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EE 313: Basic Electrical Engineering I

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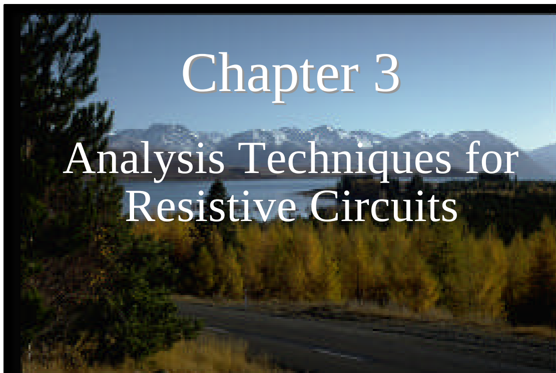
Microsoft PowerPoint® Presentation Graphics

For Part 1 of

Introduction to Electrical Engineering, 2/e

by C.R. Paul, S.A. Nasar and L.E. Unnewehr



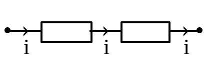
Introduction to Electrical Engineering

Chapter 3: Analytic Techniques for Resistive Circuits

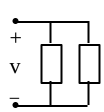
3.1 Series and Parallel Connections of Resistors

- Elements in series share the same *physical** current
- Elements in parallel share the same *physical** voltage

* *Physical* as opposed to *numerical*; e.g., two elements having the same numerical current are not necessarily in series, etc.



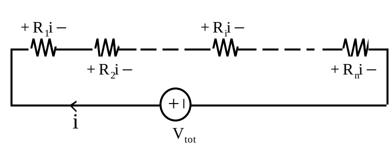
Two elements in series



Two elements in parallel

3.1 Series and Parallel Connections of Resistors

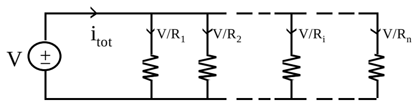
- Resistors in series add: $R_{tot} = R_1 + R_2 + \ldots + R_n$



$$\text{KVL: } V_{tot} = \sum_{j=1}^{j=n} R_j i = i \sum_{j=1}^{j=n} R_j = R_{tot} i$$

3.1 Series and Parallel Connections of Resistors

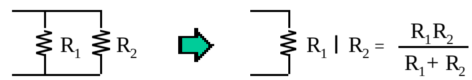
- Resistors in parallel add reciprocally:
  $R_{tot}^{-1} = R_1^{-1} + R_2^{-1} + \ldots + R_n^{-1}$
- And conductances in parallel add directly:
  $G_{tot} = G_1 + G_2 + \ldots + G_n$ (See text p. 60)



KCL: $i_{tot} = \sum_{j=1}^{j=n} V/R_j = V \sum_{j=1}^{j=n} R_j^{-1} = V R_{tot}^{-1}$

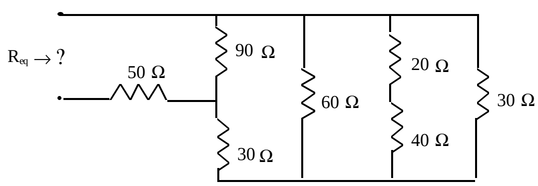
3.1 Series and Parallel Connections of Resistors

- Special case: Two Resistors in parallel:
  $R_1 \| R_2 = (R_1 R_2)/(R_1 + R_2)$
- N.B.: Product-over-sum rule and notation (see text p. 61)—memorize!



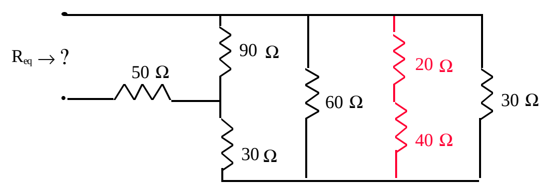
3.1 Series and Parallel Resistors: Example 3-1

Example 3-1: Calculate R_{eq}



3.1 Series and Parallel Resistors: Example 3-1

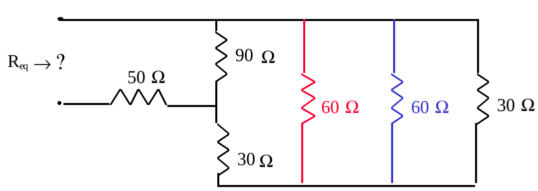
Example 3-1: Calculate R_{eq}



Step 1: 20 Ω + 40 Ω = 60 Ω (two series resistors)

3.1 Series and Parallel Resistors: Example 3-1

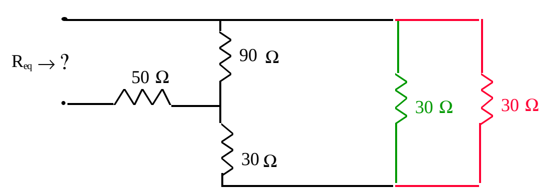
Example 3-1: Calculate R_{eq}



Step 2: 60 Ω | 60 Ω = 30 Ω (two parallel resistors)

3.1 Series and Parallel Resistors: Example 3-1

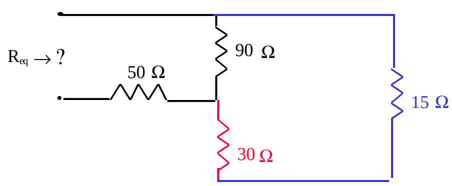
Example 3-1: Calculate R_{eq}



Step 3: 30 Ω | 30 Ω = 15 Ω (two parallel resistors)

