

PHYS 375: Introduction

- Some general remarks
- Note on labs
- Today's lecture:
 - Storing electric energy
 - Voltage, Current, Power
 - Conductivity, Ohm's law
 - Resistor
 - Kirchhoff's laws
 - Series and parallel circuits
 - Thevenin & Northon equivalent circuits

Introduction

- Instructors:
 - *Philippe Piot* (NIU/FNAL/ANL) at NIU on Mondays this semester; lectures, labs, and homeworks
 - *Nikolai Vinogradov* at NIU most of the time will take care of the labs execution and grading.
- Book (required):
 - *An Introduction to Modern Electronics* by William L. Faissler.
- Course web page see:
http://nicadd.niu.edu/~piot/phys_375/
- Grading:
labs: 30 %, homework: 30 %, midterm: 20 %, final 20 %

LAB: Octave <http://www.gnu.org/software/octave/>

- Example how to make a plot:

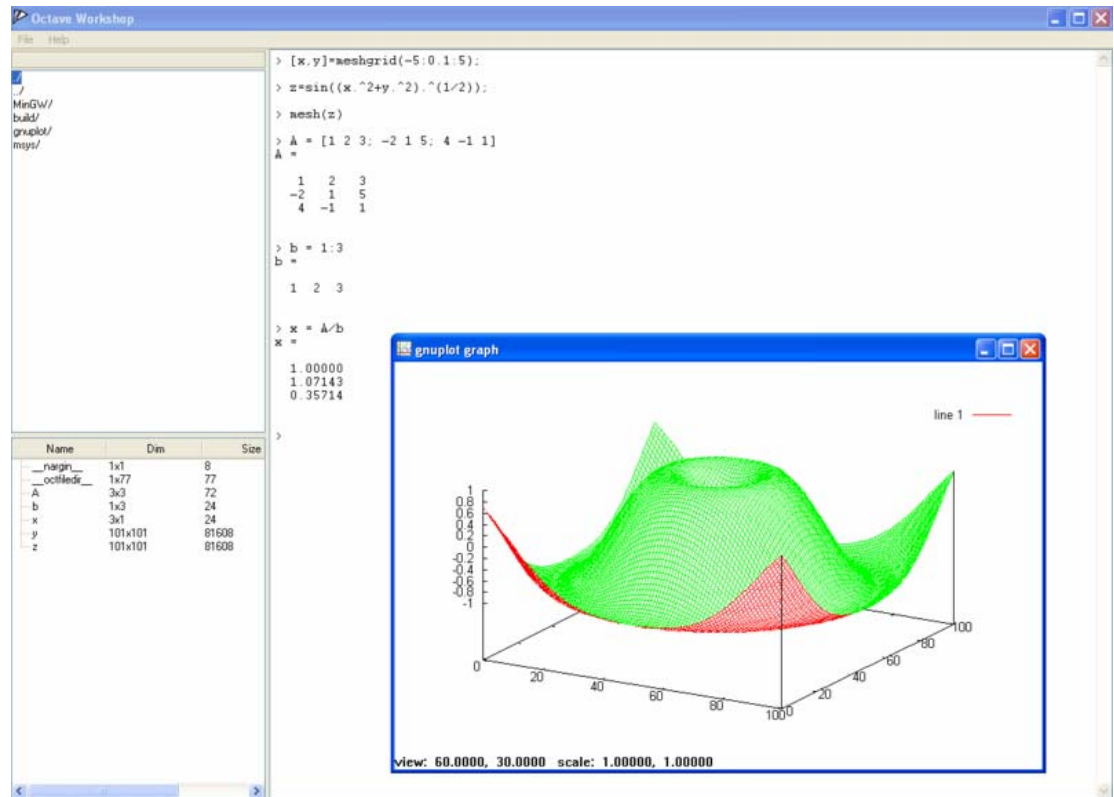
```
> v=[0, 3, 5, 10, 40, 23]
> i=[0, 4, 2, 1, 0.1, 0.01]
> plot (i,v)
```

- For log or log-log plot

```
> semilogx(i,v)
> semilogy(i,v)
> loglog(i,v)
```

- Other features:

- Can work with complex number
- Polynomial fits,...
- Can numerically solve ODE
-



LAB: Error bars

- When providing some experimentally measured value you will need to provide the uncertainty or errorbar on this value

- If

$$C = A + B$$

- Then the uncertainty on C is ΔC :

$$|\Delta C| = |\Delta A| + |\Delta B|$$

- If

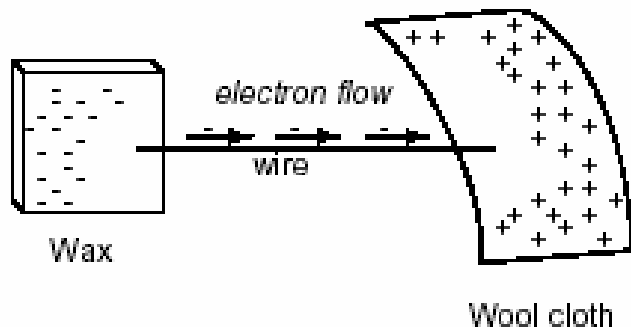
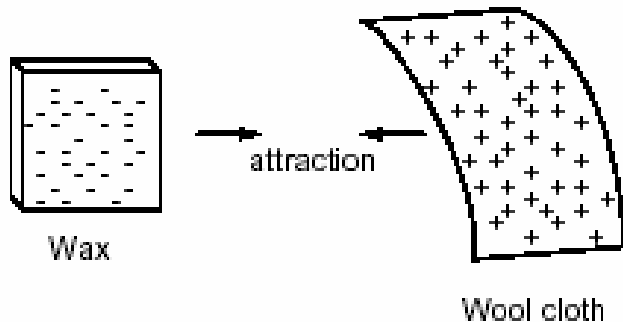
$$C = AB$$

- Then the uncertainty on C is ΔC :

$$|\Delta C| = |B\Delta A| + |A\Delta B|$$

- for more complex equation take the log and differentiate...

