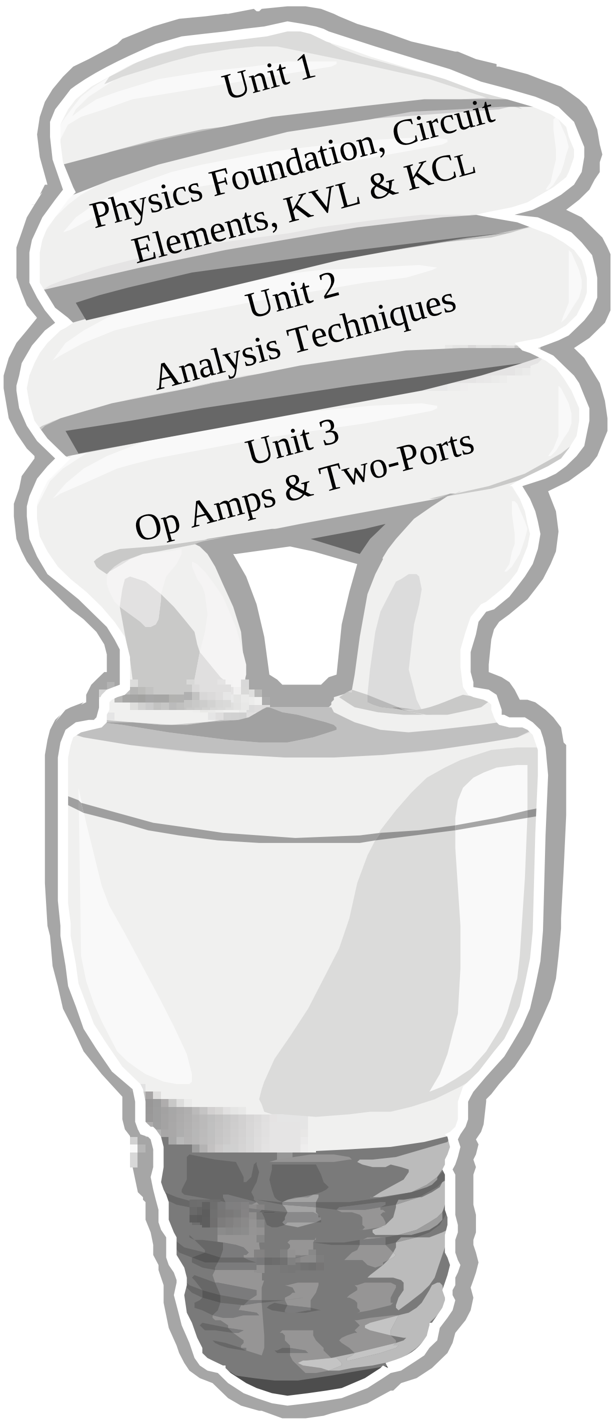
ECE 203
DC Circuits
Study Guide



C.A. Berry

ECE 203 DC Circuits — Winter 09 - 10

Course Information and Syllabus

Description:

ECE 203 DC Circuits 3R-3L-4C F, W, S

Prerequisite: MA 111 and PH 112

Definition of voltage, current, energy and power. Ohm's Law. Non-ideal voltage and current sources. Measurement of voltage, current and resistance. Kirchhoff's Laws. Circuit simplification by series and parallel reduction. Thevenin, Norton and Maximum Power Theorems. Superposition Theorem. Mesh and Nodal Analysis. Two-Port Circuits. Operational Amplifiers. Integral laboratory.

Instructor:

Dr. Carlotta A. Berry
Moench, D-211
812-877-8657
berry123@rose-hulman.edu

Textbook: J.W. Nilsson & S.A. Riedel, *Electric Circuits,* 8th edition, Prentice Hall, 2008.

What is expected of You:

First and foremost, professional work is the norm in this course. All of your written work and your conduct in class are to be at the level of one who is studying a profession—the profession of engineering. This means a number of things:

1. Your work is neatly done in a professional manner, using formats specified.
2. Your work is honestly done. You are encouraged to discuss course material with classmates to help each other understand and assimilate the concepts. Nevertheless, distinguish between helping someone understand concepts and providing them with specific answers. You are expected to work individually on homework without reference to others' work.
3. Your work is done on time. As a rule of thumb, expect to put in **eight** hours per week outside of class doing homework, reading the text, and studying.
4. You are attentive and engaged in the lecture (i.e. not sleeping, reading the newspaper, surfing the web, doing homework for other courses, disturbing others with electronics).

Grading:

Grades will be assigned at the end of the quarter based on the grade weights and grading scale shown below:

Midterm Test I	12%	A	90 – 100
Midterm Test II	12%	B+	85 – 89
Midterm Test III	12%	B	80 - 84
Final Exam	24%	C+	75 - 79
Homework	10%	C	70 - 74
Laboratory assignments	15%	D+	65 - 69
Lab Practical Tests	10%	D	60 - 64
Quizzes	5%	F	Below 60

Independent of point totals:

- You must satisfactorily *complete* each of the eight lab projects in order to receive a passing grade in the course,
- You must earn a *passing* overall weighted midterm and final exam average in order to receive a passing grade in the course.

Examinations:

In this course, examinations make up **70%** of the grade and warrant careful preparation. Examination questions will be based on the lecture material, textbook, homework, and laboratory work. The three midterm tests will be fifty minutes in duration during the regular class meeting time. Midterms and final examinations will be closed book and closed notes. You will be provided with an excerpt from the NCEES FE Reference handbook that includes some formulas. It is your responsibility to memorize or derive any formula missing from this document.

Quizzes:

There will be weekly quizzes that involve solving short problems or answering questions on required reading. The purposes for these quizzes are:

- to give me feedback on the current level of understanding of the class
- to give you feedback on your current level of understanding
- to give you practice on problems similar to the exam format
- to encourage collaborative learning in the classroom
- to also take attendance

Homework:

The homework is intended to help you to understand the concepts presented in the course, and to provide you with practice in problem solving.

- **Problem sets are due each Thursday in class before the bell rings at the beginning of class.** Answers and solutions will be distributed using ANGEL.
- Homework turned in after the bell rings is late and will incur a **20%** penalty.
- Homework turned in after 5 pm on the due date will **not** be accepted.
- Arrange to turn in homework early if you will be away for job interviews, athletic events, etc.
- The required format is described in the document on Angel and in the ECE Department's guidelines and standards for writing assignments. It is your responsibility to make your methods and results clear to the grader. http://ece-1.rose-hulman.edu/ece/images/stories/files/ecewritingstandards.pdf

Laboratory Supplies:

Each student team must purchase an ECE203 kit with breadboard from the parts room before the first lab. Each individual student is required to purchase a laboratory notebook (10" x7-7/8", 80 sheets, 5x5 Quad Ruled, #26-251, available at the bookstore). The format for notebook entries can be found under the ECE Department's guidelines and standards for writing assignments. Additional specifications are provided in the *ECE203 – DC Circuits Laboratory Manual*

Prelabs:

Prelab exercises are due the day before lab at the beginning of class before the bell rings. Each student should do the pre-lab in their lab notebook and make a photocopy to turn in. The solutions to the prelab may be presented at the start of the lab period. Any student that has not completed the prelab must do it at the beginning of lab for zero credit. This team must still finish the laboratory project within the allotted time.

Laboratory Notebooks:

Laboratory notebooks will be collected at the conclusion of each laboratory period. The laboratory notebook will be graded and both members of the team share the notebook grade. Each team member must alternate submission of the lab notebook as well as circuit building on a weekly basis.

Re-grades:

All requests for re-grades must be made in writing within one week of the return of the assignment or exam. The student should not make any marks on the document and must attach a memorandum that details a technical justification for the reason for the submission. It should be noted that based upon the request, the grade may increase, decrease or remain the same.

Attendance:

Regardless of whether formal attendance is taken, attendance at each class is expected. As a rule of thumb you should consider yourself seriously behind if you miss more than four classes in a four credit-hour course. According to our Academic Rules and Procedures, "A student whose total absences in a course, excused or unexcused, exceed two per credit is liable to fail the course." ***Eight absences in this course are grounds for failure.*** Missing an attendance check due to lateness may be counted as an absence.

