Embedded Systems

C Programming and Software Tools

N.C. State Department of Computer Science

Adapted from "EE498/ EE578 Real-Time Embedded Systems" by Nannan He, Minnesato State University at Mankato (2014)

http://mavweb.mnsu.edu/hen/lec/RTES_fundamental.pptx

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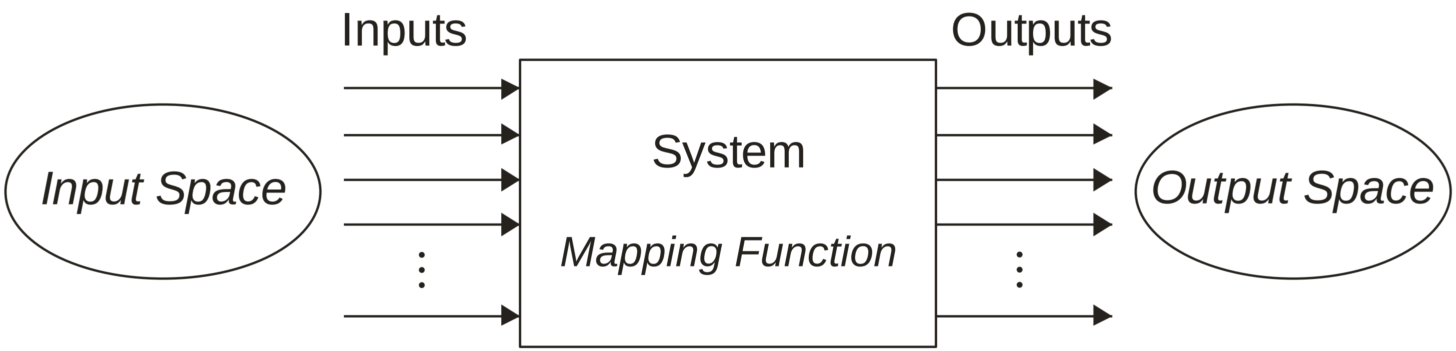
Definition: System

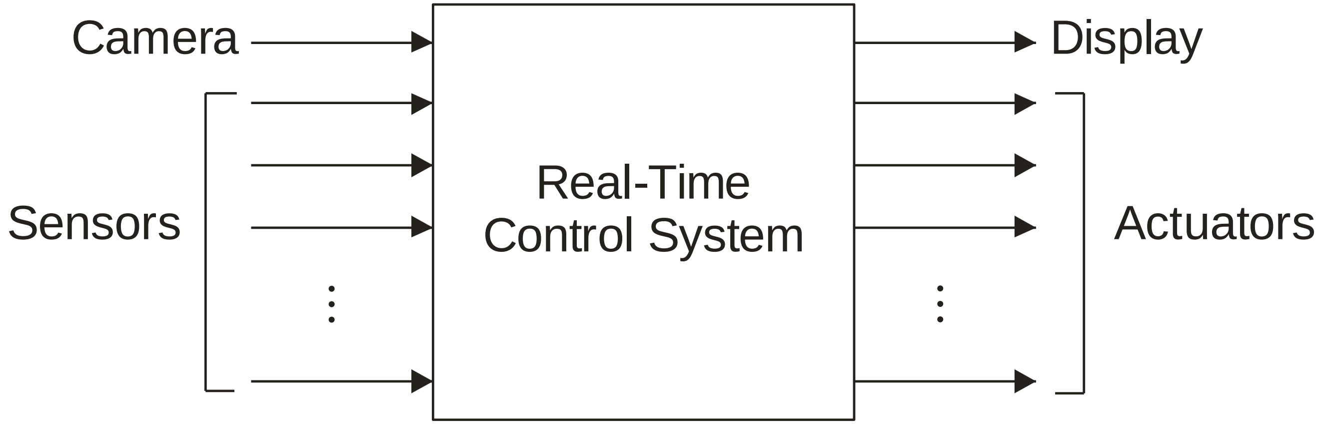
A system is a mapping of a set of inputs into a set of outputs.



1. A system is an assembly of components connected together in an organized way
2. A system is fundamentally altered if a component joins or leaves it
3. It has a purpose
4. It has a degree of permanence
5. It has been defined as being of particular interest

Example: A Real-Time Control System

- Inputs are *excitations* and outputs are corresponding *responses*
- Inputs and outputs may be digital or analog
- Inputs are associated with sensors, cameras, etc.
- Outputs with actuators, displays, etc.



Definition: Response Time

The time between the presentation of a set of inputs to a system and the realization of the required behavior, including the availability of all associated outputs, is called the response time of the system

- How fast and punctual does it need to be?
  - Depends on the specific real-time system
- But what is a real-time system?