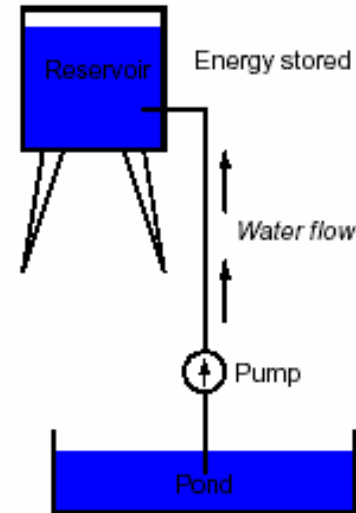
Storing energy: static electricity example



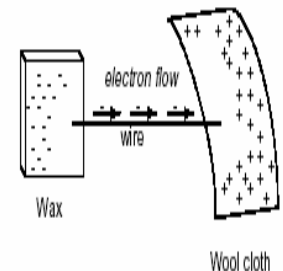
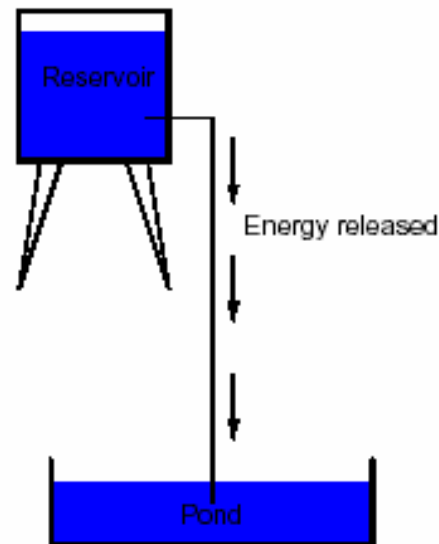
- Rubbing a wool cloth on a piece of wax create a charge unbalance
 - Wax has an excess of electrons
 - Wool has a deficit of electrons
- Wax and wool are attracted via an Electric force that tries to bring back the electron at their original position around the nuclei
- If a wire is contacted to the wax and wool cloth electron will flow from wax to wool cloth
- By rubbing the two elements we stored energy in the system {Wax + Wool cloth} this is potential (electric) energy

Storing energy: gravity example

- A similar example of energy storing system is a water reservoir and pond
- Pumping the water from the pond into a reservoir provide the necessary work needed to stored energy (here “gravitational” potential energy, $U=mgh$) – this is analogous to rubbing the piece of wax against the wool cloth
- Turning off the pump and letting the water drain back to the pond is analogous to contacting a wire on the wax and cloth to let the electron flowing back to their initial state



*Rubbing
wax and
wool cloth
together*



Voltage

- The potential energy stored in a system is capable of provoking electron to flow in a conductor.
- Potential electric energy is $U=eV$ where V is the **voltage**, and e the electron charge

$$V = \int_A^B \vec{E} \cdot d\vec{l} = \Phi_B - \Phi_A$$

- The **voltage** is the required work to move a charge from a point to another point

$$W = \int \vec{F} \cdot d\vec{l} = e \int \vec{E} \cdot d\vec{l} = eV$$

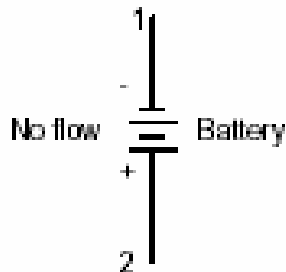
- The flow of electron is called **current**: it is the charge flow per unit of time:

$$I \equiv \frac{dQ}{dt} = e \frac{dN}{dt}$$

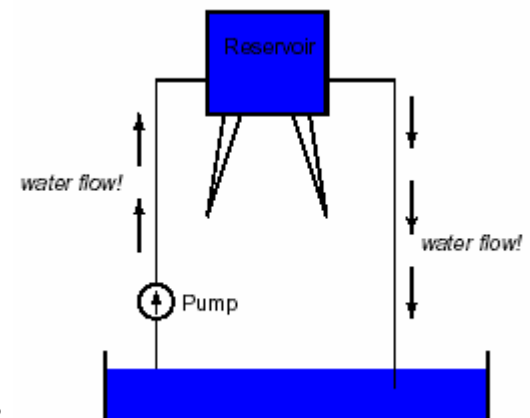
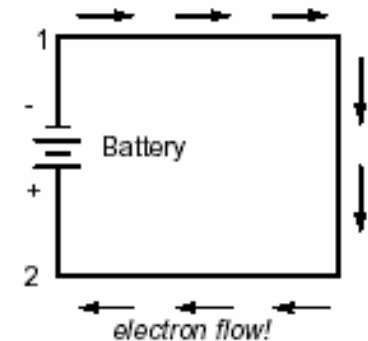
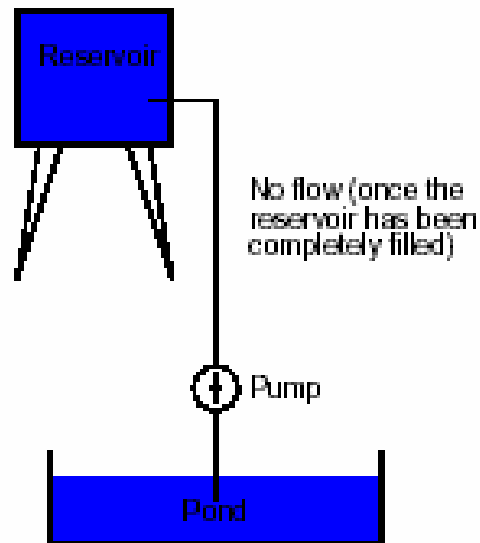
Storing electric energy: battery

- In essence the example of {wax + wool cloth} system can be seen as a battery.
- Practically battery are mainly based on chemical reaction (e.g. a series of plate bathing in a liquid or semi-solid medium)

*Symbol for
battery*

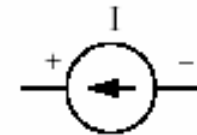


Water analogy



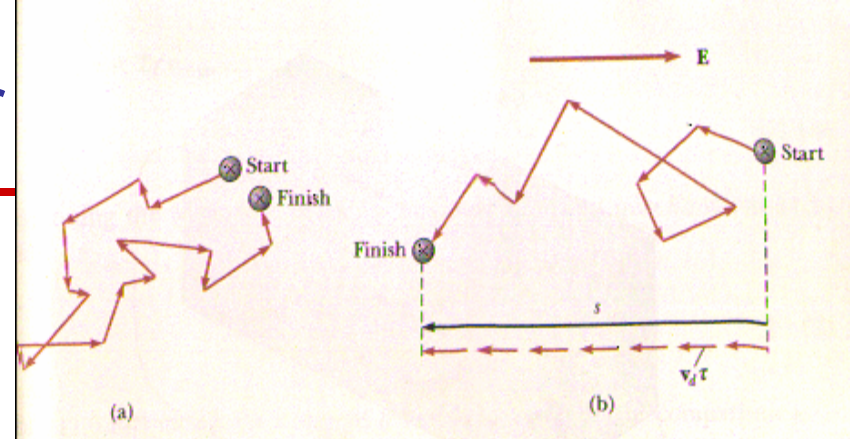
Current versus Voltage source

- In practical situation there are
 - Voltage sources, and
 - Current sources.
- Voltage sources: ideally provide a voltage value for any load
- Current sources: ideally provide a current value for any load



Drude model of a conductor

- Model of conduction elaborated by Paul Karl Ludwig Drude (1863-1906)



- The equation of motion in a conductor under the influence of an electric field is

$$m \frac{d\vec{v}}{dt} = e\vec{E} - \frac{m}{\tau} \vec{v}$$

Drag force due to scattering

Motion due to E-field

- For large time after the electric field has been established the velocity is constant (steady state) $\vec{v} \xrightarrow{t \rightarrow \infty} \vec{v}_f$.