If you miss a lab with an excused absence you need to make it up within 1 week without penalty. If you miss a lab without an excused absence, you need to make it up within 1 week and you will receive a grade of zero. ***If you come to lab more than 15 minutes late you need to complete the lab on your own.***

Missed exams will not be made up. ***The final exam grade will be used to replace a missing test grade in the case of excused absences.*** An excused absence from an examination normally requires advance approval or formal documentation of an emergency. An examination that is missed for an unexcused reason will be given a grade of zero. Students are not excused from scheduled exams for intramural athletics or fraternity events.

Calculators & Computers:

You will need a calculator that can perform arithmetic with complex numbers (TI-83 plus or better). You are encouraged to practice doing the homework with the same calculator you will use on the exam. It is important to learn to do simultaneous equations (or matrix) calculations with your calculator to be successful in this course. Maple can be used on the homework problems, but not in the exams.

Academic accommodation:

Those students with documented special needs may request extra time on timed tests. Students need to contact me at least 2 business days prior to each exam to make the necessary arrangements.

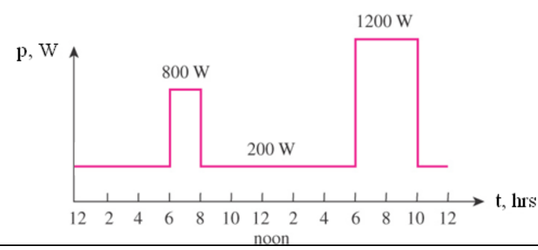
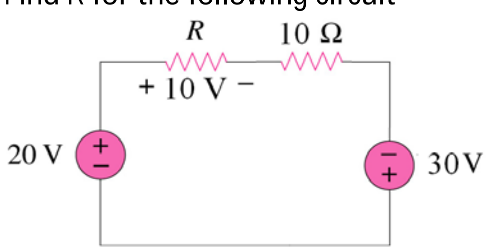
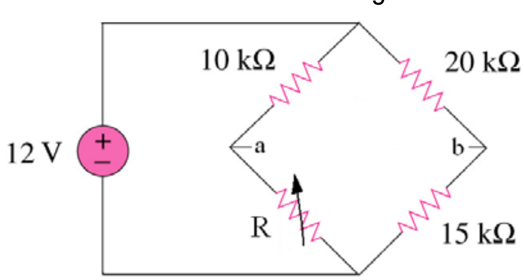
Course Calendar

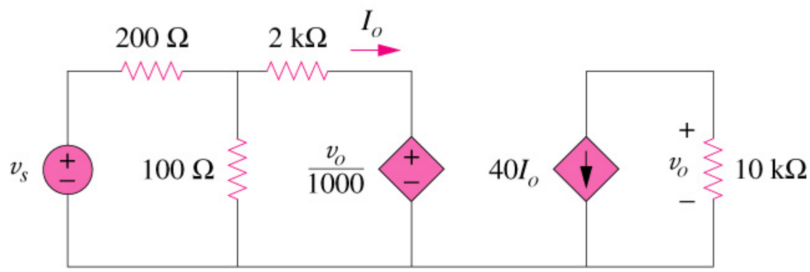
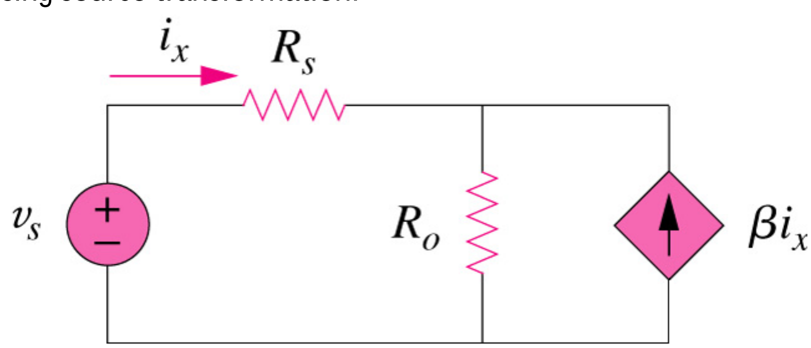
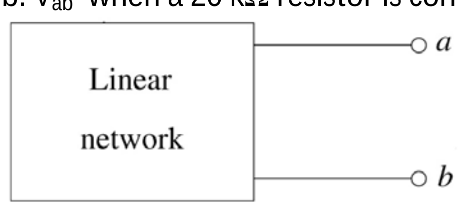
Class	Day	Date	Topic	Reading	Due
1-1	M	11/30	Syllabus, Introduction, Circuit Analysis Overview	1.1- 1.3	
1-2	T	12/1	Voltage, current, power, energy, passive sign convention	1.4 – 1.6	Prelab 1
1-L	W	12/2	*Lab 1. Introduction to Laboratory Techniques*		
1-3	R	12/3	Sources, Resistors, Ohm's Law, Power Calculations	2.1 – 2.3	HW 1
2-1	M	12/7	Kirchhoff's Laws	2.4 – 2.5	Quiz
2-2	T	12/8	Kirchhoff's Laws	2.4 – 2.5	Prelab 2
2-L	W	12/9	*Lab 2. Ohm's Law, KVL, and KCL*		
2-3	R	12/10	Resistors in parallel and series	3.1 – 3.2	HW 2
3-1	M	12/14	Voltage and Current Divider	3.3 – 3.4	Quiz
3-2	T	12/15	Wheatstone Bridge and Delta-Wye Equivalents	3.5 – 3.7	Prelab 3
3-L	W	12/16	*Lab 3. Voltage and Current Divider*		HW 3
3-3	R	12/17	**Midterm Test 1 (up through Chapter 3)**		
			WINTER BREAK (12/19/09 – 01/03/10)		
4-1	M	1/4	Node-voltage method	4.1 – 4.2	
4-2	T	1/5	Node-voltage method (dependent sources, super nodes)	4.3 – 4.4	Prelab 4
4-3	W	1/6	*Lab 4. Node-voltage method*		
4-L	R	1/7	Mesh-current method	4.5	HW 4
5-1	M	1/11	Mesh-current method (dependent sources, super meshes)	4.6 – 4.7	Quiz
5-2	T	1/12	Source Transformations	4.9	Prelab 5
5-L	W	1/13	*Lab 5. Mesh-current method*		
5-3	R	1/14	Thevenin and Norton Equivalents	4.10 – 4.11	HW 5
6-1	M	1/18	Thevenin and Norton Equivalents	4.10 – 4.11	Quiz
6-2	T	1/19	Maximum Power Transfer	4.12	
6-L	W	1/20	***Lab 6. Lab Practical Test I***		
6-3	R	1/21	Superposition	4.13	HW 6
7-1	M	1/25	Introduction to Operational Amplifiers	5.1 – 5.2	Quiz
7-2	T	1/26	**Midterm Test 2 (up through Chapter 4 section 12)**		
7-L	W	1/27	*Lab 7. Source Transformations, Thevenin and Norton Equivalents*		Prelab 7
7-3	R	1/28	Inverting and Summing Op Amps	5.3 – 5.4	HW 7
8-1	M	2/1	Noninverting, Cascaded, Difference Op Amps	5.5 – 5.6	Quiz
8-2	T	2/2	More realistic Op Amps	5.7	Prelab 8
8-L	W	2/3	*Lab 8. Operational Amplifiers*		
8-3	R	2/4	Operational Amplifier Applications		HW 8
9-1	M	2/8	Terminal Equations, Two-Port Parameters	18.1 – 18.2	Quiz
9-2	T	2/9	**Midterm Test 3 (up through Chapter 5)**		Prelab 9
9-L	W	2/10	*Lab 9. Inverting and Noninverting Op Amps*		
9-3	R	2/11	Two – Port Parameters	18.2	HW 9
10-1	M	2/15	Terminated Two-Port circuits	18.3	Quiz
10-2	T	2/16	Cascaded two-port networks	18.4	
10-L	W	2/17	***Lab 10. Lab Practical Test II***		
10-3	R	2/18	Final Review, Course Evaluations		HW 10

