Review of Basic Electronics

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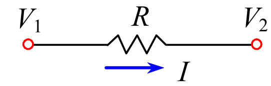
Latest revision: 27 August 2014

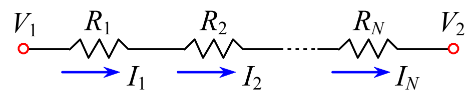
Introduction

- Electronic circuits are critical components in most laboratory instruments.
- Here, we review the basics of electronic circuits; we use this material throughout the rest of the course.

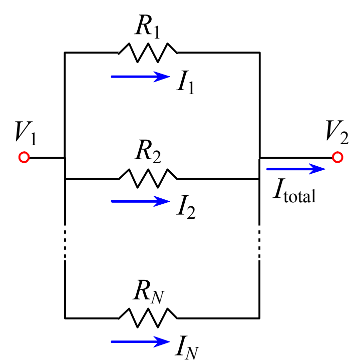
Resistance



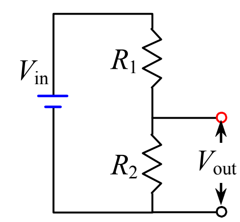
- A ***resistor*** impedes the flow of both DC and AC currents.
- The schematic diagram for a resistor is shown to the right, where R is the ***resistance*** in ohms (Ω), $\Delta V = V_1 - V_2$ is the voltage drop across the resistor in volts (V), and I is the current flowing through the resistor in amperes (A).
- *Note*: Sometimes we use E instead of V for voltage (or ***electric potential***); E and V are used interchangeably.
- The definition of ***ohm*** is as follows: A one-Ω (ohm) resistor with one V (volt) across it has a current of one A (ampere) flowing through it, or $\boxed{1\ \Omega = 1\ \frac{\text{V}}{\text{A}}}$. Expressed as a unity conversion ratio, $\boxed{\left(\frac{1\ \Omega}{1\ \text{V/A}}\right) = 1}$.
- The current through a resistor and the voltage drop across a resistor change instantaneously with time.
- At any instant in time, ***Ohm's law*** holds: $\boxed{\Delta V = IR}$.
- Ohm's law is valid for both DC and AC signals; *time is not a factor in circuits that contain only resistors*.
- Resistors in ***series*** (as sketched to the right):
  - The total resistance for resistors in series is $\boxed{R_{\text{total}} = R_1 + R_2 + \ldots + R_N}$, and $\boxed{I = I_1 = I_2 = \ldots = I_N}$.
  - For resistors in series, the current is the same through each resistor, but the voltage drop may differ across each individual resistor.



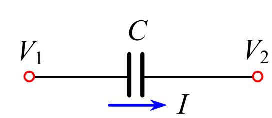
- Resistors in ***parallel*** (as sketched to the right):
  - The total resistance for resistors in parallel is $\boxed{R_{\text{total}} = \dfrac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2} + \ldots + \dfrac{1}{R_N}}}$, and $\boxed{I_{\text{total}} = I_1 + I_2 + \ldots + I_N}$.
  - For resistors in parallel, the voltage drop is the same across each resistor, but the current through each individual resistor may differ.



- As a simple example of a useful circuit containing only resistors, consider a ***voltage divider***, as sketched to the right.
  - The symbol ⊥ on the left of the circuit represents a battery or some other DC voltage supply that provides the input voltage V_{in}.
  - The output voltage V_{out} is smaller than the input voltage V_{in} by a linear ratio between the resistances, $\boxed{V_{\text{out}} = V_{\text{in}} \dfrac{R_2}{R_1 + R_2}}$. [We are assuming that V_{out} is read by an ideal voltmeter that has infinite input impedance, as will be discussed later in this course.]

