



HAM Radio Board of Education

NEVER STOP LEARNING

Antenna Summit

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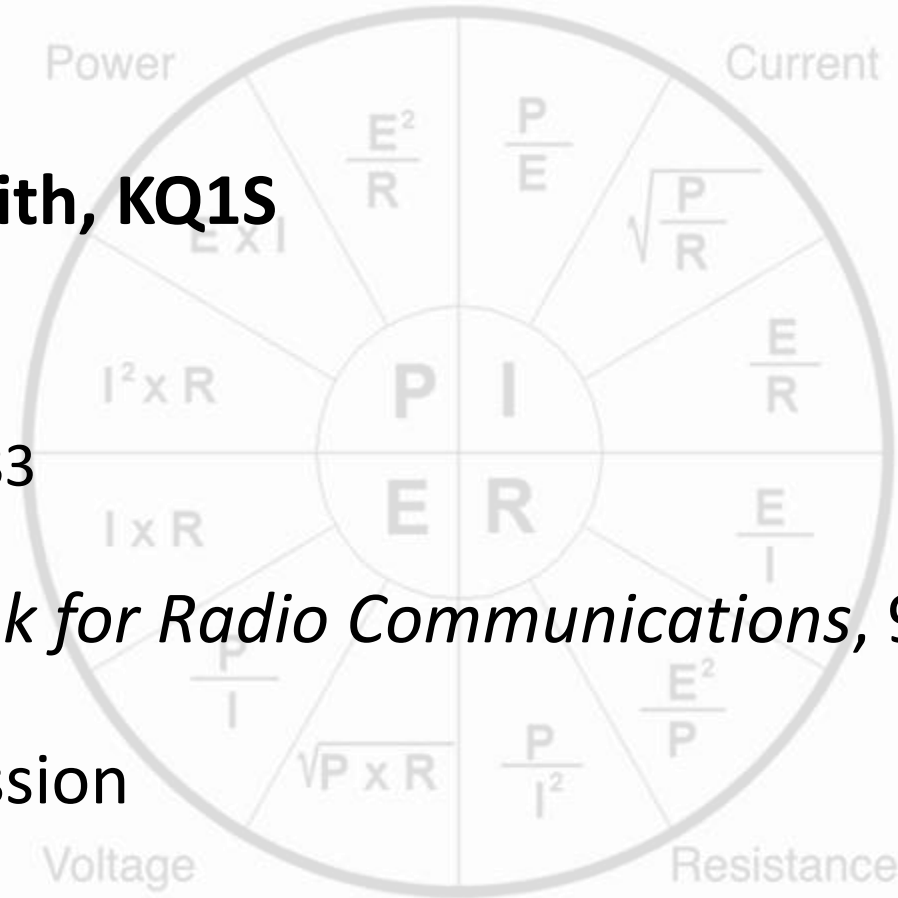
Introduction

- **Instructor : Bill Smith, KQ1S**

- Amateur Extra
- Licensed since 1983

- *The ARRL Handbook for Radio Communications*, 98th Edition, 2021

- Q & A at end of session



Course Overview

- Mathematics Review
- Electricity, Power, and Energy
- Basic Circuit Principles
- Resistance, Conductance, Capacitance, and Inductance
- Kirchhoff's Laws
- Thevenin's and Norton's Theorems
- Power and Energy

Easy Math Review

Order of mathematics operations - Remember BODMAS

- Work within Brackets first
- (Order of the operations is important)
- Perform Divisions and Multiplications as you encounter them – Inside of brackets first, then outside
- Perform Additions and Subtractions as you encounter them – Inside of brackets first, then outside
- Let's look at a few examples...

Easy Math Review

Remember - **BODMAS**

- **Ex. 1** **$10 - 2 \times 3$**

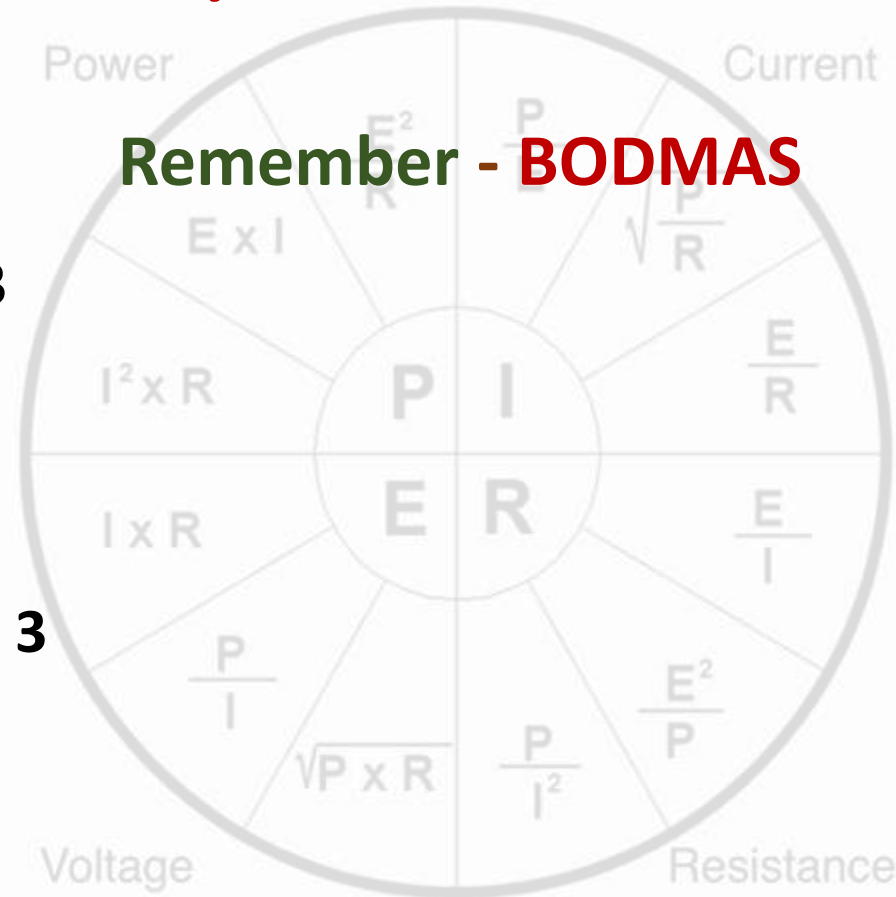
$$= 10 - 6$$

$$= 4$$

- **Ex. 2** **$(10 - 2) \times 3$**

$$= 8 \times 3$$

$$= 24$$



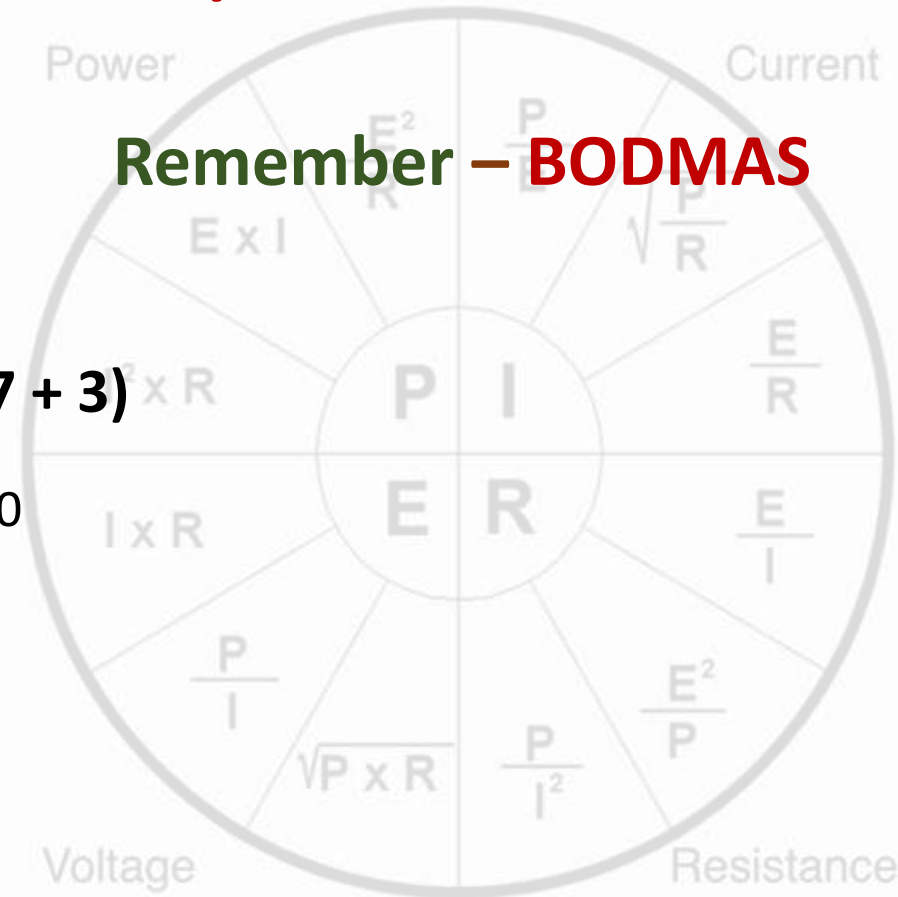
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Easy Math Review

Remember – **BODMAS**

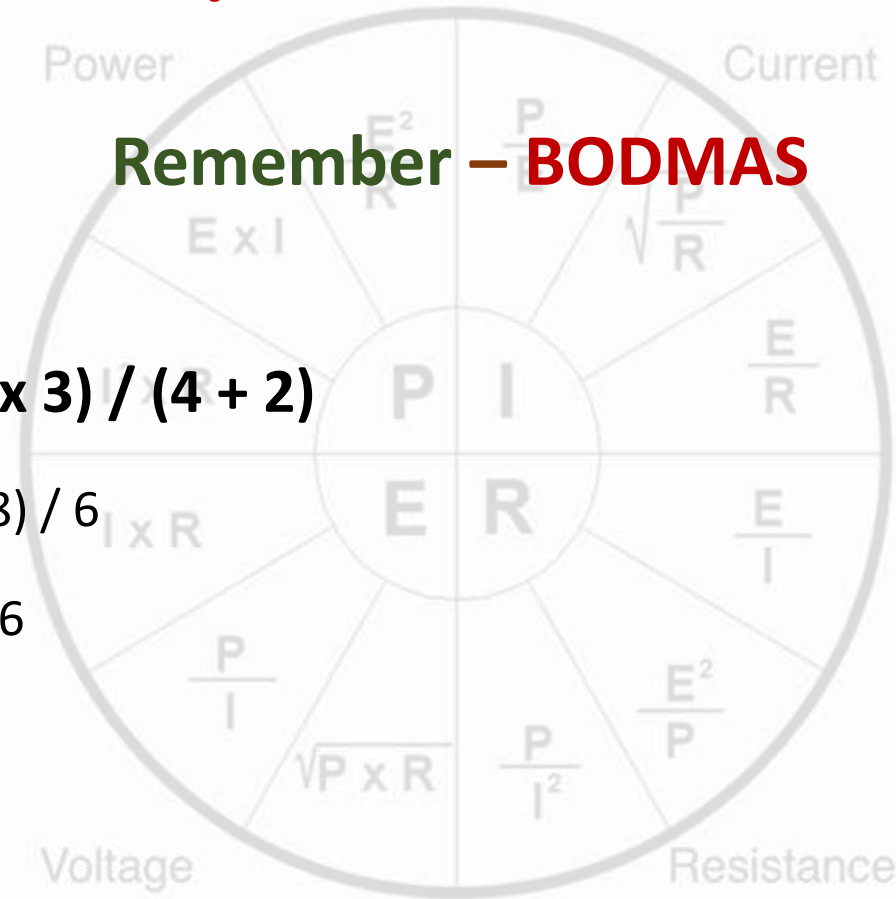
- **Ex. 3** $-4 + 5 \times (7 + 3)^2 \times R$
 $= -4 + 5 \times 10$
 $= -4 + 50$
 $= 46$



Easy Math Review

Remember — **BODMAS**

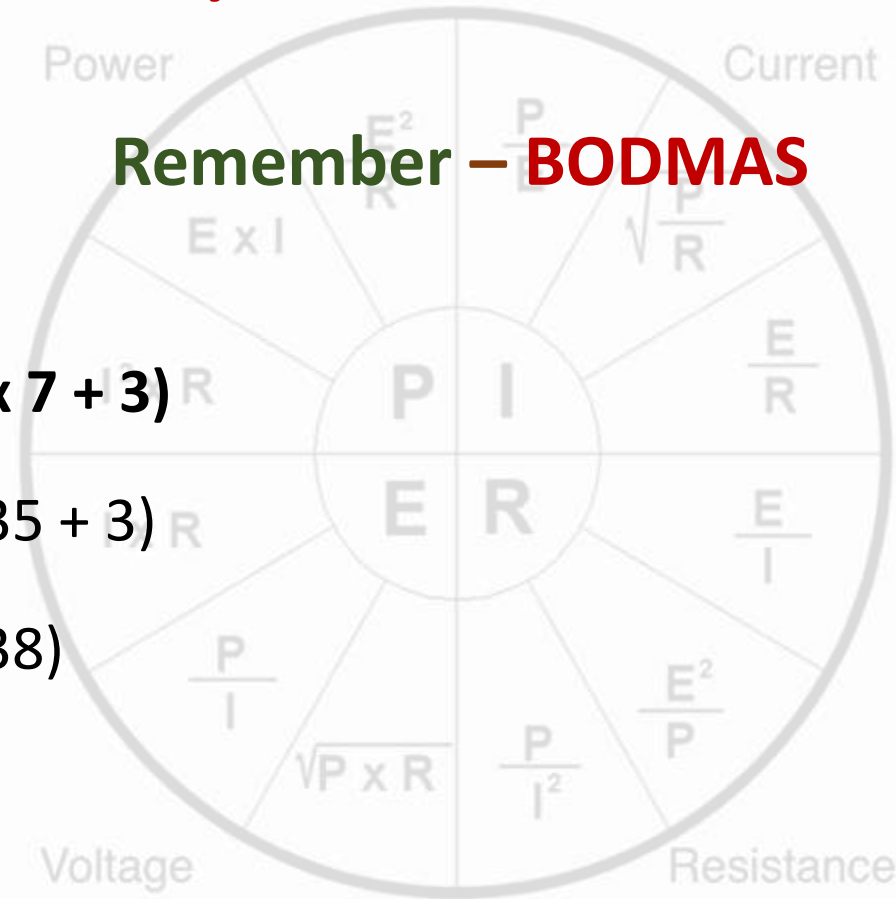
- **Ex. 4** **$12 (5 + 6 \times 3) / (4 + 2)$**
 $= 12 (5 + 18) / 6$
 $= 12 \times 23 / 6$
 $= 276 / 6$
 $= 46$



Easy Math Review

Remember – **BODMAS**

- Ex. 5 $-2 (x + 5 \times 7 + 3)$
 $= -2 (x + 35 + 3)$
 $= -2 (x + 38)$
 $= -2x - 76$



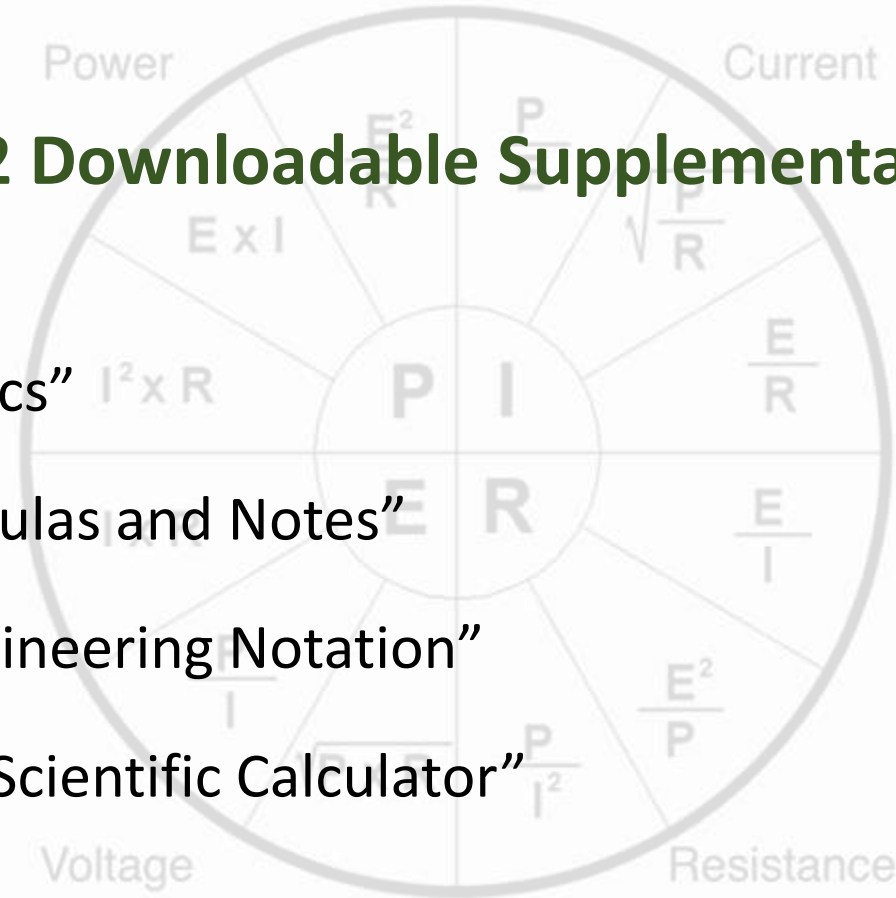
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Additional Math Resources

