SECTION 1: ELECTRICAL FUNDAMENTALS
Introduction
Electricity – what is it?

- Fundamental form of **energy**
  - Resulting from charge differentials

- **Electrons** are the carriers of electrical charge
  - Electron is negatively charged
  - **Hole** – absence of an electron – is positively charged

- May occur naturally
  - Lightning, static electricity

- May be produced by conversion from other forms of energy
  - Generator, battery, solar panel
Electricity – why do we care?

- Electricity can do work for us
  - Mechanical, heat, light, etc.

- Efficient means of energy transmission
  - Large regions supplied by a single power plant

- Used to process and transmit information
  - Computers, mobile phones, TV, radio, etc.
  - Instrumentation and measurement
Electrical Energy

- Energy is conserved, but may be converted from one form to another
- Electrical energy – charge differentials – produced from other forms of energy
  - Generator – mechanical energy
  - Battery – chemical energy

http://www.trimainternational.com/Products/de.htm
Electrical energy can be converted into other useful forms of energy

- Motor – mechanical energy
- Heater – thermal energy
- Charged battery – chemical energy
Energy Transmission

- Electricity is an efficient means of energy transmission
  - Energy is transmitted broadly from a single power plant
  - No longer need to grind our wheat at the windmill

- Imagine other modes of energy transmission
  - Hydraulic, pneumatic, cables, rotating shafts
  - Pneumatic was used in some European cities and was proposed for transmission of energy from Niagara to Buffalo in late 19th century
Relevance for **ALL** Engineers

- **Energy**
  - Efficient means of transmission & distribution
  - Efficient conversion
    - Efficiency of motors vs. engines

- Very few engineered systems without electronics
  - Aircraft, automobiles, robotics, etc.

- **Instrumentation and measurement**
  - All engineered products and systems must be tested, measured, and evaluated
  - Electronic measurements are fast, accurate, repeatable, and can be automated
What is Electrical Engineering?

- Many categories of electrical engineers
- Most fall into one of two areas:

  - **Electronics**
    - Computers
    - Communications
    - Instrumentation and measurement
    - Controls/robotics
    - Energy systems

  - **Power systems**
    - Power generation, transmission, distribution, storage
    - Electric drives
    - Controls/robotics
    - Energy systems
Where We Are Going
ENGR 201/202

- **ENGR 201 – Electrical Fundamentals I**
  - DC circuits

- **ENGR 202 – Electrical Fundamentals II**
  - AC circuits

- **Objectives** of these courses:
  - Develop an *understanding of electrical circuit theory*
  - To prepare you for courses in:
    - Energy conversion systems – ESE 450
    - Electrical power systems – ESE 470
    - Energy storage systems – ESE 471
    - Electronics/circuit design
    - System dynamics and Controls
    - Robotics
ENGR 201 – Course Overview

- **ENGR 201 – Electrical Fundamentals I**
  - DC circuit analysis

  - **Section 1**: Electrical Fundamentals
  - **Section 2**: Resistive Circuit Analysis I
    - Fundamental laws
  - **Section 3**: Resistive Circuit Analysis II
    - Circuit analysis methods
  - **Section 4**: Operational Amplifiers
  - **Section 5**: Capacitance and Inductance
Electronic Photo Flash Circuit

- **Electronic photo flash circuit**
  - Simple, yet very interesting circuit example
  - Preview of what you will learn in ENGR 201

- **The problem:**
  - Use small, rechargeable battery to fire the camera flash

- **The details:**
  - 4 V battery – maximum output power: \(~1\) W
  - Flash tube requires 100s of volts, \(~1000\) W

- By the end of ENGR 201, you’ll understand:
  - How this works – how the required voltage and power are supplied
  - How we determine the appropriate model for the battery
  - How long the battery will last – how many flashes
Electrical Fundamentals
Potential or voltage or electromotive force (emf)