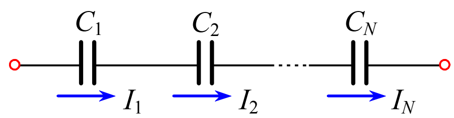


Capacitance

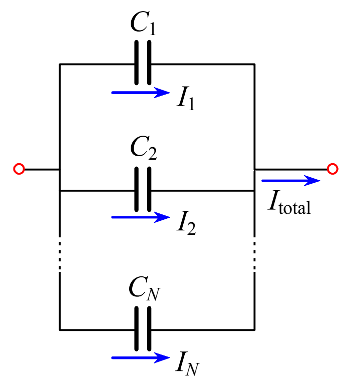


- A ***capacitor*** stores an electrical charge, and therefore *blocks* DC current.
- The schematic diagram for a capacitor is shown to the right, where C is the ***capacitance*** in farads (F), $\Delta V = V_1 - V_2$ is the voltage drop across the capacitor in volts (V), and I is the current flowing through the capacitor in amperes (A).
- The definition of ***farad*** is as follows: A one-F (farad) capacitor with one V (volt) across it stores one C (coulomb) of charge, or $\boxed{1\ \text{F} = 1\ \frac{\text{C}}{\text{V}}}$. Expressed as a unity conversion ratio, $\boxed{\left(\frac{1\ \text{F}}{1\ \text{C/V}}\right) = 1}$.
- Farad is a very large unit, so most capacitors use units of microfarads (μF) instead, where $1\ \mu\text{F} = 10^{-6}\ \text{F}$.
- Capacitors not only ***store*** electrical energy, but also ***discharge*** electrical energy.
- Unlike resistors, capacitors do not adjust to voltage changes instantaneously with time; rather *time is a factor in circuits with capacitors*.
- At any instant in time, $\boxed{I = C\dfrac{dV}{dt}}$ across a capacitor. In other words, *current can flow through a capacitor only if the voltage across the capacitor is changing with time*.

- Some consequences of the above statement:
  - For *DC signals*, there is *no current flow* through a capacitor, but *there is a voltage drop*. (The capacitor acts like an *open* switch – a switch that is turned *off*.)
  - For *AC signals*, *the current through a capacitor changes as the voltage changes with time*, according to the above equation. At very high frequencies, AC signals easily pass through a capacitor, almost like a *closed* switch. Capacitors offer little impedance to very high frequency signals.
- *Capacitors* ***block*** *DC signals, but merely* ***impede*** *AC signals*.
- Capacitors in ***series*** (as sketched to the right):



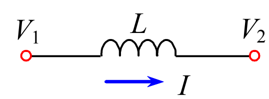
  - The total capacitance for capacitors in series is $C_{\text{total}} = \dfrac{1}{\dfrac{1}{C_1}+\dfrac{1}{C_2}+...+\dfrac{1}{C_N}}$, and $I = I_1 = I_2 = ... = I_N$ at any instant.
  - For capacitors in series, the current through each capacitor must be identical, but the voltage drop may differ across each individual capacitor.



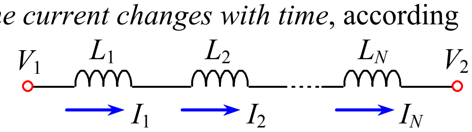
- Capacitors in ***parallel*** (as sketched to the right):
  - The total capacitance for capacitors in parallel is $C_{\text{total}} = C_1 + C_2 + ... + C_N$, and $I_{\text{total}} = I_1 + I_2 + ... + I_N$ at any instant in time.
  - For capacitors in parallel, the voltage drop is the same across each capacitor, but the current may differ across each individual capacitor.

Inductance

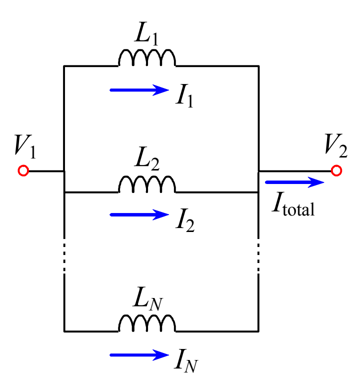
- An ***inductor*** allows DC currents to flow, but *impedes* AC currents.
- An inductor is also called a ***choke*** when it is used in an electrical circuit to isolate AC frequency currents, e.g., in a power supply filter.