3.1 Series and Parallel Resistors: Example 3-1

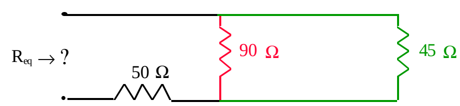
Example 3-1: Calculate R_{eq}



Step 4: 30 Ω + 15 Ω = 45 Ω (two series resistors)

3.1 Series and Parallel Resistors: Example 3-1

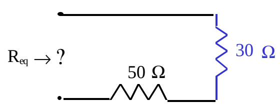
Example 3-1: Calculate R_{eq}



Step 5: 90 Ω | 45 Ω = 30 Ω (two parallel resistors)

3.1 Series and Parallel Resistors: Example 3-1

Example 3-1: Calculate R_{eq}



Step 6: 50 Ω + 30 Ω = 80 Ω (two series resistors)

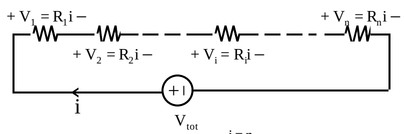
3.1 Series and Parallel Resistors: Example 3-1

Example 3-1: Calculate R_{eq}

Step 7: Ergo, R_{eq} = 80 Ω

3.2 Voltage and Current division

- Voltage division: Series resistor voltages divide in proportion to resistances



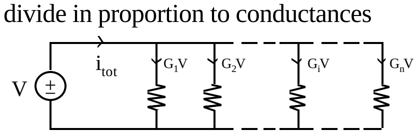
KVL: $V_{tot} = R_{tot} i = (\sum_{j=1}^{j=n} R_j) i$ (I)

Ohm's Law: $V_i = R_i i$ (II)

(II) ÷ (I) yields: $\frac{V_i}{V_{tot}} = \frac{R_i}{R_{tot}}$ Memorize!

3.2 Voltage and Current division

- Current division: Parallel resistor currents divide in proportion to conductances



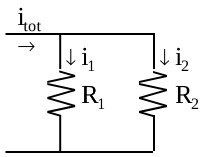
KCL: $i_{tot} = G_{tot} V = (\sum_{j=1}^{j=n} G_j) V$ (I)

Ohm's Law: $i_i = G_i V$ (II)

(II) ÷ (I) yields: $\frac{i_i}{i_{tot}} = \frac{G_i}{G_{tot}}$ Memorize!

3.2 Voltage and Current division

- Special case: Two Resistors in parallel: $i_1/i_{tot} = R_2/(R_1 + R_2)$, etc. (see below)
- N.B.: "Other" resistor over sum of resistors (see text p. 68)—memorize!



$$\frac{i_1}{i_{tot}} = \frac{R_2}{R_1 + R_2}$$

$$\frac{i_2}{i_{tot}} = \frac{R_1}{R_1 + R_2}$$

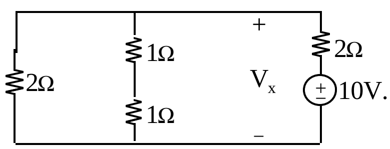
Memorize!

Circuit Analysis Tool kit: Recapitulation

- Single-loop circuit analysis
- Single-node-pair circuit analysis
- Source transformations
- Series-parallel resistance combinations
- Voltage division
- Current division

Example 3-2

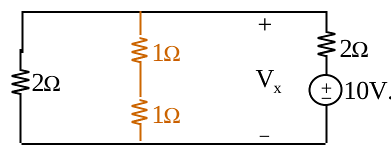
Find V_x



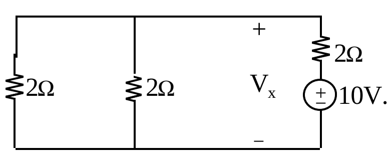
N.B.: See text Problem 3.9, p. 97.

Example 3-2 cont.

Step 1: 1Ω + 1Ω = 2Ω

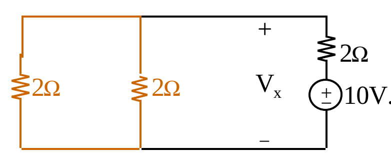


Example 3-2 cont.

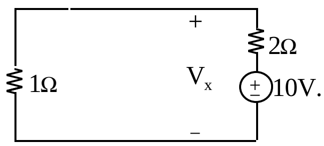


Example 3-2 cont.

Step 2: 2Ω | 2Ω = 1Ω



Example 3-2 cont.

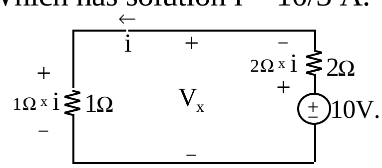


Example 3-2 cont.

Step 3: Single-loop circuit

KVL: 10 V. – 2Ω x i – 1Ω x i = 0 V.

Which has solution i = 10/3 A.

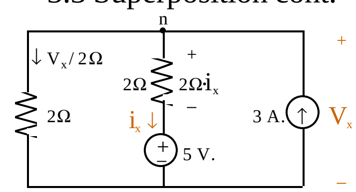


So what's V_x ?

3.3 Superposition

- *Superposition* is the defining (inherent) property of linear systems
- Ergo, *linearity* and *superposition* are synonymous
- Electric circuits are electrical systems
- The behavior of all voltages and currents in electric circuits consisting of constant valued resistors and (independent) voltage and/or current sources is governed by *linear algebraic equations* in these voltages and currents; e.g., consider ...