Chapter 2 Downloadable Supplemental Material

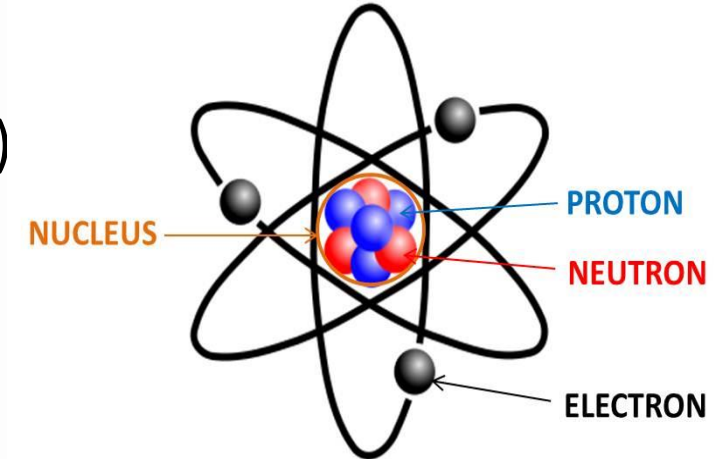
- “Radio Mathematics”
- “Radio Math Formulas and Notes”
- “Scientific and Engineering Notation”
- “Understanding a Scientific Calculator”



Electrical Fundamentals

Atoms and Molecules

- **Atom** – Primary building block of all matter
- **Construction** – Nucleus (Protons, Electrons, Neutrons)
 - **Protons** – Positively (+) charged
 - **Electrons** – Negatively (-) charged
 - **Neutrons** – No charge
- **Molecule** – Two or more atoms bonded together



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Electrical Fundamentals

Atoms and Molecules

- **Electrically Neutral** – Atoms and Molecules carry no charge until acted upon a chemical, mechanical, or electrical process
- **Positively (+) Charged Atom or Molecule** = More protons than electrons
- **Negatively (-) Charged Atom or Molecule** = More electrons than protons
- **Ions** – Charged atoms or molecules
 - **Free Electrons** – (Not bound to an atom) because they are negatively (-) charged

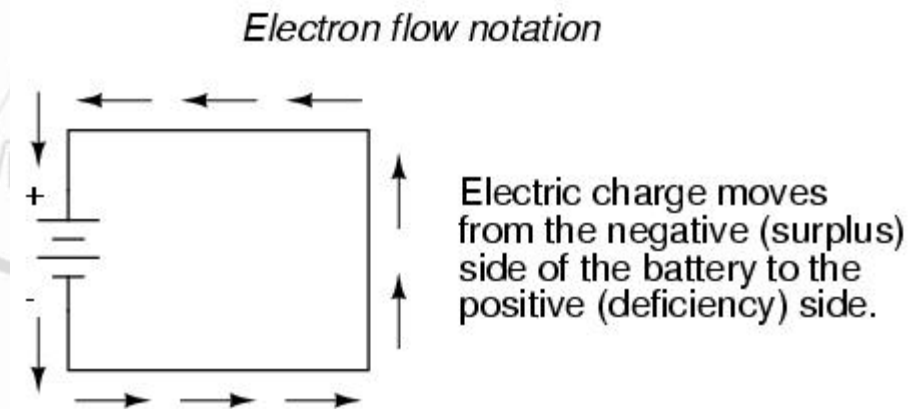
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Electrical Fundamentals

Electrical Charge, Voltage, and Current

- **Current** – Movement of electrical charge between poles of voltage source
- **Current Flow Conventions**
 - **Electron Current** – Negative charges (electrons) move from the negative voltage pole to the positive voltage pole



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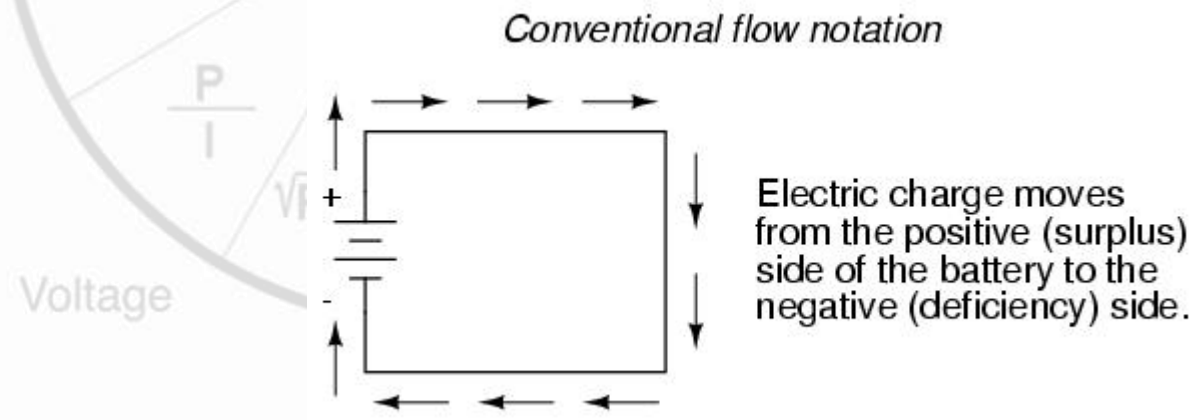


Electrical Fundamentals

Electrical Charge, Voltage, and Current

- **Current Flow Conventions**

- **Conventional Current** – Positive charges move from the positive voltage pole to the negative voltage pole – Used throughout “The ARRL Handbook”



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Electrical Fundamentals

Units of Measurement

- **Volt (V)** – The difference in electrical protentional between two points
- **Ampere (A)** – Amount of current flow between voltages
- **Coulomb (C)** – Electrical charge = 6.25×10^{18} electrons or protons

Electrical Fundamentals

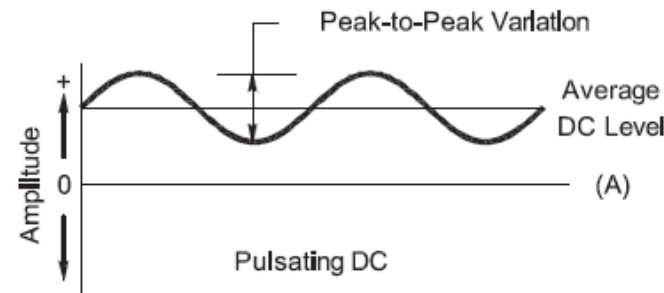
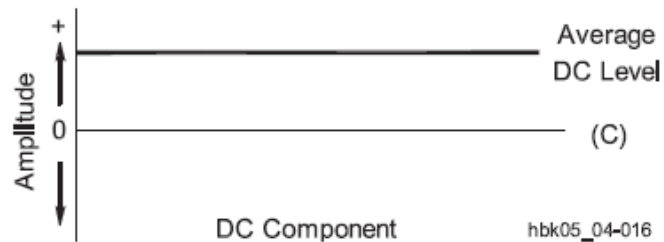
Types of Current

Direct Current (DC) – Electrical current allowed by the voltage source to flow in only one direction (e.g., A battery with positive and negative poles)

Steady State DC – Current is positive relative to zero and does not vary

Pulsating DC – Current is always positive relative to zero, regardless of variation

Intermittent DC – Current is positive but periodically reaches zero

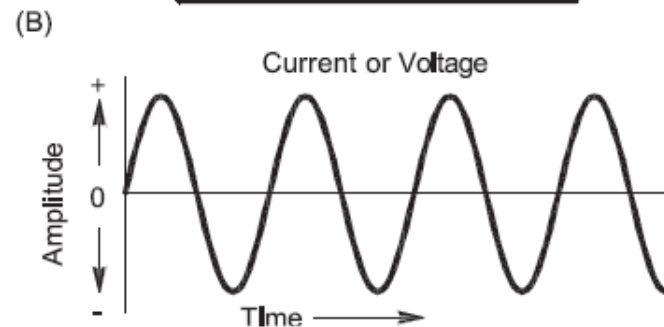


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Electrical Fundamentals

Types of Current



Alternating Current (AC) – Electrical current allowed by the voltage source to flow alternating in both directions (e.g., Regular household current)

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Electrical Fundamentals

Resistance and Conductance

- **Conductor** – Material in which electrons or ions can move (flow) easily
- **Insulator** – Material within which electrons or ions have difficulty moving
- **Resistance** – Essentially the difficulty that moving charges encounter when flowing in a conductor
- **Resistor** – A component made of material exhibiting a certain amount of resistance
- **Ohms (Ω)** – The amount of resistance to current flow

Electrical Fundamentals

Resistance and Conductance

- **Conductance (G)** – The reciprocal of resistance ($1/R$)
- **Siemens (S)** – The modern unit of measure of conductance
 - Siemens has replaced the obsolete unit Mho
 - A resistance of 1 Ohm = conductance of 1 Siemens ($1/1$)
 - A resistance of 1,000 Ohms = conductance of 0.001 Siemens ($1/1,000$)

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Electrical Fundamentals

Resistance and Conductance

- The amount of current that may flow in a conductor when a certain voltage is applied varies with the resistance of the conductor (**Resistivity**)
- **1 Ohm (Ω)** = Amount of resistance that allows 1 Ampere of current to flow between points having a potential difference
- **Standard of Resistivity** – Conductors are compared to annealed copper
 - (See Table 2.1 – Annealed copper = 1.00)

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Electrical Fundamentals

Resistance and Conductance

- Ohm's Law

$$R = E / I$$

where

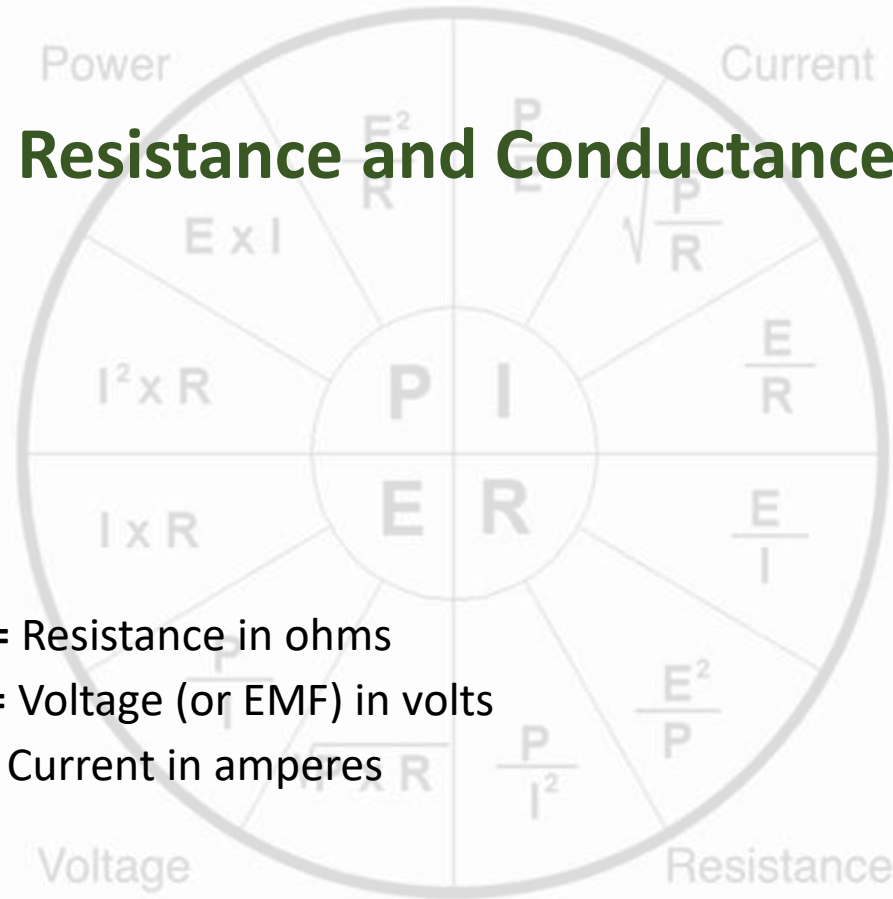
R = Resistance in ohms

E = Voltage (or EMF) in volts

I = Current in amperes

$$E = I \times R$$

$$I = E / R$$



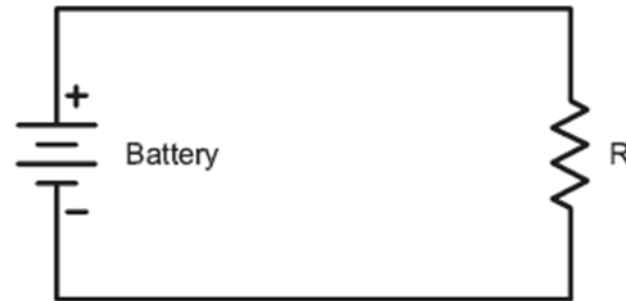
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Electrical Fundamentals

Resistance and Conductance

Let's do a few calculations using the following simple circuit:



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Electrical Fundamentals

Resistance and Conductance

- When $E = 150$ volts and $I = 2.5$ amperes, *what does R equal?*

$$R = E / I$$

$$R = 150 / 2.5$$

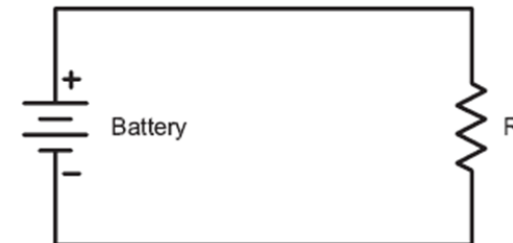
$$R = 60 \text{ Ohms}$$

- When $E = 250$ volts and $R = 5,000$ ohms, *what does I equal?*

$$I = E / R$$

$$I = 250 / 5000$$

$$I = 0.050 \text{ Amperes or } 50 \text{ mA}$$



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Electrical Fundamentals

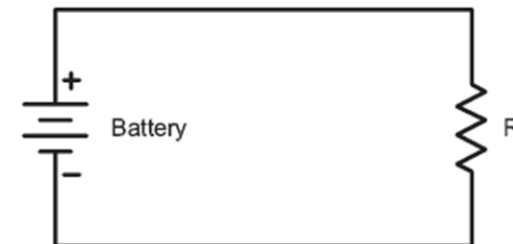
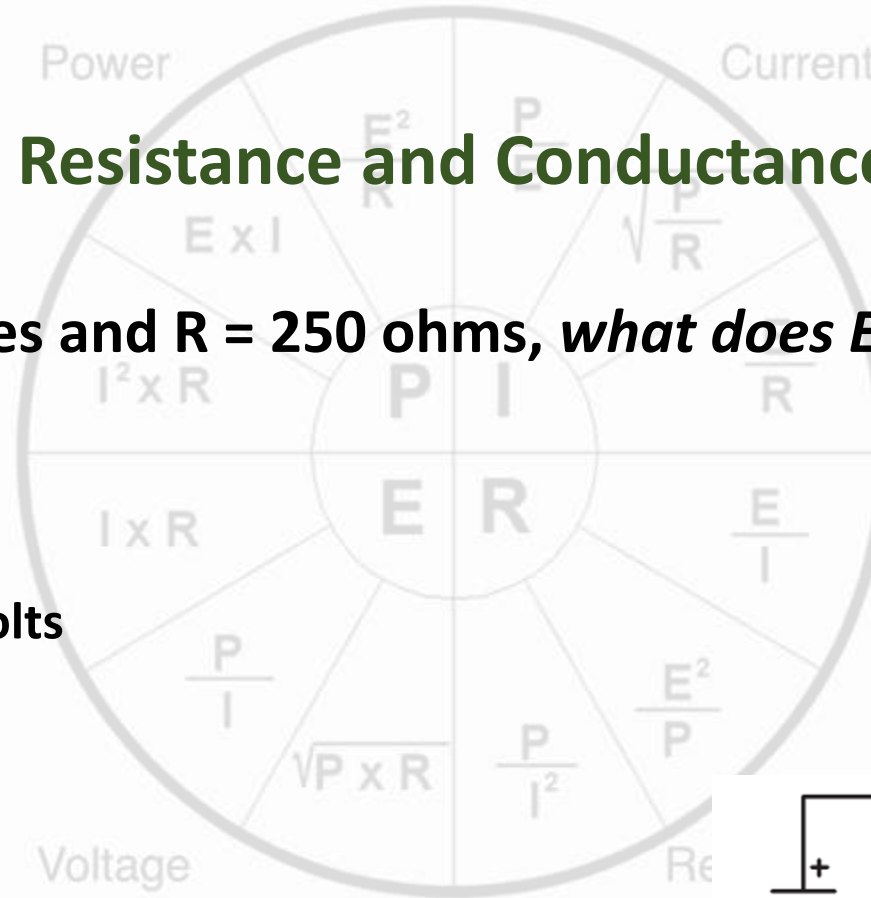
Resistance and Conductance