- A measure of electrical energy
- The energy required to move one unit of electrical charge from one point to another
  - Units of potential: volts (V)
  - Units of electrical charge: coulombs (C)
  - Units of energy: joules (J)

\[ 1 V = 1 \frac{J}{C} \]
Electrical Potential

- Electrical potential is a **differential quantity**
  - Voltage *between* two points in a circuit
  - Voltage between a point and a *ground reference*

- No such thing as an *absolute* voltage at a location, but...
  - We do talk about **node voltages**
    - Always referenced to ground
  - For example,
    - Node voltages:
      \[ V_a = 10 \text{ V}, \quad V_b = 5 \text{ V} \]
    - Differential voltage:
      \[ V_{ab} = V_a - V_b = 5 \text{ V} \]
**Electric Field**

- **Electric field**
  - A field of force experienced by positively-charged particles
  - Points from positive to negative charge (positive to negative potential)
  - Positive charge wants to move in the direction of the E-field, toward negative charge
  - Units: newtons per coulomb (N/C) or volts per meter (V/m)
  - The negative gradient of the potential
  - Electrical energy is stored in the electric field
Electrical current (I) is the flow of positive charge

- Voltage is the driving potential
- Units: amperes or amps (A) – coulombs per second (C/s)
  - A rate of charge flow:
    \[ 1A = 1 \frac{C}{s} \]

- Current wants to flow from high to low potential
- Analogous to fluid flow or heat flow
  - Fluid flows from high to low pressure
  - Heat flows from high to low temperature
Current – what’s really flowing?

- Current is defined as the **flow of positive charge**
- Really, current is the **flow of negatively-charged electrons in the opposite direction**
  - Electrons flow from low potential to high potential
  - Negative charge flow in one direction is equivalent to positive charge flow in the opposite direction
Conductors and Insulators

- Electrical current flows more easily in some materials (**conductors**) than in others (**insulators**)

- Good conductors:
  - Copper
  - Aluminum
  - Gold
  - Silver

- All have a single valence electron
  - Easy for electrons to move from one atom to the next

- Good insulators have full valence bands

http://elpaso.apogee.net/foe/fbbr.asp
Electrical-Mechanical Analogies

- Electrical systems are analogous to:
  - *Fluid systems*
  - *Thermal systems*

<table>
<thead>
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<th>Driving potential</th>
<th>Flowing quantity</th>
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<td>Heat</td>
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Electrical Circuits
Electrical Networks – Schematics

- Electrical circuits represented graphically with *schematics*
  - Schematic symbols represent circuit elements
  - Schematics detail connections between circuit elements
  - Schematics describe paths for the flow of electrical current

- Some examples:
### Electrical Networks – Branches & Nodes

#### Nodes
- Connection points for circuit elements
- Node voltages given with respect to a reference node (0 V, ground)
  - E.g. $V_3 = 0$ V, here
- Current flows into and out of nodes

#### Branches
- Paths for current to flow
- Connections between nodes
- Branches are the components that comprise the circuit
- Voltage across a branch is the difference between node voltages at either end
Electrical Signals & Waveforms
Electrical Signals

- **Voltage** and **current** are the two properties of electrical circuits that we are most often concerned with.

  - Voltages and currents may be **constant as functions of time**
    - Direct current, **DC**
  
  - Or they may be **time-varying**
    - Alternating current, **AC**

We can refer to these quantities as electrical **signals**

- They carry information
- More appropriate terminology in the world of electronics than power systems

- Voltages and currents can be plotted as functions of time – **waveforms**
DC vs. AC

- **DC** (direct current) electrical signals (voltages, currents) are *time-invariant*
  - In ENGR 201, we will primarily focus on DC signals

- **AC** (alternating current) electrical signals are *time-varying*
  - Possibly *periodic*
Some Typical Waveforms

**Sinusoid:**

**Square wave:**

**Triangle wave:**

**Noise:**
In ENGR 202, we will see that **sinusoidal** signals are of particular interest in the field of electrical engineering.

$$v(t) = V_p \cos(\omega t + \phi) = V_p \cos(2\pi f t + \phi)$$

Sinusoidal signals defined by three parameters:

