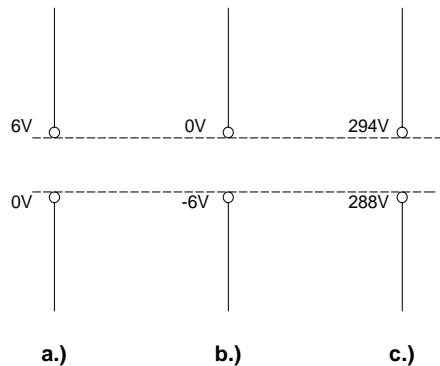


DC CIRCUITS

INTRODUCTION (Volts, Amps, and Ohms)

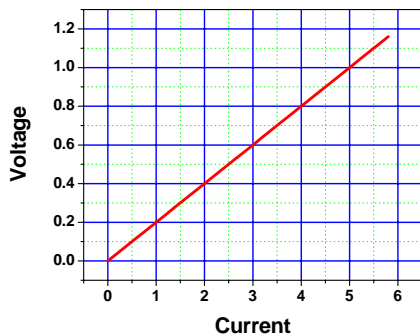
Two basic electrical quantities are central to all electrical and electronic circuits; these are **voltage** and **current**. Voltage expresses the energy per unit of charge, and current expresses the flow of charge (as a rate). When a **one Coulomb** charge loses or gains **one Joule**, it has passed through an **electric potential difference** of **one Volt**. An important point is that only **voltage differences** are significant. For example, all cases in the illustration show the same difference in voltage between the two points indicated by circular terminals and are equivalent. Since voltage expresses a **difference**, one point is **higher** than the other and can be regarded as **positive** or **+** (relative to the other point). Positive charge spontaneously moves from higher to lower voltages, or from **+** to **-**. "Forcing" positive charge to go from lower to higher voltages requires external energy. Two main points about voltage are: **(1)** + charge "naturally" flows from **+** to **-**; **(2)** voltage is a difference, so the appropriate prepositions to use with voltage are **between** or **across**. ("**Through**" is never appropriate to use with voltage.)



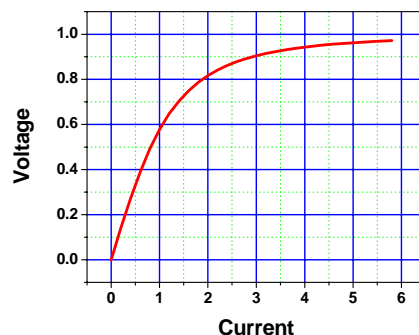
Examples of equivalent "voltage" differences

When a voltage difference exists between two points, charges can move and thus a **current** can flow. **Current** expresses the rate at which charge flows, *i.e.*, current = charge / time. When **one coulomb** of charge flows in **one second**, the current is **one Ampere**. Obviously, there is a connection between voltage and current: voltage is the influence **tending to make charge flow** and current is the **rate at which charges actually flow**. (Of course, "through" is the appropriate preposition to use for current.)

Although charges can move through space (*e.g.*, an electron beam in a vacuum), our concern is with charges moving within solid materials, a process called **conduction**. Consequently, we are also concerned with the "effect" of the conducting path on the flow of charge—will it be "easy" or "difficult" to "make" charge flow? For this reason, this concept of **resistance** is useful in many cases for relating voltage (differences) and current through the "common-sense" relation: Current = Voltage / Resistance. In this relation, current is the "result" of the voltage and the difficulty of making charges flow. When resistance is high ("difficult"), little current will flow; when the resistance is low ("easy"), the current can be high. Using the typical symbols of *I* for current,



Linear Voltage-Current Relation



Non-Linear Voltage-Current Relation

V for voltage, and R for resistance, the standard relation is $I = \frac{V}{R}$, or $V = IR$. However, it is not necessary

that I and V are proportional for all values. Two possibilities are illustrated in the graphs. The linear V - I case is common (and useful) enough to be given its own name: **Ohm's Law**. Thus,

$$\text{Ohm's Law : } V = IR, \text{ or } I = \frac{V}{R}, \text{ or } R = \frac{V}{I}.$$

Ohm's Law provides the basis for defining the **units of resistance**: when **one ampere** of current flows through a conductor with a voltage (difference) of **one volt**, the resistance is **one Ohm**. The abbreviation for Ohms is the Greek letter capital omega, or Ω .

Finally, when a circuit element exhibits a linear relation between voltage and current, it is said to "obey Ohm's Law." It is important to note that **resistors**, which are common circuit elements, obey Ohm's law; however, many other electronic components do not exhibit Ohm's law behavior. In non-Ohm's law cases, resistance as a numerical value is not very useful since it is not constant. In fact, we will abandon resistance as a numerical value useful for circuit components when we introduce **diodes** about one-third of the way into this course. Nevertheless, circuits in which resistors are the main electrical component are very important and particularly useful for introducing circuit-analysis techniques.

