

ECE 241L Fundamentals of Electrical Engineering

Experiment 2 DC Resistive Circuits

NAME

PARTNER

A. Objectives:

- I. Use Kirchhoff's Voltage Law to calculate the magnitude and polarity of voltages and currents in a series circuit
- II. Use a voltage divider and a potentiometer to design circuits to provide a desired output voltage, given a specified source voltage
- III. Apply Thevenin Equivalent to simplify the circuit of an electrical source

B. Equipment:

Breadboard, resistors, potentiometer, wire (student lab kit)
Power Supply: Tektronix PS2520G
Digital Volt-Ohm Meter (DVM): Fluke 189 (or equivalent)

C. Introductory Notes:

1. Basic Concepts

Ohm's Law

The first continuous electrical source was the electrochemical battery, discovered by the Italian scientist Alessandro Volta in 1800. The French scientist Andre-Marie Ampere made the first precision measurements of current in 1820. Ohm's Law, attributed to the German scientist Georg Simon Ohm in 1826, states that the current through a resistance is directly proportional to the voltage across the resistance. Consider the circuit in Figure E1-1 consisting of an electrical source such as a battery, and a resistance.

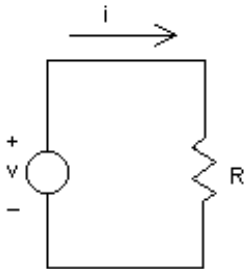


Figure E1-1 A source [V] and a resistance [R] connected in a closed circuit.

The source has voltage [v] and when connected to a resistance [R] the current [i] is related to the voltage by the equation known as Ohm's Law. The equation can be written three forms, and the student is advised to **memorize all three forms** to save time in future calculations.

$$v = Ri \quad i = v/R \quad R = v/i \quad \text{OHM'S LAW (RESISTANCE)}$$

Polarity

There is more to learn from this simple circuit. The **polarity** of both voltage and current are extremely important in the analysis of more complicated circuits. In Figure E1-1 the polarity marked +/- for the voltage, and the arrow --> marked for the current, correspond to the conventional notation used for the flow of **positive current** in electric circuits. Note that for a resistance "load," positive current flows **into** the end

with the voltage marked + , whereas for a "source" such as a battery the positive current flows out of the terminal marked +.

Physics of current flow

The convention for positive current was established by Benjamin Franklin in the 1700s. Current is actually carried in metal conductors by electrons, which flow in the opposite direction to positive current. However, in liquids current is carried by both positive and negative ions flowing in opposite directions, while in gasses current is carried by positive and negative ions and by electrons. In semiconductors such as Silicon, current is carried not only by electrons but also by "holes" in the crystal lattice that would otherwise be occupied by valence electrons. Further details of the physics of conduction on a microscopic scale are beyond the scope of these notes.

Electrical Power

Electrical power is calculated from the product of voltage and current, as stated in 1840 by the English scientist James Prescott Joule. Using the Franklin convention, power is positive for a load and negative for a source. Positive power in a resistance is converted into heat. Negative power from a source must be supplied from outside the system represented by the circuit, for example from mechanical power turning an electric generator or from chemical energy in a battery. We will not consider the nature of the source in our calculations and just assume that the source is given. From Ohm's Law, the Joule's Law formula for electric power can be stated in three forms and should be **memorized by the student**.

$$p = vi \qquad p = i^2R \qquad p = v^2/R \qquad \text{JOULE'S LAW (POWER)}$$

Resistivity:

Specific resistivity is a property of a material, whereas resistance is a property of a particular circuit element. Resistance is related to resistivity by a formula that includes the cross-section area and thickness of the material.

$$R = \rho L/A$$

where ρ = specific resistivity (ohm-meters)
 L = length of element (meters)
 A = cross section area of element (square meters)

The resistivity of metals is quite low, since the crystal lattice is flooded with free electrons. In order to measure resistivity in the laboratory it is necessary to have a long specimen with small cross section area, in other words a length of wire. Copper is the most commonly used material for electric wires because of its low resistivity and relatively low cost compared to silver, the best conductor. Aluminum is also an inexpensive material with low resistivity, but requires special treatment since it grows an insulating oxide when exposed to air that must be removed to make an electrical connection. The oxide also prevents aluminum from being easily soldered. Aluminum conductors are used in integrated circuit chips because they can be deposited on the silicon substrate by evaporation in vacuum. In the 1950s Aluminum wire was used for house wiring, but was discontinued because screw connections became corroded causing high resistance and occasional fires. Where corrosion is a major problem, gold plated conductors are used.

Carbon is frequently used to manufacture resistors for electronic applications. The resistivity of the element carbon depends greatly on its crystalline form. In the black form as found in coal (and also as the principal constituent of pencil lead) the resistivity of carbon is much greater than metals, but much less than than the resistivity of diamond, another form of carbon. A high resistivity alloy of iron, nickel, and chrome call **Nichrome** is used in toasters, stoves, and other applications where electricity is used for heating.

Tungsten has been used in incandescent lamps for the last century, superseding the carbon filaments used by Edison in his first electric lights because it can be heated white-hot in vacuum without evaporating. A special combination of metals (**Iron** wire and a bronze alloy wire called **Constantan**) when welded together develop a voltage proportional to temperature and are used to form a "thermocouple" for the measurement of temperature in harsh environments.

The resistivity of **metals** increases with temperature because of collisions between the electrons flowing in the metal and the atoms in the crystal lattice. For this reason, metals deviate somewhat from Ohm's Law if

they are allowed to become hot from electrical power input. The resistance is not a constant, in which case the material is called "non-Ohmic". If the temperature increases, the resistance also increases rather than being a constant. One way of representing this effect is by making a graph of current vs. voltage, called the v-i characteristic. For metals the graph is concave downward since the current does not increase as rapidly as the voltage, as the metal becomes hotter.

Human Skin Surface Contact Resistance, and Electrical Safety

The high surface contact resistance of human skin is the only reason it is possible to use electricity safely for household lighting and appliances. The interior of the body is mostly salt water, a very good conductor. Skin resistivity varies widely depending on the surface condition. The natural oils of the skin provide most of the protection, with a resistance of more than 100,000 ohms. The factor that is critical for safety is the current, not the voltage. Extreme precautions are taken in medical environments in which the skin is penetrated, such as surgery.

