Unit 1

Circuit Basics
KVL, KCL, Ohm's Law
LED Outputs
Buttons/Switch Inputs
VOLTAGE AND CURRENT
Current and Voltage

- Charge is measured in units of Coulombs.
- Current – Amount of charge flowing through a specific point in a certain time period
  - Measured in Amperes (A) = Coulombs per second
  - Current is usually denoted by the variable, $I$
- Voltage – Electric potential energy
  - Analogous to mechanical potential energy (i.e. $F = mg$)
  - Must measure across two points
  - Measured in Volts (V)
  - Common reference point: Ground (GND) = 0V
    - Often really connected to the ground
Current / Voltage Analogy

Charge = Water

Voltage Source = Water Pressure

Voltage Source = Water Pressure

$$\text{Voltage Source} = \text{Water Pressure}$$

$$\text{Charge} = \text{Water}$$

$$U_2 + v_2 - v_1 + v_3 - i$$
Meet The Components

• Most electronic circuits are modeled with the following components

• Resistor
  – Measures how well a material conducts electrons

• Capacitor & Inductor
  – Measures material's ability to store charge and energy

• Transistor
  – Basic amplification or switching technology
Kirchhoff's Laws

- Common sense rules that govern current and voltage
  - Kirchhoff's Current Law (KCL)
  - Kirchhoff's Voltage Law (KVL)

- Kirchhoff's Current Law (KCL)
  - The current flowing into a location (a.k.a. node) must equal the current flowing out of the location
  - ...or put another way...
  - The sum of current at any location must equal 0

\[ i_1 + i_2 = i_3 + i_4 \]
Kirchhoff's Current Law

- Reminder: KCL says \textbf{current\_in = current\_out}
- Start by defining a direction for each current
  - It does not matter what direction we choose
  - When we solve for one of the currents we may get a "negative" current
  - "Negative" sign simply means the direction is opposite of our original indication
- In the examples to the right the top two examples the directions chosen are fine but physically in violation of KCL...
- ...but KCL helps us arrive at a consistent result since solving for one of the current values indicates...
  - The magnitude of \(i_1\) and \(i_2\) are the same
  - They always flow in the opposite direction of each other (if one flows in the other flows out or vice versa)
Kirchhoff's Laws

- Kirchhoff's Voltage Law (KVL)
  - The sum of voltages around a loop (i.e. walking around and returning to the same point) must equal 0
  - Define "polarity" of voltage and then be consistent as you go around the loop...obviously when you solve you may find a voltage to be negative which means you need to flip/reverse the polarity

```
KVL says:
\( v_1 + v_2 + v_3 = 0 \)
\( v_1 + v_2 + v_4 + v_5 = 0 \)
\( -v_3 + v_4 + v_5 = 0 \)
```

```
KVL says:
\( v_1 - v_2 - v_3 = 0 \)
\( v_1 = v_2 + v_3 \)
```

```
U2
- V2 +
U4
- V4 +

U1
- V1 +
U3
+ \( \varepsilon \Lambda \) -
U5
- V5 +
```

```
+ V2 -
U2

U1
- V1 +
U3
+ \( \varepsilon \Lambda \) -
```
Nodes

- **(Def.)** An **electric node** is the junction of **two or more devices** connected by wires.
- Same voltage at any point of the node.
- How many nodes exist in the diagram to the right?
Practice KCL and KVL

- **Use KCL to solve for i3, i4, and i6**
  - Node A: i9 = i4 + 1A
    - 2 Unknowns...find another node
  - Node D: i9 = 1A + 1A = 2A
  - Node A: 2A = i4 + 1A, thus i4=1A
  - Node C: 0.5A + i3 = i8
    - i8 must be 1A so i3 = 0.5A
  - Node B: i4 + i6 = 1A + i3 + 0.5A
    - i3 is 0.5A, i4 is 1A, and i6 has to be 1A
    - So check: 2A = 1A + 0.5A + 0.5A

- **Use KVL to solve for v3, v8, v5**
  - Loop {U3,U7}: -V3 -5V = 0
    - V3 = -5V
  - Loop {U5,U6,U4}: -V5 -3V + 4V = 0
    - V5 = 1V
  - Loop {U1,U2,U3,U8}: 2V + 5V + (-5V) - v8 = 0
    - V8 = 2V

**Hint:** Find a node or loop where there is only one unknown and that should cause a domino effect
Resistance and Ohms Law

- Measure of how hard it is for current to flow through the substance
- **Resistance** = **Voltage / Current**
  - How much pressure do you have to put to get a certain current to flow
- Measured in Ohms (Ω)
- **Ohm's Law**
  - $I = \frac{V}{R}$ or $V = IR$
  - $R \uparrow \Rightarrow I \downarrow$

Schematic Symbol for a Resistor

http://usc.scout.com/2/926916.html
http://www.zimbio.com/photos/Marquise+Lee/Oregon+v+USC/9qQqBuy838Z
Series & Parallel Resistance

• Series resistors = one after the next with no other divergent path

• Parallel resistors = Spanning the same two points

• Series and parallel resistors can be combined to an equivalent resistor with value given as shown...