Two specific cases often referred to deserve special attention insofar as their resistance is concerned: a **short circuit** is a path of **zero resistance**, while an **open circuit** is a path of **infinite resistance**. The **voltage difference** between any two points connected by a short circuit is always **zero** no matter how high the current, and the **current through** any path connected by an open circuit is always **zero** no matter how high the voltage.

KIRCHOFF'S LAWS

Two basic facts of physics, Kirchoff's Voltage and Current Laws, govern analysis of electric circuits, and study of DC circuits is where they are usually introduced. Kirchoff's Voltage Law (**KVL**), which comes directly from the **conservation of energy principle**, can be stated as follows:

(KVL): "The **algebraic sum** of **all voltage drops** around a **closed loop** is **zero**."

"Algebraic sum" means the voltage is put into the sum as a positive value or a negative value according to the direction of progressing around the loop. Basically, KVL provides the basis for a relation: "**sum of voltages**" = 0. For example, in the illustration shown to the side, the KVL relation can be developed by starting at the "X," progressing around the loop as indicated by the arrows, and arriving back at the "start." For the illustration, the relation is $0 = V_1 - V_2 - V_3 + V_4$. Note that V_1 and V_4 are "rises" (- to +), while V_2 and V_3 are "drops" (+ to -) for the "bookkeeping" direction chosen. Note also that the equation will be the same for the opposite bookkeeping direction since the only changes will be swapping the rises and drops.

Kirchoff's current Law (**KCL**), which comes directly from the **conservation of charge principle**, can be stated as follows:

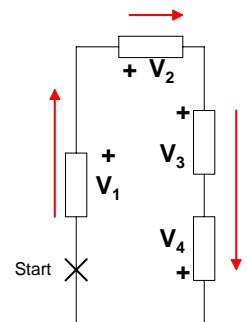


Illustration of KVL

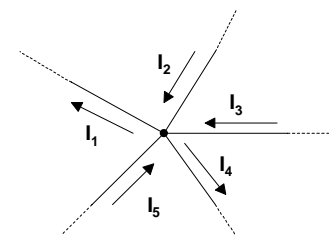


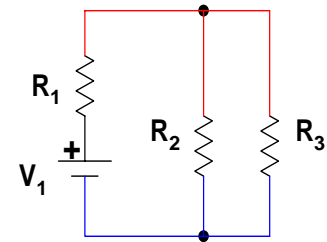
Illustration of KCL

Kirchoff's Current Law (KCL): "The **sum of all currents entering a junction** equals the **sum** of all currents **leaving** the junction." This "Law" also leads to an equation: "**current entering**" = "**current leaving**." In the illustration, I_2 , I_3 , and I_5 are "entering," while I_1 and I_4 are "leaving," so the relation is: $I_1 + I_4 = I_2 + I_3 + I_5$.

COMBINATION OF KIRCHOFF'S AND OHM'S LAWS

The most basic (but still useful) circuit consists only of a voltage source, wires, and resistors as shown in the illustration. As a first step in setting up the analysis of such circuits, we need to introduce some conventions:

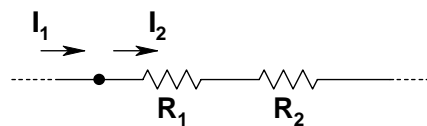
1. Current is the flow of positive charge; therefore, current enters the + end of resistors. In fact, the direction of current and the + end of a resistor are **always** related in this way. **In other words, the current arrow tells the + end of the resistor, and the + end of the resistor tells the current arrow.** (This definition of current is referred to as "conventional current" and is that commonly used in engineering. However, in vacuum tubes and metals, the actual charge carriers are electrons which led some military-based course materials to make use of electron-flow as the definition of current. Since electrons are negative charges, they move spontaneously through voltage differences opposite to positive charges. The consequence in setting up the analysis of a circuit is that the current arrows and + sides of resistors are opposite to that described above. However, changing the directions does not alter the **amounts** of currents calculated from the procedures. The only change will be the indicated direction.)



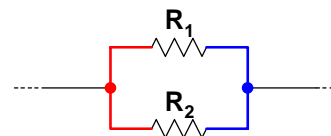
Basic DC Circuit

2. "Straight lines" are paths of zero resistance. This means there is **no voltage difference between any two points connected by straight lines**. Specifically, since $V = IR$, $V = 0$ no matter the value of I if $R = 0$. For the example circuit, all points in blue are at the same voltage, which is that of the lower terminal of the battery. Also, all points in red are at the same voltage, but the red points are separated from the battery's upper terminal by resistor R_1 and therefore by the voltage (difference) across R_1 .

Series and Parallel Connection: Circuit elements are in **series** if the current flowing through one must be the same as the current in the other; circuit elements are in **parallel** if their ends are connected together by "straight lines." Both cases are illustrated below.