- When $I = 5$ amperes and $R = 250$ ohms, *what does E equal?*

$$E = I \times R$$

$$E = 5 \times 250$$

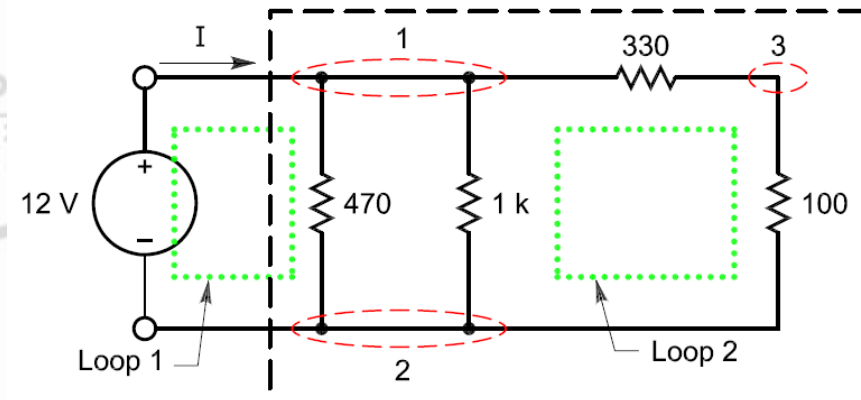
$$E = 1250 \text{ Volts}$$



Electrical Fundamentals

Basic Circuit Principles

- **Nodes** – Any point in a circuit at which current can divide between paths
- **Loops** – A series of branches making a complete current path from the voltage source back to the opposite side of the voltage source
- **Branches** – Any unique conducting path between nodes

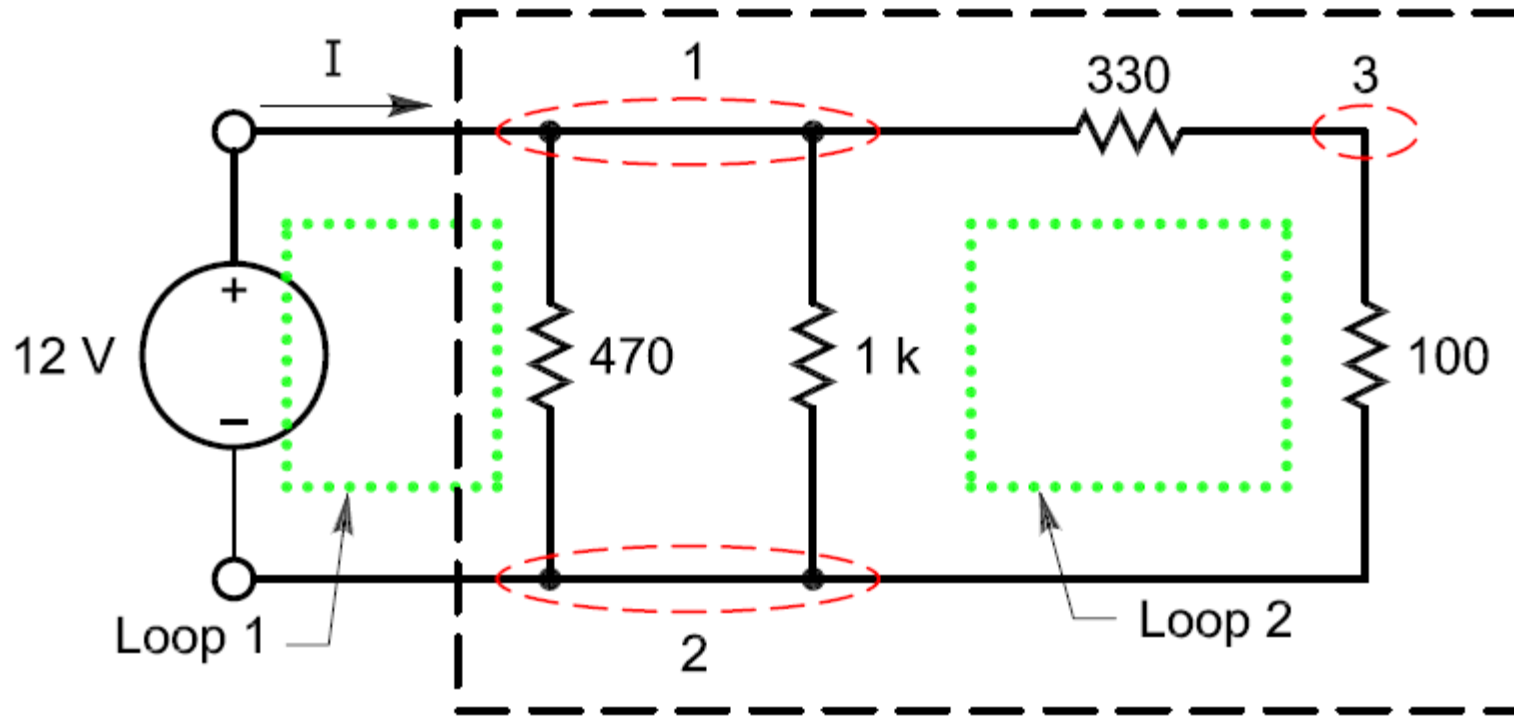


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Electrical Fundamentals

Basic Circuit Principles

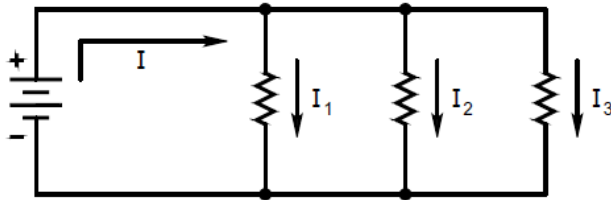


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Electrical Fundamentals

Parallel Circuit



Basic Circuit Principles Resistors in Parallel

- Resistors in parallel can be represented as a single ***equivalent resistance***
- The ***equivalent resistance*** will be a value less than the lowest resistor value
- If all parallel resistors have the same value, divide the resistor value by number of resistors to find parallel resistance value
 - **Example:** five 25 k Ω resistors in parallel = $25\text{ k}\Omega / 5 = 5\text{ k}\Omega$

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Electrical Fundamentals

Basic Circuit Principles Resistors in Parallel

The formula for finding *equivalent resistance*, sometimes referred to as the *Reciprocal of Reciprocals* formula:

$$R_{EQUIV} = \frac{1}{\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} + \frac{1}{R4} \dots}$$

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Electrical Fundamentals

Basic Circuit Principles Resistors in Parallel

Example: Given three resistors in parallel (5.0 k Ω + 20.0 k Ω + 8.0 k Ω) – ***What is R_{equiv} ?***

$$R = \frac{1}{\frac{1}{5 \text{ k}\Omega} + \frac{1}{20 \text{ k}\Omega} + \frac{1}{8 \text{ k}\Omega}} = 2.67 \text{ k}\Omega$$

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Electrical Fundamentals

Basic Circuit Principles Resistors in Parallel

If **only two resistors in parallel**, then the following formula can be used. (*This can also be used to combine parallel resistors two at a time to keep from having to do the Reciprocal of Reciprocals formula*)

$$R_{\text{EQUIV}} = \frac{R1 \times R2}{R1 + R2}$$

Electrical Fundamentals

Basic Circuit Principles

- **Kirchhoff's Current Law** – *The sum of all currents flowing into a node and all currents flowing out of a node is equal to zero.*
- For resistors in parallel
- **Expressed Mathematically**

$$(I_{in1} + I_{in2} + \dots) - (I_{out1} + I_{out2} + \dots) = 0$$

or

$$(I_{in1} + I_{in2} + \dots) = (I_{out1} + I_{out2} + \dots)$$

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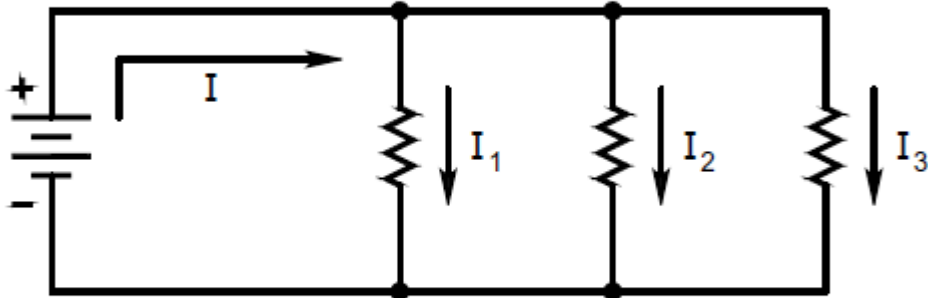


Electrical Fundamentals

Basic Circuit Principles

Kirchhoff's Current Law Example

Parallel Circuit



$$I = I_1 + I_2 + I_3$$

(KCL)

Calculate current flow through each resistor (I_x) and circuit current total (I_{Total})

$E = 250$ Volts

$R_1 = 5.0 \text{ k}\Omega$; $I_1 = E/R_1 = 250/5.0\text{k} = 50.0 \text{ mA}$

$R_2 = 20.0 \text{ k}\Omega$; $I_2 = E/R_2 = 250/20.0\text{k} = 12.5 \text{ mA}$

$R_3 = 8.0 \text{ k}\Omega$; $I_3 = E/R_3 = 250/8.0\text{k} = 31.2 \text{ mA}$

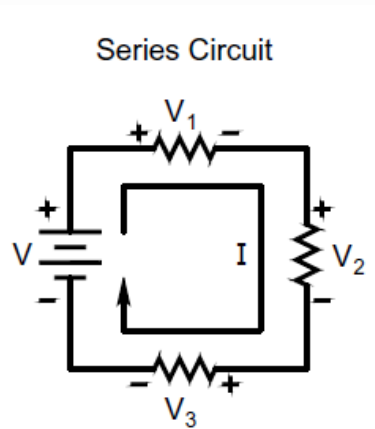
$I_{\text{Total}} = 50.0 \text{ mA} + 12.5 \text{ mA} + 31.2 \text{ mA} = \mathbf{93.7 \text{ mA}}$

$I_{\text{in}} (93.7 \text{ mA}) - I_{\text{out}} (93.7 \text{ mA}) = 0$

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Electrical Fundamentals



Basic Circuit Principles Resistors in Series

- Resistors in series can be represented as a single ***equivalent resistance***
- The ***equivalent resistance*** will be the sum of the individual resistors

$$R_{\text{equiv}} = R_1 + R_2 + R_3 + \dots$$

$$\text{Example: } R_{\text{equiv}} = 5.0 \text{ k}\Omega + 20.0 \text{ k}\Omega + 8.0 \text{ k}\Omega = 33 \text{ k}\Omega$$

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Electrical Fundamentals

Basic Circuit Principles

- **Kirchhoff's Voltage Law** – *The sum of all voltages around a closed current loop is zero.*
- ***Used for resistors in series***
- **Expressed Mathematically**

$$E_1 + E_2 + E_3 + \dots = 0$$

or Voltage

$$(E_{\text{source1}} + E_{\text{source2}} + \dots) = (E_{\text{sink1}} + E_{\text{sink2}} + \dots)$$

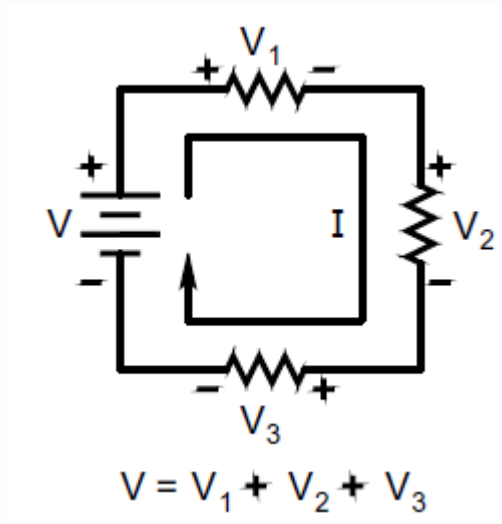
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Electrical Fundamentals

Basic Circuit Principles

Kirchhoff's Voltage Law Example



1. *Solve for current (I)*

$$V_{\text{Batt}} = 250 \text{ Volts}; R_1 = 5.0 \text{ k}\Omega; R_2 = 20.0 \text{ k}\Omega; R_3 = 8.0 \text{ k}\Omega$$

$$\begin{aligned} V_{\text{Drop}} &= -250 + (I \times R_1) + (I \times R_2) + (I \times R_3) = 0 \\ &= -250 + I(33 \text{ k}\Omega) = 0 \end{aligned}$$

$$\begin{aligned} I &= -250 + I(R_1 + R_2 + R_3) \\ &= 250/33 \text{ k}\Omega = 0.00758 \text{ A or } \mathbf{7.58 \text{ mA}} \end{aligned}$$

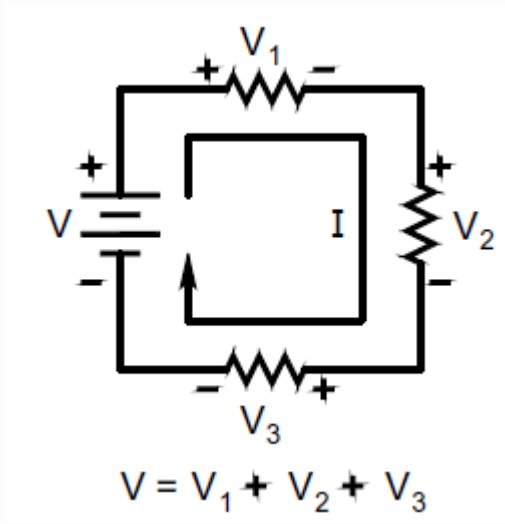
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Electrical Fundamentals

Basic Circuit Principles

Kirchhoff's Voltage Law Example



2. Solve for individual voltage drops

$$V_1 = I \times R_1 = 7.58 \text{ mA} \times 5.0 \text{ k}\Omega = 37.9 \text{ Volts}$$

$$V_2 = I \times R_2 = 7.58 \text{ mA} \times 20.0 \text{ k}\Omega = 151.6 \text{ Volts}$$

$$V_3 = I \times R_3 = 7.58 \text{ mA} \times 8.0 \text{ k}\Omega = 60.6 \text{ Volts}$$

$$V_{\text{Total}} = V_1 + V_2 + V_3$$

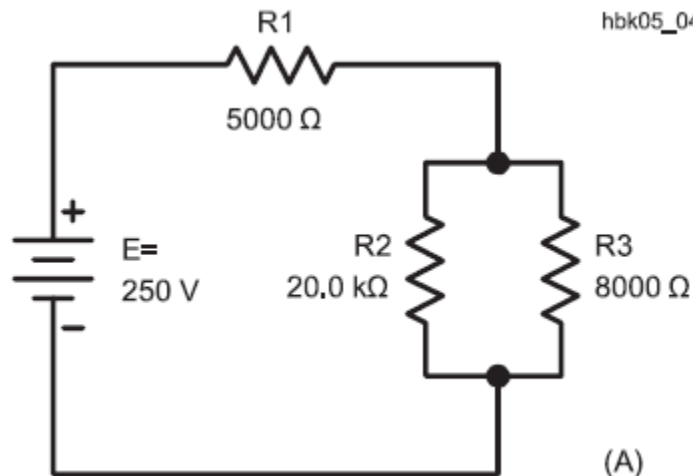
$$V_{\text{Total}} = 37.9 \text{ Volts} + 151.6 \text{ Volts} + 60.6 \text{ Volts} = \mathbf{250 \text{ Volts}}$$