A current of 0.05 amperes (50 milliamps) through the heart can be lethal.

Therefore a voltage of 120 volts would produce a current of $120/100K = 1.2$ milliamps, enough to cause a tingling sensation and to serve as a warning of an unsafe condition. **Clean, wet skin is the most dangerous condition** with a resistance that may be as low as 1000 ohms, corresponding to 120 milliamps at 120 volts.

Standard electrical safety industrial regulations require a grounded metal enclosure or double insulation for circuits with over 40 volts. The maximum voltage available in the ECE electronics lab is 40 volts.

2. Kirchoff's Laws

(a) Kirchoff's Current Law

Ohm's Law was further developed by Gustav R. Kirchoff in 1846. There are two forms of Kirchoff's Law, one for voltage and one for current. We will consider Kirchoff's Current Law (KCL) at this time.

KCL: The algebraic sum of all currents into a "node" is equal to zero.

Parallel Circuit

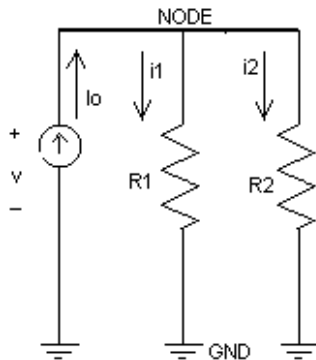


Figure E1-2. The bold "wire" connecting the circuit elements is called a "node", electrically equivalent to a single point. The "ideal current source" is represented by an arrow within a circle. Resistances are zig-zag lines. The triple lines identify the terminal designated as a common (ground) voltage reference point. There is therefore another node at GND. The "wires" connecting all ground points are conventionally omitted from the circuit diagram.

Consider the parallel circuit in Figure E1-2. In a **parallel** circuit the elements are connected together between two nodes. In this example one of the nodes is a common ground. In a parallel circuit the **voltage is the same across all elements**. According to KCL the currents add algebraically.

$$I_o - i_1 - i_2 = 0$$

It is also conventional practice to collect all currents flowing into a node on one side of the equation, and all

currents out of a node on the other side.

$$I_o = i_1 + i_2$$

The current through each resistance can be calculated from Ohm's Law.

$$i_1 = v/R_1 \qquad i_2 = v/R_2$$

$$I_o = v/R_1 + v/R_2$$

The ratio of current-to-voltage is called "conductance", which is the reciprocal of resistance. **In a parallel circuit, conductances add.**

$$I_o/v = 1/R_1 + 1/R_2$$

This formula can be extended to any number of resistances in parallel. However, if only two resistances are considered, there is a special formula that simplifies the calculation. Let us define a resistance R_p as the equivalent resistance of the two resistances in parallel, with the conductance equal to $1/R_p$.

$$1/R_p = 1/R_1 + 1/R_2 \qquad \text{PARALLEL CONDUCTANCE FORMULA}$$

Solving this equation for R_p

$$R_p = 1/[1/R_1 + 1/R_2] \text{ which can be rearranged into the conventional formula}$$

$$R_p = R_1 R_2 / (R_1 + R_2) \qquad \text{PARALLEL RESISTANCE FORMULA}$$

This important formula should be **memorized** by the student, to save time in circuit calculation. The notation $R_1 // R_2 = R_p$ is often used as an abbreviation for this formula.

The formula can be rearranged to demonstrate another important fact.

$$R_p = R_1 / (1 + R_1/R_2) = R_2 / (1 + R_2/R_1)$$

Note that R_p is always LESS than the SMALLER of the resistors R_1 and R_2 .

Current Divider

Another useful formula gives the current through one branch in terms of the input current and the parallel resistances. For example, the current in R_2 can be easily calculated by eliminating the common voltage.

$$i_2 = v/R_2 = I_o R_p / R_2 \\ = I_o R_1 R_2 / [R_2 (R_1 + R_2)]$$

$$i_2 = I_o R_1 / (R_1 + R_2) \qquad \text{CURRENT DIVIDER FORMULA}$$

Note that the resistance in the numerator of the current divider formula is the one that the desired current does **not** flow through! This formula can be easily remembered by comparing it to the voltage divider formula below for series circuits and Kirchoff's Voltage Law.

For analysis of a circuit using KCL the currents are referred to an arbitrary assignment of current direction given by an arrow for each element, since it is often not possible by inspection of a complicated circuit to determine the actual current direction that would be observed. The arrows can be thought of as representing ideal ammeters reading the current. However, the "ammeter" method of analysis still works, since the result of calculations will merely result in the "ammeter reading negative" if the arbitrarily assigned current direction does not correspond to the actual current through that element. The polarities of all sources are always assumed to be known. If the current through R_1 had been marked with an arrow pointed upward toward the node, the solution of KCL would have the result that i_1 would be a negative current. We may apply KCL by using the following rules:

1. Identify the node under consideration. Consider current into the node as the positive direction
2. For each element connected to the node:
write down the magnitude and direction of the assumed current.
3. Add up all the currents flowing into the node algebraically. Set the algebraic sum to zero.

Rheostat (Variable Resistor)

Variable current can be achieved in a particular branch of a circuit using a variable resistor, called a "rheostat". In practice, a rheostat is actually realized using two of the three terminals of a "potentiometer".

A potentiometer is a resistor with a sliding contact along the length of the resistor. Note that a potentiometer has three terminals, one at each end and one on the slider. By moving the slider, the amount of resistance between either end-terminal and the slider can be varied. A potentiometer is represented on a circuit diagram as a resistance with an arrow pointing at a place somewhere along the length of the resistor. When a potentiometer is used as a rheostat, the unused terminal can either be left with no connection, or connected to the slider. (Why does this not make any difference?) In the Figure E1-3, the total resistance of the potentiometer is $(R_x + R_y) = R_o$. In this case the value of $R_x = R_2$ can be varied from zero to R_o , and hence i_2 can be varied from zero to I_o . What is the current through R_y ?