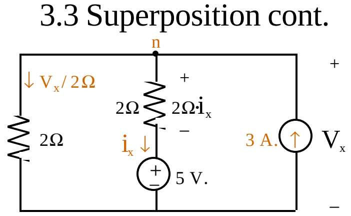
3.3 Superposition cont.



N.B.: See text Problem 3.23, p. 99.

Find V_x and i_x

3.3 Superposition cont.



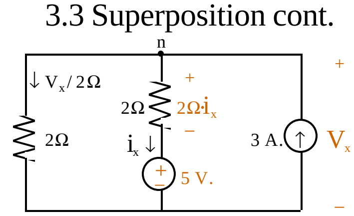
N.B.: See text Problem 3.23, p. 99.

KCL at n

V_x / 2Ω + i_x – 3 A. = 0 A.

(Which is linear in V_x and i_x)

3.3 Superposition cont.



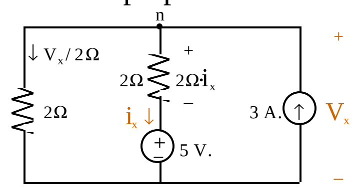
N.B.: See text Problem 3.23, p. 99.

KVL (right mesh)

5 V. + 2Ω•i_x – V_x = 0 V.

(Also linear in V_x and i_x)

3.3 Superposition cont.



N.B.: See text Problem 3.23, p. 99.

$V_x / 2\Omega + i_x - 3\text{ A.} \quad = 0\text{ A.}$

$5\text{ V.} + 2\Omega \cdot i_x - V_x \quad = 0\text{ V.}$

Have solution

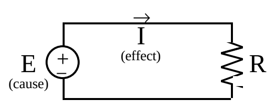
$V_x = 5.5\text{ V.}$ and $i_x = 0.25\text{ A.}$

3.3 Superposition cont.

- What is the definition of the *Superposition* property?
- *If* effect E_1 results from cause C_1
- *And if* effect E_2 results from cause C_2
- *And if* effect $K \cdot E_2$ results from cause $K \cdot C_2$ (where K is a constant)
- *Then* cause $(C_1 + K \cdot C_2)$ results in effect $(E_1 + K \cdot E_2)$
- And the cause-effect relationship (system) possessing the above *superposition* property is said to be *linear*

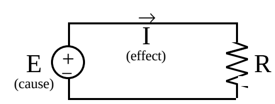
3.3 Superposition cont.

- Are the aforementioned electric circuits linear systems?
- Yes! Consider the one-variable case below where there is one independent voltage source (the cause) and one dependent current variable (the effect)
- Then the cause-effect relationship is mathematical and manifests itself as the linear algebraic equation I = E/R (Ohm's Law) in the dependent variable I



3.3 Superposition cont.

- Then if $E = E_1$, $I = I_1 = E_1/R$ and …
- And if $E = E_2$, $I = I_2 = E_2/R$ and …
- And if $E = K \cdot E_2$, $I = K \cdot E_2/R = K \cdot I_2$
- So that when $E = (E_1 + K \cdot E_2)$
- $I = (E_1 + K \cdot E_2)/R = E_1/R + K \cdot E_2/R = I_1 + K \cdot I_2$
- Ergo, superposition applies!



3.3 Superposition cont.

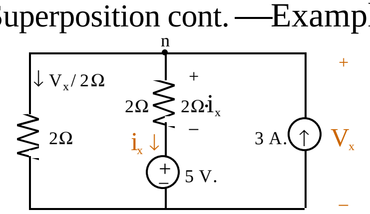
What's the practical use of this property; i.e., what's its application?

One-source-at-a-time superposition!

Which works because, in a linear system, partial effects caused by partial causes can be added to produce the total effect resulting from the sum-total of the partial causes

The key to the method's success lies in partitioning a given problem into single-source sub-problems (which are relatively easy to solve) and then applying superposition to the sub-problems' solutions—by just adding them up!

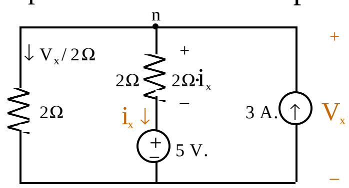
3.3 Superposition cont.—Example 3-3



N.B.: See text Problem 3.23, p. 99.

Find V_x and i_x using one-source-at-a-time superposition

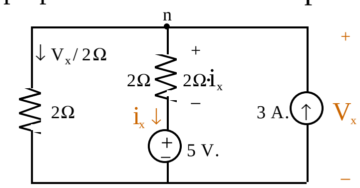
3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 1</u>: Calculate the components of V_x and i_x that are caused by the 5 V. voltage source *only*. This begs the question "how is the influence of the 3 A. current source to be withdrawn from consideration?"

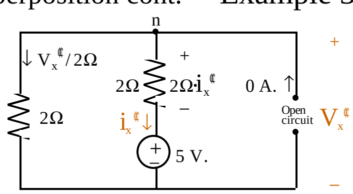
3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 1 (cont.)</u>: The answer is to replace it with a zero (no) Ampere current source (i.e., an open circuit)—no current, no influence!

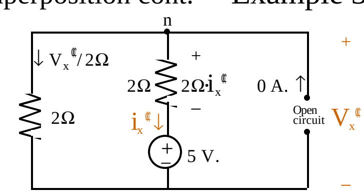
3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 1 (cont.)</u>: N.B.: The *partial* answers (caused by the 5 V. voltage source only) have been flagged with primes.