- **Amplitude**: $V_p$
- **Frequency**: $\omega$ or $f$
- **Phase**: $\phi$
Amplitude

- **Amplitude** of a sinusoid is its **peak** voltage, $V_p$

- **Peak-to-peak voltage**, $V_{pp}$, is twice the amplitude
  - $V_{pp} = 2V_p$
  - $V_{pp} = V_{max} - V_{min}$

$v(t) = V_p \cdot \sin(\omega t + \phi) = V_p \cdot \sin(2\pi ft + \phi)$

![Graph showing sinusoidal wave with amplitude and peak-to-peak voltage labeled](image)
Frequency

- **Period** ($T$)
  - Duration of one cycle

- **Frequency** ($f$)
  - Number of periods per second
    
    \[ f = \frac{1}{T} \]

- **Ordinary frequency**, $f$
  - Units: hertz (Hz), sec$^{-1}$, cycles/sec

- **Angular frequency**, $\omega$
  - Units: rad/sec
    
    \[ \omega = 2\pi f, \quad f = \frac{\omega}{2\pi} \]

![Graph showing a wave with labeled period and frequency](image)
Phase

Angular constant in signal expression, $\phi$

$$v(t) = V_p \sin(\omega t + \phi)$$

Requires a time reference

Interested in relative, not absolute, phase

Here,

$v_1(t)$ leads $v_2(t)$

$v_2(t)$ lags $v_1(t)$

Units: radians

Not technically correct, but OK to express in degrees, e.g.:

$$v(t) = 170 \, V \sin(2\pi \cdot 60Hz \cdot t + 34^\circ)$$
**RMS Value**

- **Root mean square (rms) voltage/current**
  - Square root of the time average of the voltage/current squared
  - AC voltage applied across a resistor results in same power dissipation as a DC voltage where \( V_{DC} = V_{rms} \)

- For **sinusoids**:
  
  \[
  V_{rms} = \frac{V_p}{\sqrt{2}}
  \]
  
  \[
  v(t) = \sqrt{2} \cdot V_{rms} \sin(\omega t + \phi)
  \]
Electrical Energy & Power
Energy and Power

- True understanding of electrical systems comes from understanding how they behave in terms of **energy**
  - True for dynamic systems in any domain – mechanical, electrical, etc.

- Electrical components can do one of four things:
  - Supply energy
  - Store energy
  - Dissipate energy
  - Transform/transmit/convert energy

- We’re also concerned with the **rate** at which energy is supplied, stored, dissipated, or transformed

- **Power** is the **rate of energy flow**
  - Unit of energy: joule (J)
  - Unit of power: watt (W), $1 \, W = 1 \frac{J}{s}$
Energy and Power

- Power is the **rate** of energy flow
  - The **time derivative** of energy
    \[ P = \frac{dE}{dt} \]
    
    \[ [W] = \left[ \frac{J}{s} \right] \]

- Similarly, energy is given by the **integral** of power
  \[ E = \int p(t)dt \]

- For constant power, this simplifies to the product of power and time
  \[ E = P \cdot t \]
  
  \[ [J] = \left[ \frac{J}{s} \right] \cdot [s] \]
Electrical Energy

- The power utility company charges us for energy, not power
  - Units: watt-hours (Wh or kWh)
  - For example: $0.12/kWh

- One watt-hour (1 Wh):
  - Quantity of energy equivalent to the consumption of 1 W for 1 hour

\[
1 \text{ Wh} = \frac{J}{s} \cdot 1 \text{ h} = \frac{J}{s} \cdot 1 \text{ h} \cdot \frac{3600 \text{ s}}{1 \text{ hr}} = 3600 \text{ J}
\]

\[
1 \text{ Wh} = 3.6 \times 10^3 \text{ J} = 3.6 \text{ kJ}
\]

\[
1 \text{ kWh} = 3.6 \times 10^6 \text{ J} = 3.6 \text{ MJ}
\]
Electrical Power

- A circuit component will have voltage across it and current flowing through it
  - In general, both are functions of time: $v(t)$ and $i(t)$