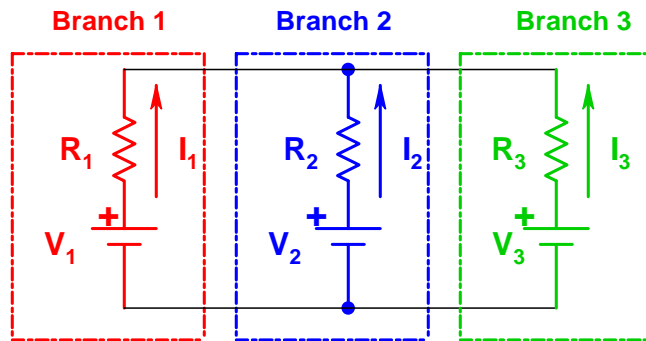
Series Connection



Parallel Connection

An important result from KCL is that the current is the same for all elements connected in series. This deduction is the simple result of the fact that any point within the series "arrangement" is "virtual" junction with only two connections, "in" and "out." Since the current entering the "junction" must equal the current leaving, the current at all points must therefore be the same (for series connection). Thus, in the illustration of series connection, $I_1 = I_2$ as the "junction" moves through the whole series-connected arrangement. Likewise, KVL dictates that the voltage (difference) is the same across all elements in a parallel connection because the ends are connected only by "straight lines." This is indicated by the blue and red coloring of the lines in the illustration.

Branches and Loops: Kirchoff's Voltage Law describes the behavior of "voltages around a closed loop."



Branches in a Multi-Loop DC Circuit

Because this principle is fundamental to much of our discussion throughout this course, it is useful to introduce terminology common in engineering. Specifically, as indicated in the circuit diagram a **branch** is a portion of the circuit connected in parallel with other branches. The example shown consists of three branches; from these, up to three loops can be identified: (1) **branch 1 + branch 2**, (2) **branch 2 + branch 3**, and (3) **branch 1 + branch 3**. Note also that the diagram shows current arrows for each branch. These are included only for setting up the problem since the **actual** currents may be in the opposite directions.

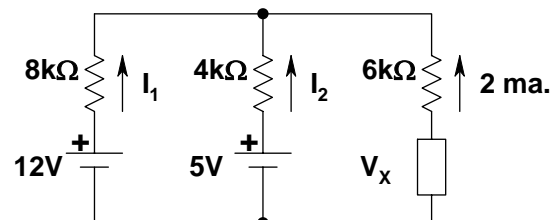
It is important to note that the set-up of the problem with current arrows as indicated also defines the "+" sides of the resistors. Since the positive side is the one where the current enters, the lower end of each R is positive for the current arrows shown. Also, it is important to note that the upper and lower "straight lines" of the circuit defines "junctions" as introduced in the KCL statement. (These junctions are also referred to as "nodes.") With this background, we can write the set of relations (equations) available for describing the circuit:

1. **Loop 1 (Branch 1 + Branch 2):** $0 = V_1 - I_1 R_1 + I_2 R_2 - V_2$ (Clockwise from "-" of V_1)
2. **Loop 2 (Branch 2 + Branch 3):** $0 = V_3 - I_3 R_3 + I_2 R_2 - V_2$ (Counterclockwise from "-" of V_3)
3. **Loop 3 (Branch 1 + Branch 3):** $0 = V_1 - I_1 R_1 + I_3 R_3 - V_3$ (Clockwise from "-" of V_1)
4. **Upper Junction:** $0 = I_1 + I_2 + I_3$ (All currents entering the junction)
5. **Lower Junction:** $I_1 + I_2 + I_3 = 0$ (All currents leaving the junction)

Obviously, equations 5 and 6 are the same so that only one is "distinct." Also note that only two of equations 1 through 3 are distinct. For example, "equation 1" minus "equation 2" equals "equation 3," "equation 2" plus "equation 3" equals "equation 1," etc.; thus only two of these are "distinct." In summary, therefore, for a three-branch circuit as shown, KCL and KVL provide three "distinct" (or linearly independent) equations. From principles of algebra relating to systems of simultaneous equations, we know that we can solve these for up to three unknowns. Since the parameters in the circuit are **V's, I's, and R's**, we can calculate any three of these if we are given (or can figure out from other considerations) all the others.

Example 1: Calculate the values and actual directions of currents I_1 , I_2 , and the voltage V_x for the circuit shown. (The symbol "k" indicates the prefix "kilo" meaning $\times 10^3$, and the symbol "m" indicates the prefix "milli" meaning $\times 10^{-3}$.)

Solution: From KVL with loop 1 defined by the left and right branches, and loop defined by the center and right branches, we obtain the following equations:



Example 1

- Loop 1 (CW from "-" end of 12V):** $0 = 12V - 8kI_1 + (6k)(2ma) - V_x = 24V - 8kI_1 - V_x$
Loop 2 (CW from "-" end of 5V): $0 = 5V - 4kI_2 + (6k)(2ma) - V_x = 17V - 4kI_2 - V_x$
KCL at upper junction: $I_1 + I_2 + 2ma = 0$.