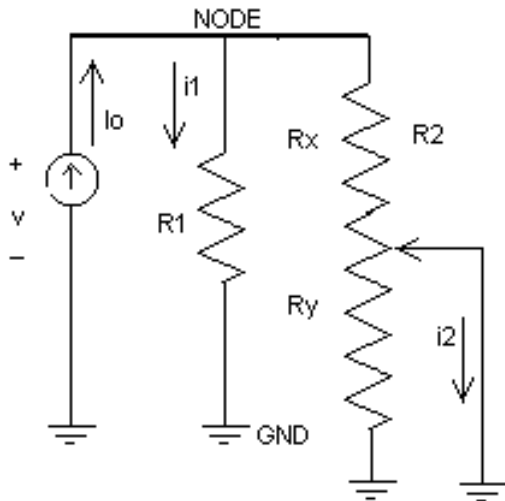


Figure E1-3. A rheostat is a variable resistor with a slider connected somewhere along it. It is considered good practice to connect the unused end of the resistor to the slider, although this is not necessary. Note that R_y is "short circuited" by the connection between the slider and ground.

Electric Power Calculation in Parallel Circuits

It is important to keep in mind that there is only one voltage in a parallel circuit. Power is easily calculated for each element using the form of Joule's Law relating power to voltage and resistance.

$$P = v^2/R_1 + v^2/R_2$$

Therefore in a parallel circuit the most power is dissipated by the **smallest** resistance.

(b) Kirchhoff's Voltage Law

Ohm's Law was further developed by Gustav R. Kirchhoff in 1846. There are two forms of Kirchhoff's Law, one for voltage and one for current. We will consider Kirchhoff's Voltage Law (KVL) at this time. Sources are said to produce a voltage "rise", while resistances are said to produce a voltage "drop".

KVL: The algebraic sum of all voltage "rises" and voltage "drops" around a closed path in a circuit is equal to zero.

Series Circuit

Consider the "series" circuit in Figure E1-4

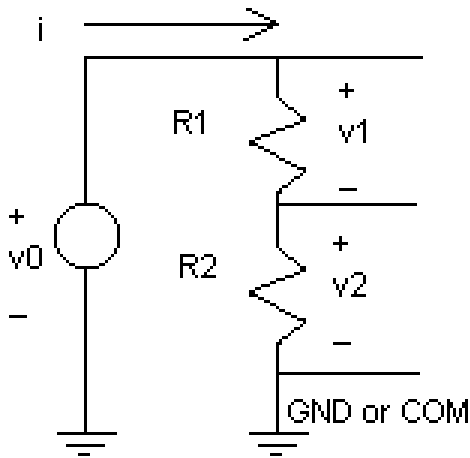


Figure E1-4. A series circuit consists of a single, continuous current path. The "ideal voltage source" is represented in this circuit diagram by circle, the resistances by zig-zag lines. The triple lines identify the terminal designated as a common voltage reference point. The "wires" connecting the common ground points are conventionally omitted from a circuit diagram.

In a **series** circuit the elements are connected together with **only one path for the current**. For this reason the **current is the same through all elements**. The voltage across each resistance can be calculated from Ohm's Law.

$$v_1 = R_1 i \quad v_2 = R_2 i$$

According to KVL the voltages drops add, and therefore must equal the voltage rise of the source.

$$-V_0 + v_1 + v_2 = 0$$

It is also conventional practice to collect all voltage rises on one side of the equation, and all drops on the other side.

$$V_0 = v_1 + v_2$$

By substituting Ohm's Law in KVL, the equivalent resistance R_s of resistances in series can be calculated.

$$V_0 = (R_1 + R_2) i$$

$$R_s = V_0/i$$

$$\mathbf{R_s = (R_1 + R_2)}$$

SERIES CIRCUIT FORMULA

Therefore in a series circuit, resistances add. This formula is easily extended to the series connection of more than two resistances. The student should **memorize** this formula to save time in analyzing circuits. Note that R_s is always greater than the largest resistance in the series circuit.

Measuring Voltage Polarity

Note that at the junction of R_1 and R_2 there appears to be both a [+] and a [-] sign! A useful interpretation is to think of each +/- pair **across an element** as the red/black wires from a "voltmeter". If the polarity of the red wire is positive **with respect to** the black wire the meter reads positive voltage. If both wires of the meter are connected to the same point, such as the junction between the resistances, it will read zero.

Therefore a single point in the circuit cannot be said to be either positive or negative by itself. The voltage must be referred to some other point. It is conventional to designate a common reference point for voltages (COM). The reference is usually also called ground (GND) on circuit diagrams.

For analysis of a circuit using KVL the voltages are referred to an arbitrary assignment of polarity for each element, since it is often not possible by inspection of a complicated circuit to determine the actual polarity that would be observed. However, the "voltmeter" method of analysis still works, since the result of calculations will merely result in the "voltmeter reading negative" if the arbitrarily assigned polarity does not correspond to the actual voltage drop across that element. The polarities of all sources are always assumed to be known. If the polarity across R_1 had been marked with the + at the junction between R_1 and

R_2 the solution of KVL would have the result that v_1 would be a negative voltage. We may apply KVL by using the following rules:

1. Choose an arbitrary starting point. Go clockwise around a closed path in the circuit (a "loop")
2. For each element write down the first polarity sign you encounter as you reach the element, and the absolute magnitude of the voltage.
3. When you arrive at your starting point again, set the algebraic sum to zero.

Open Circuit Voltage

If the continuity of the current path is broken, an "open circuit" condition results. In this case the current is forced to be zero, and the voltage from the ideal voltage source will be present across the gap and all voltages across resistances will be zero according to Ohm's Law.

Short Circuit Current

If all resistances in the path are zero, a "short circuit" condition results. In this case there is no limitation on the current imposed by the resistances and the current is theoretically infinite. An ideal voltage source can supply as much current as required by the circuit. Therefore an **ideal voltage source cannot be connected to an ideal short circuit**, as a logical inconsistency results. An ideal voltage source can be closely approximated with an electronic power supply. However, a current limit is imposed as a safety feature.

Measuring Current Polarity

When considering the current in a circuit, a conventional notation is to draw an arrow beside a "wire" in the region between the elements. The terminals of an ammeter are conventionally marked +/- rather than with an arrow. If the circuit were to be "broken open" and an ammeter inserted between the broken ends to complete the circuit, the meter would be connected with its + terminal at the tail of the arrow. In other words, positive current flows into the + terminal of an ammeter to cause the meter to read positive. In practice, current is rarely actually measured with an ammeter. Normally current is calculated by measuring the voltage across a known resistance. A small resistance is sometimes built into a circuit, the only purpose for the resistor being to facilitate the measurement of current.