- Power flowing to/from that component is given by the product of voltage and current

\[
p(t) = v(t) \cdot i(t)
\]

- **Instantaneous power**
  - A function of time

- If $i(t)$ and $v(t)$ are constant (DC) then $p(t)$ is constant as well

\[
P = V \cdot I
\]
Power – Passive Sign Convention

- **Power** can be *supplied* or *absorbed* by electrical components.
- For any component, power is given by
  \[ p(t) = v(t) \cdot i(t) \]
- Use the **passive sign convention** to determine if power is supplied or absorbed:
  - Positive current flows into the positive voltage terminal.
  - **Positive** power \((p > 0)\) indicates power *absorbed*.
  - **Negative** power \((p < 0)\) indicates power *supplied*.
Batteries store electrochemical energy

- Amount of energy stored is **capacity**
  - Typically specified in units of **ampere-hours** (Ah)

For example, a 90 Ah battery could supply the equivalent of 90 A for 1 hour

\[
90 \text{ Ah} = 90 \text{ A} \cdot 1 \text{ h} = 90 \frac{\text{C}}{\text{s}} \cdot 1 \text{ h} \cdot \frac{3600 \text{ s}}{1 \text{ h}} = 324 \times 10^3 \text{ C}
\]

- Or, 1 A for 90 hours (or any other equivalent combination)

\[
90 \text{ Ah} = 1 \text{ A} \cdot 90 \text{ h} = 1 \frac{\text{C}}{\text{s}} \cdot 90 \text{ h} \cdot \frac{3600 \text{ s}}{1 \text{ h}} = 324 \times 10^3 \text{ C}
\]

- Clearly, this is a quantity of **charge, not energy**
To relate capacity in Ah to energy storage, we must know the battery’s voltage.

For example, consider a 90 Ah, 12 V battery.

If discharging at 1 A, for example, the power supplied is

$$P = V \cdot I = 12 \, V \cdot 1 \, A = 12 \, W$$

At this rate the battery can discharge for 90 h, so the total stored energy is

$$E = P \cdot t = 12 \, W \cdot 90 \, h = 1080 \, Wh = 1.08 \, kWh$$

Energy capacity in Wh is given by the product of capacity in Ah and the battery voltage:

$$E = (\text{capacity in Ah}) \cdot (\text{battery voltage})$$
Example Problems
How much charge is stored in an 80 Ah battery?

\[ Q = 80 \text{ Ah} \cdot \frac{1 \text{ C/s}}{1 \text{ A}} \cdot \frac{3600 \text{ s}}{1 \text{ hr}} = 288 \text{ kC} \]
A 24 V battery pack will be used to power a 100 W load for 3 hours. What is the required battery capacity in Ah? In Wh? In J?

\[ P = VI \rightarrow I = \frac{P}{V} \]

\[ I = \frac{100 \text{ W}}{24 \text{ V}} = 4.167 \text{ A} \]

Capacity = 3hr \cdot 4.167 A = 12.5 \text{ Ah}

or

Capacity = 3hr \cdot 100 \text{ W} = 300 \text{ Wh}

or

Capacity = 300 \text{ Wh} \cdot \frac{3600 \text{ s}}{1 \text{ hr}} \cdot \frac{1 \text{ J/s}}{1 \text{ W}} = 1.08 \text{ MJ}
A daily load profile for a building is shown. How much energy is consumed each day?

If the cost of electricity is $0.11/kWh, what is the daily cost of electricity? What is the yearly cost?