Combining the KCL equation & loop 2 yields: $0 = 25V - 4kI_1 - V_x$;

Combining this with Loop 1 yields:

$$0 = 74V - 3V_x, \text{ and } V_x = 74V / 3 (= 24.67V);$$

With this value of V_x , we can calculate:

$$I_1 = (V_{x1} - 25V)/4k = -(1/12)ma (= -0.083ma)$$

With I_1 and the KCL equation, we get:

$$I_2 = -(2ma + I_1) = -(2 - 1/12)ma = -23/12 ma (= -1.92 ma)$$

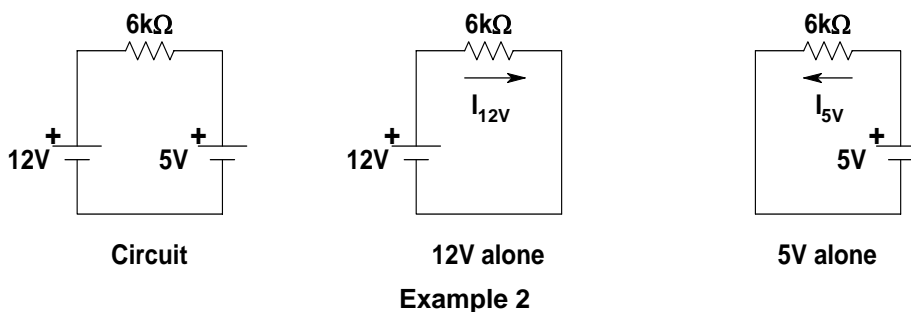
The “-” signs for the currents mean the actual directions are opposite to those indicated for setting up the problem.

METHODS FOR ANALYZING CIRCUITS

While KVL and KCL are the basic principles governing electric circuit behavior, the relations obtained from directly applying these principles yield a set of N simultaneous equations. Although algebraic procedures for extracting the N unknowns are well-developed, the mathematics and algebra may hide useful electrical insight. In addition, the algebraic procedures for solving a set of simultaneous equations are usually tedious. For these reasons, we will examine three additional methods for circuit analysis, each of which will bring advantages in computational simplification and in electrical insight. These three methods are: **(1) the superposition principle, (2) the nodal method, and (3) Thevenin’s Theorem.**

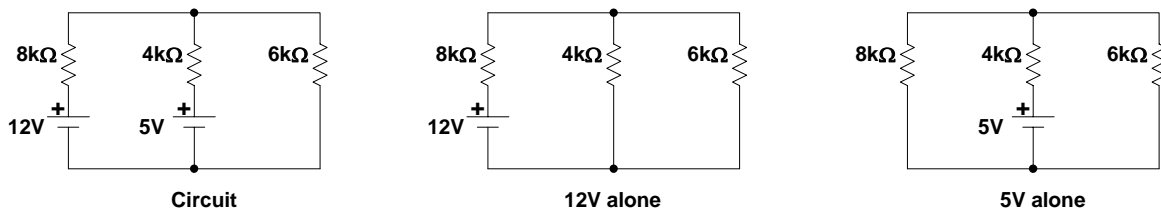
Superposition: The superposition principle is applicable when the circuit contains more than one source. The basic idea is that the current through each circuit element is partially the result of each source. Application of the principle as a circuit-analysis method requires a valid procedure for calculating the “partial currents.” It turns out that the procedure for doing so is to **replace one at a time all the voltage sources but one with short circuits; the currents calculated for each circuit element in this way are the “partial currents” from the actual source included in the “partial” circuit.** In the systematic repetition of this procedure for each source, the result will be calculation of the full set of “partial currents” from which the actual currents can be calculated by adding the partial currents (while keeping careful track of the directions as some may be opposite to others).

Example 2: Use superposition to calculate the current in the resistor in the circuit shown:



Solution: Actually, this is a near-trivial example chosen to illustrate the basic idea. In fact, the “answer” is obvious from an in-head calculation: $I = 7/6 \text{ ma, to the right}$. However, using the superposition procedure for the 12V source alone, we get $I_{12V} = 2ma, \text{ to the right}$; repeating this for the 5V alone, we get $I_{5V} = 5/6 \text{ ma, to the left}$. Adding these together yields $(2 - 5/6)ma, \text{ to the right, or } 7/6ma, \text{ to the right}$. This is the same as the result obtained by the in-head calculation using KVL.

Example 3: Use the principle of superposition to calculate the currents in the resistors of the circuit shown.



Example 3: Application of Superposition

Solution: First for the “12v alone” case— 12V “sees” 8k in series with the 4k - 6k parallel combination. So

the total resistance “facing” the 12V source is $R_{eq,12V} = 8k \text{ series } (4k // 6k) = 8k + \frac{12k}{3+2} = \frac{52k}{5}$.

Thus the 8k partial current is: $I_{8k,12V} = \frac{12V}{R_{eq}} = \frac{12V}{52k/5} = \frac{15}{13} \text{ ma } \uparrow$. (The arrows indicate direction.)

One way to get the other currents is to calculate the voltage across the parallel 4k and 6k resistors:

$$V_{4k,12V} = V_{6k,12V} = 12V - I_{8k,12V} 8k = 12V - \frac{120}{13} V = \frac{36}{13} V.$$

From this, $I_{4k,12V} = \frac{36V/13}{4k} = \frac{9}{13} \text{ ma } \downarrow$, and $I_{6k,12V} = \frac{36V/13}{6k} = \frac{6}{13} \text{ ma } \downarrow$.