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Electrical Fundamentals

Basic Circuit Principles Resistors in Series-Parallel

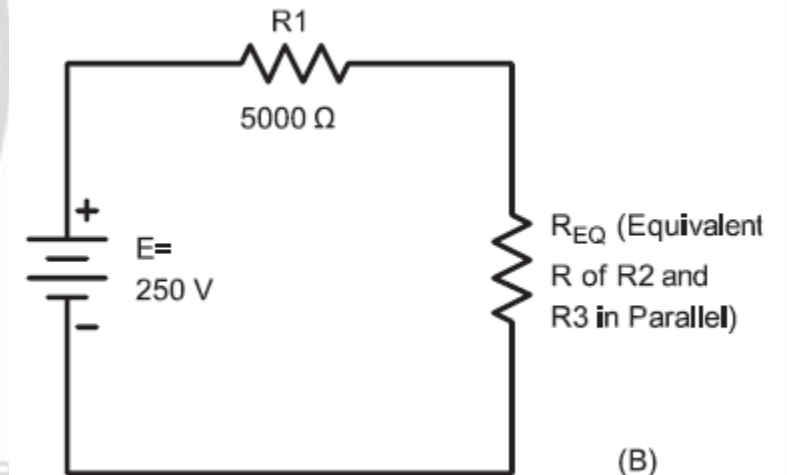


1. Create an equivalent resistance for R_2 & R_3 and calculate R_{EQ}

$$\begin{aligned} R_{EQ} &= (R_2 \times R_3) / (R_2 + R_3) \\ &= (20\text{ k}\Omega \times 8\text{ k}\Omega) / (20\text{ k}\Omega + 8\text{ k}\Omega) \\ &= 1.6 \times 10^8\text{ k}\Omega / 28\text{ k}\Omega \\ &= 5.714\text{ k}\Omega \end{aligned}$$

2. Add R_1 & R_{EQ} together as series resistors to calculate R_{total}

$$\begin{aligned} R_{total} &= 5\text{ k}\Omega + 5.714\text{ k}\Omega \\ &= 10.714\text{ k}\Omega \end{aligned}$$



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Electrical Fundamentals

Basic Circuit Principles Conductances in Series

- Conductance (G) is the reciprocal of resistance, **$G = 1/R$**
- Therefore, conductances in series are calculated like resistors in parallel

$$G = \frac{1}{\frac{1}{G_1} + \frac{1}{G_2} + \frac{1}{G_3} + \frac{1}{G_4} \dots}$$

Electrical Fundamentals

Basic Circuit Principles Conductances in Series

If **only two conductances in series**, then the following formula can be used. (*This can also be used to combine parallel conductances two at a time to keep from having to do the Reciprocal of Reciprocals formula*)

$$G_{\text{EQUIV}} = \frac{G1 \times G2}{G1 + G2}$$

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Electrical Fundamentals

Basic Circuit Principles Conductances in Parallel

- Conductance (G) is the reciprocal of resistance, **$G = 1/R$**
- Therefore, conductances in parallel are calculated like resistors in series

$$G_{\text{TOTAL}} = G1 + G2 + G3 + G4 \dots$$

Electrical Fundamentals

Basic Circuit Principles Thevenin's Theorem

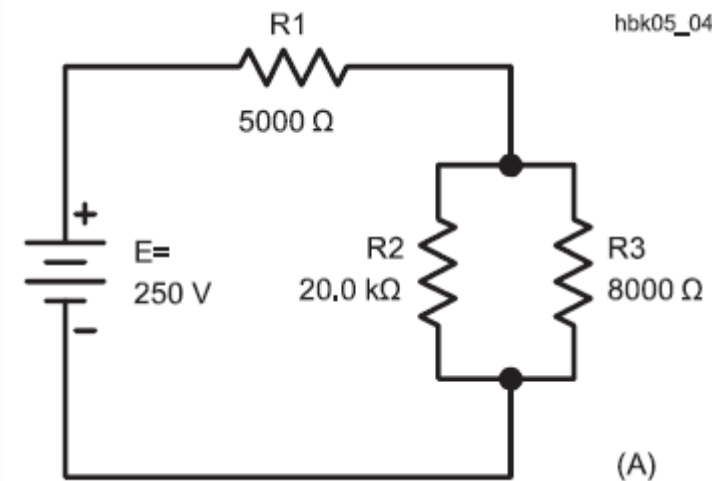
- Introducing the term ***network***, the formal name for a circuit
- **Thevenin's Theorem** – *“Any two-terminal network made up of resistors and voltage or current sources can be replaced by an equivalent network made up of a single voltage source and a series resistor”*

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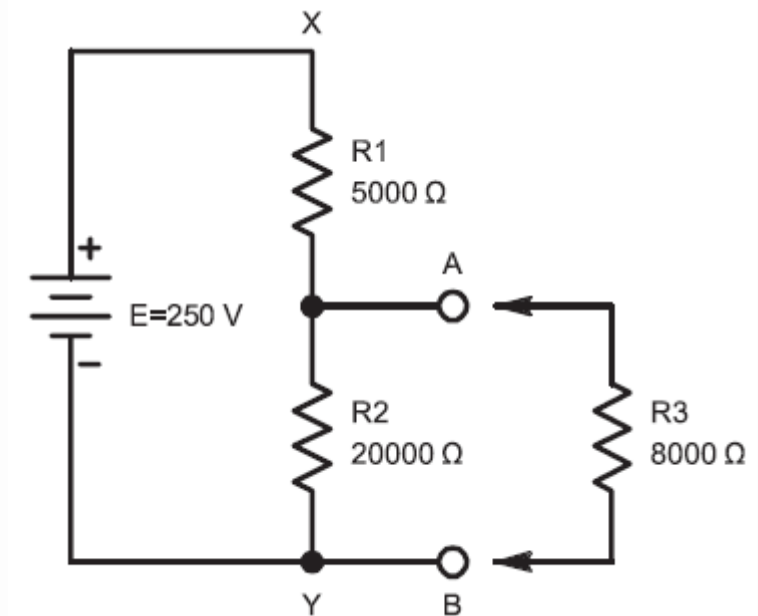
Electrical Fundamentals

Basic Circuit Principles Thevenin's Theorem



Step 1: Isolate R_3 by redrawing the circuit such that R_1 and R_2 form a voltage divider, with R_3 as the load. (The current across R_3 is the voltage across R_3 divided by its resistance) - ($I_{R_3} = V_{R_3} / R_3$)

Note: that the R_2 influences the voltage across R_3 and vice versa. The two need to be separated by some mechanism to solve for I .



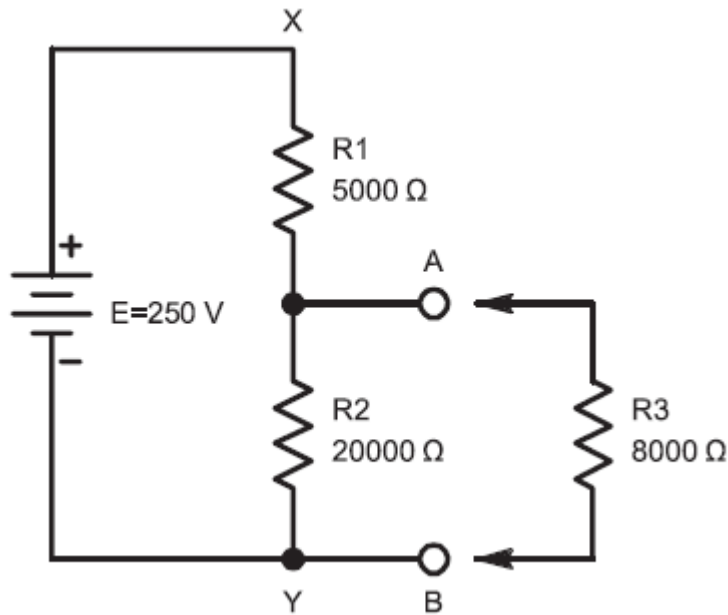
Example: What is the current (I) through R_3 ?

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Electrical Fundamentals

Basic Circuit Principles Thevenin's Theorem



Step 2A: Construct a *Thevenin Equivalent Circuit* to replace everything connected to **A** and **B** with a single voltage source and a series resistor

Step 2B: Calculate the *open circuit voltage* across **A** and **B** with no load. Simply apply Ohm's Law – The total current (**I**) in the circuit is calculated:

$$I = E / (R1 + R2)$$

$$= 250\text{ V} / (5\text{ k}\Omega + 20\text{ k}\Omega)$$

$$= 250\text{ V} / 25\text{ k}\Omega = 0.010\text{ A or } 10\text{ mA}$$

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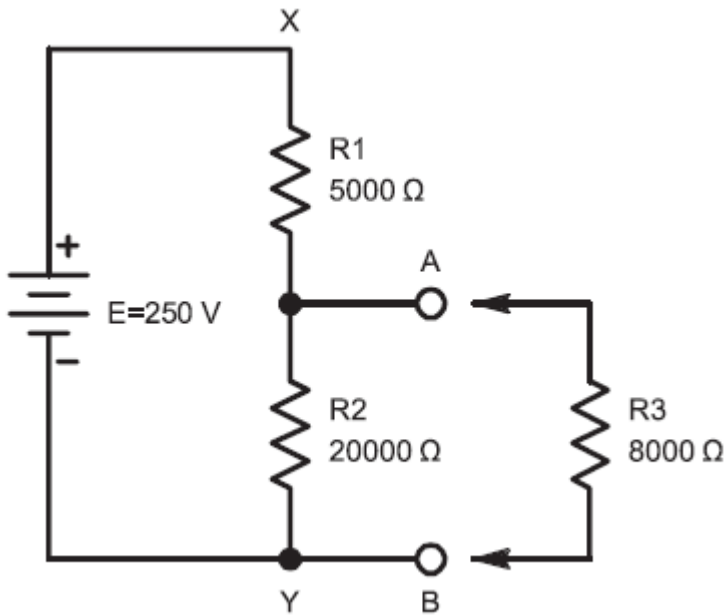


Electrical Fundamentals

Basic Circuit Principles Thevenin's Theorem

Step 2C: Calculate the *open circuit voltage* across **A** and **B** with no load. Simply apply Ohm's Law – The total current (**I**) in the circuit is calculated:

$$\begin{aligned} I &= E / (R1 + R2) \\ &= 250 \text{ V} / (5 \text{ k}\Omega + 20 \text{ k}\Omega) \\ &= 250 \text{ V} / 25 \text{ k}\Omega = 0.010 \text{ A or } \mathbf{10 \text{ mA}} \end{aligned}$$



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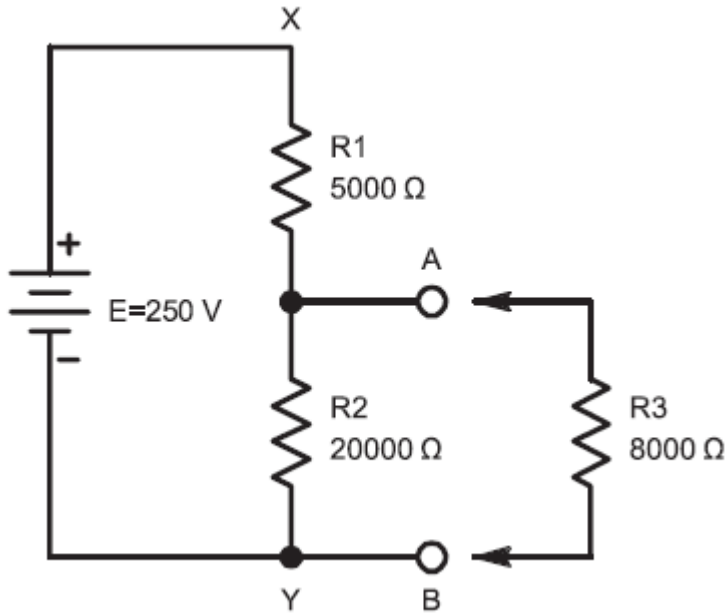
Electrical Fundamentals

Basic Circuit Principles Thevenin's Theorem

Step 3: Calculate the *Thevenin Equivalent Voltage* (E_{Thev}) – $E_{\text{Thev}} = I \times R$.

- We can express I as $E / R1 + R2$ (Step 2B)

$$\begin{aligned} E_{\text{thev}} &= (R2 / R1 + R2) \times E \\ &= (20 \text{ k}\Omega / 5 \text{ k}\Omega + 20 \text{ k}\Omega) \times 250 \text{ V} \\ &= (20 \text{ k}\Omega / 25 \text{ k}\Omega) \times 250 \text{ V} \\ &= 0.80 \text{ k}\Omega \times 250 \text{ V} = \mathbf{200 \text{ V}} \end{aligned}$$



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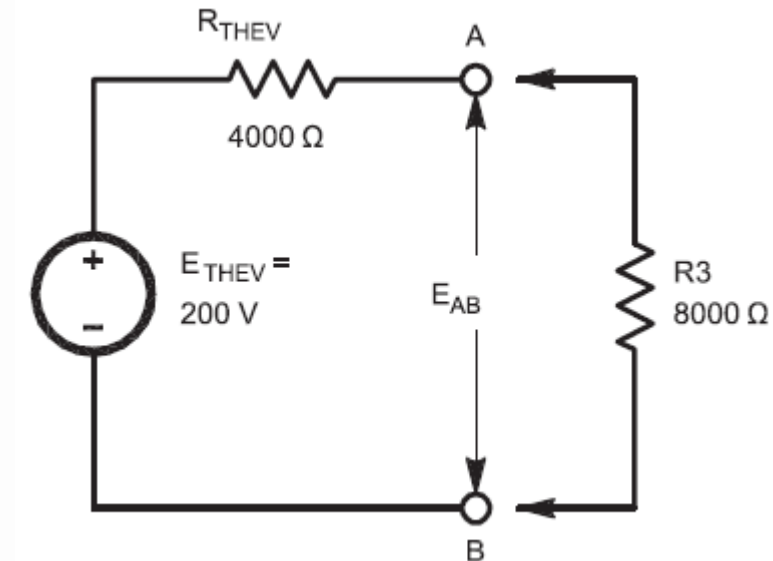
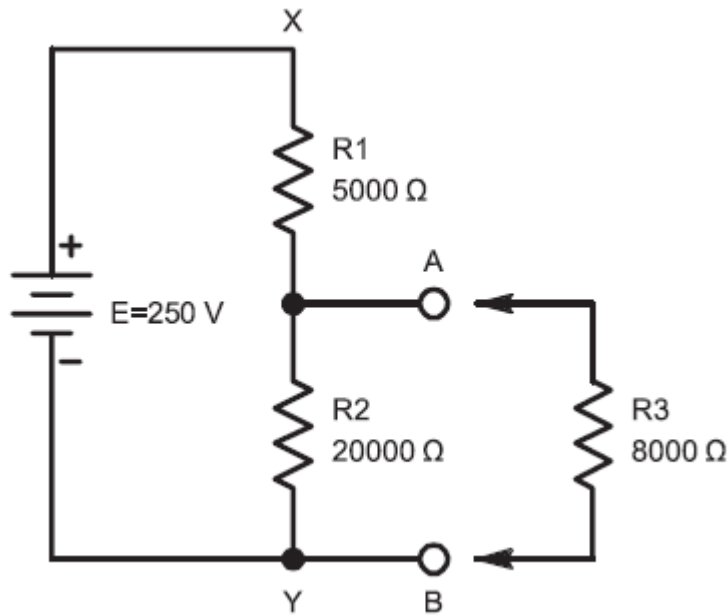


Electrical Fundamentals

Basic Circuit Principles Thevenin's Theorem

Step 4: Calculate the *Thevenin Equivalent Resistor* (R_{Thev})

$$\begin{aligned} R_{Thev} &= (R1 \times R2) / (R1 + R2) \\ &= (5 \text{ k}\Omega \times 20 \text{ k}\Omega) / (5 \text{ k}\Omega + 20 \text{ k}\Omega) \\ &= 1.0 \times 10^8 \Omega / 25 \text{ k}\Omega \\ &= 4000 \Omega \text{ or } 4 \text{ k}\Omega \end{aligned}$$

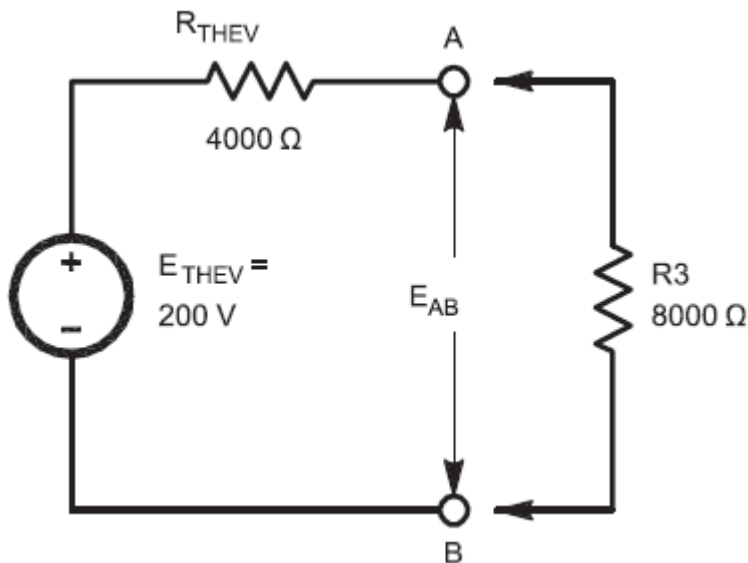


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Electrical Fundamentals

Basic Circuit Principles Thevenin's Theorem



Step 5: Calculate *the current through the load R_3* :

$$\begin{aligned} I_{R3} &= E_{Thev} / (R_{Total}) \\ &= 200\text{ V} / 4\text{ k}\Omega + 8\text{ k}\Omega \\ &= 200\text{ V} / 12\text{ k}\Omega \\ &= 0.0167\text{ A or } \mathbf{16.7\text{ mA}} \end{aligned}$$

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Electrical Fundamentals

Basic Circuit Principles Norton's Theorem

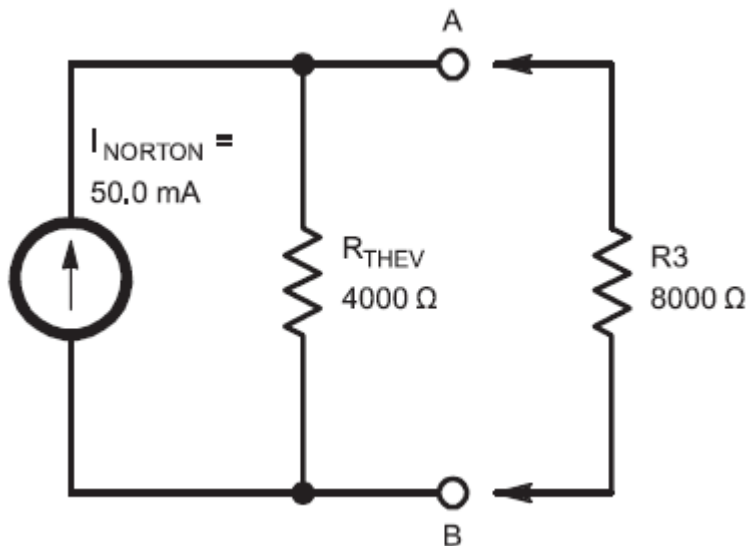
- **Norton's Theorem** – *“Any two-terminal network made up of resistors and voltage or current sources can be replaced by an equivalent network made up of a single current source and a parallel resistor”*
- Very similar to Thevenin's Theorem, but for current sources rather than voltage sources

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Electrical Fundamentals

Basic Circuit Principles Norton's Theorem



Step 1: Isolate R_{Thev} by replacing the load resistor R_3 with a short circuit.