\[
E = (100 \text{ W} \cdot 6 \text{ hr}) + (900 \text{ W} \cdot 6 \text{ hr}) + (1800 \text{ W} \cdot 6 \text{ hr}) \\
\quad + (400 \text{ W} \cdot 3 \text{ hr}) + (100 \text{ W} \cdot 3 \text{ hr})
\]

\[
E = 600 \text{ Wh} + 5400 \text{ Wh} + 10800 \text{ Wh} + 1200 \text{ Wh} + 300 \text{ Wh}
\]

\[
E = 18,300 \text{ Wh} = 18.3 \text{ kWh}
\]
\[
\text{Cost/\text{day}} = \frac{E}{\text{Day}} \cdot \frac{\$}{\text{kWh}} = 18.3 \text{ kWh} \cdot \frac{\$0.11}{\text{kWh}}
\]
\[
\text{Cost/\text{day}} = \$2.013
\]
\[
\text{Cost/\text{year}} = \text{Cost/\text{day}} \cdot \frac{365.25 \text{ day}}{\text{Year}}
\]
\[
\text{Cost/\text{year}} = \$2.013 \text{ day} \cdot \frac{365.25 \text{ day}}{\text{Year}}
\]
\[
\text{Cost/\text{year}} = \$735.25
\]
A typical 9 V battery has a capacity of 170 mAh. How many batteries would have to be connected in parallel to drive an 80 W load for 2 hours?

Total energy required is

\[ E = 80 \text{W} \cdot 2\text{h} = 160 \text{Wh} \]

Capacity of each 9 V cell in Wh:

\[ E_{\text{cell}} = 170 \text{mAh} \cdot 9\text{V} = 1.53 \text{Wh} \]

Required # of cells:

\[ \text{#cells} = \frac{E}{E_{\text{cell}}} = \frac{160 \text{Wh}}{1.53 \text{Wh}} = 104.6 \text{ cells} \]

\[ \text{#cells} = 105 \]
Determine the power for the source and for each branch element in the following circuit. Show that power is conserved.

\[
P_3 = 10V \times (-10A) = -100\text{W} \quad \text{(supplied)}
\]

\[
P_1 = 10V \times (2A) = 20\text{W}
\]

\[
P_2 = 4V \times (8A) = 32\text{W}
\]

\[
P_3 = 6V \times (8A) = 48\text{W}
\]

\[
P = P_3 + P_1 + P_2 + P_3
\]

\[
P = -100\text{W} + 20\text{W} + 32\text{W} + 48\text{W}
\]

\[
P = -100\text{W} + 100\text{W} = 0\text{W} \quad \text{power is conserved}
\]

\[
\]
How much energy is delivered by a 20 hp motor in 15 minutes?

If the motor is 92% efficient, how much energy is consumed by the motor during that time? (1 hp = 746 W)

\[
E_{out} = P_{out} \cdot t = 20 \text{ hp} \cdot \frac{746 \text{ W}}{1 \text{ hp}} \cdot 15 \text{ min} \cdot \frac{60 \text{ s}}{1 \text{ min}} \cdot \frac{1 \text{ J/s}}{1 \text{ W}}
\]

\[
E_{out} = 14.92 \text{ kW} \cdot 900 \text{ s} \cdot \frac{1 \text{ J/s}}{1 \text{ W}}
\]

\[
E_{out} = 13.43 \text{ MJ}
\]

\[
E_{in} = \frac{E_{out}}{\eta} = \frac{13.43 \text{ MJ}}{0.92}
\]

\[
E_{in} = 14.96 \text{ MJ}
\]
50

Electrical Circuit Components
Circuit Components

- **Independent voltage source**
  - **Schematic symbol:**
  - **Description:**
    - Generates a fixed voltage between its terminals
    - DC or AC
  - **Units:** volts (V)

- **Independent current source**
  - **Schematic symbol:**
  - **Description:**
    - Generates a fixed current
    - DC or AC
    - Current flows in one terminal and out the other
  - **Units:** amperes (A)
Circuit Components

- **Dependent voltage source**
  - **Schematic symbol:**
    
    ![Schematic Symbol for Dependent Voltage Source]
    
  - **Description:**
    - Generates a voltage that is a function of another voltage or current in the circuit
    - Voltage-controlled voltage source (VCVS) or current-controlled voltage source (CCVS)
  - **Units:** volts (V)

- **Dependent current source**
  - **Schematic symbol:**
    
    ![Schematic Symbol for Dependent Current Source]
    
  - **Description:**
    - Generates a current that is a function of another current or voltage in the circuit
    - Current-controlled current source (CCCS) or voltage-controlled current source (VCCS)
  - **Units:** amperes (A)
Circuit Components