Similarly, for the “5V alone” case, the 5v source “sees” 4k series (8k // 6k), so $R_{eq,5V} = \frac{52k}{7}$.

With this, we obtain:

$$I_{4k,5V} = \frac{35}{52} \text{ ma } \uparrow;$$

$$V_{8k,5V} = V_{6k,5V} = 5V - I_{4k,5V} 4k = (5 - \frac{35}{13})V = \frac{30}{13} V.$$

$$I_{8k,5V} = \frac{30V/13}{8k} = \frac{15}{52} \text{ ma } \downarrow$$

$$I_{6k,5V} = \frac{30V/13}{6k} = \frac{5}{13} = \frac{20}{52} \text{ ma } \downarrow.$$

Finally (Whew!!!),

$$I_{8k} = I_{8k,12V} + I_{8k,5V} = \frac{15}{13} \text{ ma } \uparrow + \frac{15}{52} \text{ ma } \downarrow = \frac{45}{52} \text{ ma } \uparrow$$

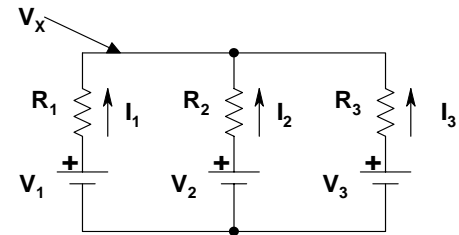
$$I_{4k} = I_{4k,12V} + I_{4k,5V} = \frac{9}{13} \text{ ma } \downarrow + \frac{35}{52} \text{ ma } \uparrow = \frac{1}{52} \text{ ma } \downarrow$$

$$I_{6k} = I_{6k,12V} + I_{6k,5V} = \frac{6}{13} \text{ ma } \downarrow + \frac{5}{13} \text{ ma } \downarrow = \frac{11}{13} \text{ ma } \downarrow$$

The Nodal Method: This method is based on Ohm's law and KCL. For example, KCL dictates that $I_1 + I_2 + I_3 = 0$ for the arrows shown;

$$I_1 = \frac{V_1 - V_x}{R_1}; \quad I_2 = \frac{V_2 - V_x}{R_2}; \quad I_3 = \frac{V_3 - V_x}{R_3}, \text{ so that}$$

$$0 = I_1 + I_2 + I_3 = \frac{V_1 - V_x}{R_1} + \frac{V_2 - V_x}{R_2} + \frac{V_3 - V_x}{R_3}.$$



Basic Idea for Nodal Method

likewise, from Ohm's Law, the individual currents are:

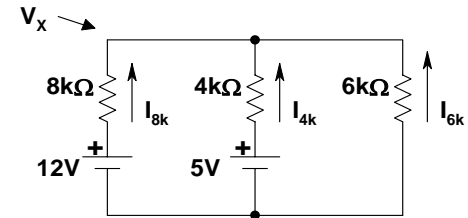
V_x is the (unknown) voltage at the junction; however, in the usual case, it is the **only** unknown in the equation. Thus the result of the nodal method is one equation and one unknown. Of course, to get the actual currents, it is necessary to use the value of V_x and the individual Ohm's-law-based relations.

Example 4: Apply the nodal method to the circuit of example 3. From the nodal procedure, we get the relation

$$0 = I_{8k} + I_{4k} + I_{6k} = \frac{12 - V_x}{8k} + \frac{5 - V_x}{4k} + \frac{0 - V_x}{6k}$$

$$0 = 3(12 - V_x) + 6(5 - V_x) + 4(0 - V_x) = 66V - 13V_x$$

$$V_x = \frac{66}{13} V.$$



Example 4

Using the value of V_x in the relations for the specific currents yields:

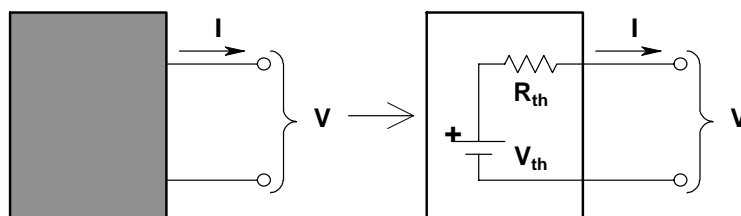
$$I_{8k} = \frac{12V - \left(\frac{66V}{13}\right)}{8k} = \frac{45}{52} \text{ ma} \uparrow;$$

$$I_{4k} = \frac{5V - \left(\frac{66V}{13}\right)}{4k} = -\frac{1}{52} \text{ ma} \uparrow;$$

$$I_{6k} = \frac{0V - \left(\frac{66V}{13}\right)}{6k} = -\frac{11}{13} \text{ ma} \uparrow.$$

For I_{4k} and I_{6k} , the “-” signs with the upward arrow mean that the actual current is down. Note that these are the same answers as from the superposition procedure. (If otherwise, it would be worrisome!!)