Voltage Divider

One of the most useful circuits in electrical engineering is the "voltage divider". A voltage divider consists of two resistances connected in series with a voltage source. Voltage dividers are used to obtain a desired voltage, given a specified source voltage. Note that the desired voltage must be less than or equal to the source voltage. Consider the series circuit of Figure E1-5.

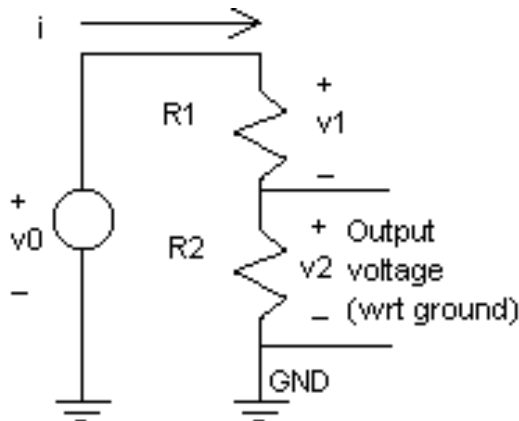


Figure E1-5. A voltage divider is a series circuit with the desired voltage across one of the resistors.

Since both resistors must have the same current, KVL can be written factoring out the common current.

$$V_o = (R_1 + R_2) i$$

Assume that the desired voltage is $v_2 = R_2 i$. By substituting in KVL above, the current can be eliminated, and the equation can be solved for the desired voltage.

$$v_2 = V_o \frac{R_2}{(R_1 + R_2)} \quad \text{VOLTAGE DIVIDER FORMULA}$$

The student should **memorize** this formula to save time in future circuit calculations. Note that this formula gives the desired voltage as the product of the source voltage and a ratio formed by the resistance across which the desired voltage is to be obtained, divided by the sum of the resistances in the circuit. This ratio is the fraction of the total resistance in the circuit represented by the "divider" resistance. This idea can be extended to series circuits with more than two resistors. The desired voltage is taken with respect to ground reference for the divider in this example. However, it is also possible to take the voltage across R_1 .

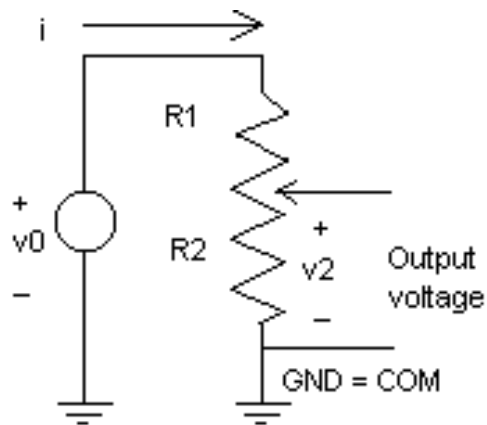
Potentiometers

Voltage dividers can be made to obtain variable voltages by using a device called a "potentiometer". A potentiometer is a resistor with a sliding contact along the length of the resistor. Note that a potentiometer has three terminals, one at each end and one on the slider. By moving the slider the amount of resistance can be varied between either end-terminal and the slider. However, the resistance between the ends remains constant. A potentiometer is represented on a circuit diagram as a resistance with an arrow pointing at a place somewhere along the length of the resistor. In Figure E03-3, the total resistance of the potentiometer is $(R_1 + R_2) = R_S$ and the output voltage is v_2 .

However, in this case the value of R_2 can be varied from zero to R_S , and hence v_2 can be varied from zero to V_o . A potentiometer is used in a radio to control the volume of the sound from the loudspeaker. If the range of variation of the output is to be restricted to less than the full $0 < v_2 < V_o$ range, additional resistances can be

connected in series with the potentiometer.

Figure E1-6 A potentiometer is a single resistor with a slider connected somewhere along it.



Electric Power Calculation in Series Circuits

In a series circuit, there is only one value of current. Power is easily calculated using the form of Joule's Law that relates power to current and resistance.

$$P = i^2 R_1 + i^2 R_2$$

Therefore, in a series circuit, the most power is dissipated by the largest resistance.

3. Circuit Theorems

(a) Superposition Theorem

The Superposition Theorem is a useful way to analyze circuits with more than one source. All sources but one at a time are "turned off". Voltages and currents can be calculated for each source being turned on independently, and the results added ("superposed" on top of each other).

The primary fact for the student to learn is that each **voltage source** that is "**turned off**" is replaced by a **short circuit**, each **current source** that is "**turned off**" is replaced by an **open circuit**.

As each source is activated one at a time, all resulting voltages and currents are calculated and recorded. When all sources have been accounted for, the **algebraic sums** of the voltages and currents for each circuit element are calculated. It is very important that an **assumed polarity** for each voltage and current be clearly assigned at the outset, and the polarity of all values calculated be carefully noted. An example is given below in Figure E1-7.

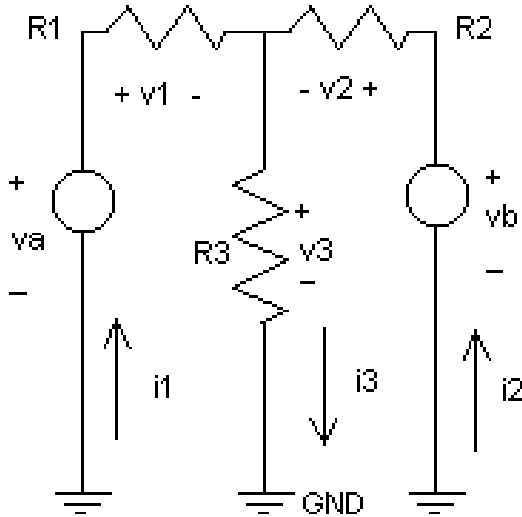
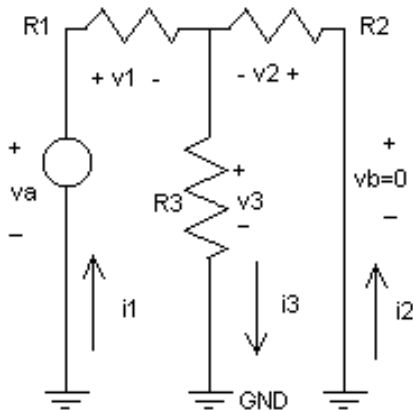


Figure E1-7. A circuit with more than one source. Currents and voltages are found by application of the Superposition Theorem.