Step 2: Calculate the current (I_{Norton}) through R_{Thev} :

$$I_{\text{norton}} = E / R_{\text{Thev}} \\ = 250 \text{ V} / 5 \text{ k}\Omega = 0.050 \text{ A or } 50 \text{ mA}$$

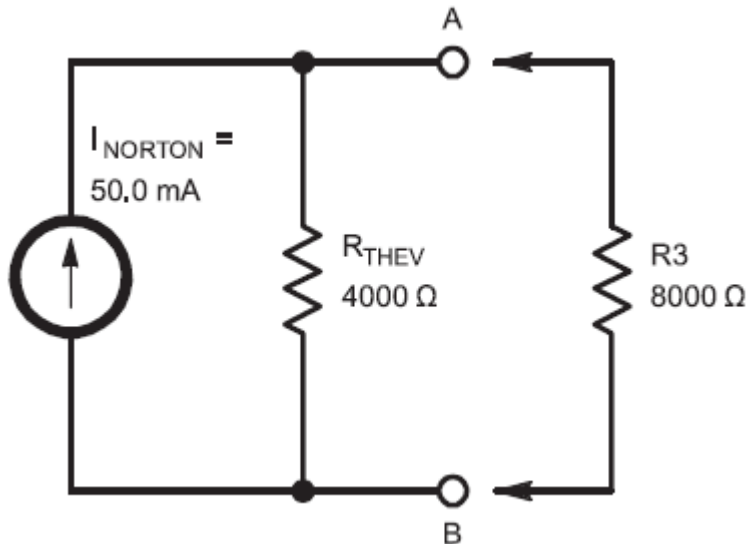
Example: What is the current (I) through R_3 ?

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Electrical Fundamentals

Basic Circuit Principles Norton's Theorem



Step 3: Reinsert the load resistor R_3 across A and B.

Step 4: Calculate the circuit current (I) through R_3 :

- R_3 is $2/3$ the resistance of R_{Thev}
- R_3 will therefore have $1/3$ the current through it

Step 5: Calculate I_{R_3}

Recall that I_{Norton} was calculated in **Step 2** to be **50 mA**

- **What is $1/3$ of 50 mA?**

$$50 \text{ mA} / 3 = 16.7 \text{ mA}$$

Therefore, the current (I) through $R_3 = 16.7 \text{ mA}$

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Electrical Fundamentals

Basic Circuit Principles Thevenin's & Norton's Theorems Final Thoughts

- Thevenin- and Norton-equivalent circuits can be transformed back and forth
- The equivalent resistor is the same in both cases
- The Thevenin equivalent voltage source value is the same voltage as the drop across a Norton-equivalent resistor
- The Norton equivalent current source value is equal to the short circuit current provided by the Thevenin source

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Electrical Fundamentals

Power and Energy

- **Power** – Measure of the rate at which energy is generated or used
- One **watt (W)** of power is defined as the generation or use of one **joule (J)** of energy or work per second
- One **joule (J)** is the amount of energy or work done when a force of one newton is applied to an object that is moved one meter in the direction of the force

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Electrical Fundamentals

Power and Energy

- One **watt (W)** is also defined as one **volt (V)** of electromotive force (**EMF**) causing one **ampere (I)** of current to flow through a resistance
(*Discussion applies to DC circuits only):

$$P = I \times E$$

P = Power in watts

I = Current in amperes

E = EMF in volts

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Electrical Fundamentals

Power and Energy Power

- Power may also be expressed as **horsepower (hp)**

$$746\text{W} = 1 \text{ horsepower}$$

- Assumes lossless (100% efficiency) conversion between mechanical and electrical power
- Especially useful measure of work when dealing with motors

Electrical Fundamentals

Power and Energy Energy

- **Energy** is an expression of **work**
- Energy is generally measured as **watt-hours (Wh)**, which is power multiplied by time:

$$Wh = P \times t$$

Wh = Energy in watt-hours

P = Power in watts

t = Time in hours

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Electrical Fundamentals

Power and Energy Energy

- Power companies bills in **kilowatt-hours (kWh)**
- Batteries generally are rated in **milliampere-hours (mAh)**
- *Note that a small amount of power used over a long has the same effect as a large amount of power used over a short time*

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Electrical Fundamentals

Power and Energy Energy

- Practical application for Ham Radio:
 - A handheld radio has a fully charged battery storing **900 mAh** of energy, and the radio draws **30 mA** on receive. ***How long will the radio continue to stay on in receive mode?***

$$\begin{aligned} t &= 900 \text{ mAh} / 30 \text{ mA} \\ &= 900 \text{ mAh} / 30 \text{ mA} \\ &= \mathbf{30 \text{ hours}} \text{ (* Assuming 100\% efficiency)} \end{aligned}$$

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Electrical Fundamentals

Power and Energy Efficiency

- No circuit is 100% lossless
- Every circuit experiences losses as **heat** or **other form of energy**
 - **Law of Conservation of Energy** – Energy can neither be created nor destroyed, only converted from one form to another.
- Energy lost to conversion to another form is a **loss of efficiency**

Electrical Fundamentals

Power and Energy Efficiency

- Power converted to heat is considered a loss because it is not useful power
- The ratio of **power output** to **power input** results in a **measure of efficiency (Eff)** usually **expressed as a percentage**
 - Expressed mathematically:

$$\text{Eff} = P_o / P_i$$

Eff = Efficiency as a value or fraction between 0 and 1

P_o = Power output in watts (W)

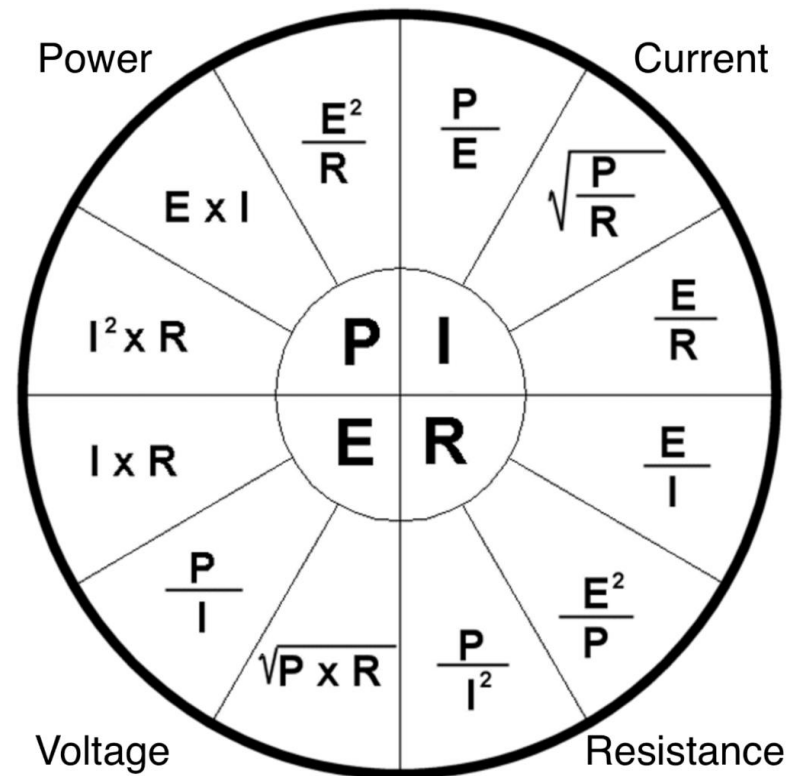
P_i = Power input in watts (W)

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Electrical Fundamentals

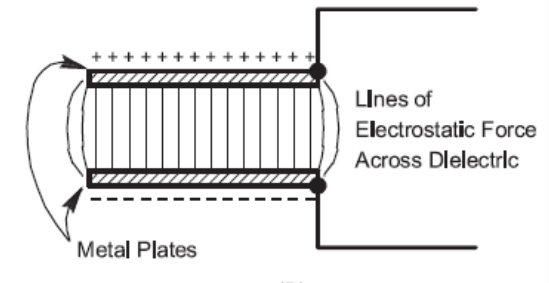
Voltage, Current, Resistance, & Power Equation Summary



Electrical Fundamentals

Capacitance and Capacitors Electrostatic Fields and Energy

- **Electrostatic Field** – Created whenever a voltage exists between two points
 - The field causes electrical charges to feel a force in the direction of the field
 - If the charges are not free to move, then it is **potential energy**
 - If the charges are free to move, then it is **kinetic energy**
- The field is represented by **lines of force** showing the direction of the force
- The field's strength is measured in **volts per meter (V/m)**

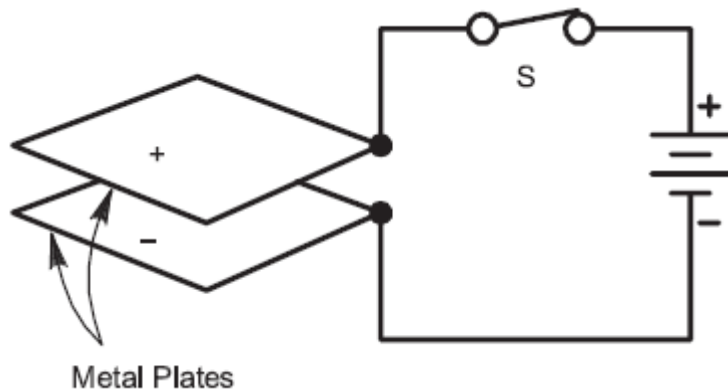


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Electrical Fundamentals

Capacitance and Capacitors



- **Capacitor** – A device with the property of storing electrical energy in an electrical field
- **Capacitance** – The amount of electrical energy that a capacitor can store

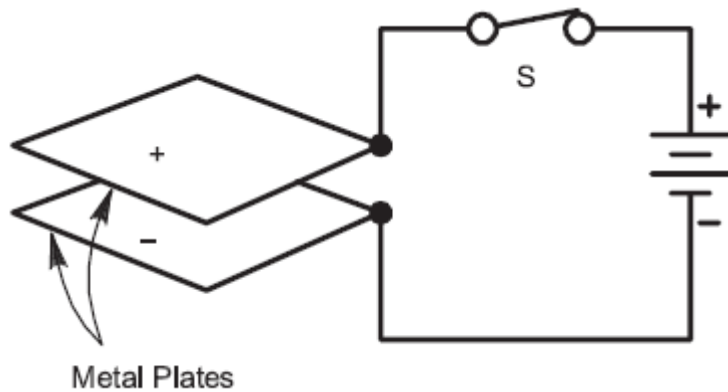
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Electrical Fundamentals

Capacitance and Capacitors

The Capacitor



1. Two flat metal plates placed close to each other without touching and connected to a battery through a switch
2. The switch (S) is closed, electrons are attracted from upper plate to (+) terminal of battery
3. The same number of electrons are repelled from the (-) terminal and pushed to the lower plate

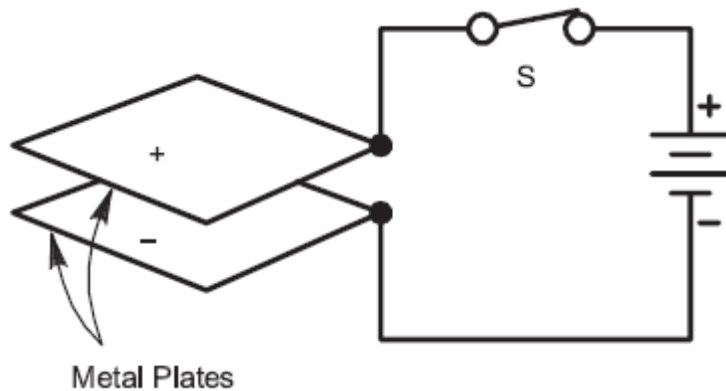
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Electrical Fundamentals

Capacitance and Capacitors

The Capacitor



4. Creates an imbalance between the plates resulting in a voltage appearing
5. Eventually the plates reach equilibrium opposing further current flow
6. At this point, electrical energy is being stored between the plates

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Electrical Fundamentals

Capacitance and Capacitors

- The ***amount of electrical charge*** (potential energy) that a capacitor can hold is proportional to the voltage applied and its capacitance:

$$Q = C \times V$$

where

Q = Charge in coulombs

C = Capacitance in farads (F)

V = Electrical potential in volts

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Electrical Fundamentals

Capacitance and Capacitors

- The ***amount of electrical energy*** (ability to do work) that a capacitor can store is similarly calculated:

$$W = V^2C / 2$$

where

W = Energy in joules (J) or watt-seconds

C = Capacitance in farads (F)

V = Electrical potential in volts

Electrical Fundamentals

Capacitance and Capacitors

- **Farad** – The basic unit of measure of the ability to store electrical energy in an electrostatic field (***capacitance***)
 - Three common measures of capacitors:
 - **microfarad (10^{-6} F)** – one millionth of a farad
 - **nanofarad (10^{-9} F)** – one thousandth of a microfarad (one billionth of a farad)
 - **picofarad (10^{-12} F)** – one millionth of a microfarad (one trillionth of a farad)

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Electrical Fundamentals

Capacitance and Capacitors

Capacitors in Parallel

- Total capacitance of capacitors in parallel is calculated similarly to resistors in series – The total capacitance is equal to the sum of the individual capacitors

$$C_{\text{total}} = C_1 + C_2 + C_3 + \dots$$

Example: $C_{\text{total}} = 1.0 \text{ }\mu\text{F} + 2.0 \text{ }\mu\text{F} + 4.0 \text{ }\mu\text{F} = 7 \text{ }\mu\text{F}$

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Electrical Fundamentals

Capacitance and Capacitors

Capacitors in Series

- Total capacitance of capacitors in series is calculated similarly to resistors in parallel – Apply the ***reciprocal of reciprocals*** formula

$$C_{\text{total}} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots + \frac{1}{C_n}}$$

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Electrical Fundamentals

Capacitance and Capacitors Capacitors in Series

- Example: What is the total capacitance of three capacitors in series when $C_1 = 1.0 \text{ uF}$, $C_2 = 2.0 \text{ uF}$, and $C_3 = 4.0 \text{ uF}$, and the voltage across each capacitor?

Step 1. Calculate total circuit capacitance:

$$\begin{aligned}C_{\text{total}} &= 1 / ((1 / 1.0 \text{ uF}) + (1 / 2.0 \text{ uF}) + (1 / 4.0 \text{ uF})) \\&= 1 / ((1) + (0.5) + (0.25)) \\&= 1 / 1.75 \\&= 0.571 \text{ uF}\end{aligned}$$

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Electrical Fundamentals

Capacitance and Capacitors

Capacitors in Series

Step 2. Calculate the voltage across each capacitor?