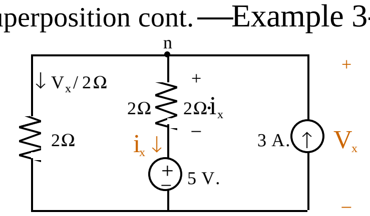
3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 1 (cont.)</u>: What's left is just a one-loop circuit having (by Ohm's Law) a counterclockwise current of $V_x' / 2\Omega = 5\text{ V.} \div (2\Omega + 2\Omega) = 1.25\text{ A.}$ $\therefore$ $V_x' = 2.5\text{ V.}$ and KCL at node n yields $i_x' = -1.25\text{ A.}$

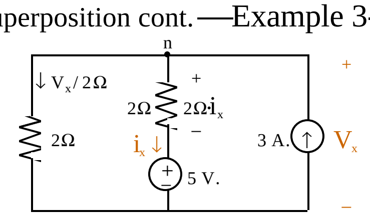
3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 2</u>: Calculate the components of V_x and i_x that are caused by the 3 A. current source *only*. This begs the question "how is the influence of the 5 V. voltage source to be withdrawn from consideration?"

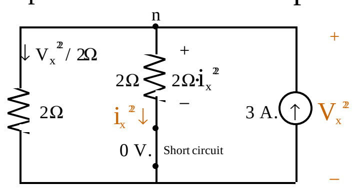
3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 2 (cont.)</u>: The answer is to replace it with a zero (no) Volt voltage source (i.e., a short circuit)—no voltage, no influence!

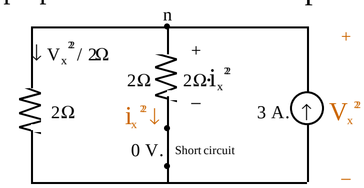
3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 2 (cont.)</u>: N.B.: The *partial* answers (caused by the 3 A. current source only) have been flagged with double primes.

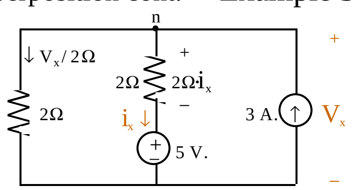
3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 2 (cont.)</u>: What's left is just a two-(equal) resistor current divider for which $i_x'' = [2\Omega / (2\Omega + 2\Omega)] \bullet 3$ A. = 1.5 A. so that $V_x'' = 2\Omega \bullet i_x'' = 2\Omega \bullet 1.5$ A. = 3 V.

3.3 Superposition cont.—Example 3-3 cont.



N.B.: See text Problem 3.23, p. 99.

<u>Step 3</u>: Calculate each answer by summing its respective components; i.e., $i_x = i_x' + i_x'' = -1.25$A. + 1.5A. = 0.25 A.
and: $V_x = V_x' + V_x'' =$ 2.50V. + 3.0V. = 5.50 V.

3.3 Superposition cont.

Does superposition work for power?

No! If it did (it *doesn't*), the power absorbed by the 2Ω resistor (the one through which i_x flows) would be $2\Omega \cdot (i_x')^2 + 2\Omega \cdot (i_x'')^2 = 2\Omega \cdot (-1.25\text{A.})^2 + 2\Omega \cdot (1.5\text{A.})^2 = 7.625$ W.

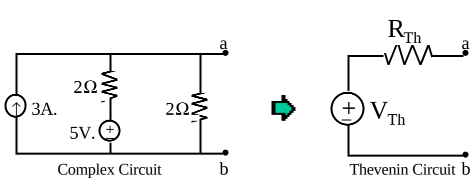
However, the power actually is $2\Omega \cdot (i_x)^2 = 2\Omega \cdot (0.25\text{A.})^2 = 0.125$ W.

Why didn't superposition work for power?

Because $(i_x)^2 = (i_x' + i_x'')^2 = (i_x')^2 + 2 \cdot i_x' \cdot i_x'' + (i_x'')^2 \neq (i_x')^2 + (i_x'')^2$ (i.e., the quadratic's cross-product term is missing)

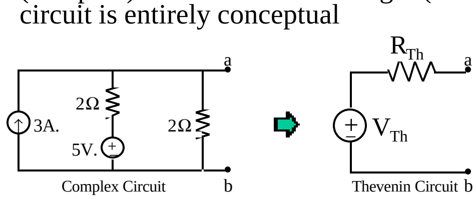
3.4 Thevenin and Norton Equivalent Circuits

- The basic idea is to replace a relatively complex (linear) circuit with a simple *single-loop circuit* having a single voltage source and a single resistor—which is called the complex circuit's *Thevenin Equivalent Circuit*



3.4 Thevenin and Norton Equivalent Circuits

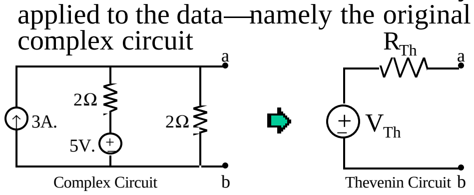
- What's needed are rules for how to calculate V_{Th} and R_{Th}
- Note that all of the numerical data is in the left (complex) circuit whereas the right (Thevenin) circuit is entirely conceptual