Thevenin's Theorem: Of the three methods, Thevenin's Theorem provides the most insight into electric circuit behavior. In addition, it sets up the idea of “equivalent circuits” since the central point is that the **electrical behavior** of a circuit can be accomplished many ways. The basic idea behind Thevenin's theorem



Thevenin's Theorem

is that the only **detectable electrical parameters** are **voltage** and **current**. Therefore **electrical behavior** means “how much current and voltage are available at the terminals.” All circuits behaving the same in this respect are **electrically equivalent** regardless of the circuit details.

This idea is embodied in the **Thevenin equivalent circuit**. Specifically, the electrical behavior of a circuit (relative to a pair of terminals) can be represented by the very simple one-source, one-resistance circuit shown. As a tool in circuit analysis, the objective is use the details of the actual circuit to derive the **Thevenin equivalent voltage and resistance**. One element of insight it gives into circuit behavior is that the electrical characteristics, and therefore the information we can obtain about a sealed circuit (a “black box”), are no more than those shown in the diagram.

The procedures for obtaining the **Thevenin equivalent voltage and resistance** (for the terminals indicated) are available by inspection of the “uncovered” equivalent in the illustration above. Specifically:

- (1) The **open-circuit** voltage at the terminals equals V_{th} . This is evident since no current flows through an open circuit so there is no voltage across R_{th} .
- (2) Likewise, R_{th} is either of the following:
 - (a) the equivalent resistance between the terminals with V_{th} replaced by a short circuit, or
 - (b) the ratio V_{th} / I_{sc} , where I_{sc} is the current with the terminals connected by a short circuit.

One important point with Thevenin’s theorem is that it applies to a **pair of terminals**. For this reason, the discussions above inserted the phrase “for the terminals indicated.” This is important for use of Thevenin’s theorem to analyze circuits. Specifically, the approach amounts to a “virtual” division of the total circuit in such a way as to create a pair of terminals.

Example 5: Apply **Thevenin’s theorem** to calculate the current through the $6k\Omega$ resistor in the circuit of example 3.

Solution: Since the objective is to find the current through the $6k\Omega$ resistor, the obvious approach is to divide the circuit (virtually) at the “X’s” indicated to create the simpler circuit shown in the “Thevenin View.” If we can successfully calculate V_{th} and R_{th} , calculation of the current is straightforward:

$$I_{6k} = \frac{V_{th}}{R_{th} + 6k}$$

From the circuit “to be replaced,” we can see that V_{th} is the voltage “between the X’s.” For the values given, the current, R_{th} , and V_{th} can be calculated as follows:

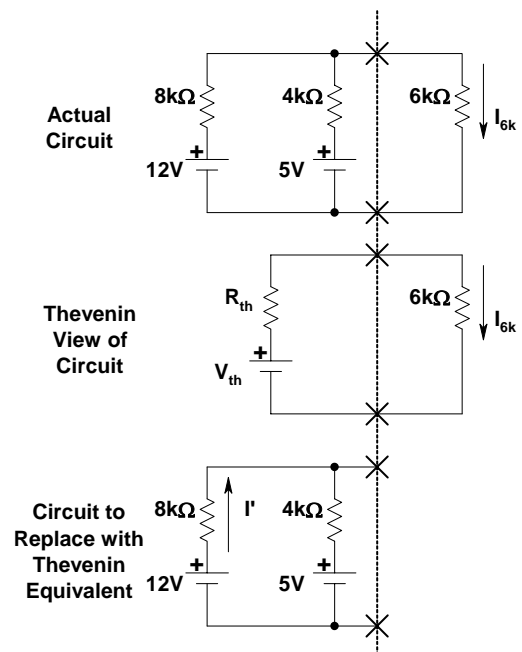
$$R_{th} = 4k // 8k = \frac{8k}{3}$$

$$I' = \frac{(12 - 5)V}{(4k + 8k)} = \frac{7V}{12k} = \frac{7}{12} \text{ ma.}$$

$$V_{4k} = (4k) \frac{7}{12} \text{ ma} = \frac{7}{3} \text{ V}$$

$$V_{th} = \frac{7}{3} \text{ V} + 5V = \frac{22}{3} \text{ V}$$

$$\text{Thus, } I_{6k} = \frac{V_{th}}{R_{th} + 6k} = \frac{\left(\frac{22}{3}\right)V}{\left(\frac{8k}{3}\right) + 6k} = \frac{11}{13} \text{ ma} \downarrow .$$

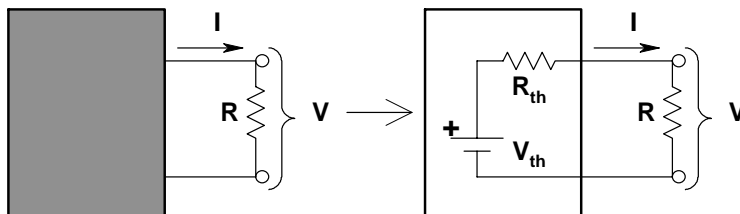


Example 5

It is important to note that the Thevenin equivalent will be different, for example, if the goal is to calculate the current through the 4k resistor: a different set of “virtual” terminals will be appropriate for that case (and for the current through the 8k resistor).