Let us label the superposition process as step (a) and step (b), after which the results are added to form the superposition in step (c).

(a) In order to calculate i_{1a} , first set $V_b = 0$.

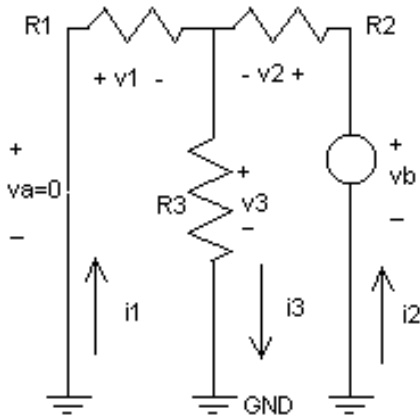


The circuit can now be solved with $R2//R3$ in series with $R1$:

$$i_{1a} = V_a / (R1 + R2//R3)$$

$$\text{where } R2//R3 = R2 R3 / (R2 + R3)$$

(b) Now set $V_a = 0$.



To calculate i_{1b} it is necessary to first find the voltage at the node between the three resistances. (This voltage is the same as v_3 .)

$$v_{3b} = V_b \frac{R_3/R_1}{R_3/R_1 + R_2}$$

Note also that in this case $v_{3b} = -v_{1b}$.

Now i_{1b} can be calculated from Ohm's Law. Note that i_{1b} polarity is negative.

$$i_{1b} = v_{3b} / R_1$$

Finally, by superposition:

$$i_{1c} = i_{1a} + i_{1b}$$

Electric Power Dissipation

Superposition does not apply to electric power dissipation, since the theorem applies only to linear equations such as KVL and KCL. For example, in circuit (a) the power dissipated in R_1 is given by

$$P_{1a} = (i_{1a})^2 R_1$$

and in circuit (b) the power in R_1 is given by

$$P_{1b} = (i_{1b})^2 R_1$$

After superposition, the power is

$$P_{1c} = (i_{1c})^2 R_1$$

$$\text{but } (i_{1c})^2 = (i_{1a} + i_{1b})^2 = (i_{1a})^2 + (i_{1b})^2 + 2(i_{1a})(i_{1b})$$

Therefore the electric power calculation cannot be done separately.

(b) Thevenin Equivalent Source

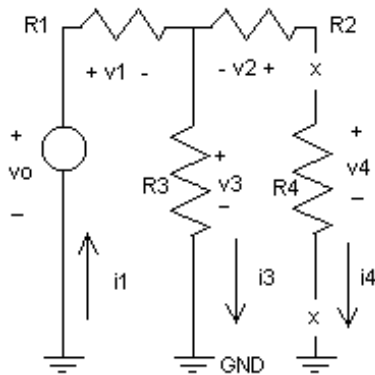


Fig E1-8

Circuit to be simplified by the Thevenin Equivalent

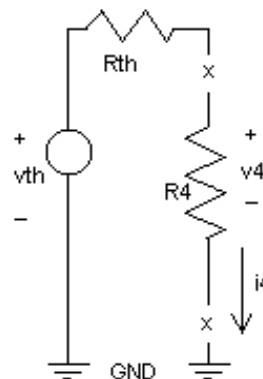


Fig E1-9

Simplified Thevenin Equivalent circuit

The Thevenin Equivalent provides a means of reducing a complicated circuit contain a voltage source to a simplified circuit with only two elements, usually designated V_{th} and R_{th} . This theorem also makes it clear why the voltage of a practical source decreases when current is supplied to a load resistance. Consider the circuit below. Everything in Figure E1-8 to the left of points x-x can be reduced to a Thevenin Equivalent to the circuit shown in Figure E1-9.

Resistance R_4 is considered to be the "load". The rest of the circuit is a complicated "source" that can be reduced to two elements, V_{th} and R_{th} . Application of the Thevenin Equivalent consists of three steps.

(a) The Thevenin voltage V_{th} is the "open circuit" voltage resulting from removal of the load resistance between the points x-x (in this example it is R_4). With resistance R_4 removed there is no current in R_2 so that $v_4 = v_3$ which can be calculated using the voltage divider formula.

$$V_{th} = V_o R_3 / (R_1 + R_3)$$

(b) The Thevenin resistance R_{th} is the equivalent resistance "looking backward" into the open circuit terminals, when the voltage source V_o is turned off (replaced by a short circuit). In this example when the source $V_o = 0$ we find the parallel combination $R_1 // R_3$, in series with R_2 .

$$R_{th} = R_2 + R_1 // R_3 \quad \text{where } R_1 // R_3 = R_1 R_3 / (R_1 + R_3)$$

Another way of deriving the Thevenin resistance can be obtained from a test made by placing a short circuit between the points x-x and measuring the "short-circuit current" $I_{s.c.} = i_4$. From this measurement the Thevenin Resistance is given by the ratio of open circuit voltage to short circuit current.

$$R_{th} = V_{o.c.} / I_{s.c.}$$

(c) After evaluating the Thevenin Equivalent circuit, the voltage at v_4 is easily calculated for any value of R_4 without recalculating all the other voltages and currents in the circuit, by simply applying the voltage divider formula.

$$v_4 = V_{th} R_4 / (R_4 + R_{th})$$

Practical Sources

A practical source such as a battery can be analyzed as a Thevenin Equivalent source after making suitable measurements, even though there is no actual resistor in the circuit.

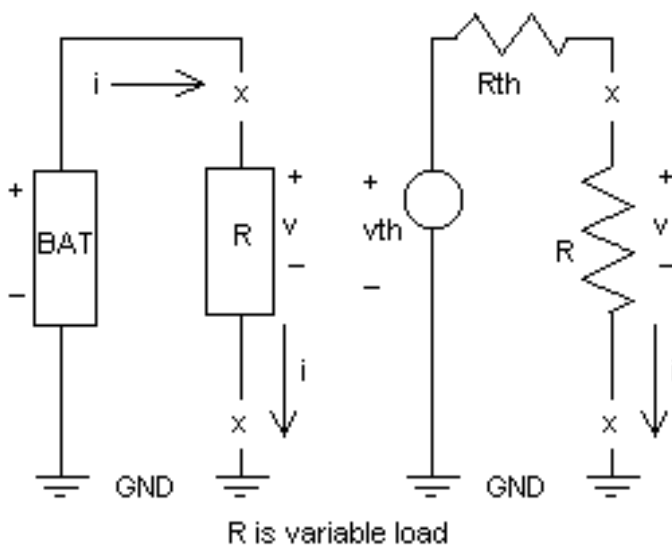


Figure E1-10 Thevenin Equivalent circuit of a battery source. The **terminal** voltage from the battery will decrease as more current is drawn by a decreasing load resistance.