So

$$0 = eE - \frac{m}{\tau} v_f \Leftrightarrow \tau^{-1} = \frac{eE}{mv_f} \equiv \frac{e}{m\mu}$$

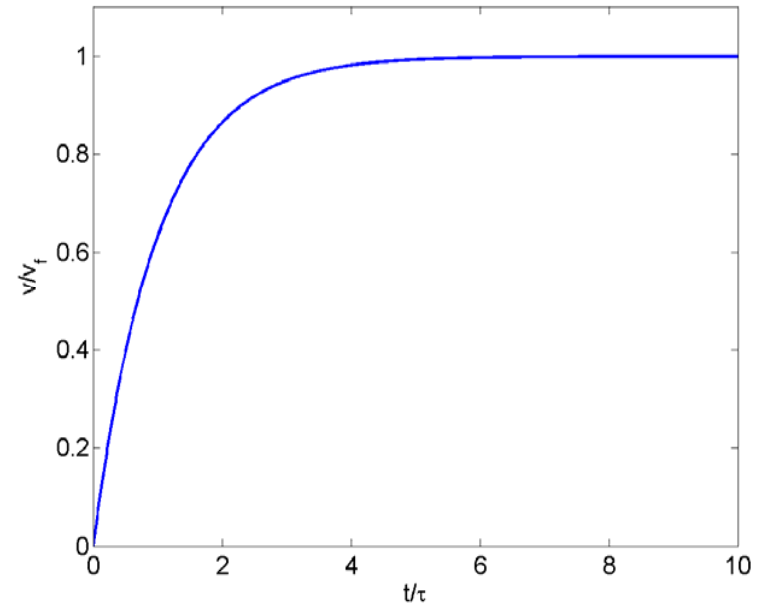
Electron mobility

Drude model of a conductor

- Solution of previous equation is simply

$$v(t) = v_f \left(1 - e^{-\frac{t}{\tau}} \right)$$

wherein τ is the relaxation time. Here we considered one electron only



- The current associated to a collection of electron with electronic density n (i.e. n is a number of electron per unit of volume) is:

$$J = nev_f = \frac{Ne^2\tau}{m} E$$

- So we have a generally **linear** vectorial relation between J and E :

conductivity

$$\vec{J} = \sigma \vec{E} \equiv \frac{1}{\rho} \vec{E}$$

resistivity

Ohm's law

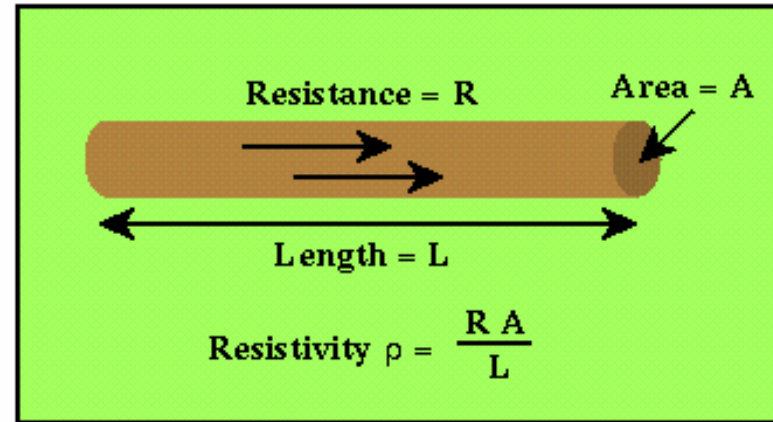
- J is a current density, the current, I , is the surface integral

$$I = \iint \vec{J} \cdot d\vec{S} = \iint \sigma \vec{E} \cdot d\vec{S} = \frac{A\sigma}{L} V \equiv \frac{1}{R} V$$

- many assumption are “buried” in the previous equation: we assume the E -field is constant over the conductor cross-section and length. L is the considered length within the conductor and A the cross-sectional area. R is the conductor **resistance**

$$V = RI$$

- Ohm's law generally written as appeared in *Die galvanische Kette, mathematisch bearbeitet*. Between 1825-27, Georg Simon Ohm (1789-1854), had been studying electrical conduction following as a model Fourier's study of heat conduction.



Georg Simon Ohm (1789-1854),

Some units...

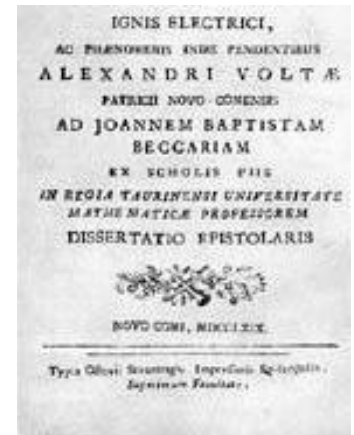
- V , the voltage is measured in **Volt** (Alessandro Volta); symbol is V
- I , the current is measured in **Ampère** (André Ampère); symbol is A
- R , the resistance is measured in **Ohm** (Georg Ohm); symbol is Ω



André Marie Ampère (1775 - 1836)



Alessandro Volta (1747-1827)



Power & alternative expression of Ohm's law

- Another measure of the free electrons activity in a metal is the power. The power is the amount of work done per unit of time

$$P = \frac{dW}{dt} = \frac{d(eNV)}{dt} = V \frac{d(eN)}{dt} = VI$$

- The power is measured in Watt (symbol W)
- Using Ohm's law the power can be expressed as:

$$P = RI^2 = \frac{V^2}{R}$$

Refer to as Joule's law

- So resistance dissipates power (Joule's heating)



James Watt (1736-1819)



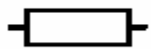
James Prescott Joule (1818-1889)

Resistors

- Resistance is useful if its value is controlled
- Resistors are special components made for the express purpose of creating a precise quantity of resistance for insertion in an electric circuit.
- Typically made of metal wire or carbon and engineered to maintain a precise, stable value of resistance over a wide range of environmental conditions.
- Resistors produce heat that needs to be dissipated



Symbols for resistor



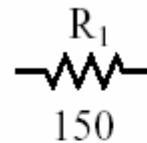
The most commonly used symbol



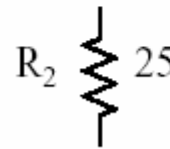
variable resistance



... or ...