The Thevenin concept is often used to describe the equivalent behavior of a complex actual circuit. This leads to the next example based on “testing” a hypothetical circuit:

Example 6: A sealed box as indicated below contains an electrical circuit of some type. In the effort to figure out what is inside it, you connect two known resistors to the terminals and measure the resulting voltage across each obtaining the following data: **for $R = 3k$, $V = 4.5V$; for $R = 12k$, $V = 6.75V$** . What is the equivalent R_{th} and V_{th} “inside” the box?



Example 6

Solution: First, let me congratulate you on your careful forethought in designing this measurement. Obviously, since the best we can do is to find two characteristics (V_{th} and R_{th}), we must have two independent measurements. Your wise choice enables this important task to be accomplished.

Inspection of the electrical equivalent shows that $I = \frac{V_{th}}{R_{th} + R}$. Our measurements provide I since we have

V and know R. Thus, for the two pieces of data collected:

$$I_{3k} = \frac{4.5V}{3k} = \frac{V_{th}}{R_{th} + 3k} \Rightarrow 1.5ma(R_{th} + 3k) = V_{th} \Rightarrow 1.5ma(R_{th}) + 4.5V = V_{th}$$

$$I_{9k} = \frac{6.75V}{9k} = \frac{V_{th}}{R_{th} + 9k} \Rightarrow 0.75ma(R_{th} + 9k) = V_{th} \Rightarrow 0.75ma(R_{th}) + 6.75V = V_{th}$$

Subtracting these yields :

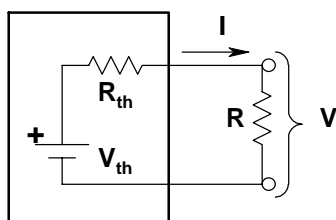
$$0.75ma(R_{th}) - 2.25V = 0 \Rightarrow R_{th} = \frac{2.25V}{0.75ma} = 3k$$

Inserting R_{th} into the second equation yields :

$$V_{th} = 0.75ma(R_{th}) + 6.75V = 2.25V + 6.75V = 9V$$

THE CONCEPT OF “LOAD”

Most circuits are designed to be connected to something; for example a battery to a radio, an amplifier to a speaker, a microphone to an amplifier, etc. However, connecting the circuit to its “load” in general leads to a change in the circuit’s output parameters. This is similar to the behavior of an electric drill when drilling through something difficult: its speed will drop and there are clear indications that the drill is under “load.” (This sometimes happens to students near the end of a semester.)



Circuit Under Load

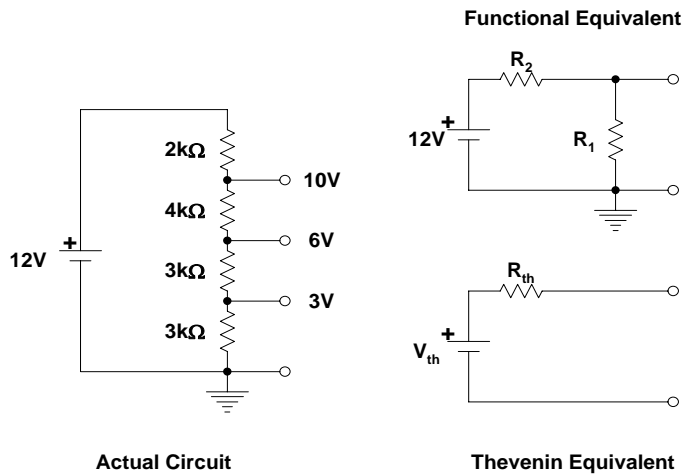
Anyway, the Thevenin concept provides the basis for predicting the behavior of a circuit under load. The “no-load” output voltage of the circuit is V_{th} ; however, connecting the circuit to its load causes current to flow and a consequent voltage drop across R_{th} (equal to $I R_{th}$).

Example 7: The circuit below is a “voltage divider” designed to use a 12V source and provide the voltages 3V, 6V and 10V using resistors as indicated. Predict the voltages at the 3V and 10V terminals if connected (separately) to loads of 15k and 150k. Specifically, fill in the table shown.

Terminal	15k Load	150k Load
3V	2.61V	2.96V
10V	9.00V	9.89V

Solution: This is an ideal case for applying Thevenin’s theorem. For each terminal, the actual circuit amounts to that shown as the “functional equivalent.” For the **3V terminal**, $R_1 = 3k$ and $R_2 = 9k$; for the **10V terminal**, $R_1 = 10k$ and $R_2 = 2k$.

Consequently, $R_{th} = 3k // 9k = 9k / 4$ for the **3V** terminals, and $R_{th} = 10k // 2k = 10k / 6$ for the **10V** terminals. In each case, the “design” voltages are the open-circuit values and thus are the respective V_{th} ’s.



Example 7

$$\text{Also, for each case, } V_{load} = IR_{load} = \left(\frac{V_{th}}{R_{th} + R_{load}} \right) R_{load}.$$

Finally, running the numbers, we get the values inserted in the table. Notice that the higher the load resistance, the nearer the “loaded” voltage is to the design value.