Course Calendar

Class	Day	Date	Topic	Reading	Due
1-1	M	11/30	Syllabus, Introduction, Circuit Analysis Overview	1.1- 1.3	
1-2	T	12/1	Voltage, current, power, energy, passive sign convention	1.4 – 1.6	
1-3	R	12/3	Sources, Resistors, Ohm's Law, Power Calculations	2.1 – 2.3	HW 1, Prelab 1
1-L	F	12/4	*Lab 1. Introduction to Laboratory Techniques*		
2-1	M	12/7	Kirchhoff's Voltage and Current Laws	2.4 – 2.5	Quiz
2-2	T	12/8	Kirchhoff's Voltage and Current Laws	2.4 – 2.5	
2-3	R	12/10	Resistors in parallel and series	3.1 – 3.2	HW 2, Prelab 2
2-L	F	12/11	*Lab 2. Ohm's Law, KVL, and KCL*		
3-1	M	12/14	Voltage and Current Divider	3.3 – 3.4	Quiz
3-2	T	12/15	Wheatstone Bridge and Delta-Wye Equivalents	3.5 – 3.7	
		12/16			HW 3
3-3	R	12/17	**Midterm Test 1 (up through Chapter 3)**		
3-L	F	12/18	*Lab 3. Voltage and Current Divider*		Prelab 3
			WINTER BREAK (12/19/09 – 01/03/10)		
4-1	M	1/4	Node-voltage method	4.1 – 4.2	
4-2	T	1/5	Node-voltage method (dependent sources, super nodes)	4.3 – 4.4	
4-L	R	1/7	Mesh-current method	4.5	HW 4, Prelab 4
4-3	F	1/8	*Lab 4. Node-voltage method*		
5-1	M	1/11	Mesh-current method (dependent sources, super meshes)	4.6 – 4.7	Quiz
5-2	T	1/12	Source Transformations	4.9	
5-3	R	1/14	Thevenin and Norton Equivalents	4.10 – 4.11	HW 5, Prelab 5
5-L	F	1/15	*Lab 5. Mesh-current method*		
6-1	M	1/18	Thevenin and Norton Equivalents	4.10 – 4.11	Quiz
6-2	T	1/19	Maximum Power Transfer	4.12	
6-3	R	1/21	Superposition	4.13	HW 6
6-L	F	1/22	***Lab 6. Lab Practical Test I***		
7-1	M	1/25	Introduction to Operational Amplifiers	5.1 – 5.2	Quiz
7-2	T	1/26	**Midterm Test 2 (up through Chapter 4 section 12)**		
7-3	R	1/28	Inverting and Summing Op Amps	5.3 – 5.4	HW 7, Prelab 7
7-L	F	1/29	*Lab 7. Source Transformations, Thevenin and Norton Equivalents*		
8-1	M	2/1	Noninverting, Cascaded, Difference Op Amps	5.5 – 5.6	Quiz
8-2	T	2/2	More realistic Op Amps	5.7	
8-3	R	2/4	Operational Amplifier Applications		HW 8, Prelab 8
8-L	W	2/5	*Lab 8. Operational Amplifiers*		
9-1	M	2/8	Terminal Equations, Two-Port Parameters	18.1 – 18.2	Quiz
9-2	T	2/9	**Midterm Test 3 (up through Chapter 5)**		
9-3	R	2/11	Two – Port Parameters	18.2	HW 9, Prelab 9
9-L	W	2/12	*Lab 9. Inverting and Noninverting Op Amps*		
10-1	M	2/15	Terminated Two-Port circuits	18.3	Quiz
10-2	T	2/16	Cascaded two-port networks	18.4	
10-3	R	2/18	Final Review, Course Evaluations		HW 10
10-L	F	2/19	***Lab 10. Lab Practical Test II***		

Assigned Homework Problems

Homework	Problems	Due
HW1	<u>Chapter 1</u> 1.1, 1.9, 1.15, 1.30 *P1* The following figure shows the power consumption of a certain household in one day. Calculate: a. The total energy consumed in kWh b. The average power per hour  	12/3/09
HW2	<u>Chapter 2</u> 2. 1, 2.11, 2.18, 2.29 *P2* Find R for the following circuit  	12/10/09
HW3	<u>Chapter 3</u> 3.5, 3.10, 3.14, 3.52 *P3* For the following Wheatstone bridge circuit, a. R is a 10 kΩ variable resistor, what is the range of V_{ab}? b. For what value of R is the bridge balanced? c. If a 5 kΩ resistor is placed between terminals a and b, and R = 7.5 kΩ, what is the current through the 5 kΩ resistor?  	12/16/09

<table>
<tr><td>HW4</td><td><u>Section 4.1 – 4.4</u>
4.6, 4.11, 4.17, 4.26
P4
Use the node-voltage method to determine the gain, v_o/v_s for the following transistor amplifier circuit.

</td><td>1/7/10</td></tr>
<tr><td>HW5</td><td><u>Section 4.5 – 4.9</u>
4.32, 4.37, 4.47, 4.59
P5
The following circuit models a common-emitter transistor amplifier. Find i_x using source transformation.

</td><td>1/14/10</td></tr>
<tr><td>HW6</td><td><u>Section 4.10 – 4.11</u>
4.64, 4.66, 4.69, 4.77
P6
The Thevenin equivalent terminals a-b of the linear network shown in the following figure can be determined by measurement. When a 10 kΩ resistor is connected to terminals a-b, the voltage V_{ab} is measured as 6 V. When a 30 kΩ resistor is connected to the terminals, V_{ab} is measured as 12 V. Determine:
a. The Thevenin equivalent at terminals a-b
b. V_{ab} when a 20 kΩ resistor is connected across terminals a-b