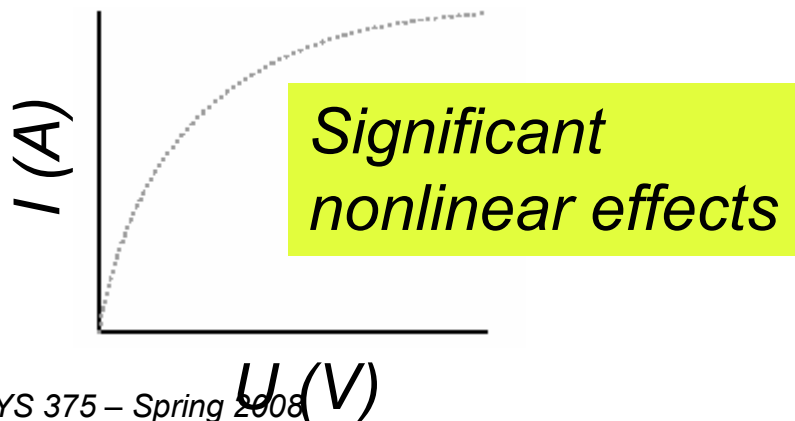
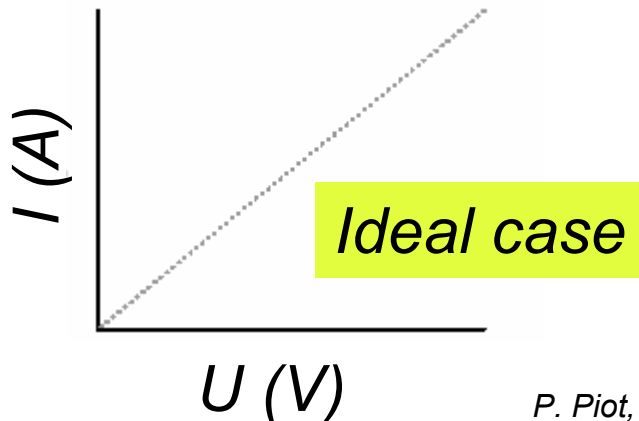
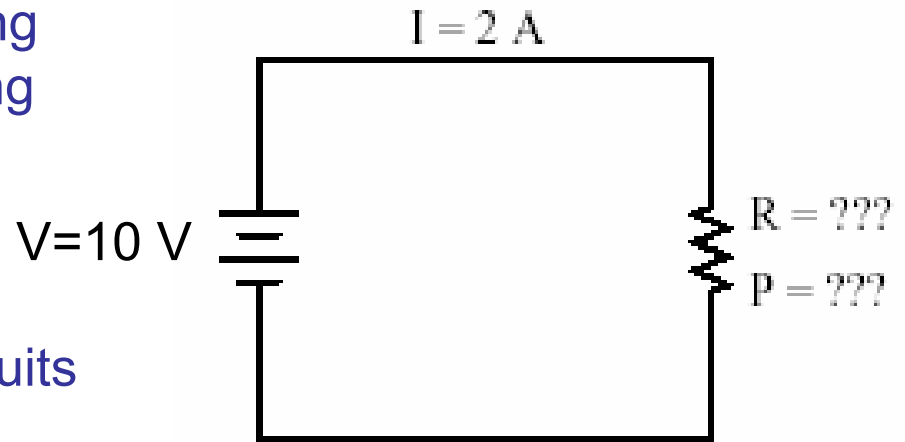
This is resistor " R_1 " with a resistance value of 150 ohms.



This is resistor " R_2 " with a resistance value of 25 ohms.

Resistor: a simple example

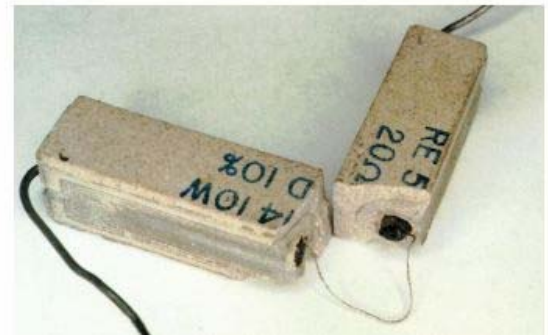
- Needed resistance and power rating for a resistance capable of proving the quoted circuit parameters?
- **$R=V/I=5\ \Omega$** , and **$P=RI^2=20\ \text{W}$** .
(Typical resistor in electronic circuits are rated for 0.25 W)
- Note that Ohm's law is an idealized law, nonlinearities might lead to higher order terms (sometime useful e.g. thermistors)



More on Resistors

- It is custom to use a color coded nomenclature to identify resistors resistance values

<div> <div>0 1 2 3 4 5 6 7 8 9</div> <div> <div>0 Black</div> <div>1 Brown</div> <div>2 Red</div> <div>3 Orange</div> <div>4 Yellow</div> <div>5 Green</div> <div>6 Blue</div> <div>7 Purple</div> <div>8 Grey</div> <div>9 White</div> </div> </div> <div> <div>±1% Brown</div> <div>±2% Red</div> <div>±5% Gold</div> <div>±10% Silver</div> </div>	<div> <div>±1% ±2% ±5% ±10%</div> <div> <div>27K EXAMPLE</div> <div>0 X1</div> <div>1 1 X10</div> <div>2 2 X100</div> <div>3 3 X1000</div> <div>4 4 X10000</div> <div>5 5 X100000</div> <div>6 6 X1000000</div> <div>7 7 X10</div> <div>8 8 X100</div> <div>9 9</div> </div> </div>	<div> <div>±1% ±2% ±5% ±10%</div> <div> <div>15K EXAMPLE</div> <div>0 0 X1</div> <div>1 1 1 X10</div> <div>2 2 2 X100</div> <div>3 3 3 X1000</div> <div>4 4 4 X10000</div> <div>5 5 5 X10</div> <div>6 6 6 X100</div> <div>7 7 7</div> <div>8 8 8</div> <div>9 9 9</div> </div> </div>	<div> <div>±1% ±2% ±5% ±10%</div> <div> <div>620K EXAMPLE</div> <div>0 0 X1</div> <div>1 1 1 X10</div> <div>2 2 2 X100</div> <div>3 3 3 X1000</div> <div>4 4 4 X10000</div> <div>5 5 5 X10</div> <div>6 6 6 X100</div> <div>7 7 7</div> <div>8 8 8</div> <div>9 9 9</div> </div> </div>
Color Codes	4 Band Resistors	5 Band Resistors	6 Band Resistors



- What is inside a resistor??