Series Connections

\[ R_{\text{eff}} = R_1 + R_2 \]

Parallel Connection

\[ R_{\text{eff}} = \left( \frac{1}{R_1} + \frac{1}{R_2} \right)^{-1} \]
Solving Voltage & Current

Given the circuit to the right, let...
- $V_{dd} = +5\text{V}$, $R_1 = 400\ \text{ohms}$, $R_2 = 600\ \text{ohms}$

Solve for the current through the circuit and voltages across each resistors (i.e. $V_1$ and $V_2$)
- Since everything is in series, KCL teaches us that the current through each component must be the same, let's call it $i$
  - $i = \frac{V_{dd}}{R_1 + R_2} = \frac{5}{1000} = 5\ \text{mA}$
- This alone lets us compute $V_1$ and $V_2$ since Ohm's law says
  - $V_1 = i \times R_1$ and $V_2 = i \times R_2$
  - $V_1 = 2\text{V}$ and $V_2 = 3\text{V}$
- Though unneeded, KVL teaches us that
  - $V_{dd} - V_1 - V_2 = 0$ or that $V_{dd} = V_1 + V_2$
Voltage Supply Drawings

- The voltage source (Vdd) in the left diagram (i.e. the circle connected to the "Rest of Circuit") is shown in an alternate representation in the right diagram (i.e. the triangle labeled "Vdd")
- In the left diagram we can easily see a KVL loop available
- There is still a KVL loop available in the right diagram

This diagram is an equivalent to the one above.
Voltage Dividers

- Original Problem
  - \( V_s = +5V, \ R_1 = 400 \text{ ohms}, \ R_2 = 600 \text{ ohms} \)

- Recall our solution
  - \( i = \frac{V_s}{(R_1 + R_2)} = \frac{5}{1000} = 5 \text{ mA} \)
  - \( V_1 = i \times R_1 = 2V \) and \( V_2 = i \times R_2 = 3V \)

- When two resistors are in series we can deduce an expression for the voltage across one of them
  - \( i = \frac{V_{tot}}{(R_1 + R_2)} \)
  - \( V_1 = i \times R_1 \) and \( V_2 = i \times R_2 \)
  - Substituting our expression for \( i \):
    
    \[
    V_1 = V_{tot} \left( \frac{R_1}{R_1 + R_2} \right) \quad \text{and} \quad V_2 = V_{tot} \left( \frac{R_2}{R_1 + R_2} \right)
    \]

- The voltage across one of the resistors is proportional to the value of that resistor and the total series resistance
  - If you need 10 gallons of gas to drive 500 miles, how much gas you have you used up after driving 200 miles?
    - Gas = Voltage, Mileage = Resistance

\[ \text{If two resistors } R_x \text{ and } R_y \text{ are in series then voltage across } R_x \text{ is:} \]

\[ V_x = V_{tot} \times \frac{R_x}{(R_x + R_y)} \]

Memorize this. We will use it often!
Solving Voltage & Current

• Reconsidering the circuit to the right with...
  – $V_s = +5V$, $R_1 = 400$ ohms, $R_2 = 600$ ohms

• Solve for the current through the circuit and voltages across each resistors (i.e. $V_1$ and $V_2$)
  – We can use the voltage divider concept to immediately arrive at the value of $V_2$
  – $V_2 = V_{dd} \left[ \frac{R_2}{R_1 + R_2} \right]$
Solving Voltage & Current

Consider the circuit on the right...

What is the relationship between $V_1$ and $V_3$?
- $V_1 = V_3$...Do a KVL loop around $R_3$ to $R_1$

Can you solve for the voltage $V_1$ (in terms of $V_s$, $R_1$, $R_2$, $R_3$)?
- Combine $R_1$ and $R_3$ using parallel resistor relationship
- $R_1$ and $R_3$ can be combined to $R_{eff} = (R_1R_3)/(R_1+R_3)$
- Now use voltage divider since "$R_{eff}$" and $R_2$ are in series...
- $V_1 = V_s^*\left[ \frac{R_{eff}}{R_2 + R_{eff}} \right]$

Can you solve for the voltage $V_2$ (in terms of $V_s$, $R_1$, $R_2$, $R_3$)?
- KVL says $V_s - V_1 - V_2 = 0$. We know $V_s$ and just solved for $V_1$ so we can plug into: $V_2 = V_s - V_1$
A Problem...

- Given the following parameters...
  - $V_s=5\,\text{V}$, $R_1=4$, $R_2 = 12$, $R_3 = 2$ and $R_4 = 10$ ohms.

- Can we use the voltage divider concept to immediately solve the voltage across $R_2$ or do we need to first do some manipulation? What about $R_4$?