</td><td>1/21/10</td></tr>
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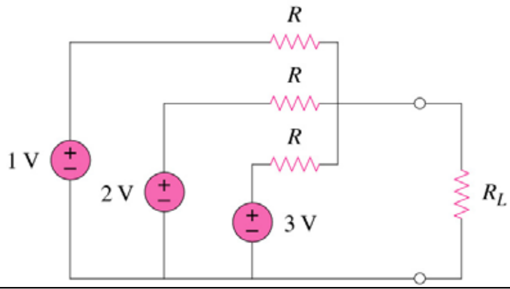
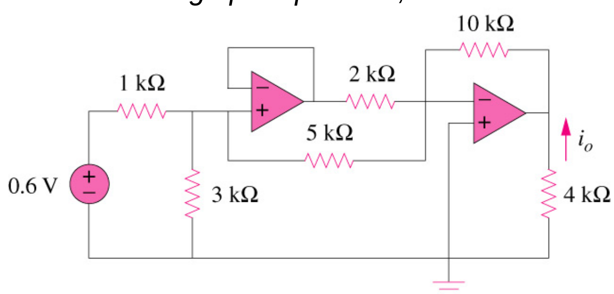
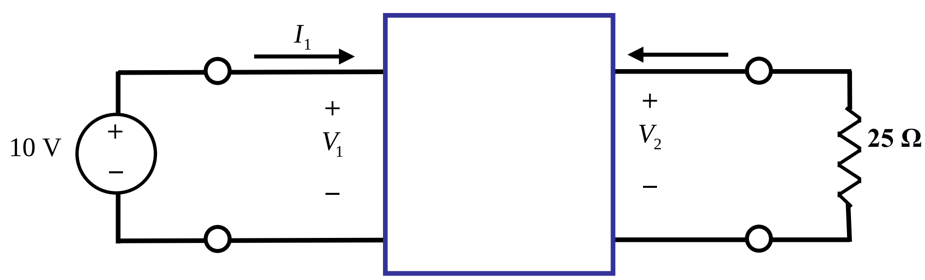
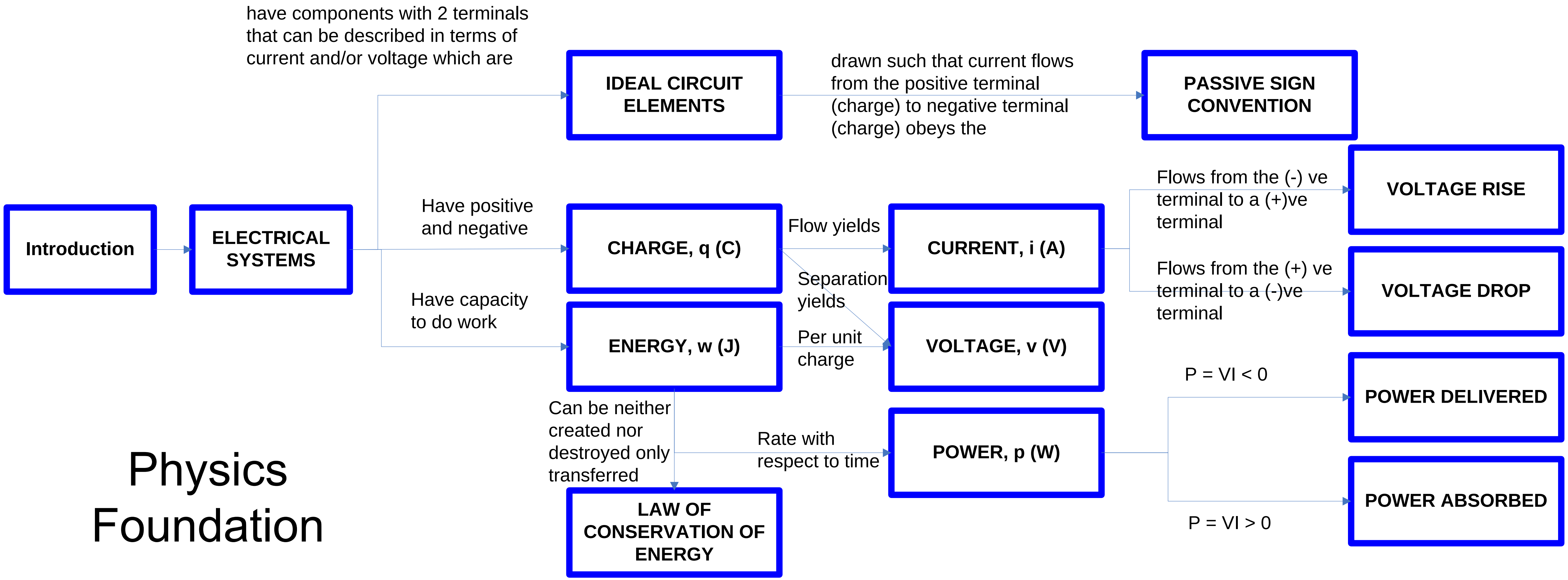
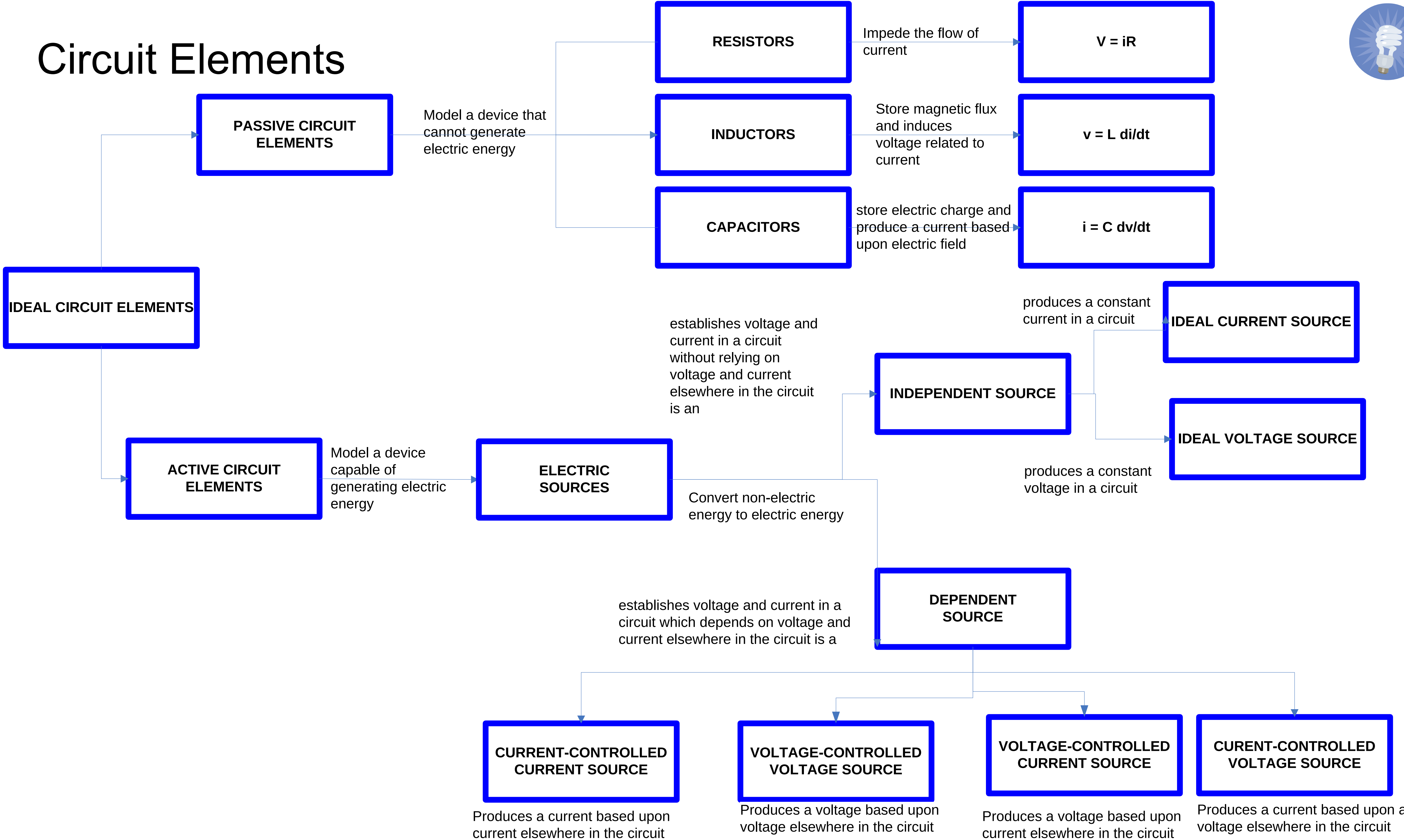
HW7	Section 4.12 – 4.13 4.81, 4.85, 4.90, 4.97 *P7* For the following circuit, determine the value of R such that the maximum power delivered to the load is 5 mW. 	1/28/10
HW8	Chapter 5 5.3, 5.11, 5.15, 5.28 *P8* *In the following op amp circuit, determine the current i_o.* 	2/4/10
HW9	Two-Port Parameters 18.4, 18.8, 18.9, 18.11, 18.19	2/10/10
HW10	Terminated and Cascaded Two-Port Networks 18.36, 18.37, 18.38. 18.39, *P10* *For the following two port circuit, if the h parameters are* *h_{11} = 16 Ω, h_{12} = 3 , h_{21} = -2, h_{22} = 0.01 S, find the power delivered to the 25Ω resistor.* 	2/18/10