In the case of a battery, it is observed that the terminal voltage decreases as more current is drawn. By plotting a graph of the voltage vs. the current, the value of V_{th} and R_{th} can be derived from the equation of the straight line that results. The value of V_{th} is the intercept on the voltage axis where $i = 0$. The value of the Thevenin resistance R_{th} is the (negative) slope of the line.

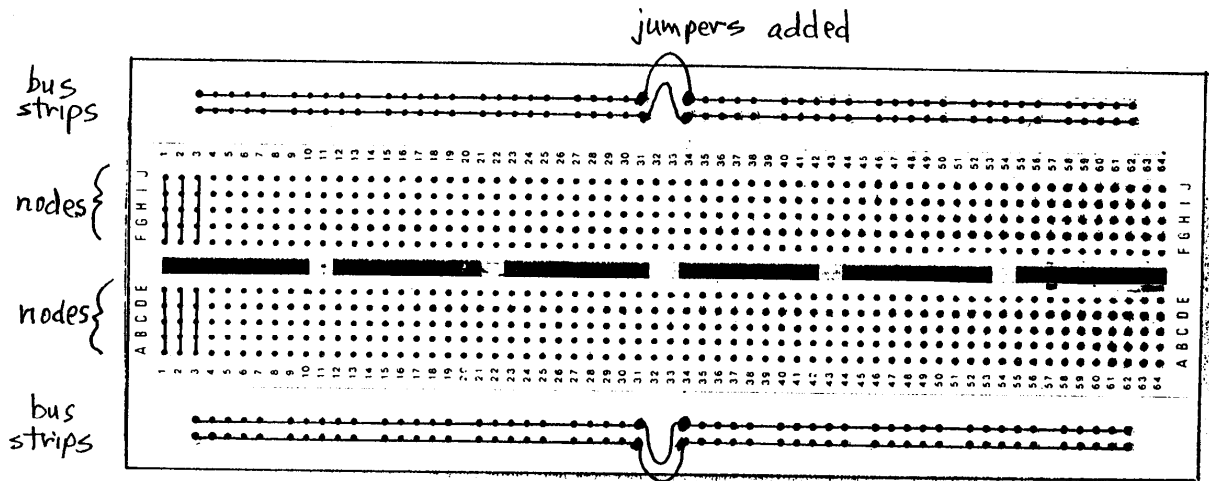
$$v = V_{th} - i R_{th} \quad R_{th} = - dv/di$$

Norton Equivalent

There exists a theoretical "dual" to the Thevenin Equivalent, called the Norton Equivalent. The Norton Equivalent source consists of an ideal current source I_{nrt} in parallel with a resistance R_{nrt} . These elements are related to the corresponding Thevenin Equivalent elements by simple formulas.

$$I_{nrt} = V_{th}/R_{th} \quad R_{nrt} = R_{th}$$

BREADBOARD INTERNAL CONNECTIONS



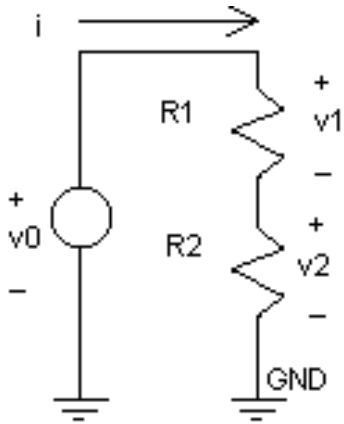
D. PROCEDURE:

I. Series Circuit

(a) Let $R_1 = 2.2K$ ohms, $R_2 = 1.5K$ ohms. (What is the color code for each?) Measure the value of each resistor using the VOM, record the values in the table below. Calculate the series resistance. Mount the two resistors on your breadboard and measure the series resistance. (Do not connect the Power Supply when making resistance measurements, even if it is turned off. Why?) _____

Resistance	Nom Value	Meas Value	Resist Error	% Error
R1	2.2K			
R2	1.5K			
Rs	3.7K			

Calculate the error between the nominal value (color code) and the measured value, for each resistor individually and for the series combination. Express the error as a percentage of the nominal value. Is it possible that there could be less percentage error for the series combination?



Why? _____

Figure P1-1 Series Circuit

(b) Set the Power Supply to produce +15 volts with respect to ground using the VOM. (Remember to select VOLTS DC). Set the Current Limit control to maximum. Turn off the Power Supply. Construct the series circuit of Figure P1-1 on your breadboard. Connect the Power Supply to the circuit on your breadboard. Switch on the supply and measure all voltages. Compare the sum of the individual measured values to the measured total voltage. Calculate the current three ways, using the measured voltages and measured resistances from part (a).

$v_1 =$ _____ $v_2 =$ _____ $V_o =$ _____ $(v_1 + v_2) =$ _____

$i = v_1/R_1 =$ _____ $v_2/R_2 =$ _____ $V_o/(R_1 + R_2) =$ _____ $avg\{i\} =$ _____

(c) Switch off the Power Supply. Break open the circuit between R_1 and R_2 . Switch on the Power Supply and measure the voltages as in part (b). Measure the voltage across each resistor, across the source voltage V_0 and across the open circuit break.

