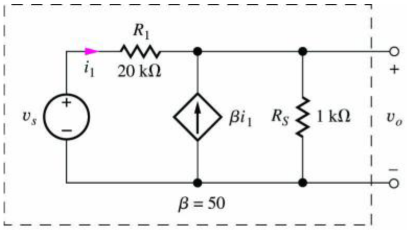
Circuit Theory Review: Find the Thévenin Equivalent Voltage (cont.)

Using the given component values:

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

and

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

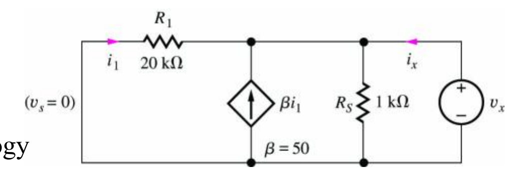


Circuit Theory Review: Find the Thévenin Equivalent Resistance

Problem: Find the Thévenin equivalent resistance.

Solution:

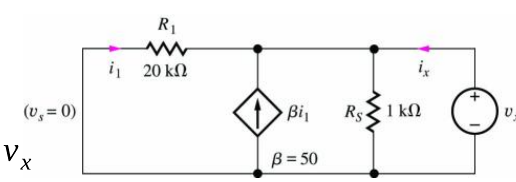
- **Known Information and Given Data**: Circuit topology and values in figure.
- **Unknowns**: Thévenin equivalent resistance R_{th}.
- **Approach**: Voltage source v_{th} is defined as the output voltage with no load.
- **Assumptions**: None.
- **Analysis**: Next slide…



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,



$$\begin{aligned} i_x &= -i_1 - \beta i_1 + G_S v_x \\ &= G_1 v_x + \beta G_1 v_x + G_S v_x \\ &= \left[G_1(\beta+1) + G_S\right] v_x \end{aligned}$$

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

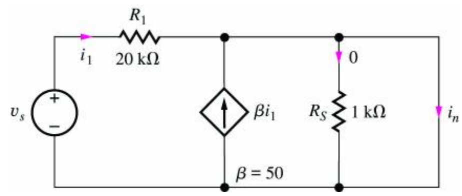
$$R_{th} = R_S \left\| \frac{R_1}{\beta+1} \right. = 1\ \text{k}\Omega \left\| \frac{20\ \text{k}\Omega}{50+1} \right. = 1\ \text{k}\Omega \| 392\ \Omega = 282\ \Omega$$

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…

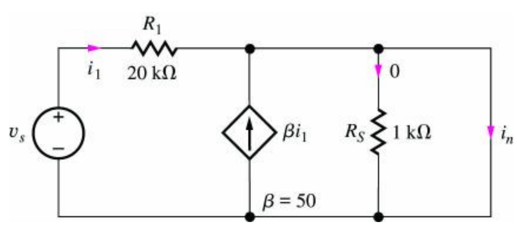


A short circuit has been applied across the output. The Norton current is the current flowing through the short circuit at the output.

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

Applying KCL,

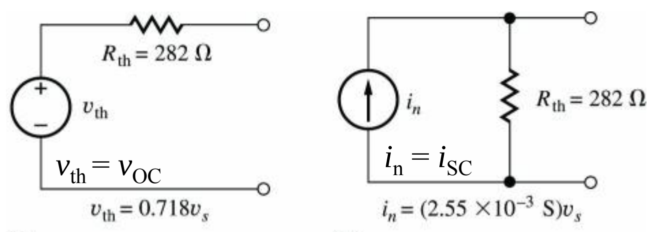
$$\begin{aligned} i_n &= i_1 + \beta i_1 \\ &= G_1 v_s + \beta G_1 v_s \\ &= G_1(\beta+1)v_s \\ &= \frac{v_s(\beta+1)}{R_1} \end{aligned}$$



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

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

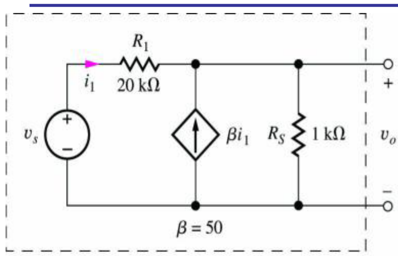
Final Thévenin and Norton Circuits

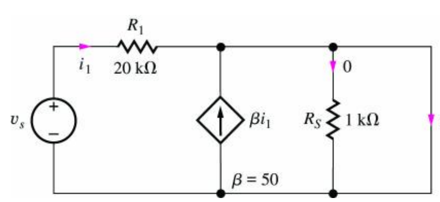


Check of Results: Note that $v_{th} = i_n R_{th}$ and this can be used to check the calculations: $i_n R_{th} = (2.55\ \mathrm{mS}) v_s (282\ \Omega) = 0.719 v_s$, accurate within round-off error.

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!