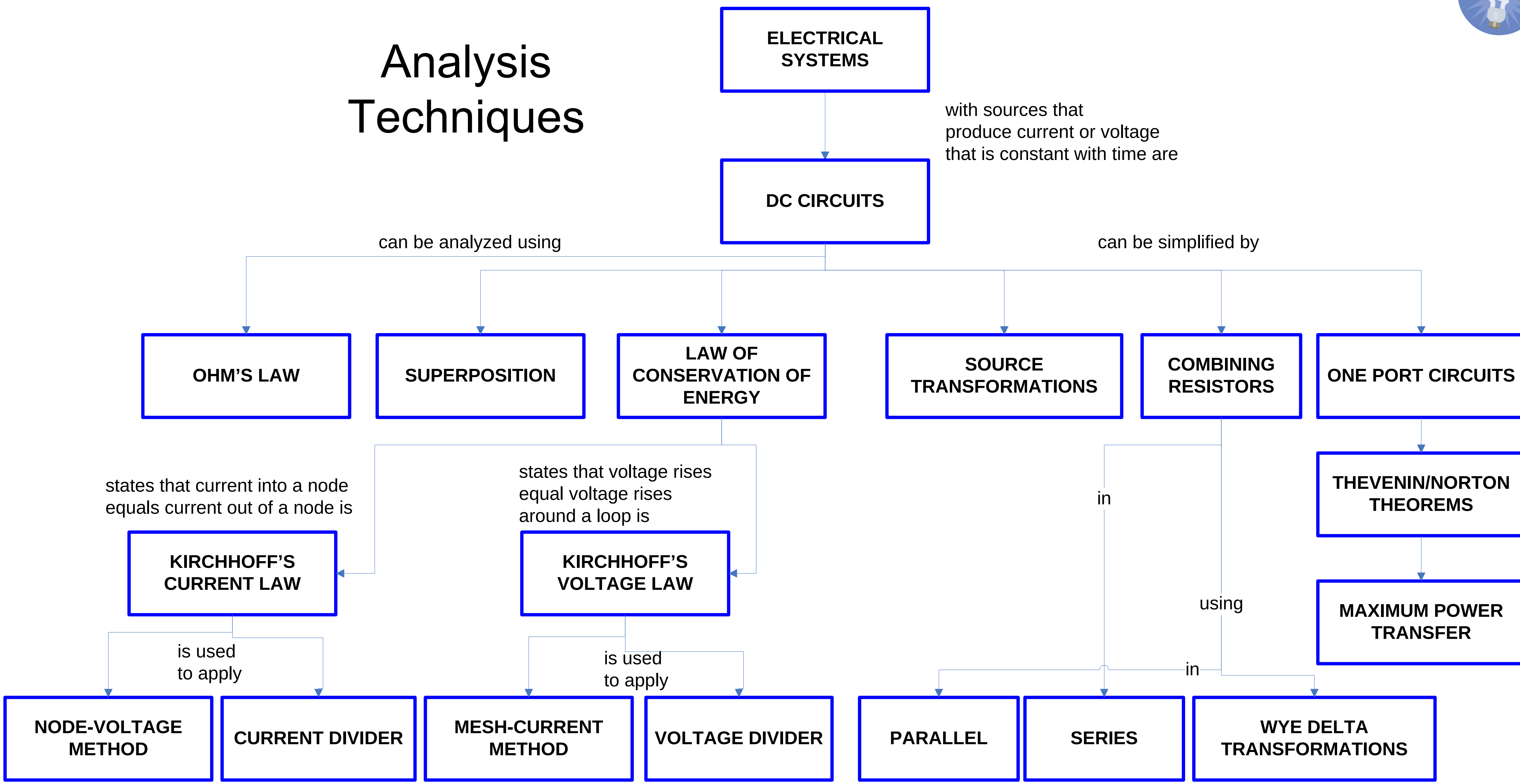
Physics Foundation



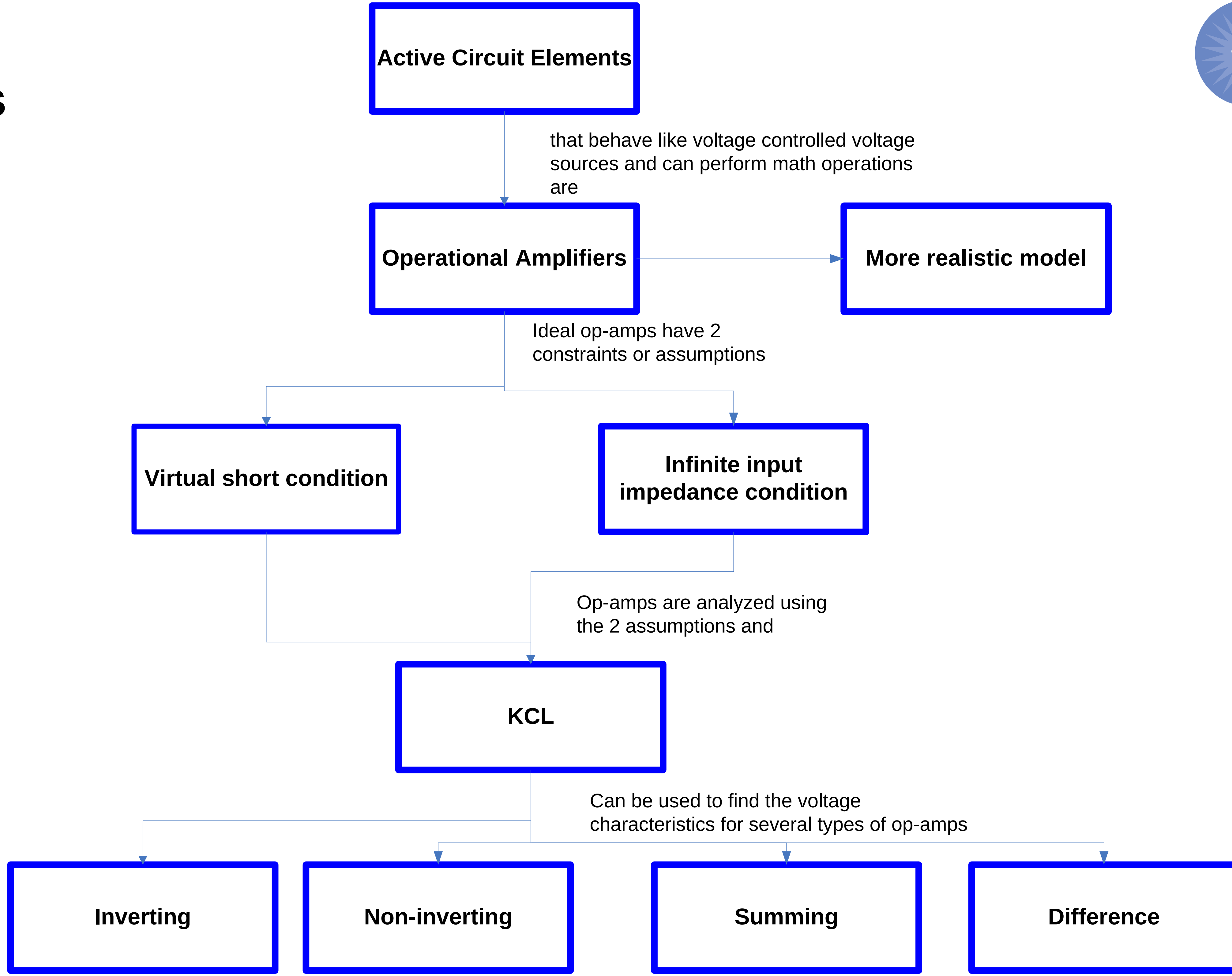
Circuit Elements



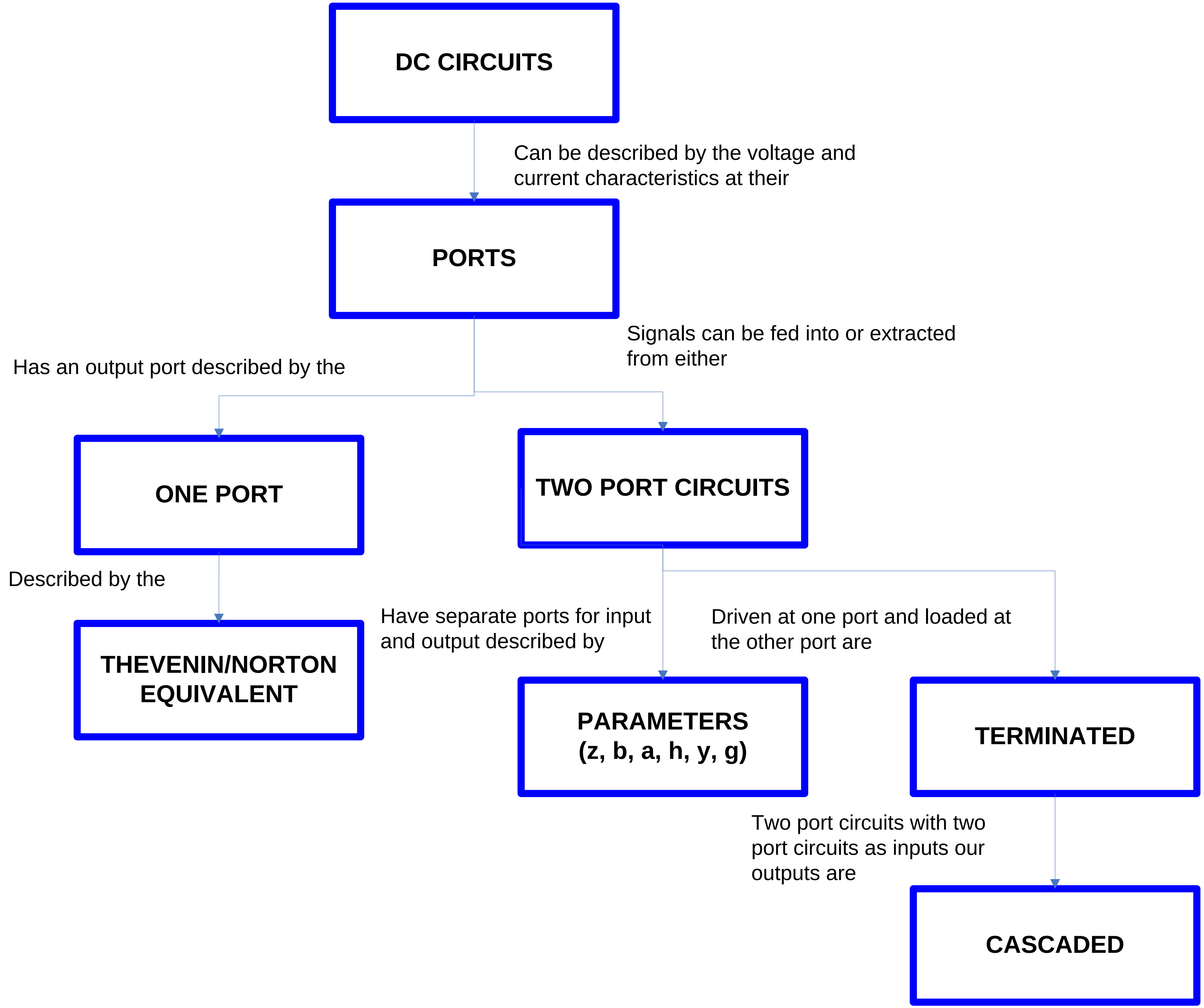
Analysis Techniques



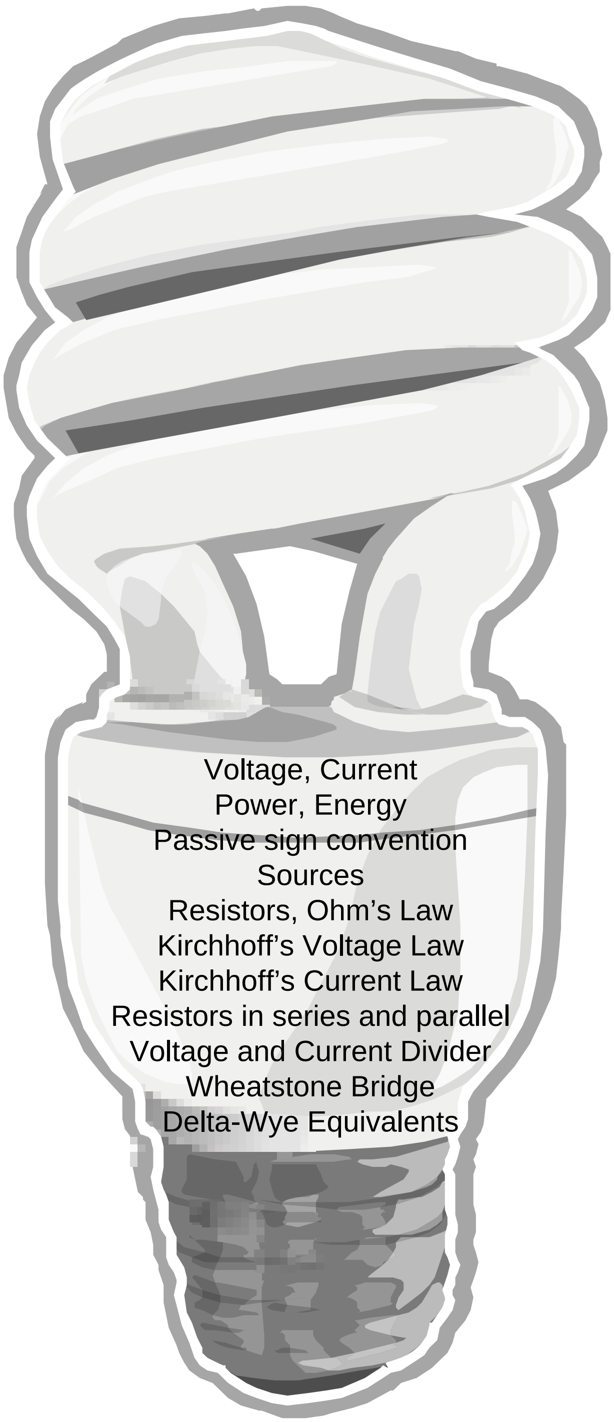
Op Amps


Active Circuit Elements
that behave like voltage controlled voltage sources and can perform math operations are
Operational Amplifiers
More realistic model
Ideal op-amps have 2 constraints or assumptions
Virtual short condition
Infinite input impedance condition
Op-amps are analyzed using the 2 assumptions and
KCL
Can be used to find the voltage characteristics for several types of op-amps
Inverting
Non-inverting
Summing
Difference

Two-Ports


DC CIRCUITS
Can be described by the voltage and current characteristics at their
PORTS
Has an output port described by the
Signals can be fed into or extracted from either
ONE PORT
TWO PORT CIRCUITS
Described by the
THEVENIN/NORTON EQUIVALENT
Have separate ports for input and output described by
Driven at one port and loaded at the other port are
PARAMETERS (z, b, a, h, y, g)
TERMINATED
Two port circuits with two port circuits as inputs our outputs are
CASCADED

ECE 203
DC Circuits
Unit I



C.A. Berry

Lecture 3-2

Wheatstone Bridge and Delta-Wye Equivalents