$v_1 =$ _____ $v_2 =$ _____ $V_0 =$ _____

$V_{\text{open circuit}} =$ _____ $(v_1 + v_2) =$ _____

Does KVL still hold true? _____ Does Ohm's Law hold true for R_1 and R_2 ? _____

What are the symptoms of a break in a series circuit? _____

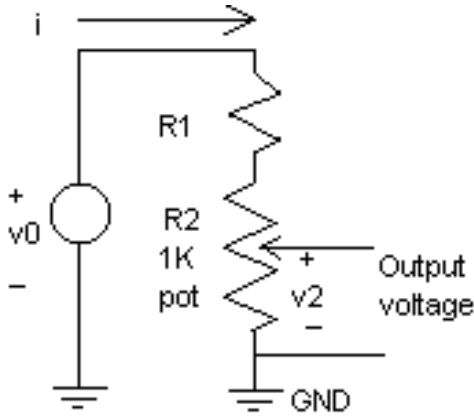
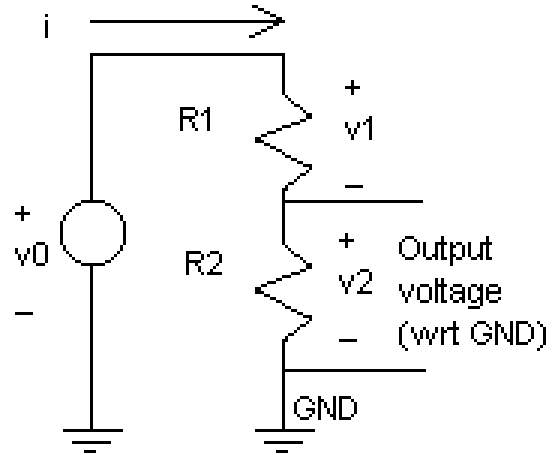
(d) With the meter still inserted in the break, switch to current measurement to determine i directly.

$i =$ _____

Compare with the previous indirect measurement in ((b) above.

II. Voltage Divider

Design a voltage divider circuit using two resistors in series to provide an output voltage $v_2 = 5.0$ volts given an input voltage $V_o = 15$ volts. Use resistors greater than 1000 ohms. Build the circuit and measure the voltage actually obtained. Label the sketch to the right with the nominal values of the resistors used, the measured voltages, and the calculated current.



(b) Identify the 1.0 K potentiometer (ask the instructor if you are in doubt). The slider is adjusted by turning a small screw on the end with a special screwdriver supplied in the lab kit. Design a voltage divider using a 1.0 K potentiometer and one resistor to provide an adjustable voltage variable from 0 to 5 volts, given an input of 15 volts. Build the circuit and measure the voltage range actually obtained. Calculate the current. On the circuit to the left, label the components, the voltages, and the current.

III. Thevenin Equivalent

Construct the circuit in Figure P1-4, to investigate the Thevenin Equivalent, with $V_0 = 10$ volts.

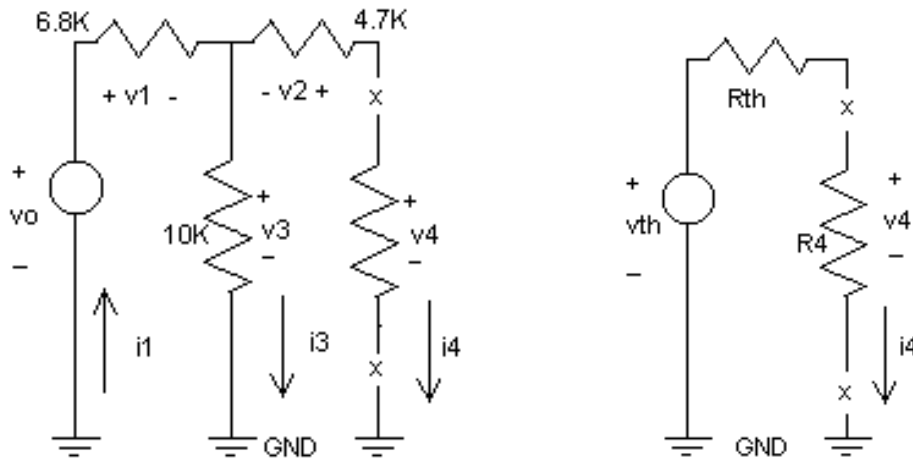


Figure P1-4 Simplification of a circuit using the Thevenin Theorem. R_4 is a variable load resistance.

(a) Do not connect any resistor as R_4 at this time. Leave this branch of the circuit open. Calculate $V_{th} = v_3$ from the circuit diagram and your measured values of the resistors. Measure the voltage actually obtained from your circuit.