- The schematic diagram for an inductor is sketched to the right, where L is the ***inductance*** in henrys (H), $V = V_1 - V_2$ is the voltage drop across the inductor in volts (V), and I is the current flowing through the inductor in amperes (A).
- The definition of ***henry*** is as follows: A one-H (henry) inductor has a one V (volt) drop across it when the current is changing at the rate of one A/s (ampere per second), or $1\text{ H} = 1\dfrac{\text{V}}{\text{A/s}}$. Expressed as a unity conversion ratio, $\left(\dfrac{1\text{ H}\cdot\text{A/s}}{1\text{ V}}\right) = 1$.
- Like capacitors, inductors do not adjust to current changes instantaneously with time; rather *time is a factor in circuits with inductors*.
- At any instant in time, $V = L\dfrac{dI}{dt}$ across an inductor. In other words, *there can be a voltage drop across an inductor only if the current through the inductor is changing*.
- Some consequences of the above statement:
  - For *DC signals*, there is *no voltage drop* across the inductor, but *there is a current flow*. (The inductor acts like a closed switch – a switch that is turned on – basically, the inductor acts like a wire.)
  - For *AC signals*, *the voltage drop across an inductor changes as the current changes with time*, according to the above equation.



- Inductors in ***series*** (as sketched to the right):
  - The total inductance for inductors in series is $L_{\text{total}} = L_1 + L_2 + ... + L_N$, and $I = I_1 = I_2 = ... = I_N$ at any instant.
  - For inductors in series, the current is the same through each inductor, but the voltage drop may differ across each individual inductor.

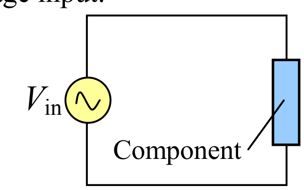


- Inductors in ***parallel*** (as sketched to the right):
  - The total inductance for inductors in parallel is $L_{\text{total}} = \dfrac{1}{\dfrac{1}{L_1}+\dfrac{1}{L_2}+...+\dfrac{1}{L_N}}$, and $I_{\text{total}} = I_1 + I_2 + ... + I_N$ at any instant in time.
  - For inductors in parallel, the voltage drop is the same across each inductor, but the current through each individual inductor may differ.
- Inductors get a little tricky when they are physically close to each other. If

their magnetic fields interact with each other, there is an additional effect called ***mutual inductance***. If the mutual inductance is significant, the above equations for series and parallel inductors are no longer reliable.

Impedance

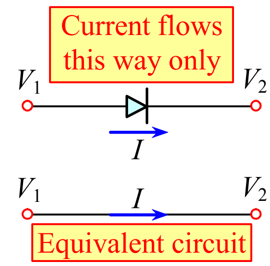
- The word ***impedance*** is a general term implying that some quantity is slowed down or resisted.
- In electronics, impedance can be defined for resistors, capacitors, and inductors, since all of these electronic components *impede* something.
- Impedance provides a way of combining the effects of resistance, capacitance, and inductance into one property, and is thus a useful tool for analyzing and designing circuits.
- The units of impedance are the same as that of resistance – ohms.
- Let $\boldsymbol{Z}$ be the impedance of some electronic component. $\boldsymbol{Z}$ is a complex number. In this module, **bold** fonts are used to denote complex numbers.
- By definition, the absolute value (magnitude or modulus) of complex number $\boldsymbol{Z}$ is the ratio of peak voltage to peak current, $|\boldsymbol{Z}| = \frac{V_{\text{peak}}}{I_{\text{peak}}}$, where V_{peak} is the peak voltage or ***amplitude*** of an AC signal ($-V_{\text{peak}} \le V \le V_{\text{peak}}$) and I_{peak} is the peak current ($-I_{\text{peak}} \le I \le I_{\text{peak}}$).
- Since there are ***phase shifts*** in AC signals, complex numbers are used to mathematically define impedance.
- To help you understand impedance, consider an input voltage signal consisting of a simple sine wave of amplitude V_{peak}, and with no phase shift or DC offset, $V_{\text{in}} = V_{\text{peak}} \sin(2\pi f t) = V_{\text{peak}} \sin(\omega t)$, where f is the frequency in Hz, and ω is the angular frequency in radians/s.
- Consider the impedance of the three basic electronic components (resistor, capacitor, and inductor) in a simple circuit as shown to the right, where the symbol ∿ implies a sinusoidal voltage input.