Data here *Concepts (theory) here*

3.4 Thevenin and Norton Equivalent Circuits

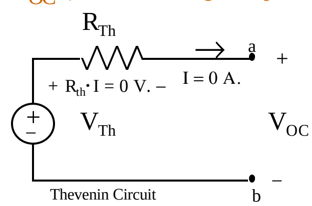
- This suggests that the rules for how to calculate V_{Th} and R_{Th} should be derivable from the Thevenin (theory) circuit and ...
- Once derived, these rules are then always applied to the data—namely the original complex circuit



Data here *Concepts (theory) here*

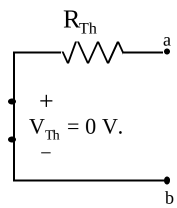
3.4 Thevenin Circuit Element Rules

- KVL applied to the Thevenin circuit *with terminals a-b open* (so I = 0 A.) yields:
- $V_{Th} - 0\ V. - V_{OC} = 0\ V. \quad \therefore$
- $V_{Th} = V_{OC}$ (Thevenin voltage = Open circuit voltage)



3.4 Thevenin Circuit Element Rules cont.

- R_{Th} is the resistance of the circuit when all independent sources of energy are removed from consideration (all voltage sources shorted, all current sources opened)

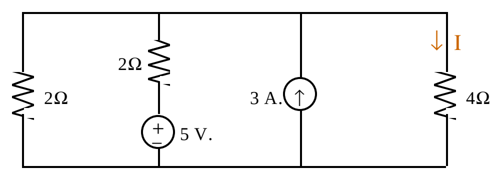


$R = R_{Th}$

3.4 Thevenin & Norton Equiv. Circuits cont.

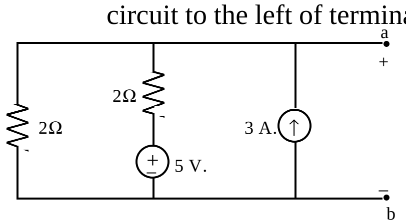
Example 3-4

Find I using Thevenin's Theorem



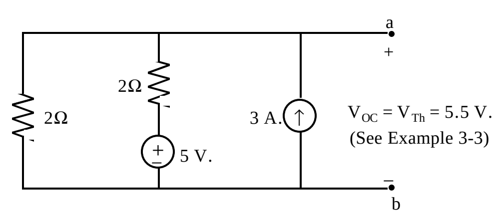
3.4 Example 3-4 cont.

Step 1: Get the Thevenin Equiv. of the circuit to the left of terminals a-b



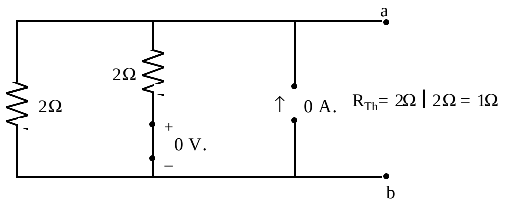
3.4 Example 3-4 cont.

Step 1a: Open circuit voltage calculation



3.4 Example 3-4 cont.

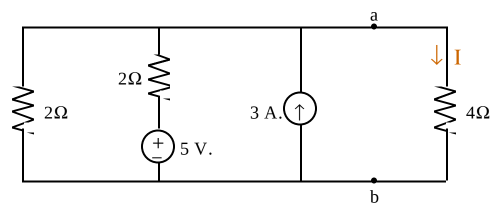
Step 1b: Determination of R_{Th}



$R_{Th} = 2\Omega \mid 2\Omega = 1\Omega$

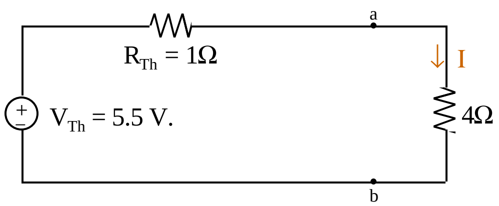
3.4 Example 3-4 cont.

Ergo, finding I using Thevenin's Theorem becomes



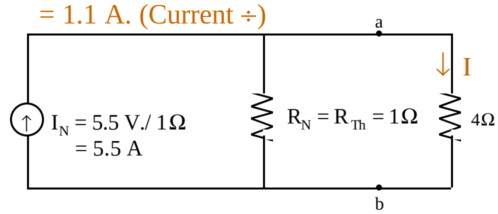
3.4 Example 3-4 cont.

I = 5.5 V. / (1 + 4) Ω = 1.1 A.
(Ohm's Law)



3.4 Example 3-4 cont.

Using source conversions, the Norton solution is: I = [1Ω /(1 + 4)Ω] × 5.5 A. = 1.1 A. (Current ÷)

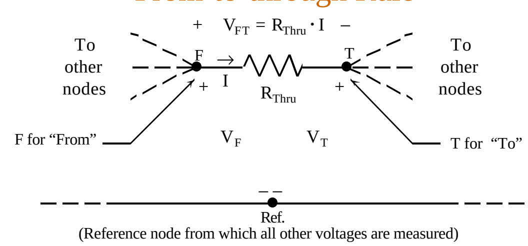


N.B.: See text pp. 76-81 for further information regarding Norton Equivalent circuits

3.5 Node & Mesh Analysis

- Node voltage analysis is just *organized* KCL(s)
- Likewise, mesh current analysis is just *organized* KVL(s)
- First consider node voltage analysis
- But before that, consider the following useful rule

From-to-through Rule



(Reference node from which all other voltages are measured)

KVL: $V_F - V_{FT} - V_T = 0 \therefore V_{FT} = V_F - V_T = R_{Thru} \cdot I$ (Ω's Law)

$$I = \frac{V_{From} - V_{To}}{R_{Thru}}$$ ← Memorize this formula!