Reading: 3.5 – 3.7

Objectives:

- Be able to identify a Wheatstone Bridge and find the resistance to balance the bridge
- Be able to analyze a Wheatstone bridge to find unknown voltages and currents
- Be able to apply delta to wye equivalents to solve simple circuits

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The purpose of the **Wheatstone Bridge** is to make precise resistance measurement**.** One application of a Wheatstone Bridge is to place a strain gauge in one leg in order to measure small changes in resistance in the range of 1 Ω to 1 MΩ to detect the strain on a device. A detector called a galvanometer can be placed in the bridge to measure current in the μA range. The bridge is **balanced** when there is no current flowing through the galvanometer.

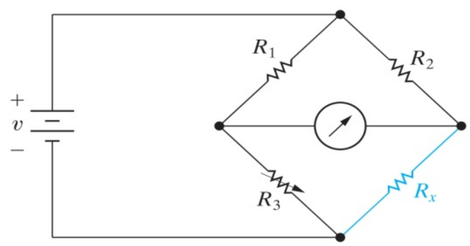


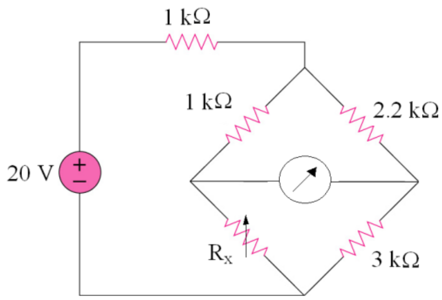
Figure: 03-26

Example 1:

Determine what value of resistance, R_x, causes the Wheatstone bridge to balance.

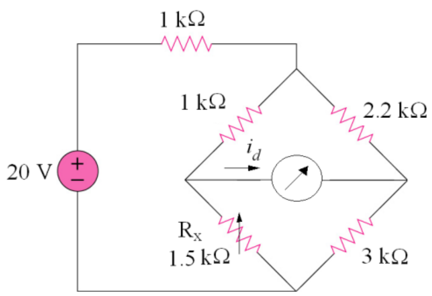
Example 2:

For the following Wheatstone bridge, determine what value of resistance, R_x, causes the bridge to balance. If these are 25 mW resistors, do any of them exceed their power-dissipating capacity?