Kirchoff's laws

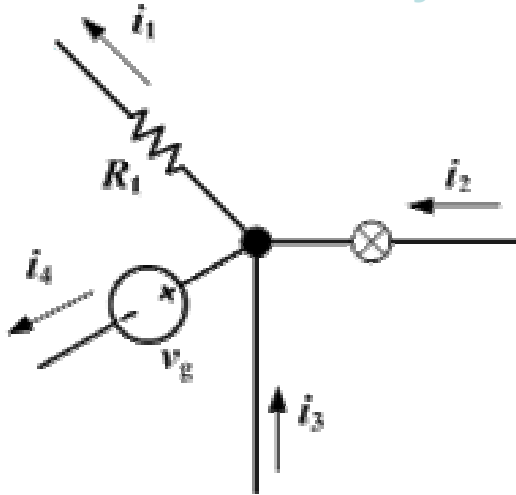
- **Current Law:** At any point in an electrical circuit where charge density is not changing in time, the sum of current flowing towards that point is equal to the sum of currents flowing away from that point.

This is a consequence of charge conservation.

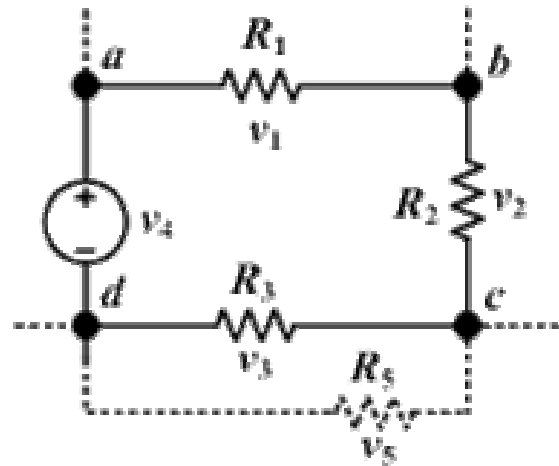
- **Voltage Law:** The directed sum of the electrical potential difference (= voltage) around a circuit must be zero.

This is a consequence of energy conservation. It can be simply obtained from the Faraday's law for static (time-independent) systems

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = 0,$$



$$i_1 + i_4 = i_2 + i_3$$



$$v_1 + v_2 + v_3 + v_4 = 0$$

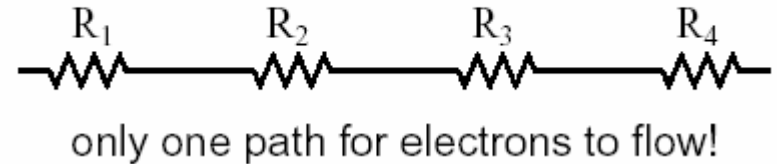


Gustav Kirchhoff (1824-1887)

Series & Parallel Circuits

- Serial circuits:** components are connected end-to-end in a line that form a single path for the electrons to flow.

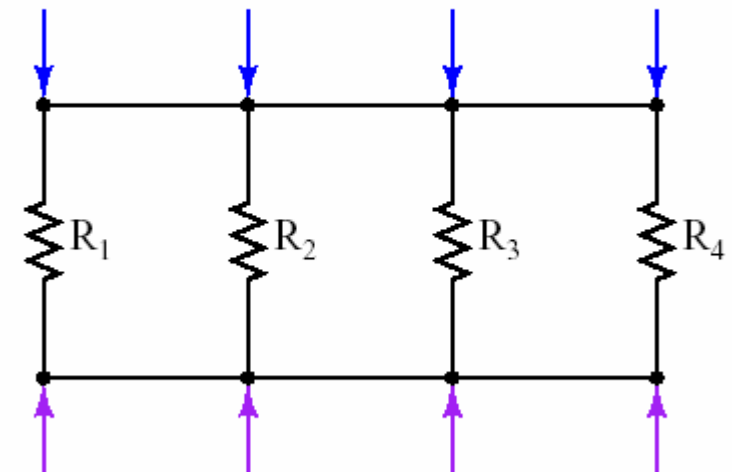
→ *Series connection*



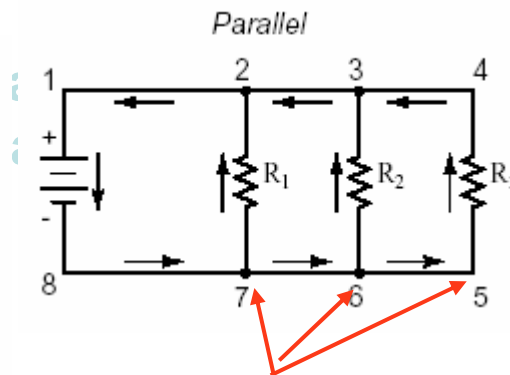
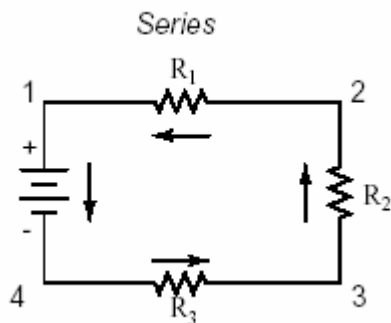
- Parallel circuits:** components are connected across each other's leads