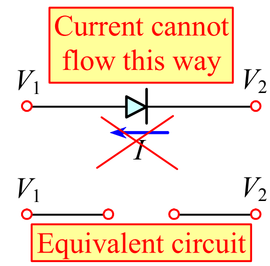
- **Resistor**:
  - The impedance $\boldsymbol{Z}$ for an ideal resistor is $\boldsymbol{Z} = R$, and it is *real*.
  - For a DC signal, $\omega = 0$, and $\boldsymbol{Z} = R$.
  - For an AC signal, $\omega \ne 0$, but still, $\boldsymbol{Z} = R$.
  - In other words, impedance is the same as resistance when considering a resistor. It does not matter whether the signal is AC or DC; the impedance of an ideal resistor is always equal to the resistance R.
- **Capacitor**:
  - The impedance $\boldsymbol{Z}$ for an ideal capacitor is $\boldsymbol{Z} = \frac{1}{i\omega C}$, and it is *imaginary*. (*Note*: $i = \sqrt{-1}$.)
  - For a DC signal, $\omega = 0$, and $\boldsymbol{Z} \to \infty$. In other words, *an ideal capacitor has infinite impedance to a DC signal*, and acts like an *open* switch to DC currents – it *completely impedes* or *blocks* DC currents.
  - For an AC signal, $\omega \ne 0$, and $\boldsymbol{Z}$ is an imaginary number, inversely proportional to the frequency and to the capacitance, as seen in the above equation – the capacitor *impedes* AC currents, but not completely.
  - As $\omega \to \infty$ (very high frequency AC signal), $\boldsymbol{Z} \to 0$. In other words, *a capacitor offers very little impedance to high frequency AC signals*.
- **Inductor**:
  - The impedance $\boldsymbol{Z}$ for an ideal inductor is $\boldsymbol{Z} = i\omega L$, and it is *imaginary*.
  - For a DC signal, $\omega = 0$, and $\boldsymbol{Z} = 0$. In other words, *an ideal inductor has no impedance to a DC signal*, and acts like a *closed* switch to DC currents – it lets DC currents pass through unaffected.
  - For an AC signal, $\omega \ne 0$, and $\boldsymbol{Z}$ is an imaginary number, proportional to the frequency and proportional to the inductance, as seen in the above equation – the inductor *impedes* AC currents, but not completely.
  - As $\omega \to \infty$ (very high frequency AC signal), $\boldsymbol{Z} \to \infty$. In other words, *an inductor has high impedance to high frequency AC signals* – it nearly completely *blocks* high frequency AC currents.
- Comparing the effect of capacitors and inductors, inductors are somewhat opposite to capacitors (capacitors offer little impedance to low frequency AC signals but let high frequency AC signals pass, while inductors greatly impede high frequency AC signals, but let low frequency AC signals pass).

Review of complex variables – See the learning module Review of Complex Variables for a general review.