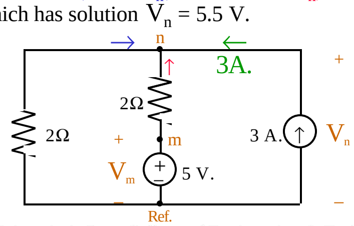
3.5 Node Voltage Analysis: Example 3-5

There are three nodes (m, n and the Ref. node)

V_m is known to be 5 V. (by inspection or by KVL)

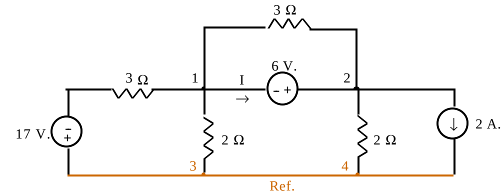
Write KCLs at nodes where the voltage is *unknown*

KCL at node n: $(0V.– V_n)/2\Omega + (5V.– V_n)/2\Omega + 3A. = 0$ A. —which has solution $V_n = 5.5$ V.



3.5 Node Voltage Analysis: Example 3-6

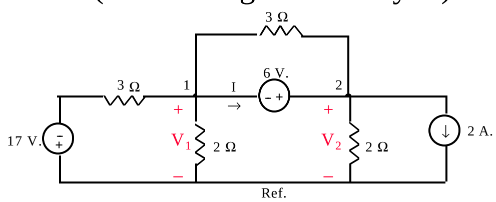
Find I using nodal analysis



The first step is to (arbitrarily) establish the "bottom" (physical nodes 3 and 4) of the circuit as the (electrical) reference node (Ref.)

Example 3-6 cont.

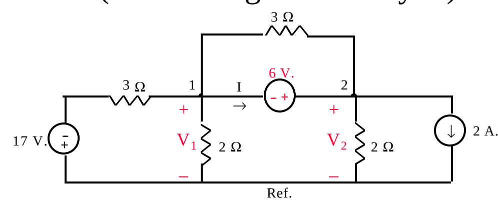
(Find I using nodal analysis)



The node voltages V_1 and V_2 are with respect to the reference (bottom) node as shown

Example 3-6 cont.

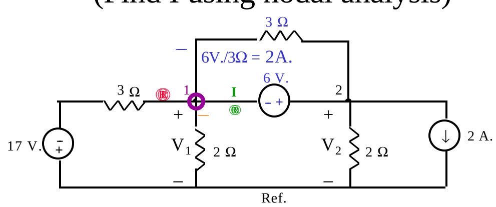
(Find I using nodal analysis)



KVL: $V_1 + 6\text{ V.} – V_2 = 0$ V. ∴ $V_2 = V_1 + 6$ (A.)

Example 3-6 cont.

(Find I using nodal analysis)

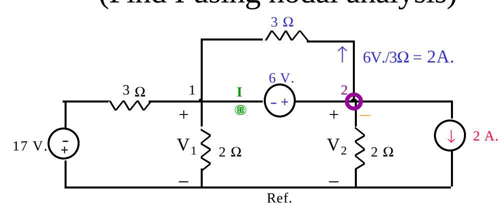


KCL at Node 1:

$[(–17\text{ V.}) – V_1]/3\Omega + 2\text{ A.} – I – V_1/2\Omega = 0$ A. (B.)

Example 3-6 cont.

(Find I using nodal analysis)

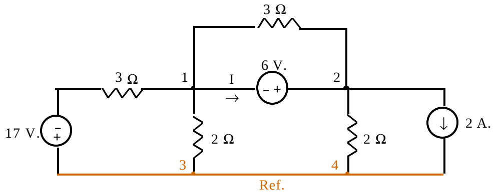


KCL at Node 2:

$I – 2\text{ A.} – 2\text{ A.} – V_2/2\Omega = 0$ A. (C.)

Example 3-6 cont.

(Find I using nodal analysis)



Equations (A.), (B.) and (C.) have solution:
$V_1 = -8$ V., $V_2 = -2$ V. and I = 3 A.
Ergo, I = 3 A.

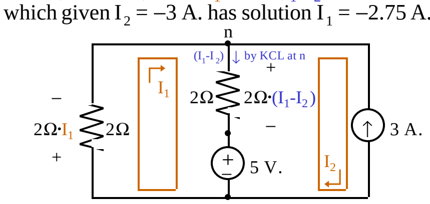
3.5 Mesh Current Analysis: Example 3-7

There are two (left & right) meshes ("window panes")

I_2 is known to be −3 A. (by inspection or by KCL)

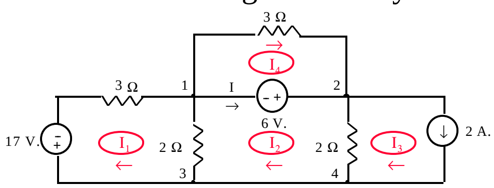
Write KVLs around meshes whose mesh currents are *unknown*

KVL (left mesh): $-2\Omega \cdot I_1 - 2\Omega \cdot (I_1 - I_2) - 5$ V. = 0 V.
which given $I_2 = -3$ A. has solution $I_1 = -2.75$ A.