POWER IN ELECTRIC AND ELECTRONIC CIRCUITS

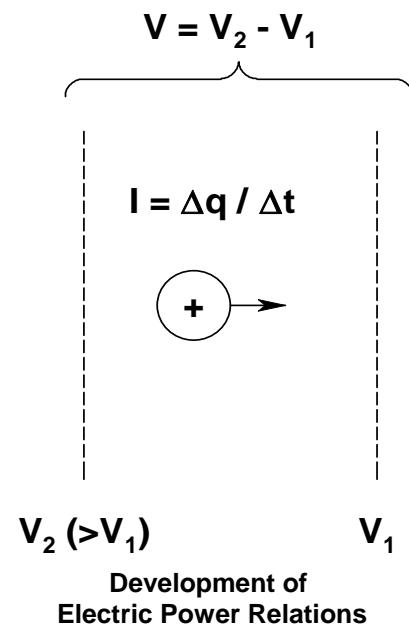
Of course, the circuits we have and will discuss require energy for operation. The main thing we will need to consider as the course develops is the rate at which energy (in the form of heat) will need to be handled. Following is a brief development of power and energy in electrical terms leading to the relations most useful for our later purposes.

First, we need to recall that power is the “rate of doing work” or

$$P = \frac{\text{work (or energy)}}{\text{time}}$$

next, we need to remember that “voltage” is **electric energy / charge**; and that current is **charge / time**. Thus, as illustrated in the diagram, when charge Δq passes through the potential difference (voltage difference) V , the **energy** is $V \Delta q$. Since charge passes through at the rate $\Delta q / \Delta t$, the product

$$V \frac{\Delta q}{\Delta t} = \frac{\text{work}}{\text{time}} = \text{Power} = VI. \text{ Thus, the } \textit{basic relation} \text{ for}$$



power is the **current times the voltage difference it passes through**, or $P=VI$.

For resistors, in which there is a direct relation between voltage and current, we can develop additional relations:

$$\text{For Resistors : } V = IR, \text{ and } I = \frac{V}{R}$$

$$\text{thus } P_R = IV = I(IR) = I^2 R, \text{ or}$$

$$P_R = \left(\frac{V}{R}\right)V = \frac{V^2}{R}.$$

For other components, however, it is necessary to use the basic relation, $P = VI$.

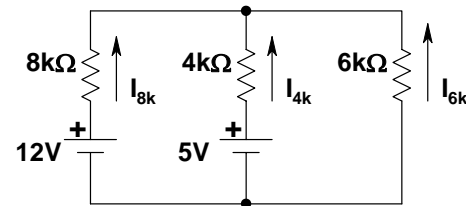
Example 8: Calculate the power in each circuit element of **Example 3**.

Solution: We already know the currents:

$$I_{8k} = \frac{45}{52} \text{ ma } \uparrow;$$

$$I_{4k} = \frac{1}{52} \text{ ma } \downarrow;$$

$$I_{6k} = \frac{11}{13} \text{ ma } \downarrow.$$



Example 8

$$\text{From these, we calculate: } P_{8k} = I_{8k}^2 R_{8k} = \left(\frac{45}{52} \text{ ma}\right)^2 8k = 5.99 \times 10^{-3} \text{ W} = 5.99 \text{ mW}$$

$$P_{4k} = I_{4k}^2 R_{4k} = \left(\frac{1}{52} \text{ ma}\right)^2 4k = 1.5 \times 10^{-6} \text{ W} = 1.5 \mu\text{W}$$

$$P_{6k} = I_{6k}^2 R_{6k} = \left(\frac{11}{13} \text{ ma}\right)^2 6k = 4.30 \times 10^{-3} \text{ W} = 4.30 \text{ mW}$$

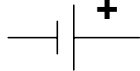
$$P_{12V} = I_{12V} V_{12V} = \left(\frac{45}{52} \text{ ma}\right) 12V = 10.4 \times 10^{-3} \text{ W} = 10.4 \text{ mW}$$

$$P_{5V} = I_{5V} V_{5V} = \left(\frac{-1}{52} \text{ ma}\right) 5V = -0.096 \times 10^{-3} \text{ W} = -96 \mu\text{W}$$

The results deserve some discussion: in **all** the resistors, power (energy) is “taken” from the circuit, and the 12V source puts power (energy) **into** the circuit. However, the 5V source has current “forced” through it “backwards.” Consequently, the 5V source also **takes** power (energy) from the circuit. For an energy accounting standpoint, there **must** be a balance such that **energy taken out = energy put in**. Doing the numbers above, we get a virtual balance (within round-off).

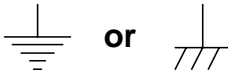
Note, however, that our main interest for future work is to calculate the power to be “dissipated” in circuit elements to specify the appropriate power-handling capability. This is a practical issue since the power is dissipated in the form of heat, and components can literally burn up if inappropriate power ratings are used.

GLOSSARY OF CIRCUIT SYMBOLS:

Voltage Source (battery): 

Resistor: 

Path of zero Resistance: 

Ground or "common:"  or 