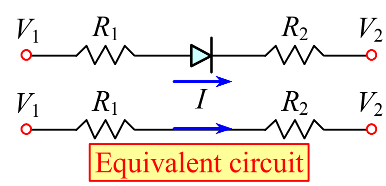
Diodes



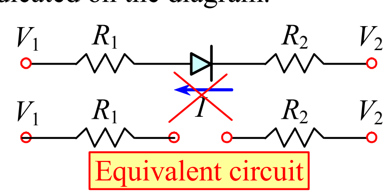
- A ***diode*** (also called a ***switching diode***) allows current to flow in one direction, but it *impedes* the flow of current in the opposite direction.
- The schematic diagram for a diode is shown to the right.
  - When current flows in the direction of the arrow symbol, we call it ***forward biased***. An ideal diode has ***zero impedance*** in the forward biased mode.
  - When current attempts to flow in the direction *against* the arrow symbol, we call it ***reverse biased***. An ideal diode has ***infinite impedance*** in the reverse biased mode.
- For an ideal diode with current flowing in the allowed direction (forward biased), the voltage does not drop across the diode: $\Delta V = V_1 - V_2 = 0$. Thus, the equivalent circuit is a closed switch or short circuit (just a wire between 1 and 2), as sketched to the right.
- A real diode, however, creates a small voltage drop in the circuit.



- If $\Delta V = V_1 - V_2 < 0$, in other words if $V_2 > V_1$, then current attempts to flow through an ideal diode in the opposite direction (reverse bias). However, the diode does not permit current to flow that way (opposite to the direction of the arrow in the schematic diagram). Thus, the equivalent circuit is an open switch or open circuit (no connection between the two leads of the diode), as sketched to the right.
- A real diode, however, has a small leakage of current through the diode.
- Procedure for the analysis of a circuit containing an ideal diode:
  - Assume that the diode is operating in forward bias mode; in other words, replace the diode with a short circuit.
  - Evaluate the circuit and calculate the direction of current flow through the diode.
  - If the calculated current is in the forward bias direction (in the direction of the arrow), then the analysis is valid, and nothing further needs to be done.
  - If the calculated current is in the reverse bias direction (in the direction opposite of the arrow), then the analysis is invalid. Replace the diode with an open circuit, force the current to be zero, and re-analyze the circuit.



- <u>Example</u>:
  Given: The circuit shown to the right.
  To do: Calculate the current through the diode for two cases: (a) $V_1 > V_2$, and (b) $V_2 > V_1$.
  Solution: We follow the procedure outlined above.
  (a) We assume that the diode is in forward bias mode, and replace the diode with a short circuit. Ohm's law yields $(V_1 - V_2) = I(R_1 + R_2)$ or $\boxed{I = \frac{(V_1 - V_2)}{(R_1 + R_2)}}$. Since $V_1 > V_2$, the predicted current $I > 0$, and our assumption is valid. Current flows as indicated on the diagram.
  (b) The same analysis applies. However, since $V_2 > V_1$, the predicted current $I < 0$, and our assumption is *not* valid. We therefore replace the diode with an open circuit, for which $\boxed{I = 0}$.



  Discussion: This analysis is for ideal diodes only. A real diode would have a small voltage drop for Part (a), and would have a small current leakage for Part (b).

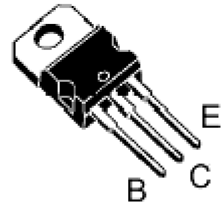
LEDs

- A ***light emitting diode*** (***LED***) is simply a switching diode that gives off light when the diode operates in the forward bias mode.
- LEDs have been in the news lately because they are now used in light bulbs. It turns out that LED light bulbs are more efficient than incandescent or fluorescent light bulbs, and last longer. They are especially good for flashlights.

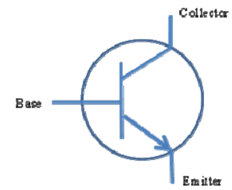
Transistors *[This section originally authored by Alison Hake as part of an honors option for M E 345]*

- A ***transistor*** is a device that contains three layers of two semiconducting materials that can be used as a switch (or relay), an amplifier, or a detector.