Alternate Approach: $R_{th} = v_{OC}/i_{SC}$





$$v_{OC}/R_S = (1+\beta)(v_S - v_{OC})/R_1$$

$$v_{OC} = [(1+\beta)v_S/R_1]/[1/R_S + (1+\beta)/R_1]$$

$$= [(1+\beta)R_S]/[R_1 + (1+\beta)R_S]$$

$$= 0.718 v_S$$

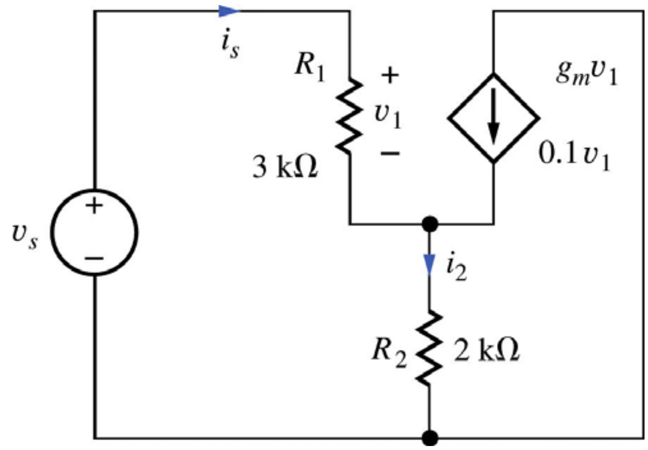
$$i_{SC} = (1+\beta)i_1 = (1+\beta)v_S/R_1$$

$$= 51 v_S/20\mathrm{k}\Omega$$

$$R_{th} = v_{OC}/i_{SC}$$

$$= R_1 R_S/[R_1 + (1+\beta)R_S] = 282\Omega$$

Fig. 1.16/Example 1.4 Circuit with VCCS (BJT CE amplifier)



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 the output.

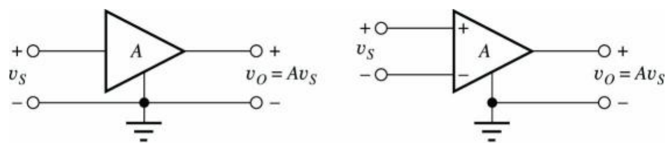
Amplifier Linearity

Given an input sinusoid: $v_s = V_s \sin(\omega_s t + \phi)$

For a linear amplifier, the output is at the same frequency, but different amplitude and phase. $v_o = V_o \sin(\omega_s t + \phi + \theta)$

In phasor notation: $\mathbf{v_s} = V_s \angle \phi \qquad \mathbf{v_o} = V_o \angle(\phi + \theta)$

Amplifier gain is: $A = \frac{\mathbf{v_o}}{\mathbf{v_s}} = \frac{V_o \angle(\phi+\theta)}{V_s \angle \phi} = \frac{V_o}{V_s} \angle \theta$

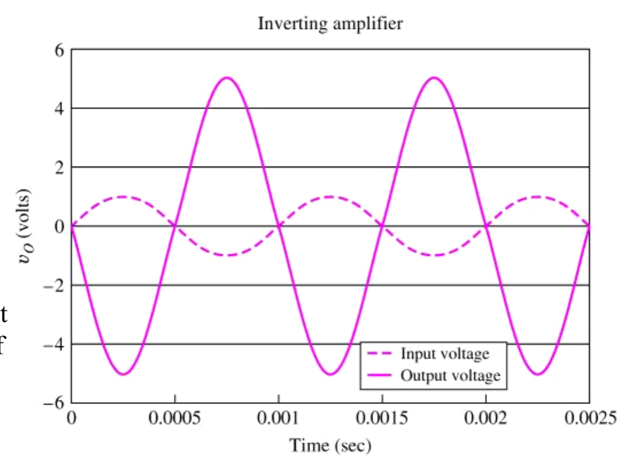


Amplifier Input/Output Response

$v_s = \sin 2000\pi t$ 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

Writing a loop equation:

$$v_s - i_s R_1 - i_2 R_2 - v_o = 0$$

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

$$i_s = i_2 = \frac{v_s - v_-}{R_1}$$

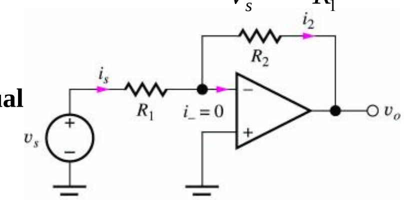
Assumption 1 requires $v_- = v_+ = 0$.

$$i_s = \frac{v_s}{R_1}$$

Combining these equations yields:

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

Assumption 1 requiring $v_- = v_+ = 0$ creates what is known as a **virtual ground**, or (more generally) a **virtual short-circuit.**



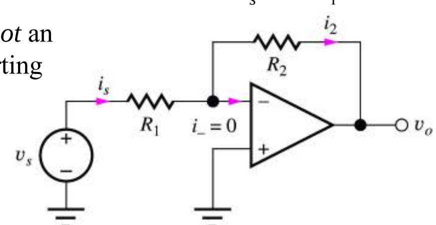
Ideal Op Amp Example (Alternative Approach)

From Assumption 2, $i_2 = i_s$:
$$i_s = \frac{v_s - v_-}{R_1} = \frac{v_s}{R_1} = i_2 = \frac{v_- - v_o}{R_2} = \frac{-v_o}{R_2}$$