3.5 Mesh Current Analysis: Example 3-8

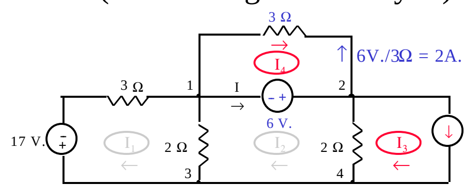
Find I using mesh analysis



The first step is to (arbitrarily) establish the mesh currents I_1, I_2, I_3 and I_4 as shown

Example 3-8 cont.

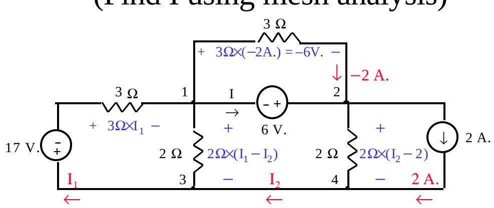
(Find I using mesh analysis)



Next, observe that $I_3 = 2$ A. and $I_4 = -6$V./3Ω = -2 A. and alter the schematic accordingly (see next slide)

Example 3-8 cont.

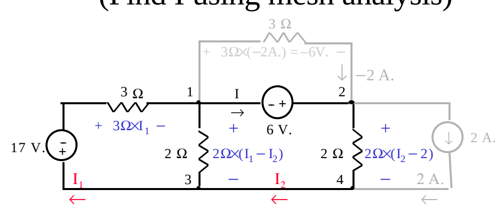
(Find I using mesh analysis)



Next, place *voltage drops* adjacent to the resistors as shown—note the use of the passive sign convention in assigning each voltage polarity!

Example 3-8 cont.

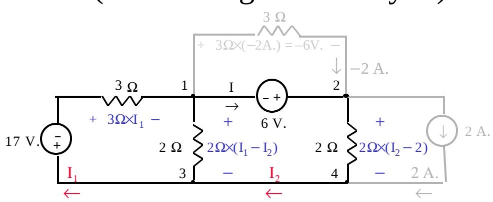
(Find I using mesh analysis)



Next, write KVLs around meshes whose mesh currents are *not* known

Example 3-8 cont.

(Find I using mesh analysis)



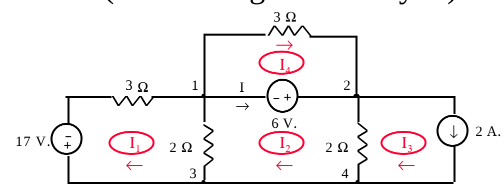
Mesh KVLs:

$-17\text{ V.} - 3\Omega \times I_1 - 2\Omega \times (I_1 - I_2) = 0\text{ V.}$ (A.)

$2\Omega \times (I_1 - I_2) + 6\text{ V.} - 2\Omega \times (I_2 - 2) = 0\text{ V.}$ (B.)

Example 3-8 cont.

(Find I using mesh analysis)



Equations (A.) and (B.) have solution $I_1 = -3$ A. and $I_2 = 1$ A. so given $I_4 = -2$ A., it follows that $I = I_2 - I_4 = 1\text{ A.} - (-2\text{ A.}) = 3$ A. ∴ I = 3 A.

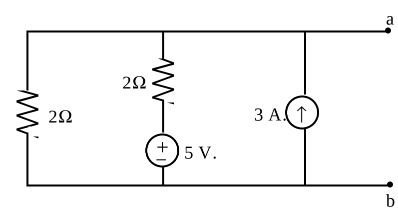
3.6 Maximum Power Transfer

To extract maximum power from a Thevenin circuit, load it with a resistance equal to R_{Th}— see text pp. 95-96 for (calculus) proof

It follows then that to extract maximum power from *any* (linear) circuit, load it with its Thevenin resistance R_{Th} with respect to the extraction point

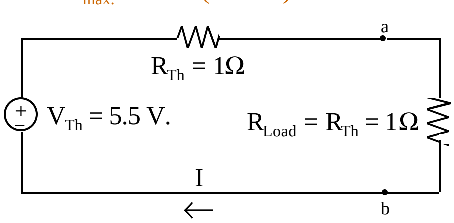
3.6 Maximum Power Transfer: Example 3-9

What's the maximum power that can be extracted from terminals a-b?



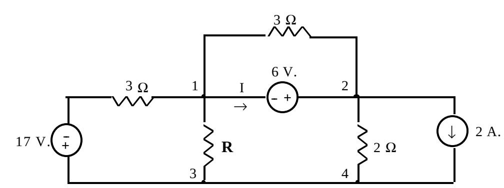
3.6 Maximum Power Transfer: Example 3-9 cont.

The circuit's Thevenin equivalent (found in Example 3-4) loaded with R_{Th} at terminals a-b yields:
I = 5.5 V./(1 + 1)Ω = 2.75 A. so the (maximum) load power is: $P_{max.} = I^2R = (2.75\text{ A.})^2 \times 1\ \Omega = 7.5625$ W.



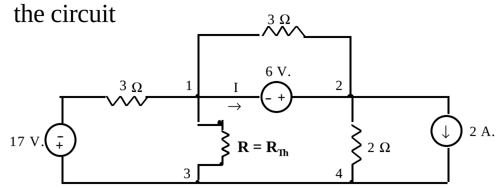
3.6 Maximum Power Transfer: Example 3-10

Determine the value of R in the circuit which will draw maximum power and calculate the corresponding maximum power.