Definitions: Real-Time System

A real-time system is a computer system that must satisfy bounded response-time constraints or risk severe consequences, including failure

A real-time system is one whose logical correctness is based on both the correctness of the outputs and their timeliness

Definition: Failed System

A failed system is a system that cannot satisfy one or more of the requirements stipulated in the system requirements specification

- Hence, rigorous specification of the system operating criteria, including timing constraints, is necessary

Definition: Embedded System

An embedded system is a system containing one or more computers (or processors) having a central role in the functionality of the system, but the system is not explicitly called a computer

- A real-time system may be embedded or non-embedded
- But it is always reactive
  - Task scheduling is driven by ongoing interaction with the environment

Degrees of "Real-Time"

- All practical systems are ultimately real-time systems
- Even a batch-oriented system—for example, grade processing at the end of a semester—is real-time
- Although the system may have response times of days, it must respond within a certain time
- Even a word-processing program should respond to commands within a reasonable amount of time
- Most of the literature refers to such systems as soft real-time systems

Soft, Hard, and Firm “Real-Time”

Definition: Soft Real-Time System

A soft real-time system is one in which performance is degraded but not destroyed by failure to meet response-time constraints

Definition: Hard Real-Time System

A hard real-time system is one in which failure to meet even a single deadline may lead to complete or catastrophic system failure

Definition: Firm Real-Time System

A firm real-time system is one in which a few missed deadlines will not lead to total failure, but missing more than a few may lead to complete or catastrophic system failure

Example: Real-Time Classification

System	Real-Time Classification	Explanation
Avionics weapons delivery system in which pressing a button launches an air-to-air missile	Hard	Missing the deadline to launch the missile within a specified time after pressing the button may cause the target to be missed, which will result in a catastrophe
Navigation controller for an autonomous weed-killer robot	Firm	Missing a few navigation deadlines causes the robot to veer out from a planned path and damage some crops
Console hockey game	Soft	Missing even several deadlines will only degrade performance

Where Do Deadlines Come from?

- Deadlines are based on the underlying physical phenomena of the system under control

Example: Where a Response Time Comes from?

- An elevator door is automatically operated and it may have a sensor to detect passengers between the closing doors so it can re-open automatically.
- What is the required system response time from when it recognizes that a passenger is between the closing door blades and starting to reopen the door?

Door Reopening Example Cont'd

This response time consists of five independent latency components:

Sensor:	$t_{\mathrm{SE\_min}} = 5\ \mathrm{ms}$	$t_{\mathrm{SE\_max}} = 15\ \mathrm{ms}$
Hardware:	$t_{\mathrm{HW\_min}} = 1\ \mu\mathrm{s}$	$t_{\mathrm{HW\_max}} = 2\ \mu\mathrm{s}$
System software:	$t_{\mathrm{SS\_min}} = 16\ \mu\mathrm{s}$	$t_{\mathrm{SS\_max}} = 48\ \mu\mathrm{s}$
Application software:	$t_{\mathrm{AS\_min}} = 0.5\ \mu\mathrm{s}$	$t_{\mathrm{AS\_max}} = 0.5\ \mu\mathrm{s}$
Door drive:	$t_{\mathrm{DD\_min}} = 300\ \mathrm{ms}$	$t_{\mathrm{DD\_max}} = 500\ \mathrm{ms}$

Now, we can calculate the minimum and maximum values of the composite response time: $t_{\mathrm{min}} \approx 305\ \mathrm{ms},\ t_{\mathrm{max}} \approx 515\ \mathrm{ms}$

The overall response time is dominated by the door drive's response time containing the deceleration time of the moving door blades.

Definitions: Event and Release Time

Definition: Event

Any occurrence that causes the program counter to change non-sequentially is considered a change of flow-of-control, and thus an event

Definition: Release Time

The release time is the time at which an instance of a scheduled task is ready to run, and is generally associated with an interrupt

Taxonomy of Events

- Synchronous or asynchronous?
  - ***Synchronous*** events: occur at predictable times in the flow-of-control
  - ***Asynchronous*** events: occur at unpredictable times, are usually caused by external sources
- Periodic, aperiodic or sporadic?
  - **Periodic:** A real-time clock that pulses regularly
  - **Aperiodic:** Events that do not occur at regular periods
  - **Sporadic:** Aperiodic events that tend to occur very infrequently

Example: Various Types of Events

Type	Periodic	Aperiodic	Sporadic
Synchronous	Cyclic code	Conditional branch	Divide-by-zero (trap) interrupt
Asynchronous	Clock interrupt	Regular, but not fixed-period interrupt	Power-loss alarm

CPU Utilization or Time-Loading Factor

- The measure of the relative time spent doing *non-idle processing* indicates how much real-time processing is occurring

Definition: CPU Utilization Factor

The CPU utilization or time-loading factor, *U*, is a relative measure of the non-idle processing taking place

Example: Calculation of *U*

Suppose, an individual elevator controller in a bank of elevators has the following tasks with execution periods of p_i and worst-case execution times of e_i, $i \in [1,2,3,4]$:

Task 1: Communicate with the group dispatcher.