- **Resistor**
  - **Schematic symbol:**
    
    [Resistor symbol]
  
  - **Description:**
    - Circuit element that resists the flow of electrical current
    - Intentional or parasitic resistance (even wires are resistive)
  
  - **Units:** ohms (Ω)

- **Ground**
  - **Schematic symbol:**
    
    [Ground symbol]
  
  - **Description:**
    - Voltage reference for a circuit
    - Ground node
    - Potential of 0 V
Circuit Components

- **Capacitor**
  - Schematic symbol:
  - Description:
    - Stores energy in an electric field
    - Two electrodes separated by a dielectric
    - Stores a charge differential between the two electrodes
  - Units: farads (F)

- **Inductor**
  - Schematic symbol:
  - Description:
    - Stores energy in a magnetic field
    - A coil of wire
  - Units: henries (H)
## Switch

- **Schematic symbol:**
  - SPST
  - SPDT

- **Description:**
  - Controls connections between multiple nodes in a circuit
  - Single-pole single-throw (SPST) switch makes/breaks connection between two nodes
  - Single-pole double-throw (SPDT) switch connects one node to one of two other nodes
  - Many other configurations, e.g. DPDT, 3PDT, 6P3T, etc.
Circuit Components

- **Diode**
  - Schematic symbol:
    - ![Schematic symbol for diode]
  - **Description:**
    - Two-terminal semiconductor device
    - Junction of p-type and n-type semiconductor – a p-n junction
    - Allows current to flow in one direction only (anode to cathode)
    - Analogous to a check valve

- **Light-emitting diode (LED)**
  - Schematic symbol:
    - ![Schematic symbol for LED]
  - **Description:**
    - Diode that emits photons in response to current flowing through it
Circuit Components

- **Transistor**
  - **Schematic symbol:**
  - **Description:**
    - Three-terminal semiconductor device
    - Small voltage on/current into one terminal controls current flow between the other two terminals
    - Primary building block of integrated circuits
    - Can be used as *switches* or *amplifiers*
    - Analogous to *valves*:
Short Circuits & Open Circuits

- **Short circuit**
  - Direct connection between multiple nodes in a circuit
  - A direct path for current to flow
  - Often refers to an unintentional connection

- **Open circuit**
  - Lack of any electrical connection between two nodes in a circuit
  - No path for current to flow
  - Again, often used to refer to an unintended condition

![Diagram of a circuit with short and open circuits highlighted](image-url)
Complete Circuits

- Electrical current always flows in a **complete circuit**
  - A return current path must always exist for current to flow
  - Consider a simple lamp:
    - Two-conductor cord – line and neutral
    - Current flows from socket, down one conductor – line
    - Current flows through the bulb
    - Current returns back along the neutral conductor to the wall, and, ultimately, to the power plant

- Ladder on a power line vs. bird on power line
Miscellany
Problem Solving

- Engineering is all about solving problems, e.g.:
  - Designing complex systems to solve problems
  - Troubleshooting malfunctioning prototypes
  - Solving homework/exam problems as a student

- All engineering problems are different, but we can apply a similar general process to all problem solving:
  1. Carefully define the problem
  2. Present everything you know about the problem
  3. Establish a list of alternative approaches to solving the problem and select the “best” approach
  4. Attempt to solve the problem
  5. Evaluate the solution and check for accuracy
  6. If the problem is solved, you’re done, if not, go to step 3
Problem Solving

- In **flowchart** form:

  1. Carefully define the problem
  2. Present everything you know about the problem
  3. Establish a list of alternative approaches to solving the problem and select the “best” approach
  4. Attempt to solve the problem
  5. Evaluate the solution and check for accuracy
  6. If the problem is solved, you’re done, if not, go to step 3
Use **SI prefixes** for unit scaling whenever possible
- Simplifies notation
- Makes quantities easier to read and prevents errors
- For example: 18 psec vs. 0.000000000018 sec

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<th>Prefix</th>
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