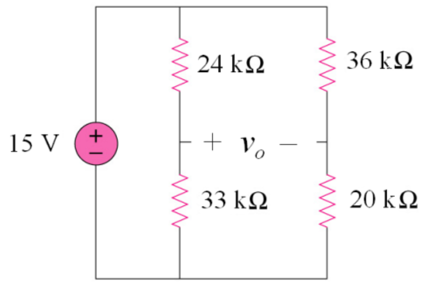
Example 3:

For the following Wheatstone bridge, determine the detector current, i_d if the voltage drop across the detector is negligible.



Example 4:

For the following circuit, what is the bridge output voltage, v_o?



Delta-Wye Equivalents

When the internal resistance of the galvanometer is modeled in the Wheatstone Bridge this creates a special configuration of resistances that is neither series nor parallel. Therefore this interconnection cannot be simplified by using series and parallel combinations. These special configurations are referred to as **Delta (Δ)** or **Wye ("Y")** interconnections and they can be transformed to equivalent representations.

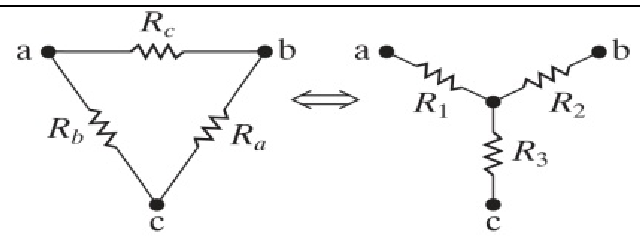


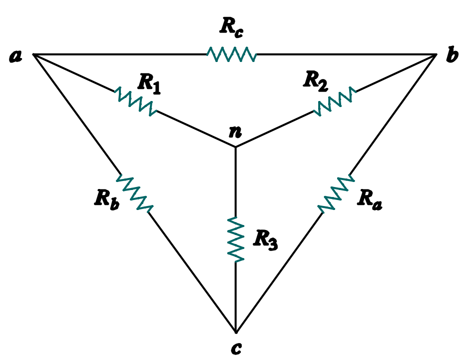
Figure: 03-31

Δ or π interconnection	Y or T interconnection
R_a = [illegible]	R_1 = [illegible]
R_b = [illegible]	R_2 = [illegible]
R_c = [illegible]	R_3 = [illegible]

NOTE: Each resistor in the Δ network is the sum of all possible products of Y resistors taken two at a time divided by the opposite Y resistor.

The Y and Δ configurations are said to be **balanced** when $R_Y = R_\Delta/3$ and $R_\Delta = 3R_Y$

The following figure is a superposition of the Y and configuration to aid in transforming from one to another.

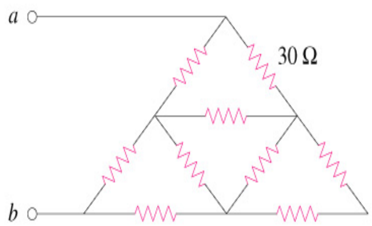


What does equivalent mean?

This means that for both configurations have the **same** voltage and current characteristics at the terminals a, b, and c. If these 2 networks were in a black box and you measured voltage and current, you could not state whether it was a Δ or Y interconnection in the box. However, you **CANNOT** state that the voltage and current across the internal resistors is the same for both.

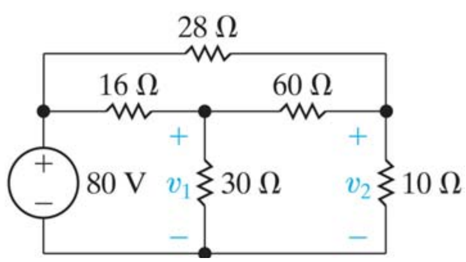
Example 5:

For the following circuit, determine the equivalent resistance at terminals a and b if all of the resistors have a value of 30Ω.

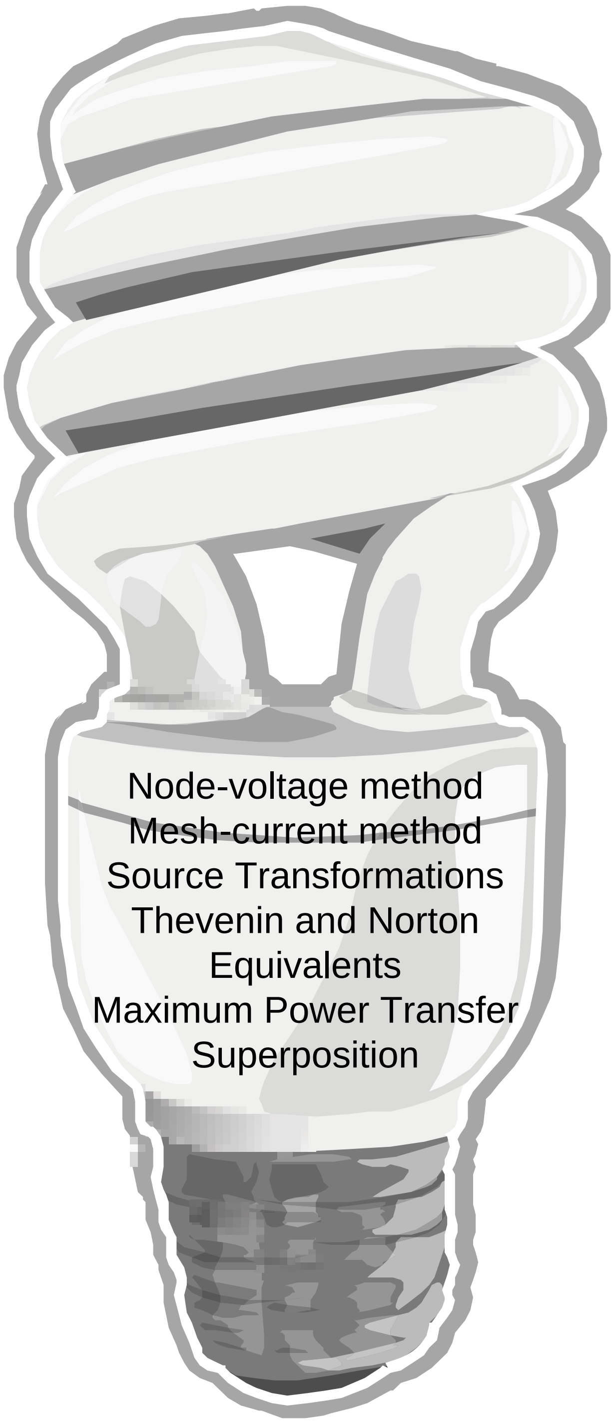


<u>*Example 6:*</u>

For the following circuit, use a Δ-to-Y transformations to find the voltages v_1 and v_2 in the circuit below.