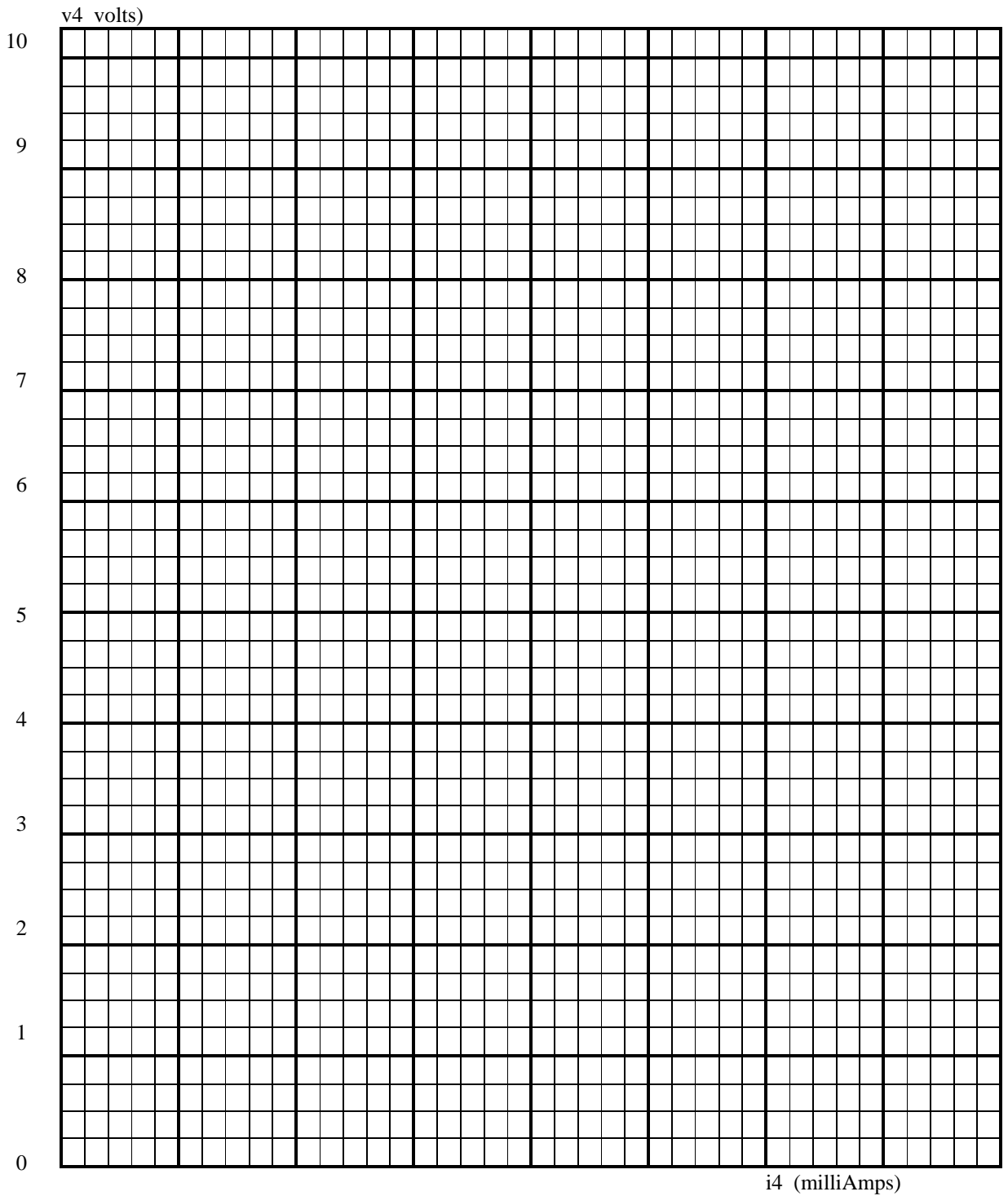
V_{th} calc _____ V_{th} meas _____

(b) Disconnect the +10V source from the power supply and replace with a short circuit jumper. Calculate the Thevenin resistance R_{th} between the outer end of the 4.7K resistor and ground. Measure the actual resistance obtained from your circuit.

R_{th} calc _____ R_{th} meas _____

(c) Reconnect the +10V supply. Connect various "load" resistors R_4 (measure their actual value first). Measure the voltage v_4 with respect to ground, and calculate the load current i_4 . Plot the graph of the voltage v_4 on the vertical axis, and the current i_4 on the horizontal axis.

R4 nominal	R4 measured	v4 measured	i4 calculated
100K			
47K			
10K			
4.7K			
1.0K			
470			
100			



Determine the value of R_{th} from the slope of the line

$$R_{th} = - dv_4/di_4 = \underline{\hspace{2cm}}$$

Compare to the values obtained previously in step III.(b).

$$R_{th} \text{ calc } \underline{\hspace{1cm}} \quad R_{th} \text{ meas } \underline{\hspace{1cm}}$$

At what value of R_4 would you expect the v_4 to equal $V_{th}/2$?

(Mark this point on your graph)

$$\text{Expected } \underline{\hspace{1cm}} \quad \text{Expt est } \underline{\hspace{1cm}}$$

E SUMMARY (To be completed at the end of lab):

State Kirchhoff's Voltage Law in words

Write the Series Circuit Formula

Write the Voltage Divider Formula

What is a potentiometer?

State Thevenin's Theorem in words

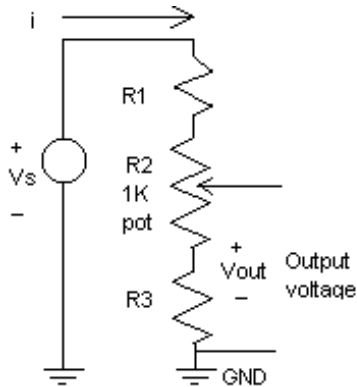
Describe how to calculate R_{th} and V_{th} when a circuit is given.

Describe various ways to calculate R_{th} and V_{th} from external measurement of a practical source.

How can the Norton Equivalent Circuit be derived from the Thevenin Equivalent?

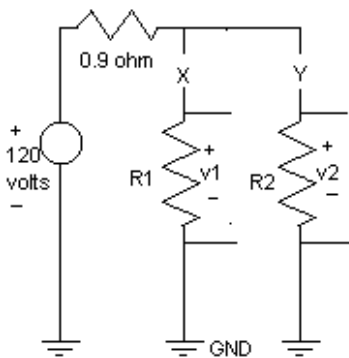
HOMEWORK:

1. Given $V_s = 15$ volts, $R_1 = 6.8K$, $R_3 = 3.3K$



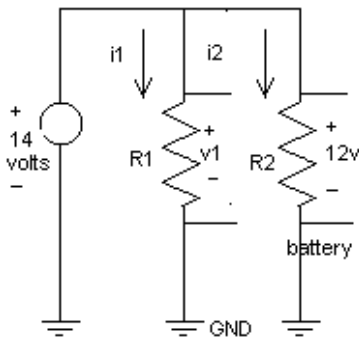
v_2 max = _____ volts v_2 min = _____ volts

3. Given R_1 is a lamp rated at 100 watts, 120 volts. R_2 is a hair dryer rated at 1500 watts, 120 volts.



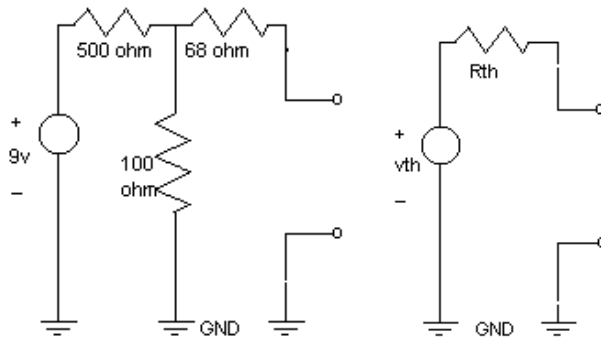
If the switch X makes contact, $v_1 =$ _____ volts; if the switch Y makes contact, $v_2 =$ _____ volts

4. The alternator in a car supplies 14 volts to the electrical system. The resistance R_1 accounts for the headlights, which are rated at 50 watts each for a total of 100 watts. The resistance R_2 is the internal resistance of the battery, equal to 0.09 ohms.



current to the headlights $i_1 =$ _____ current to charge the battery $i_2 =$ _____

5. Given the circuit below, calculate Thevenin Equivalent source voltage and resistance,



$V_{th} = \underline{\hspace{2cm}}$ $R_{th} = \underline{\hspace{2cm}}$

6. Given $R_2 = 1.2 \text{ ohm}$, use superposition to calculate

$v_2 = \underline{\hspace{2cm}}$ $i_3 = \underline{\hspace{2cm}}$