Task 2: Update the car position information and manage floor-to-floor runs as well as door control.

Task 3: Register and cancel car calls.

Task 4: Miscellaneous system supervisions.

i	e_i	p_i
1	17 ms	500 ms
2	4 ms	25 ms
3	1 ms	75 ms
4	20 ms	200 ms

$$U = \sum_{i=1}^{4} e_i/p_i = 0.31$$

31% (Very safe zone)

Goal: get to a reasonable U

- U too high? Possible chance of failure

- U too low? Not cost effective

- U = 50% for new systems,
- U = 80% for stable, well-known systems

Cost/performance tradeoff

Model	Cost	Clock	CPU type	Flash	RAM	I/O lines
ATTINY4	$0.40	12 MHz	8-bit AVR	512 B	32 B	4
ATTINY44	$0.75	20 MHz	8-bit AVR	4 kB	256 B	12
ATMEGA48	$1.23	20 MHz	8-bit AVR	4 kB	512 B	23
ATMEGA328	$1.68	20 MHz	8-bit AVR	32 kB	2 kB	23
ATXMEGA128	$2.72	32 MHz	16-bit AVR	128 kB	8 kB	50
AT32UCA1256	$8.59	66 MHz	32-bit AVR	256 kB	64 kB	69
NXP LPC4370FET256E	$11.98	204 MHz	32-bit 3-core ARM	1 MB	136 kB	83
Intel Core i7 4790K (comedy option)	$339.99	4 GHz	64-bit quad-core x86	None onboard	None onboard (max ~64GB attached)	500+ (but none are general-purpose)

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Usual Misconception

"Real-time" means "fast"?

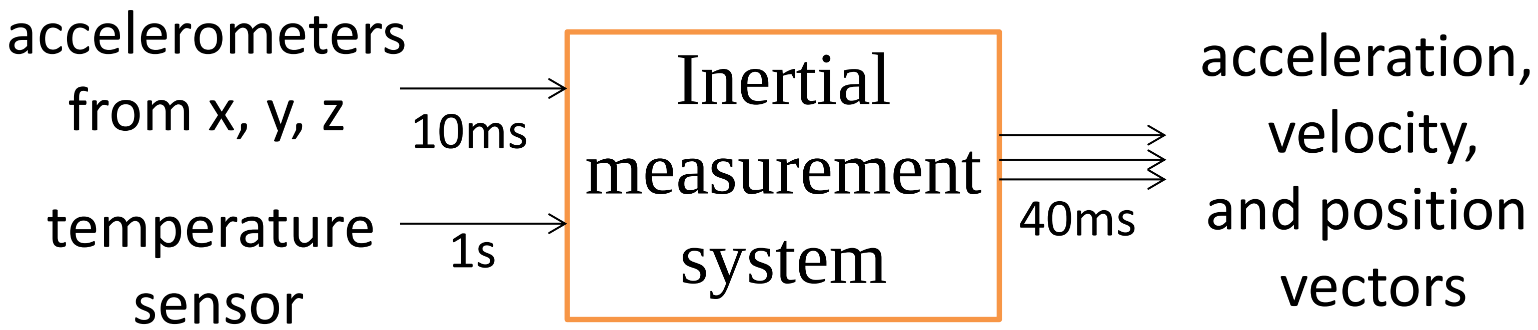
NO!!!

"Real-time" means "*predictable* timing"