The voltage across each capacitor is proportional to the total capacitance divided by the capacitance of the capacitor in question ($E = C_{\text{total}} / C_x$):

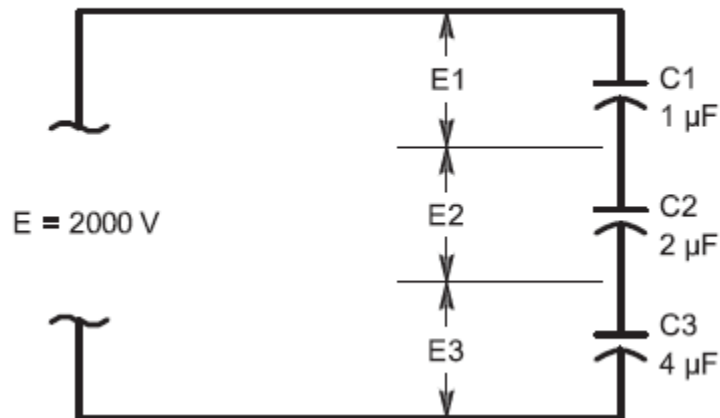
$$E1 = (0.5714 \text{ uF} / 1 \text{ uF}) \times 2000 \text{ V} = 0.5714 \times 2000 = \mathbf{1143 \text{ V}}$$

$$E2 = (0.5714 \text{ uF} / 2 \text{ uF}) \times 2000 \text{ V} = 0.2857 \times 2000 = \mathbf{571 \text{ V}}$$

$$E3 = (0.5714 \text{ uF} / 4 \text{ uF}) \times 2000 \text{ V} = 0.1429 \times 2000 = \mathbf{286 \text{ V}}$$

$$E_{\text{Total}} = 1143 \text{ V} + 571 \text{ V} + 286 \text{ V} = \mathbf{2000 \text{ V}}$$

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Electrical Fundamentals

Basic Circuit Principles Capacitors in Series

If **only two capacitors in series**, then the following formula can be used. (*This can also be used to combine series capacitors two at a time to keep from having to do the Reciprocal of Reciprocals formula*)

$$C_{\text{total}} = \frac{C1 \times C2}{C1 + C2}$$

Electrical Fundamentals

Capacitance and Capacitors

Notes for Calculations

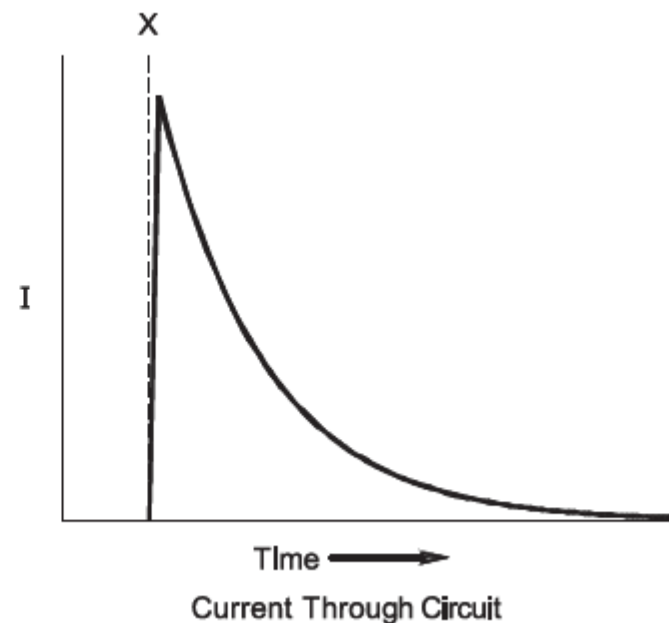
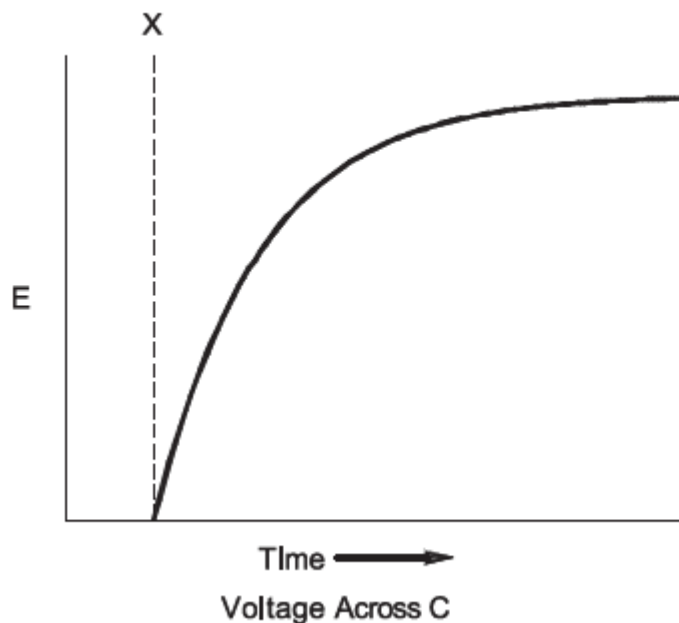
- When two or more capacitors are connected in series, the total capacitance is less than that of the smallest capacitor in the group
- When capacitors are connected in series, the applied voltage is divided between them according to Kirchhoff's Voltage Law
- The voltage rating of capacitors connected in parallel is the lowest voltage rating of any of the capacitors
- When doing calculations, the same units must be used throughout

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Electrical Fundamentals

Capacitance and Capacitors Charging and Discharging



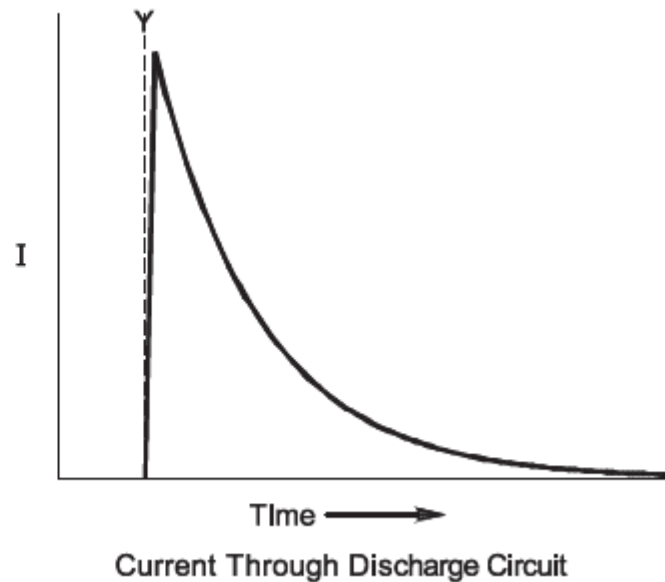
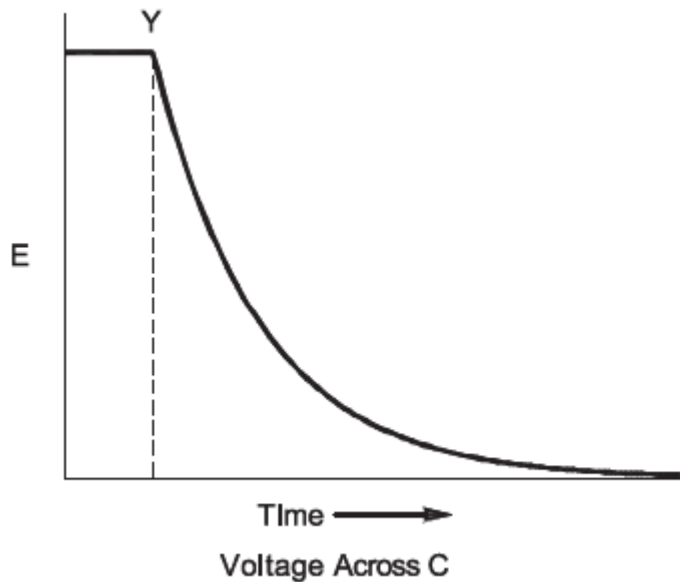
- When voltage is applied across the capacitor, current flows and the capacitor is charged.
- Full charge is reached very quickly
- Current discontinues when fully charged (*DC)

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Electrical Fundamentals

Capacitance and Capacitors Charging and Discharging



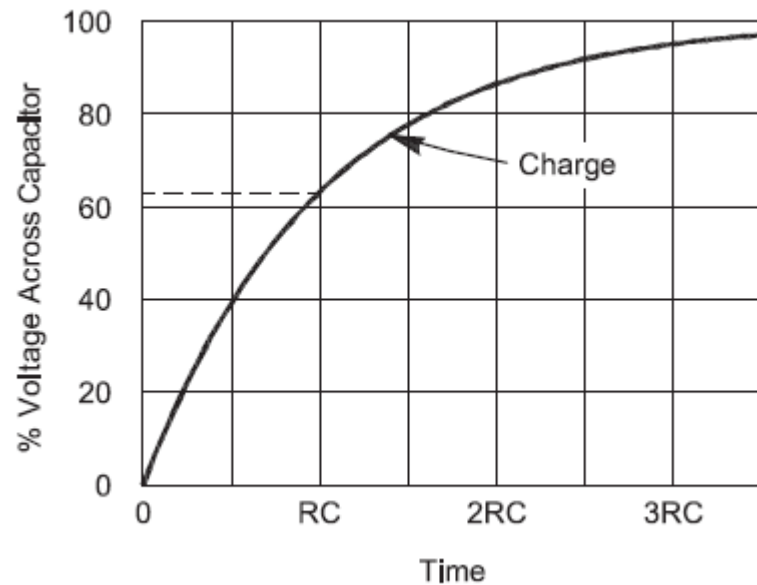
- When voltage is removed or capacitor is shorted, current flows and the capacitor is discharged.
- Zero charge is reached very quickly
- Current discontinues when fully discharged (*DC)

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Electrical Fundamentals

Capacitance and Capacitors RC Time Constant



It is usually useful to be able to control and predict with accuracy how long it takes for a capacitor to charge and discharge

This is accomplished by placing an appropriately sized resistor in series with the capacitor, thereby limiting the current and lengthening the time for the voltage to increase to source voltage

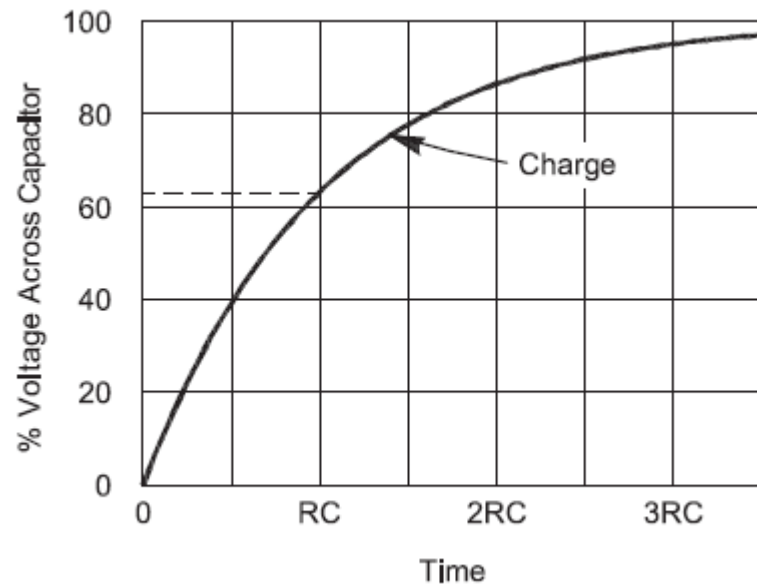
While the capacitor is being charged, the voltage between its terminals is an exponential function of time

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Electrical Fundamentals

Capacitance and Capacitors RC Time Constant



$$V(t) = E \left(1 - e^{-\frac{t}{RC}} \right)$$

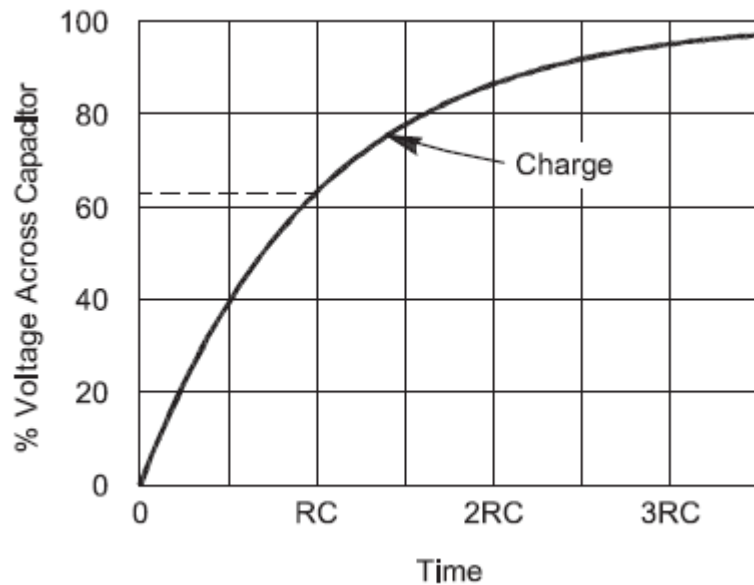
where

$V(t)$ = capacitor voltage at time t ,
 E = power source potential in volts,
 t = time in seconds after initiation of charging current,
 e = natural logarithmic base = 2.718,
 R = circuit resistance in ohms, and
 C = capacitance in farads.

Electrical Fundamentals

Capacitance and Capacitors

RC Time Constant



Because $t = RC$, the formula can be rewritten as:

$$V(RC) = E (1 - e^{-1}) = 0.632 E \quad \text{-- (0.632 is 63.2\%)}$$

The product of RC is called the ***RC time constant*** and is the time in seconds (***t***) required to charge the capacitor to **63.2%** of the applied voltage (***one time constant***)

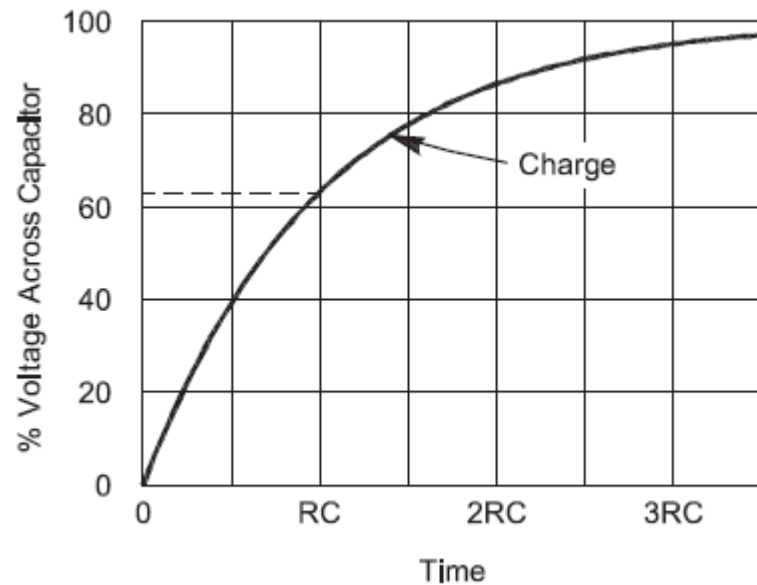
The capacitor is considered fully charged after *five time constants* ($t = 5t$) – charged to **99.3%**

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Electrical Fundamentals

Capacitance and Capacitors RC Time Constant



Amount of charge per time constant:

$$(t = 1t) = 63.2\%$$

$$(t = 2t) = 86.5\%$$

$$(t = 3t) = 95.0\%$$

$$(t = 4t) = 98.2\%$$

$$(t = 5t) = 99.3\%*$$

**At $(t = 5t)$, voltage reaches maximum value, so the circuit is considered fully charged*

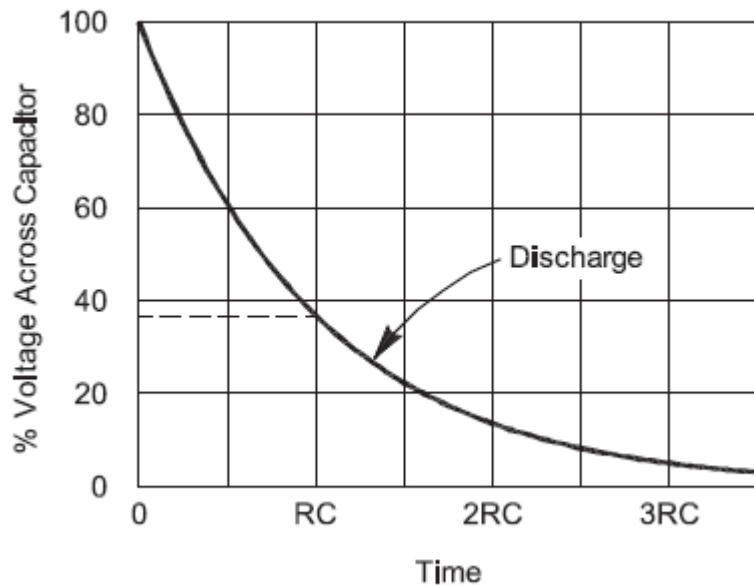
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Electrical Fundamentals