→ *Parallel connection*

These points are electrically common



These points are electrically common

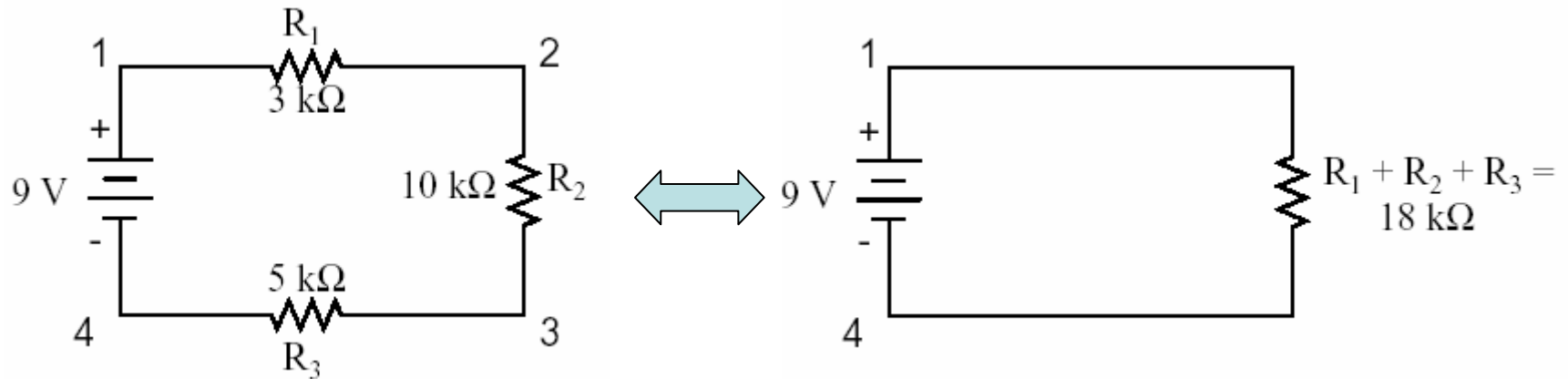


Each individual path through R_1 , R_2 and R_3 is called a branch

Series Circuits

- In a series circuits with several resistors, the total resistance is given by

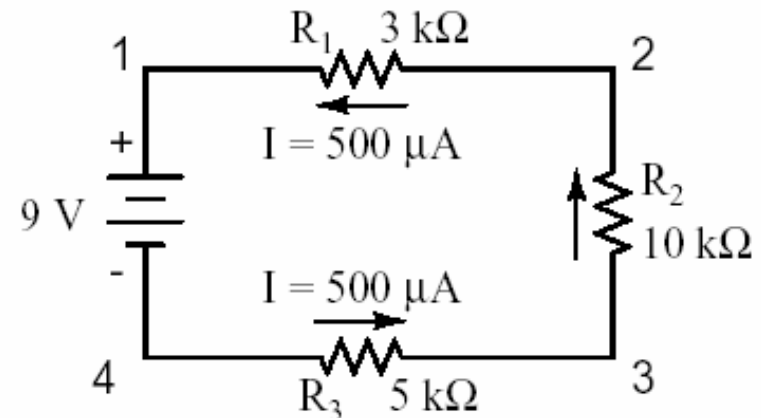
$$R_{total} = \sum_i R_i \quad I = I_i \quad \forall i \quad V = \sum_i V_i$$



$$V_1 = R_1 I_1 = 1.5 \text{ Volts}$$

$$V_2 = R_2 I_2 = 5.0 \text{ Volts}$$

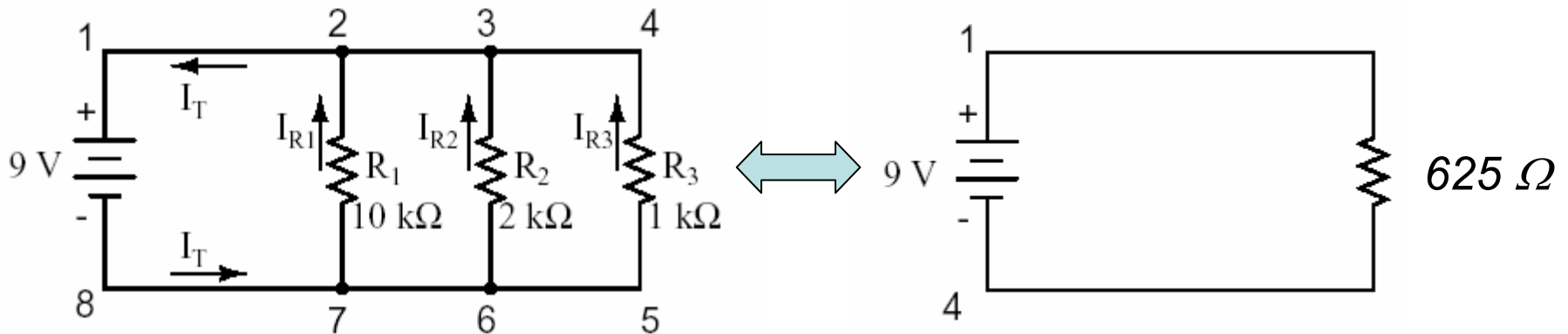
$$V_3 = R_3 I_3 = 2.5 \text{ Volts}$$



Parallel Circuits

- In a parallel circuits with several resistors, the total resistance is given by

$$1/R_{total} = \sum_i 1/R_i \quad I = \sum_i I_i \quad V = V_i \quad \forall i$$