- First, find the total equivalent resistance ($R_{eq}$) seen by $V_s$ and then solve for the voltage across each resistor.

\[
R_{tot} = R_1 + \frac{R_2 (R_3 + R_4)}{R_2 + R_3 + R_4} = 10 \, \text{ohms}
\]

\[
i_1 = \frac{V_s}{R_{tot}} = \frac{5}{10} = 0.5 \, \text{A}
\]

\[
V_1 = i_1 R_1 = 2 \, \text{V}
\]

\[
V_2 = 5 \, \text{V} - 2 \, \text{V} = 3 \, \text{V} \text{ (using KVL)}
\]

\[
V_3 = \frac{3 \times 2}{(2+10)} \text{ (volt. divider)} = 0.5 \, \text{V}
\]

\[
V_4 = \frac{V_2 \times R_4}{R_3 + R_4} \text{ (volt. divider)} = 2.5 \, \text{V}
\]
LEDS AS OUTPUTS AND SWITCHES/BUTTONS AS INPUTS
Generating Inputs & Measuring Outputs

• Where do inputs to a digital circuit originate?
  – Usually as outputs from another digital circuit (i.e. USB connecting to your laptop's main processing system)
  – For our class right now: A button/switch controlled by a human (can be on or off)

• How will we know what voltage is coming out of a digital circuit?
  – Could use a voltmeter or oscilloscope (don't be afraid to use the equipment in our lab!)
  – LEDs are commonly used to show the status of a digital output to a human

Each key on your keyboard is essentially a digital input generated by a push button (pressed or not pressed)

The status indicator on the Caps Lock button is simply an LED controlled by a digital output.
(Light-Emitting) Diodes

- The simplest output we can control is an LED (Light-emitting diode) which is like a tiny light bulb
- An LED glows ('on') when current flows through it (i.e. when there is a voltage difference across it)
- LEDs are polarized meaning they only work in one orientation (longer leg must be at higher voltage)

Main Point: The long leg of the LED must be attached to the side that will have the higher voltage.
Need for Series Resistor with LEDs

**Problem:** LEDs may allow too much current to flow which may blow out the LED

**Solution:** Use a series resistor to limit current

- Amount of current will determine brightness of LED
- \( R \uparrow \) then \( i \downarrow \) and thus LED brightness \( \downarrow \)
- \( i = \frac{V_{1}}{R_{1}} = \frac{(V_{s} - V_{\text{LED}})}{R_{1}} \)
- Usually \( R_{1} \) is a few hundred ohms (330 or 470 ohms)

A digital (gate) output will usually serve as our voltage source that can be either '0' (0V) or '1' (5V)

**Main Point:** LED's should always be connected in series with a current-limiting resistor
LED Connection Approaches

• When letting a digital output control an LED, the value (i.e. '0' = low or '1' = high voltage) that causes the LED to light up depends on how the circuit is wired
  – Note: Gates can often "sink" (take in) more current than they can "source" (push out), so option 2 may be preferred…but let's not worry about this now...let's use option 1

Main Point: LED's can light for either a logic '1' or '0' output...it depends on how they are wired.
Switch and PushButton Inputs

• Switches and pushbuttons can be in one of two configurations: open or closed
  – Switches can be opened or closed and then stay in that position until changed
  – Pushbuttons are open by default and require you to push them to close the circuit (they then open when you release)

• Can be used as an input to digital device
Switches and Pushbuttons

• Important Note 1:
  – When open a SW/PB looks like an infinite resistance (no current can flow)
  – When closed a SW/PB looks like a wire (R=0) and no voltage drops across it

• Question: What voltage does an open or closed switch (pushbutton) generate?

• Answer: NOTHING.

• Important Note 2:
  – SW or PBs don't produce digital 0's or 1's on their own, they control what voltage (PWR/GND) is connected to your device
Connecting a Switch

Switches only help control the voltage going into a device, they do not produce a voltage (0V or 5V) by themselves.

Option 1: Attach one side to GND and the other side to the device

- When the switch is open, nothing is connected to the device (a.k.a. “floating”)
- A floating input may sometimes appear as zero, and other times as a one.
- We need the inputs to logic gates to be in either the 0 or 1 state...not floating

Option 2:
- When the switch is closed => low resistance connection from power to ground = LARGE current flow...BAD!!! (This is known as a "short circuit").
Preferred Wiring of Switches

- Solution: Put GND on the far side and a "pull-up" resistor at the input side
  - "Pull-up resistor" used to hold the input high unless something is forcing it to a zero
  - SW open => Arduino input looks like inf. Resistance in series with Rp. Thus no current through Rp and thus no voltage drop across Rp...Vin = VDD = 1
  - SW closed => Direct wire from GND to input...input = GND = 0...Also current flowing from Vdd to GND is limited by Rp preventing a short circuit.
  - Usually Rp is large (10k ohms) to limit current

To calculate Vin:
- \( Vin = Vdd - V_{RP} \)
- \( Vin = Vdd - i_{RP} \times Rp \)
  - \( i_{RP} = 0 \) since in series with inf. resistance of Arduino input
  - Thus, \( Vin = Vdd \)

Main Point: Buttons & switches should have GND connected to one side & a pull-up resistor on the other
Power & Ground Connections

• Easy mistake when you're just learning to wire up circuits:
  – Wire the inputs & outputs but forget to connect power and ground
• All circuits and chips require a connection to a power source and ground
  – Digital circuits (aka "gates")
  – Switches
  – Buttons