Capacitance and Capacitors

RC Time Constant



Discharging a capacitor using an RC time constant is essentially the same process in reverse

The capacitor is **63.2%** discharged at ($t = 1t$); **86.5%** at ($t = 2t$), etc., until it reaches ($t = 5t$), at which point it is **99.3%** discharged*

**At ($t = 5t$), voltage drops to an immeasurably small value, so the circuit is considered fully discharged*

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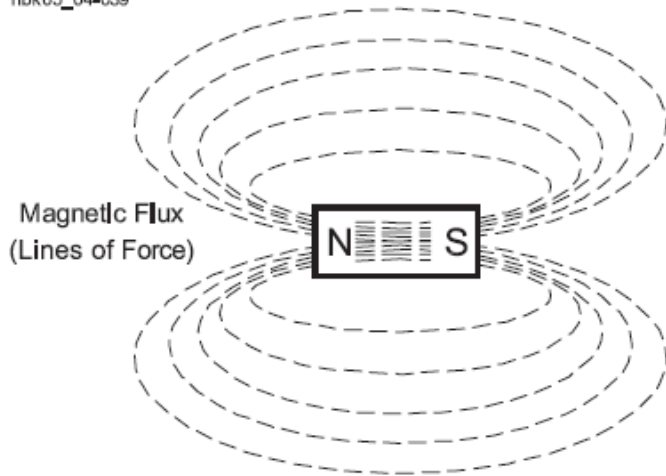


Electrical Fundamentals

Inductance and Inductors

Magnetic Fields & Magnetic Energy

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- Magnets are surrounded by **magnetic fields** in the same way that electric charges are surrounded by electric fields
- Magnetic fields are represented by lines of force called **magnetic flux** representing a **magnetic field**, which is static and unchanging
- All magnets have **north** and **south poles**
- All magnetic lines of force form a loop through the north and south poles

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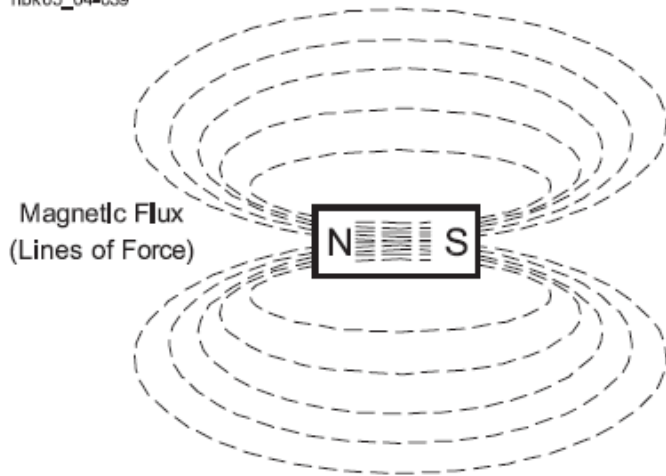


Electrical Fundamentals

Inductance and Inductors

Magnetic Fields & Magnetic Energy

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- Magnetic fields exist around two types of material
 - Permanent magnets** – Materials with high *retentivity*
 - Electromagnets** – Materials that rapidly lose their magnetic properties
- **Magnetic flux** is measured in **webers (Wb)** in non-metric systems. One weber = one volt-second (**1 Wb = 1 V-s**). In metric systems, it is measured in **maxwells (Mx)**. One maxwell = 10^{-8} weber (**1 Mx = 10^{-8} Wb**)
- Magnetic field intensity (strength) is known as **flux density (B)**, which is represented in **gauss (G)**. One gauss = 1 maxwell per square centimeter measured perpendicularly to the direction of the magnetic field (**1 G = Mx/cm²**)

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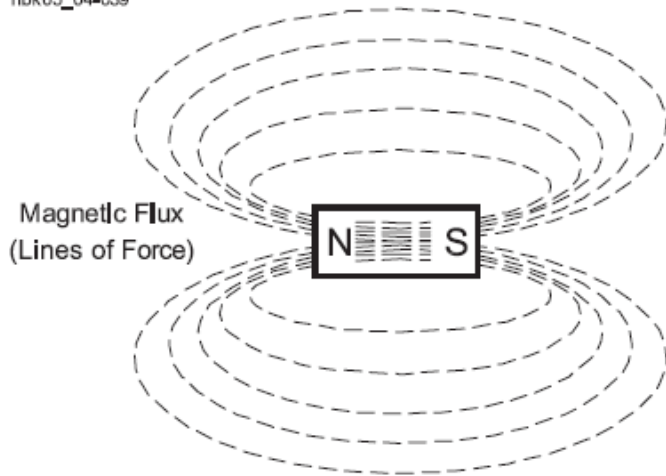


Electrical Fundamentals

Inductance and Inductors

Magnetic Fields & Magnetic Energy

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- Magnetic flux or the magnetic field is produced by **magnetomotive force (J)** measured in **gilberts (Gb)**
- The non-metric unit of magnetomotive force is the **ampere-turn (A)**. ($1 \text{ Gb} = 0.79577 \text{ ampere-turn}$)
- Magnetic field intensity (strength) is known as **flux density (B)**, which is represented in **gauss (G)**. One gauss = 1 maxwell per square centimeter measured perpendicularly to the direction of the magnetic field ($1 \text{ G} = \text{Mx} / \text{cm}^2$)

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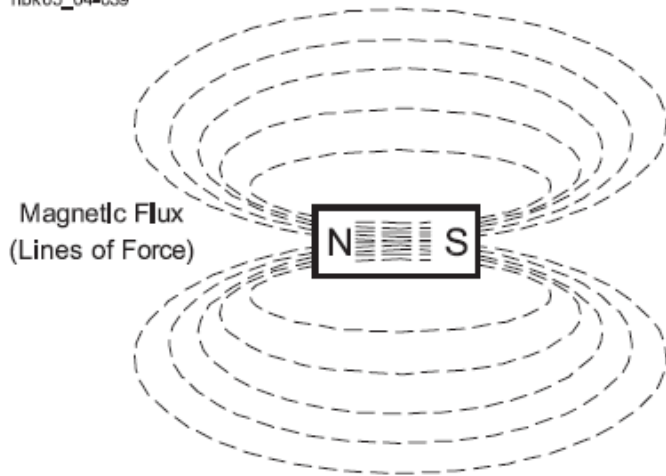


Electrical Fundamentals

Inductance and Inductors

Magnetic Fields & Magnetic Energy

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Magnetomotive force (J) is calculated by the following formula:

$$\mathfrak{J} = \frac{10 N I}{4\pi}$$

where

$\mathfrak{J}$ = magnetomotive strength in gilberts,
N = number of turns in the coil creating the field,
I = dc current in amperes in the coil, and
 $\pi = 3.1416$.

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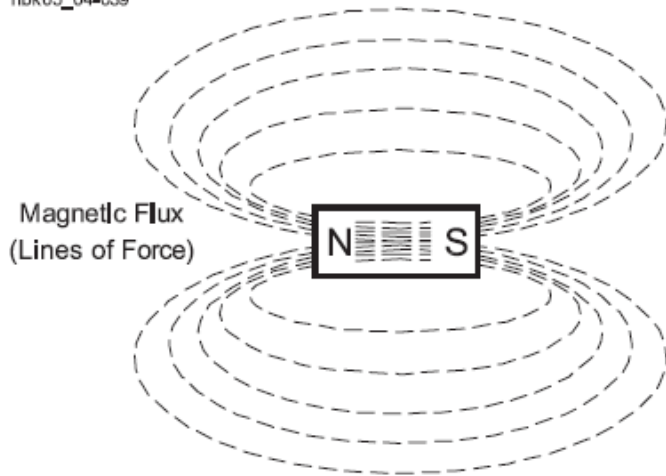


Electrical Fundamentals

Inductance and Inductors

Magnetic Fields & Magnetic Energy

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Magnetic field strength (H), measured in **oersteds (Oe)**, is calculated by the following formula:

$$H = \frac{\Im}{\ell} = \frac{10 N I}{4 \pi \ell}$$

where

H = magnetic field strength in oersteds, and
 ℓ = mean magnetic path length in centimeters.

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Electrical Fundamentals

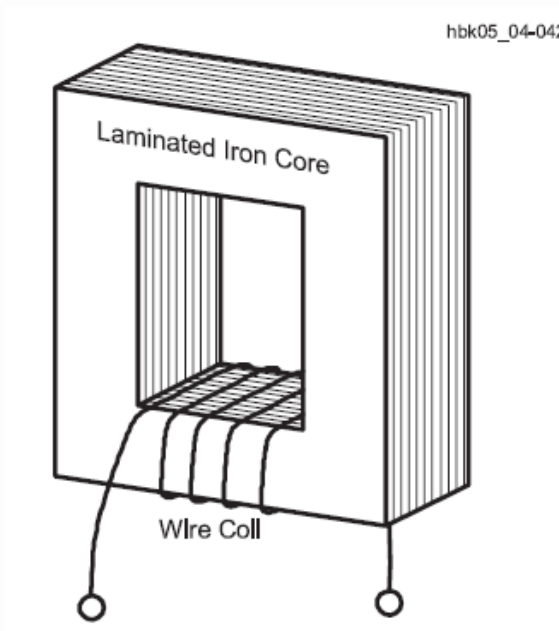
Inductance and Inductors

Magnetic Core Properties

Permeability (μ) – The ratio of flux density produced by a given material compared to the flux density produced by an air core

Permeability (μ) roughly corresponds to electrical conductivity.

- Greater **permeability (μ)** means that it is easier to establish a magnetic field
- Less **permeability (μ)** means that it is more difficult to establish a magnetic field



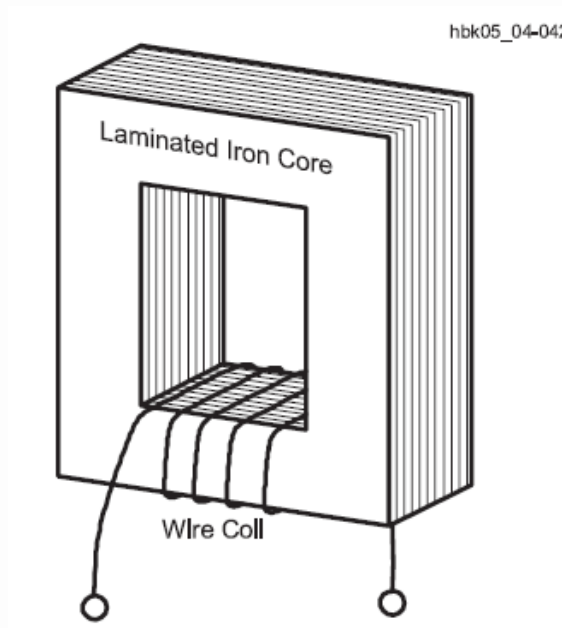
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Electrical Fundamentals

Inductance and Inductors

Magnetic Core Properties



Permeability is calculated using the following formula:

$$\mu = B / H$$

where

B is flux density in gauss (G)

H is the magnetic field strength in oersteds (Oe)

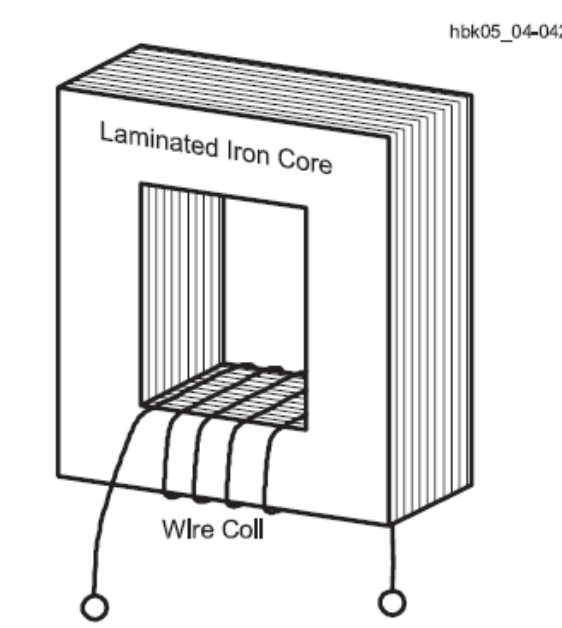
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Electrical Fundamentals

Inductance and Inductors

Magnetic Core Properties



Reluctance (R) – The reciprocal of permeability

Reluctance (R) roughly corresponds to resistance in an electrical circuit.

- Greater **reluctance (R)** means that it is more difficult to establish a magnetic field
- Less **reluctance (R)** means that it is less difficult to establish a magnetic field

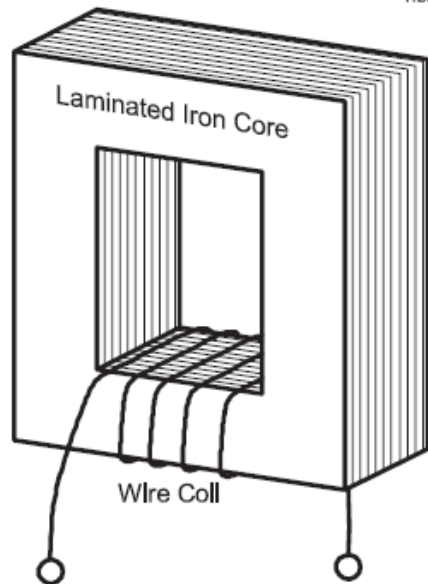
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Electrical Fundamentals

Inductance and Inductors

Magnetic Core Properties



Reluctance (R) is calculated using the following formula:

$$R = J / B$$

where

J is magnetomotive force in gilberts (Gb)

B is flux density in gauss (G)

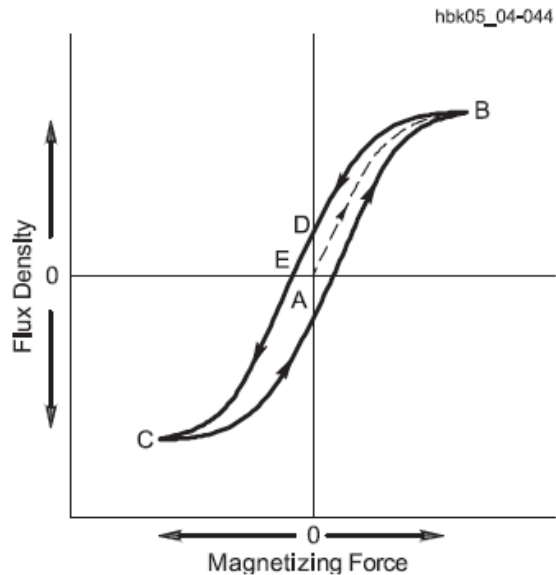
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Electrical Fundamentals

Inductance and Inductors

Magnetic Core Properties



Hysteresis – The condition of a magnetic material that causes it to retain a **residual flux** when all magnetizing force has been removed

Hysteresis represents a loss much like resistance in an electrical circuit

The **residual flux** can be removed by applying a **coercive force**

*Air cores are immune to hysteresis effects and losses

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Electrical Fundamentals

Inductance and Inductors

Magnetic Core Properties

- **Saturation** – The condition where an increase in current in an electromagnet results in no appreciable change in flux because all the magnetic material's atoms are aligned
- **Effects of saturation**
 - As long as the magnet's coil current remains below **saturation**, the coil's inductance remains constant
 - Beyond the saturation point, inductance drops off

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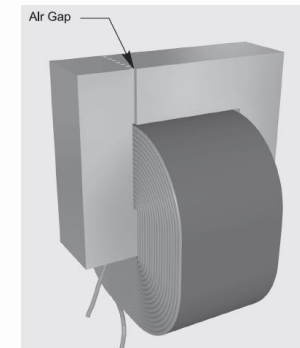
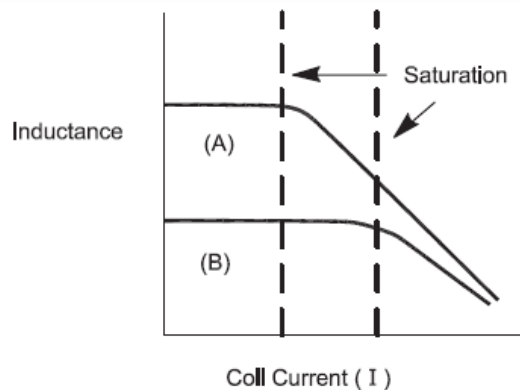
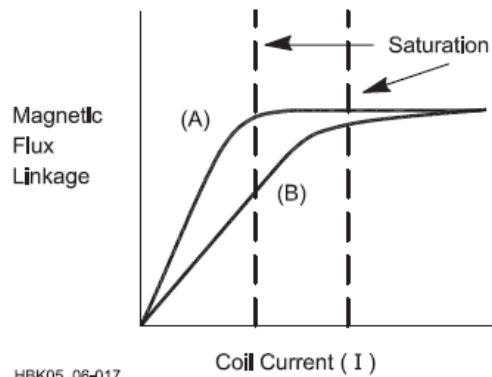
Electrical Fundamentals

Inductance and Inductors

Magnetic Core Properties

The **effect of saturation** is depicted in the images. As current increases toward saturation, inductance remains constant (line A). When **saturation** is reached, inductance rolls off

As mentioned in the text, a small air gap is cut into the core, forcing the **flux lines** to travel through air for a short distance. The effect is depicted at line B



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Electrical Fundamentals

Inductance and Inductors

Inductance and Direct Current

- **Inductor** – Any device whose operation is based on transferring energy into and out of magnetic fields
- Inductors are often referred to as ***coils*** due to their construction
- **Induced Voltage (Back Voltage)** – The basic operating principle of the inductor whereby it resists current flow until the field become constant thus preventing current from rising too rapidly

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Electrical Fundamentals

Inductance and Inductors

Inductance and Direct Current

- The amplitude of the ***induced voltage*** is proportional to the rate at which the current and magnetic field changes, and to a constant associated with the inductor, referred to as ***inductance (L)***
- The basic unit of inductance is the ***henry (H)***

Electrical Fundamentals

Inductance and Inductors

Inductance and Direct Current

- The amplitude of the ***induced voltage*** is calculated using the following formula:

$$V = -L \frac{\Delta I}{\Delta t}$$

where

V is the induced voltage in volts,
L is the inductance in henries, and
 $\Delta I / \Delta t$ is the rate of change of the current
in amperes per second.