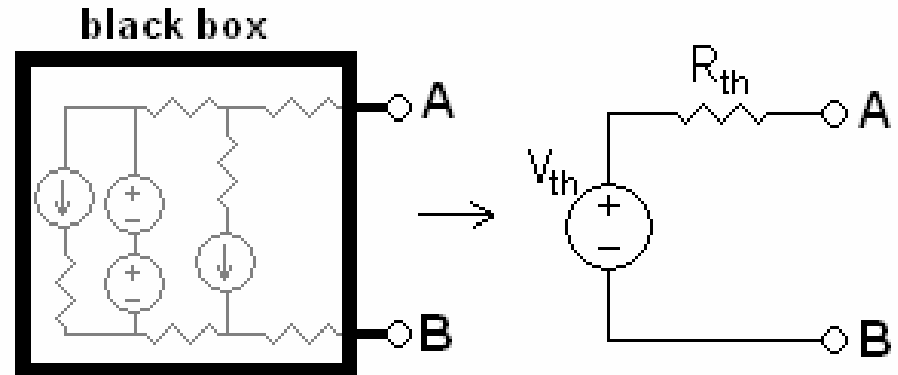
$$I_T = I_{R1} + I_{R2} + I_{R3}$$

$$V = R_1 I_{R1} = R_2 I_{R2} = R_3 I_{R3}$$

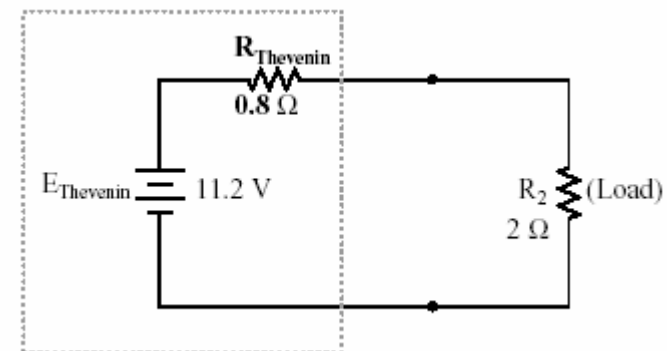
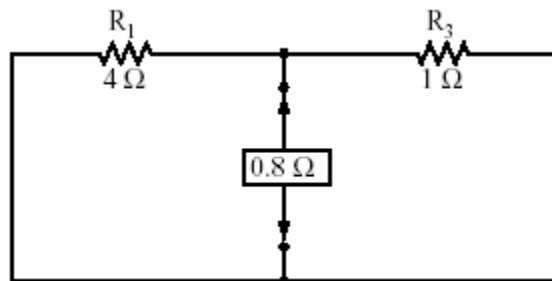
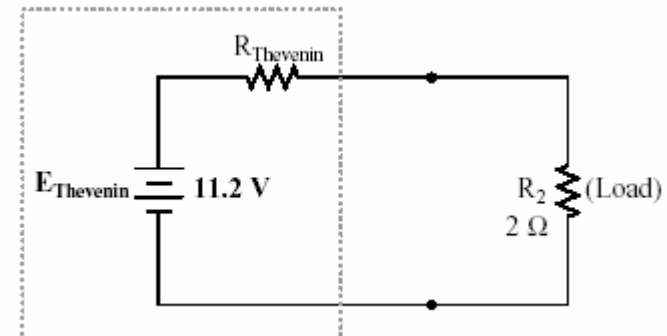
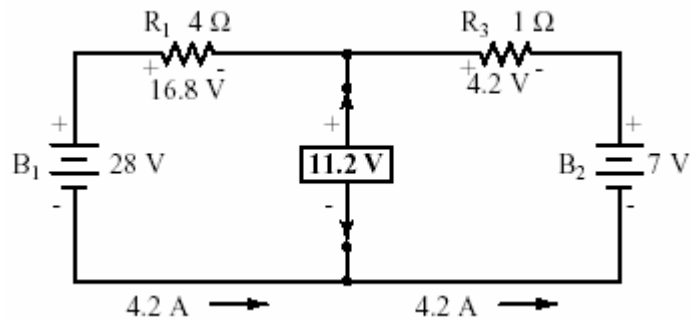
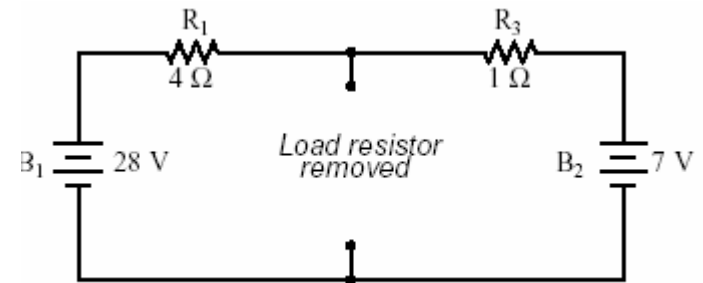
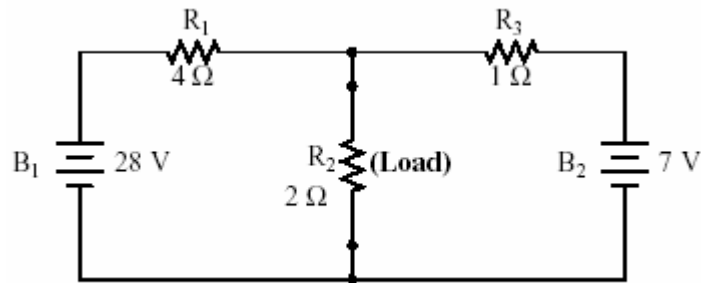
$$I_T = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

Thevenin's Theorem

- This theorem states that a circuit of voltage sources and resistors can be converted into a **Thévenin Equivalent**, which is a simplification technique used in circuit analysis.
- The circuit consists of an ideal voltage source in series with an ideal resistor.
- To calculate the equivalent circuit, one needs a resistance and a voltage - two unknowns. And so, one needs two equations. These two equations are usually obtained by using the following steps, but any conditions one places on the terminals of the circuit should also work:
 - Calculate the output voltage, V_{AB} , when in open circuit condition (no load resistor - meaning infinite resistance). This is V_{Th} .
 - Calculate the output current, I_{AB} , when those leads are short circuited (load resistance is 0). R_{Th} equals V_{Th} divided by this I_{AB} .
- The equivalent circuit is a voltage source with voltage V_{Th} in series with a resistance R_{Th} .**