Practical Embedded Systems

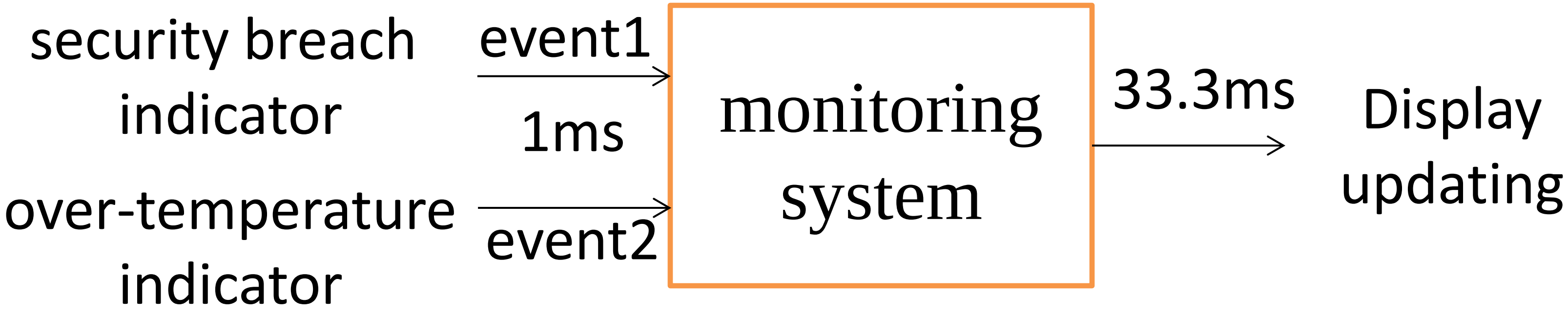
- Aerospace
  - Flight control
  - Navigation
  - Pilot interface
- Automotive
  - Airbag deployment
  - Antilock braking
  - Fuel injection
- Household
  - Microwave oven
  - Rice cooker
  - Washing machine
- Industrial
  - Crane
  - Paper machine
  - Welding robot
- Multimedia
  - Console game
  - Home theater
  - Simulator
- Medical
  - Intensive care monitor
  - Magnetic resonance imaging
  - Remote surgery

Inertial measurement system for an aircraft



The tasks execute at different rates and need to communicate and synchronize.

Monitoring system for a nuclear power plant



Ensure that the "meltdown imminent" indicator can interrupt any other processing with minimal latency.

ARDUINO STUFF

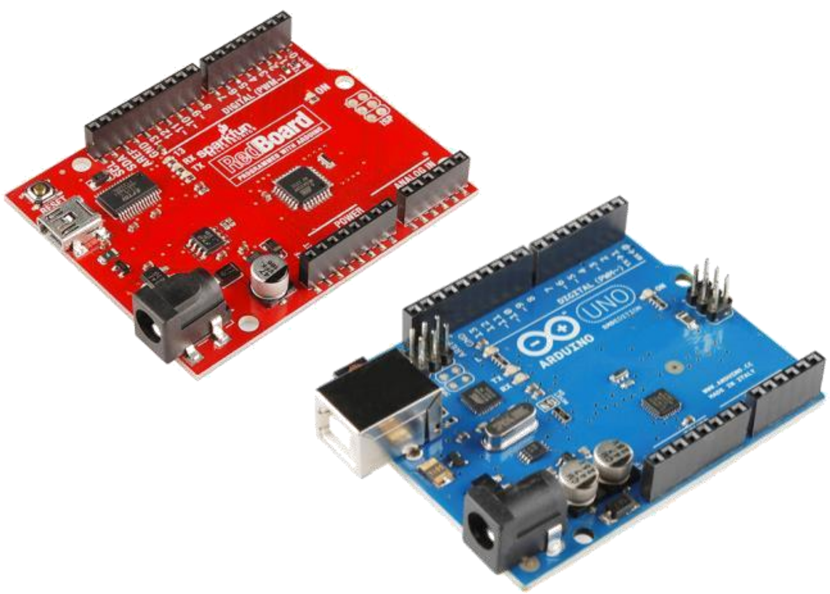
This presentation is based on an electronics seminar I put on as part of the TerrorBytes robotics team. It includes material from:

- Farzad Towhidkhah. Amirkabir University of Technology. Electrical Circuits, lecture 1. http://bme2.aut.ac.ir/~towhidkhah/Circuit/Circuit1/PPT/lec1.ppt
- Jefferson Lab. Electrical Circuits. http://education.jlab.org/jsat/powerpoint/0708_electricity.ppt
- Worldofteaching.com. Electric Circuits. http://www.worldofteaching.com/powerpoints/physics/electric%20circuits.ppt
- Sparkfun. Introduction to Electronics and Breadboarding Circuits. http://create.coloradovirtuallibrary.org/sites/default/files/Curriculum/SparkFun/Beginner/IntrotoBasicElectronics.ppt
- Sparkfun. Intro to Arduino. http://create.coloradovirtuallibrary.org/sites/default/files/Curriculum/SparkFun/Beginner/IntrotoArduino.ppt