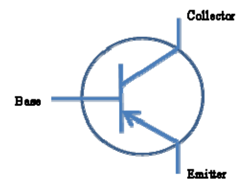
- If the transistor is being used to amplify DC current, the gain of the amplification is notated as H_{FE}. This value is typically found on the data sheet for each specific type of transistor, and is typically considered constant, however slight variations exist in H_{FE} due to changes in temperature, collector to emitter voltage, and collector current.



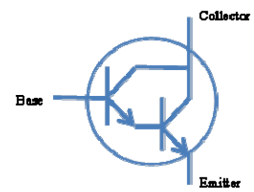
- Generally transistors look like the picture to the right, however, they can be made to be very small and incorporated into integrated circuits.
- Transistors are classified based on the order of the conducting material layers. It is possible for a transistor to be an ***NPN*** configuration or a ***PNP*** configuration, where the N-type semiconductor conducts negative charge and the P-type semiconductor conducts positive charge. NPN and PNP are also referred to as ***polarities***.
- The three prongs on the transistor are known as the ***base***, the ***collector***, and the ***emitter***. In an NPN configuration, the collector serves as the input, the base is the control, and the emitter is the output. In a PNP type transistor, the collector and the emitter switch roles, so the emitter is the input, the base is the control, and the collector is the output.
- Types
    - The most common transistors are TIP29/31, TIP30/32, and TIP122. Each is discussed below.
    - **TIP 29/31**



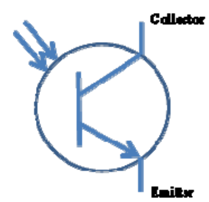
        - NPN-type; the circuit diagram for this type of transistor is shown to the right.
        - Maximum emitter-base voltage = 5 V, maximum collector-emitter voltage = 80 volts, and maximum collector-base voltage = 40 volts.
        - H_{FE} = 15 to 75, depending on the voltage across the collector and emitter and the collector current.
    - **TIP 30/32**



        - PNP-type; the circuit diagram for this type of transistor is shown to the right.
        - Maximum emitter-base voltage = -5 V, maximum collector-emitter voltage = -40 V, and maximum collector-base voltage = -40 V.
        - H_{FE} = 15 to 75, depending on the voltage across the collector and emitter and the collector current.
    - **TIP 122**



        - NPN-type; the circuit diagram for this type of transistor is shown to the right.
        - Maximum emitter-base voltage = 5 V, maximum collector-emitter voltage = 100 V, and maximum collector-base voltage = 100 V.
        - H_{FE} = 1000.
        - The TIP122 transistors are useful in applications where large voltage and current amplifications are needed since H_{FE} is so large.
- Sinking and sourcing
    - Since transistors can act as switches, they can be useful for sinking and sourcing currents.
    - If there is a voltage and current supply to a load that is in series with a transistor to ground, then the transistor is sinking the current through the load to the ground.
    - If there is a voltage and current supply passing through a transistor in series with a load and a ground, then the transistor is sourcing the current from the power supply to the load before it goes to ground.
- Phototransistors
    - A phototransistor is a light sensor that is formed from a basic transistor but that is specially designed to create a gain based on the amount of light that is absorbed.
    - In a circuit diagram, a phototransistor looks like the image to the right.



- Use in place of relays
    - A ***relay*** is a device that contains an inductor or electromagnet that, when activated by a voltage and current, creates a magnetic field that flips an internal mechanical switch. Once the switch is flipped, a higher voltage can be output from the device.
    - Since there is a mechanical switch that actually moves inside the device, relays wear out much faster than other types of switches. They are also loud, as a "click" can be heard when the switch flips.
    - Transistors have replaced the use of relays in many cases. They are smaller and much more durable, yet they perform the same function when wired correctly.