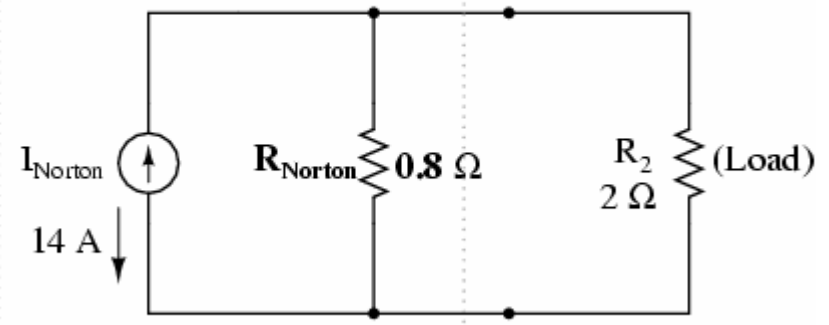
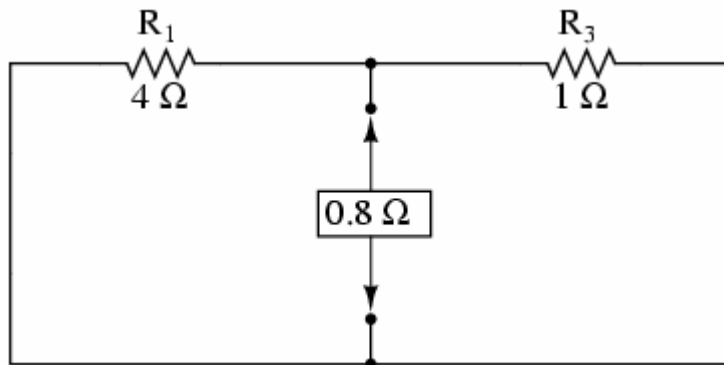
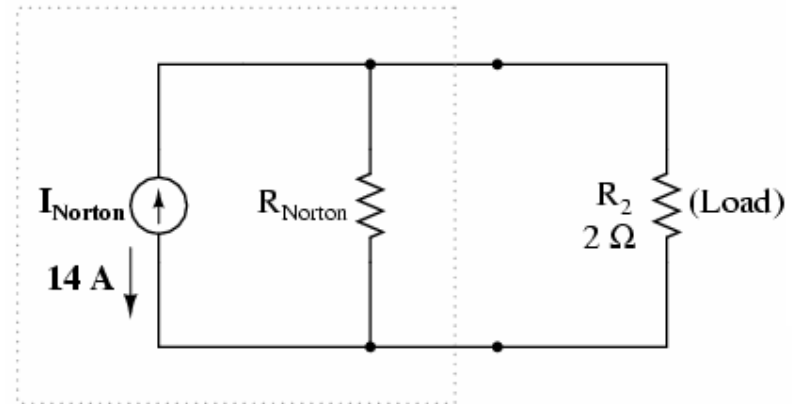
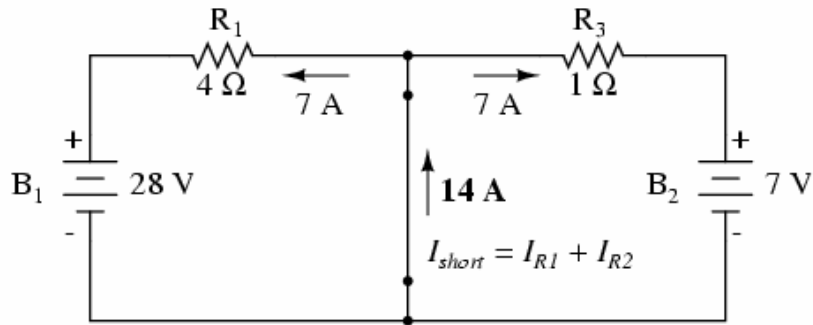
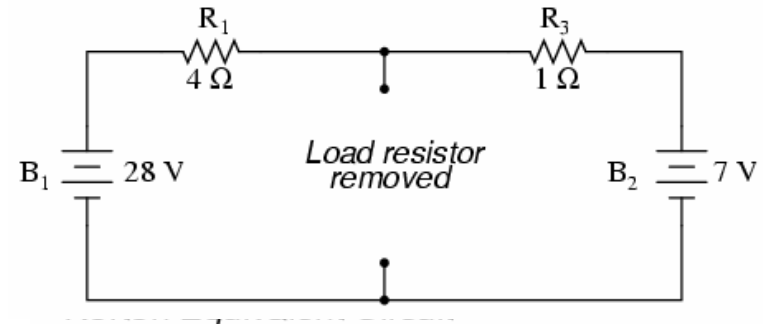
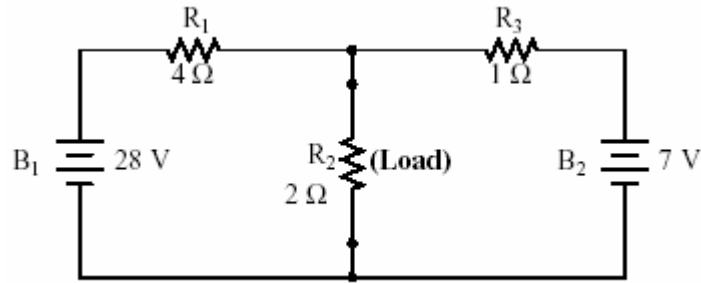
Example of computed Thévenin equivalent circuit



Norton's Theorem

- This theorem states that a circuit of voltage sources and resistors can be converted into a **Norton Equivalent**, which is a simplification technique used in circuit analysis.
- The circuit consists of an ideal voltage source in parallel with an ideal resistor.

Example of computed Thévenin equivalent circuit

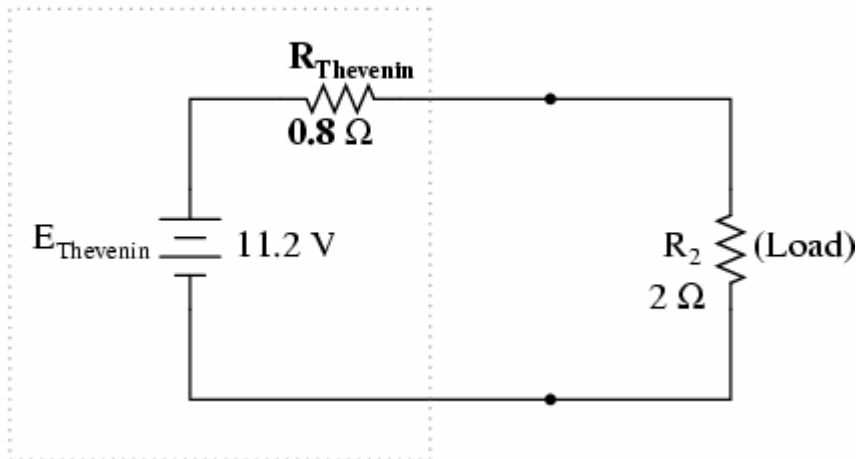


Norton-Thevenin equivalence

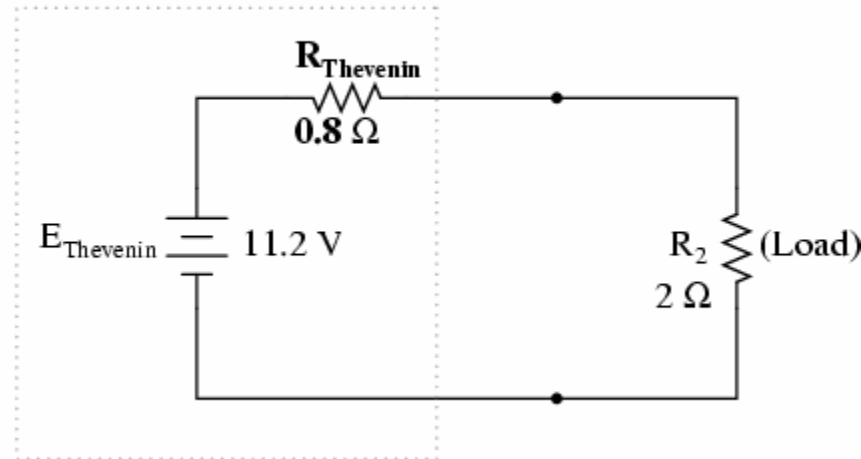
REVIEW:

- Thevenin and Norton resistances are equal.
- Thevenin voltage is equal to Norton current times Norton resistance.
- Norton current is equal to Thevenin voltage divided by Thevenin resistance.

Thevenin Equivalent Circuit



Thevenin Equivalent Circuit



$$R_{\text{Thevenin}} = R_{\text{Norton}}$$

$$E_{\text{Thevenin}} = I_{\text{Norton}} R_{\text{Norton}}$$

$$I_{\text{Norton}} = \frac{E_{\text{Thevenin}}}{R_{\text{Thevenin}}}$$