ECE 203
DC Circuits
Unit II



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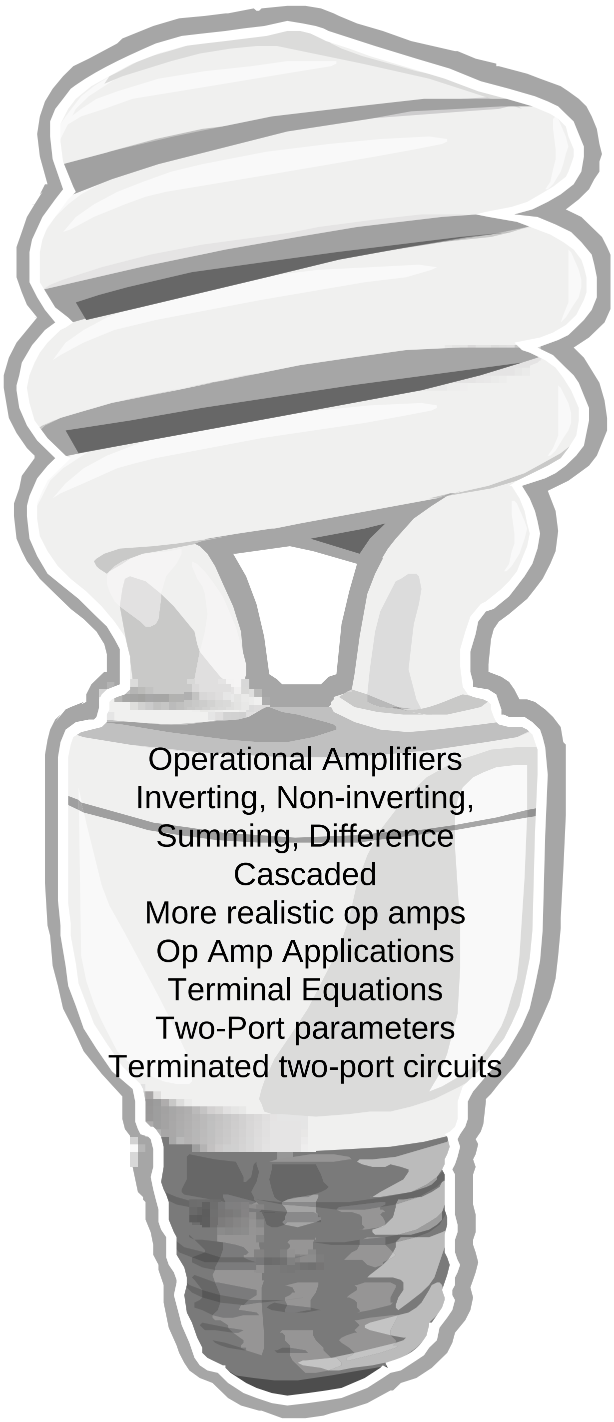
ECE 203
DC Circuits
Unit III



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ECE 203
DC Circuits
Relevant Formulas

C.A. Berry

FORMULAS

Ohms Law
$V = RI$

Current
$i(t) = dq/dt$

Voltage
$v(t) = dw/dq$

Resistors in Series
$R_{eq} = R_1 + R_2 + \cdots + R_n$

Resistors in Parallel
$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$

Special case for 2 parallel resistors
$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$$

Power Absorbed by a Resistive Element
$$P = VI = I^2 R = \frac{V^2}{R}$$

Kirchhoff's Laws
KVL: $\sum V_{rises} = \sum V_{drops}$

KCL: $\sum I_{in} = \sum I_{out}$

Thevenin/Norton Equivalent
$V_{oc} = V_{th} = I_{sc}R_{th}$

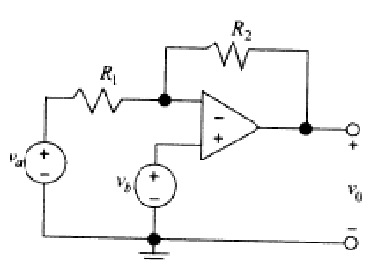
$I_{sc} = I_N = V_{oc}/R_{th}$

$Z_L = Z_{th}^*$ for maximum power transfer

Voltage divider
$$V_{R2} = \frac{R_2}{R_1 + R_2} V_s$$

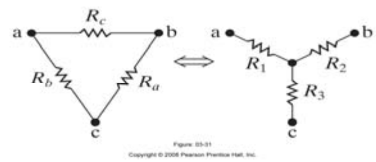
Current divider
$$I_{R2} = \frac{R_1 \| R_2}{R_2} I_s = \frac{R_1}{R_1 + R_2} I_s$$

Operational Amplifiers



$$v_0 = -\frac{R_2}{R_1} v_a + \left(1 + \frac{R_2}{R_1}\right) v_b$$

Wye-Delta Equivalents



$$R_1 = \frac{R_b R_c}{R_a + R_b + R_c}$$

$$R_2 = \frac{R_c R_a}{R_a + R_b + R_c}$$

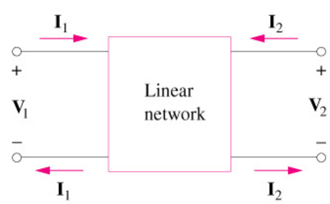
$$R_3 = \frac{R_a R_b}{R_a + R_b + R_c}$$

$$R_a = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_1}$$

$$R_b = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_2}$$

$$R_c = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_3}$$

Two-Port Relationships



Two-port network

$V_1 = z_{11}I_1 + z_{12}I_2$
$V_2 = z_{21}I_1 + z_{22}I_2$

$I_1 = y_{11}V_1 + y_{12}V_2$
$I_2 = y_{21}V_1 + y_{22}V_2$

$V_1 = a_{11}V_2 - a_{12}I_2$
$I_1 = a_{21}V_2 - a_{22}I_2$

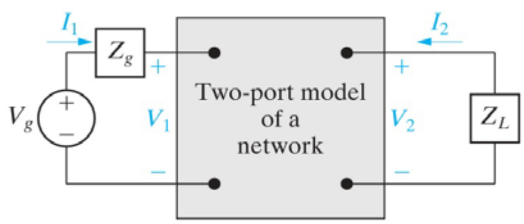
$V_2 = b_{11}V_1 - b_{12}I_1$
$I_2 = b_{21}V_1 - b_{22}I_1$

$V_1 = h_{11}I_1 + h_{12}V_2$
$I_2 = h_{21}I_1 + h_{22}V_2$

$V_2 = g_{21}V_1 + g_{22}I_2$
$I_1 = g_{11}V_1 + g_{12}I_2$

y to z parameters	z to y parameters
$z_{11} = \dfrac{y_{22}}{\Delta y}$	$y_{11} = \dfrac{z_{22}}{\Delta z}$
$z_{12} = \dfrac{-y_{12}}{\Delta y}$	$y_{12} = \dfrac{-z_{12}}{\Delta z}$
$z_{21} = \dfrac{-y_{21}}{\Delta y}$	$y_{21} = \dfrac{-z_{21}}{\Delta z}$
$z_{22} = \dfrac{y_{11}}{\Delta y}$	$y_{22} = \dfrac{z_{11}}{\Delta z}$
$\Delta y = y_{11}y_{22} - y_{12}y_{21}$	$\Delta z = z_{11}z_{22} - z_{12}z_{21}$

Terminated Two-Ports



		z parameters	y parameters
input impedance/ admittance	Z_{in}/Y_{in}	$z_{11} - \dfrac{z_{12}z_{21}}{z_{22} + Z_L}$	$y_{11} - \dfrac{y_{12}y_{21}Z_L}{1 + y_{22}Z_L}$
output current	I_2	$\dfrac{-z_{21}V_g}{(z_{11} + Z_g)(z_{22} + Z_L) - z_{12}z_{21}}$	$\dfrac{y_{21}V_g}{1 + y_{22}Z_L + y_{11}Z_g + \Delta y Z_g Z_L}$
Thevenin voltage	V_{th}	$\dfrac{z_{21}}{(z_{11} + Z_g)}V_g$	$\dfrac{-y_{21}}{(y_{22} + \Delta y Z_g)}V_g$
Thevenin impedance	Z_{th}	$z_{22} - \dfrac{z_{12}z_{21}}{z_{11} + Z_g}$	$\dfrac{1 + y_{11}Z_g}{y_{22} + \Delta y Z_g}$
current gain	I_2/I_1	$\dfrac{-z_{21}}{z_{22} + Z_L}$	$\dfrac{y_{21}}{y_{11} + \Delta y Z_L}$
voltage gain	V_2/V_1	$\dfrac{z_{21}Z_L}{z_{11}Z_L + \Delta z}$	$\dfrac{-y_{21}Z_L}{1 + y_{22}Z_L}$
voltage gain	V_2/V_g	$\dfrac{z_{21}Z_L}{(z_{11} + Z_g)(z_{22} + Z_L) - z_{12}z_{21}}$	$\dfrac{y_{21}Z_L}{y_{12}y_{21}Z_g Z_L - (1 + y_{11}Z_g)(1 + y_{22}Z_L)}$
determinant of parameter matrix		$\Delta z = z_{11}z_{22} - z_{12}z_{21}$	$\Delta y = y_{11}y_{22} - y_{12}y_{21}$