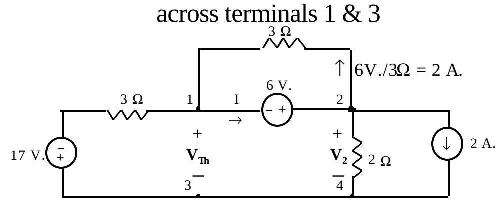
Example 3-10 cont.

Solution strategy: Determine the Thevenin circuit with respect to terminals 1 & 3 — then $R = R_{Th}$ will draw maximum power from the remainder of the circuit



Example 3-10 cont.

First find V_{Th} = open-circuit voltage across terminals 1 & 3



KCL at Node 1: $[(-17V.) - V_{Th}]/3\Omega + 2A. - I = 0$ A. (A.)

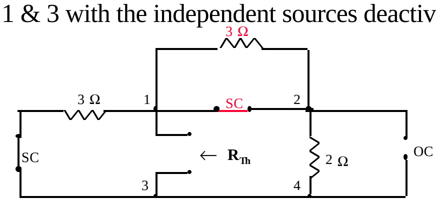
KCL at Node 2: $I - 2A. - V_2/2\Omega - 2A. = 0$ A. (B.)

KVL: $V_{Th} + 6V. - V_2 = 0$ V. (C.)

(A.), (B.) and (C.) have solution $V_{Th} = -12.8$ V.

Example 3-10 cont.

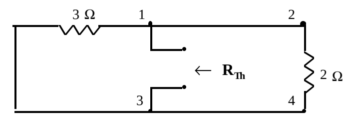
R_{Th} = Resistance across (open-circuited) terminals 1 & 3 with the independent sources deactivated



The parallel combination of the 0 Ω SC and the 3 Ω resistor is 0 Ω (another SC) so the circuit becomes (next slide) ...

Example 3-10 cont.

R_{Th} = Resistance across (open-circuited) terminals 1 & 3 with the independent sources deactivated



$R_{Th} = 3\,\Omega \parallel 2\,\Omega = 1.2\,\Omega$

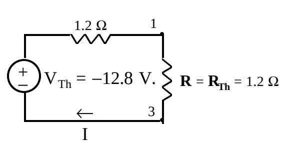
Example 3-10 cont.

The circuit's Thevenin equivalent loaded with $R = R_{Th}$ draws a current of:

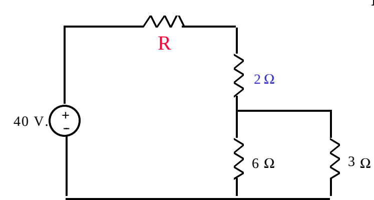
$I = V_{Th}/(R_{Th} + R) = (-12.8\text{ V.})/(1.2\,\Omega + 1.2\,\Omega) = -5\,{}^1\!/_3\text{A.}$

and the corresponding maximum power is

$P_{max.} = I^2R = (-5\,{}^1\!/_3\text{A.})^2 \times 1.2\,\Omega = 34\,{}^2\!/_{15}\text{ W.} \approx 34.13\text{ W.}$

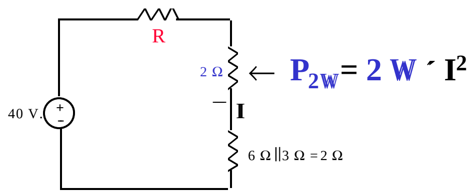


3.6 Maximum Power Transfer: Example 3-11



Calculate the value of resistance (in Ω) of the resistor R which maximizes the power absorbed by the 2 Ω resistor.

Example 3-11 cont.

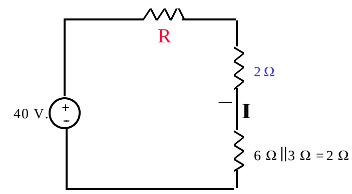


$P_{2\Omega}$ is maximized when I = 40 V. / (R + 2 Ω + 6 Ω || 3 Ω) is maximized—which occurs when **R = 0 W**

Ergo, for R = 0 Ω, I = 40 V. / 4 Ω = 10 A. so that

$P_{2\Omega,max.} = 2\,\Omega \times I^2 = 2\,\Omega \times (10\text{ A.})^2 = 200\text{ W.}$

Example 3-11 cont.



What is achieved if R = 2 Ω + 6 Ω || 3 Ω = 4 Ω ?

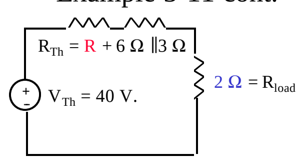
P_R is maximized—but the goal is to maximize $P_{2\Omega}$ (*not* P_R)

N.B.: If R = 4 Ω, I = 5 A. ∴ $P_{2\Omega} = 2\,\Omega\,(5\text{ A.})^2 = 50\text{ W.} < 200\text{ W.} = P_{2\Omega,max.}$

Can maximum power transfer theorem impedance matching be used to solve this problem?

Yes! (See next slide)

Example 3-11 cont.



What's required for maximum power transfer from the Thevenin circuit to the 2 Ω load?

R_{Th} = R + 6 Ω || 3 Ω = 2 Ω = R_{load} which yields:

R = 0 Ω

If the 6 Ω resistor is *removed* from the circuit, what value of R maximizes the 2 Ω resistor's power?

We welcome your questions with Enthusiasm!!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