And Assumption 1, $v_- \approx 0$
$$\frac{v_s}{R_1} = \frac{-v_o}{R_2}$$

Yielding:
$$A_v = \frac{v_o}{v_s} = -\frac{R_2}{R_1}$$

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



Circuit Element Variations

- All electronic components have manufacturing tolerances.
  - Resistors can be purchased with ± 10%, ± 5%, and ± 1% tolerance. (IC resistors are often ± 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

  $P_{nom}(1 - \varepsilon) \le P \le P_{nom}(1 + \varepsilon)$
- For example, a 10K resistor with ±5% percent tolerance could take on the following range of values:

  $10k(1 - 0.05) \le R \le 10k(1 + 0.05)$

  $9{,}500\ \Omega \le R \le 10{,}500\ \Omega$

Circuit Analysis with Tolerances

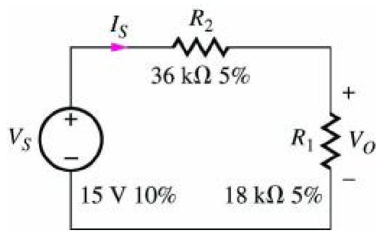
- Worst-case analysis
  - Parameters are manipulated to produce the worst-case min and max values of desired quantities.
  - This can lead to over design since the worst-case combination of parameters is rare.
  - It may be less expensive to discard a rare failure than to design for 100% yield.
- Monte-Carlo 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_S^{nom}, I_S^{min}, I_S^{max} .
- **Approach**: Find nominal values and then select R_1, R_2, and V_S values to generate extreme cases of the unknowns.
- **Assumptions**: None.
- **Analysis**: Next slides…

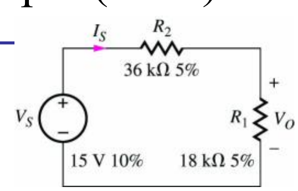


Nominal voltage solution:

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

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

Worst-Case Analysis Example (cont.)



Nominal Source current:

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

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

$$V_O = V_S \frac{R_1}{R_1 + R_2} = \frac{V_S}{1 + \frac{R_2}{R_1}}$$

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

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

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

Worst-Case Analysis Example (cont.)

Worst-case source currents:

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

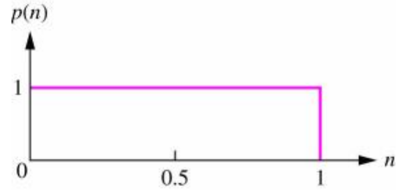
$$I_S^{min} = \frac{V_S^{min}}{R_1^{max} + R_2^{max}} = \frac{15V(0.9)}{18k\Omega(1.05) + 36k\Omega(1.05)} = 238\mu A$$

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 5% tolerance 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.

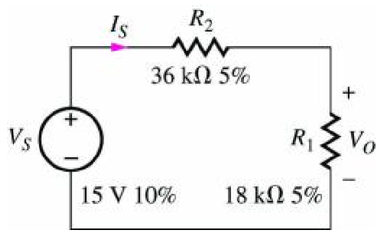


Monte Carlo Analysis Example

Problem: Perform a Monte Carlo analysis and find the mean, standard deviation, min, and max for V_O, I_S, 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_S, and P_S.
- **Approach**: Use a spreadsheet to evaluate the circuit equations with random parameters.
- **Assumptions**: None.
- **Analysis**: Next slides…



Monte Carlo parameter definitions:

$$V_S = 15(1 + 0.2(RAND() - 0.5))$$
$$R_1 = 18{,}000(1 + 0.1(RAND() - 0.5))$$
$$R_2 = 36{,}000(1 + 0.1(RAND() - 0.5))$$

Monte Carlo Analysis Example (cont.)

Monte Carlo parameter definitions:

$$V_S = 15(1 + 0.2(RAND() - 0.5))$$
$$R_1 = 18{,}000(1 + 0.1(RAND() - 0.5))$$
$$R_2 = 36{,}000(1 + 0.1(RAND() - 0.5))$$

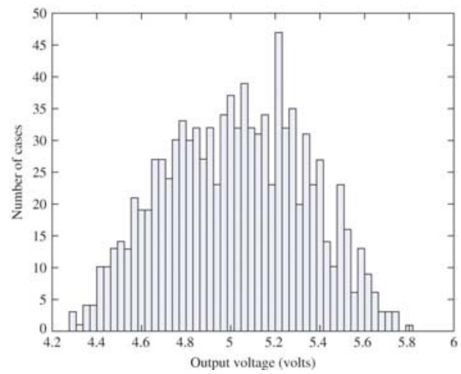
Circuit equations based on Monte Carlo parameters:

$$V_O = V_S \frac{R_1}{R_1 + R_2} \qquad I_S = \frac{V_S}{R_1 + R_2} \qquad P_S = V_S I_S$$

Excel Results:

	Avg	Nom.	Stdev	Max	WC-max	Min	WC-Min
Vo (V)	4.96	5.00	0.30	5.70	5.87	4.37	4.20
Is (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	--

MATLAB Monte Carlo Analysis Result



Histogram of output voltage from 1000 case Monte Carlo simulation.

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.

End of Lecture 1