Electrical Fundamentals

Inductance and Inductors

Inductance and Direct Current

- An ***inductance*** of **1 H** generates an ***induced voltage*** of **1 V** when the inducing current is varying at a rate of **1 A/sec**
- The **(-)** sign in the mathematical result indicates that the induced voltage is the opposite polarity of the applied current

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Inductance and Inductors

Inductance and Direct Current

- The energy stored in the magnetic field of an inductor is calculated using the following formula, which corresponds to the energy storage formula for capacitors:

$$W = \frac{I^2 L}{2}$$

where

W = energy in joules,
I = current in amperes, and
L = inductance in henrys.

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Inductance and Inductors

Inductor Notes

- The **magnetic field strength (H)** of an inductor is proportional to the number of turns in the inductor's **winding (N)** and the **permeability (u)** of its core making it proportional to both **(N)** and **(u)**
- The polarity of the induced voltage is always such that it will oppose changes in circuit current – If current increases, opposition increases by storing energy; if current decreases, the stored energy is returned to the circuit
- The effect of this opposition is similar to that of a capacitor, which opposes changes in voltage

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Inductance and Inductors

Mutual Inductance

- **Mutual Inductance (Coupling)** – The effect of inducing a voltage (and thus a current) on an inductor – or even a single wire conductor – by the charging of another inductor
- **Coupling between inductors** can be minimized by using separate closed magnetic cores for each inductor
- **Unwanted Coupling** – Coupling induced on another inductor or conductor that is not designed into the circuit, especially in fields changing at frequencies of 100 MHz or higher
 - Computer bus lines and solder traces must be separated
 - Shielding is often used when physical separation is not possible

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Inductance and Inductors

Inductors in Series

- Inductor in series are treated similarly to resistors in series assuming no coupling
- The ***total inductance*** will be the sum of the individual inductors

$$L_{\text{Total}} = L_1 + L_2 + L_3 + \dots$$

Example: $L_{\text{Total}} = 5.0 \text{ mH} + 20.0 \text{ mH} + 8.0 \text{ mH} = 33 \text{ mH}$

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Inductance and Inductors

Inductors in Parallel

Inductors in parallel are treated similarly to resistors in parallel when calculating circuit values

The formula for finding *inductors in parallel*, sometimes referred to as the ***Reciprocal of Reciprocals*** formula:

$$L_{\text{total}} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \dots + \frac{1}{L_n}}$$

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Basic Circuit Principles Inductors in Parallel

Example: Given three inductors (5.0 mH, 20.0 mH, 8.0 mH) the circuit has an *inductance* of:

$$\begin{aligned} L_{\text{total}} &= 1 / (1/5.0 \text{ mH}) + (1/20.0 \text{ mH}) + (1/8.0 \text{ mH}) \\ &= 1 / 0.20 + 0.05 + 0.125 \\ &= 1 / 0.375 \\ &= 2.67 \text{ mH} \end{aligned}$$

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Inductance and Inductors

Inductors in Parallel

If **only two inductors in parallel**, then the following formula can be used. (*This can also be used to combine parallel inductors two at a time to keep from having to do the Reciprocal of Reciprocals formula*)

$$L_{\text{total}} = \frac{L1 \times L2}{L1 + L2}$$

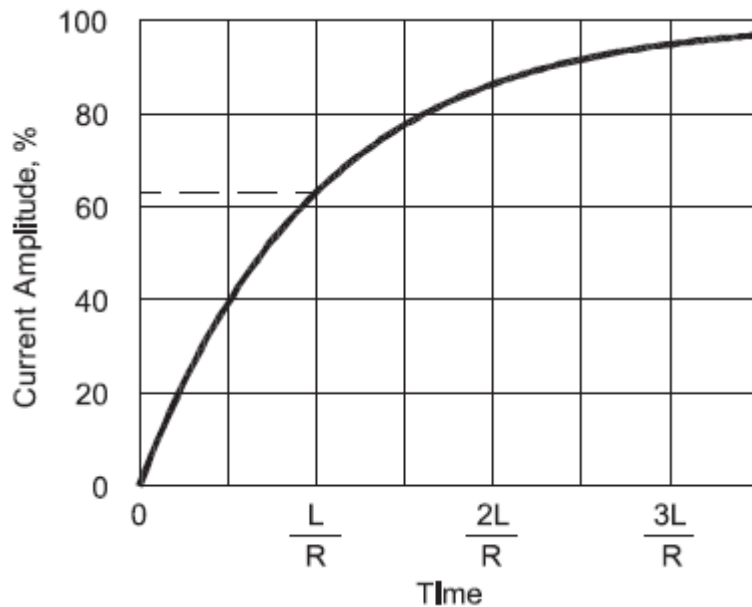
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Inductance and Inductors

RL Time Constant



As with a capacitor, it is usually useful to be able to control and predict with accuracy how long it takes for an inductor to build up and deplete full current

This is accomplished by placing an appropriately sized resistor in series with the inductor, thereby limiting the current and lengthening the time for the current to increase to source current

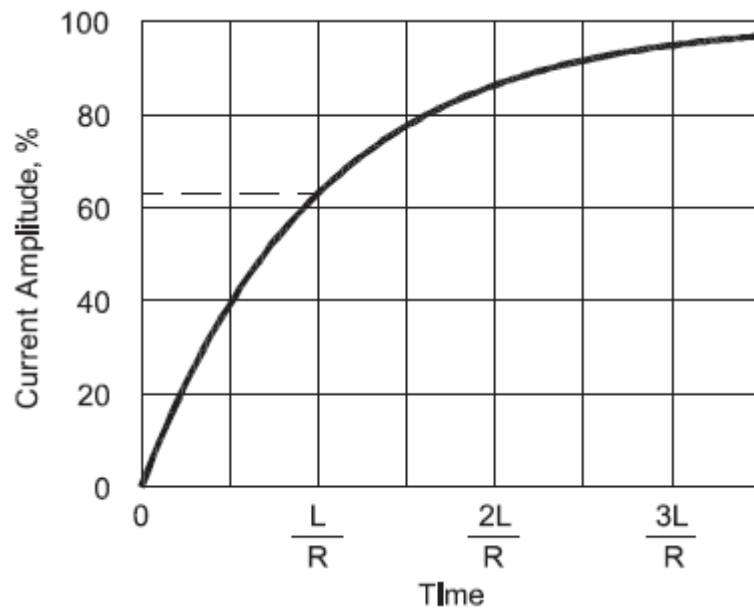
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Inductance and Inductors

RL Time Constant



$$I(t) = \frac{E}{R} \left(1 - e^{-\frac{tR}{L}} \right)$$

where

$I(t)$ = current in amperes at time t ,

E = power source potential in volts,

t = time in seconds after application of voltage,

e = natural logarithmic base = 2.718,

R = circuit resistance in ohms, and

L = inductance in henrys.

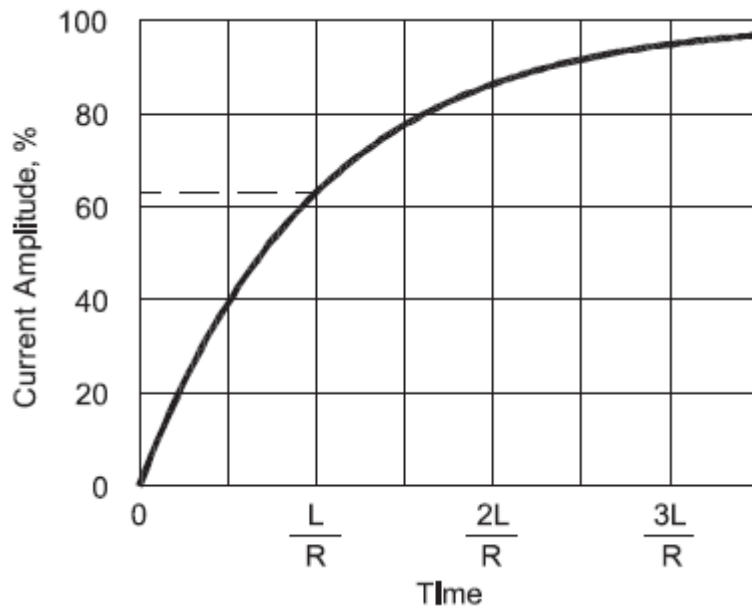
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Inductance and Inductors

RL Time Constant



Because $t = L/R$, the formula can be rewritten as:

$$V(L/R) = E/R (1 - e^{-1}) = 0.632 E/R \text{ -- (0.632 is 63.2\%)}$$

The **RL time constant** is the time in seconds (**t**) required to charge the inductor to **63.2%** of the applied voltage (**one time constant**)

Current is considered to have reached maximum value after **five time constants** (**t = 5t**) – **99.3%**

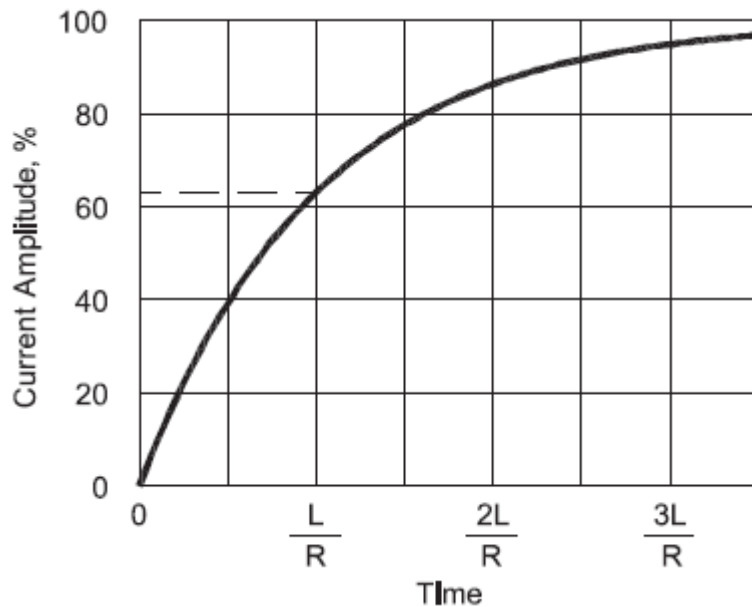
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Inductance and Inductors

RL Time Constant



Amount of charge per time constant:

$$(t = 1L/R) = 63.2\%$$

$$(t = 2L/R) = 86.5\%$$

$$(t = 3L/R) = 95.0\%$$

$$(t = 4L/R) = 98.2\%$$

$$(t = 5L/R) = 99.3\%^*$$

**At $(t = 5L/R)$, current increases to maximum value*

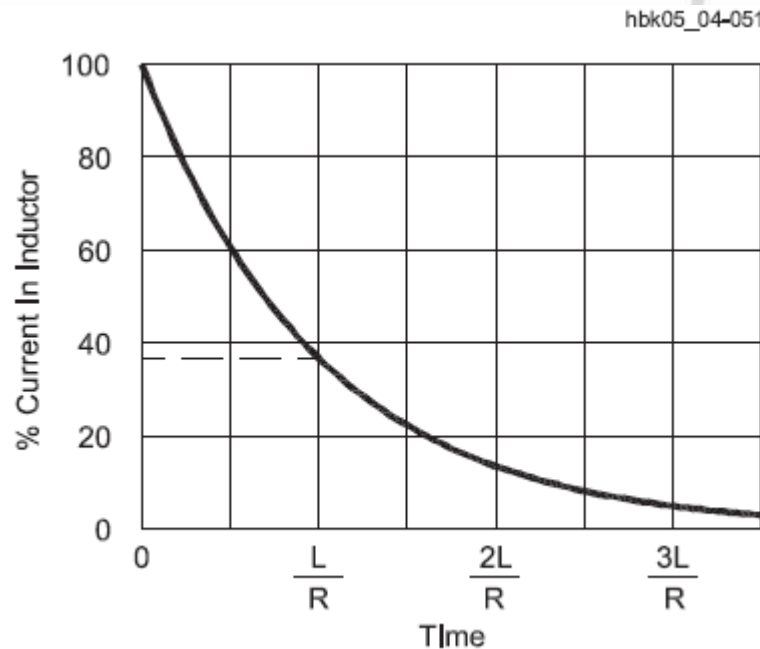
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Inductance and Inductors

RL Time Constant



Depleting an inductor's current using an RL time constant is essentially the same process in reverse

The inductor is **63.2%** discharged at ($t = 1L/R$); **86.5%** at ($t = 2L/R$), etc., until it reaches ($t = 5L/R$), at which point it is **99.3%** depleted*

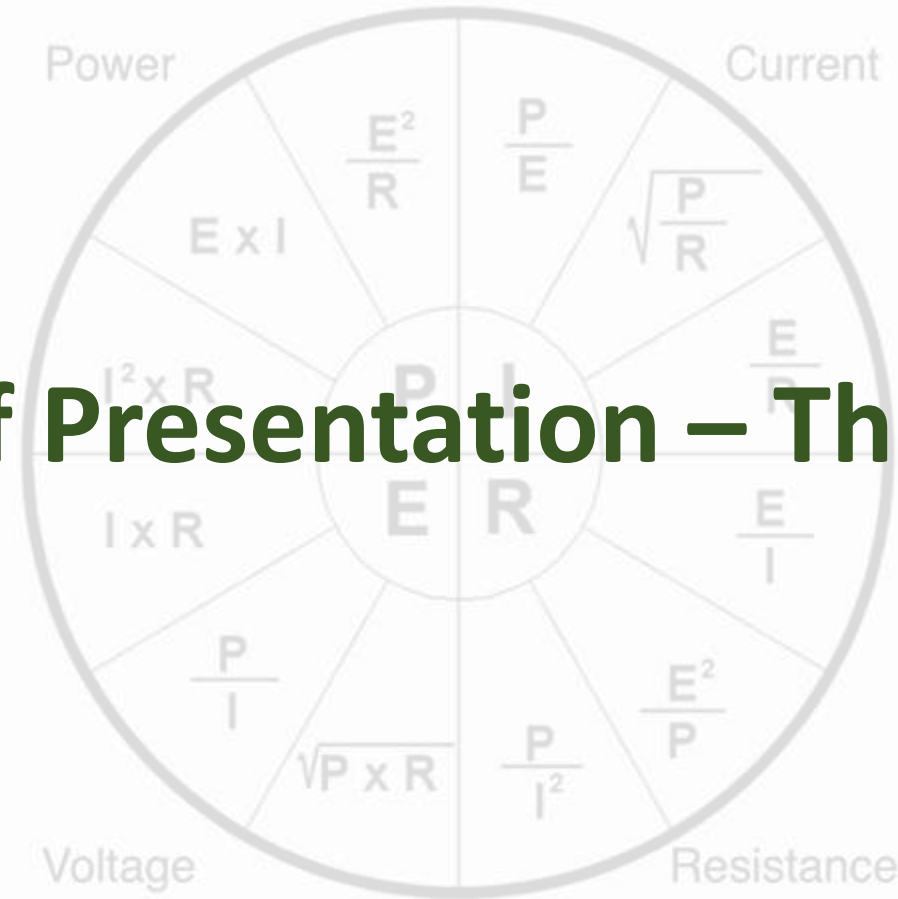
**At ($t = 5t$), current drops to an immeasurably small value*

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End of Presentation – Thank you!





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Questions?

You may email questions later to kq1s@arrl.net

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