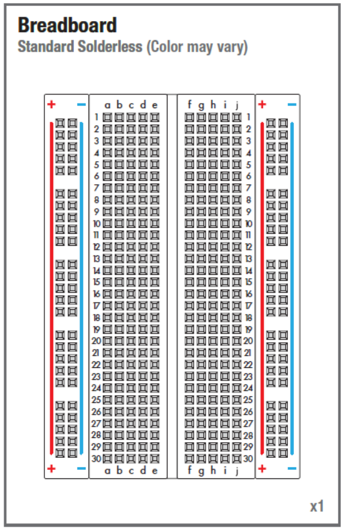
Arduino Board

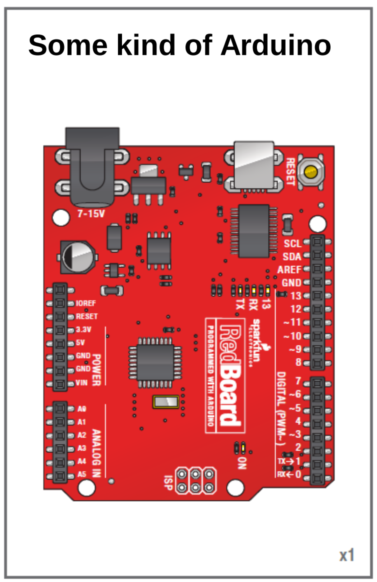
- "Strong Friend" Created in Ivrea, Italy
- in 2005 by Massimo Banzi & David Cuartielles
- Open Source Hardware
- ATMEL Processor
- Coding is accessible & transferrable → (C++, Processing, java)

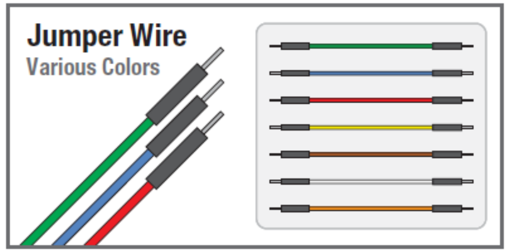
open source hardware

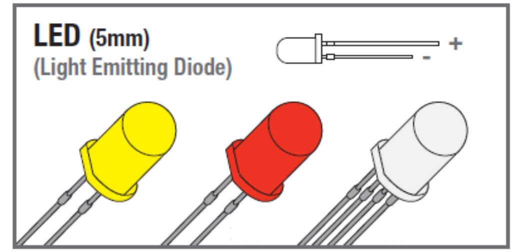


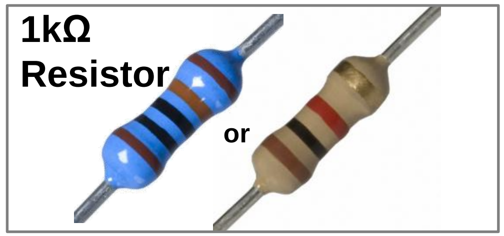
Your kit

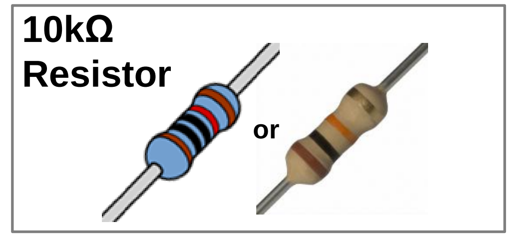


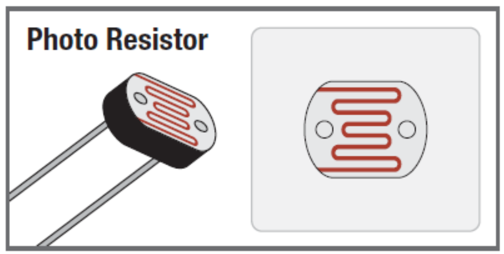


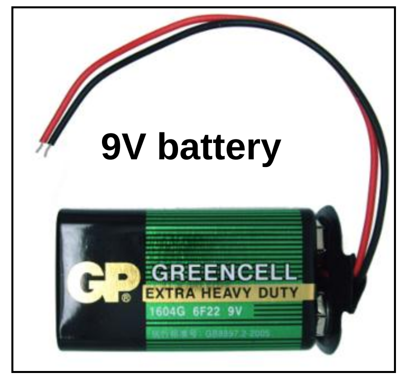


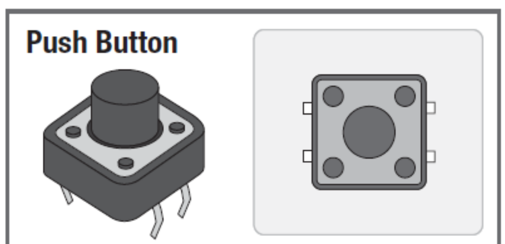












You can get all this stuff dirt cheap on ebay

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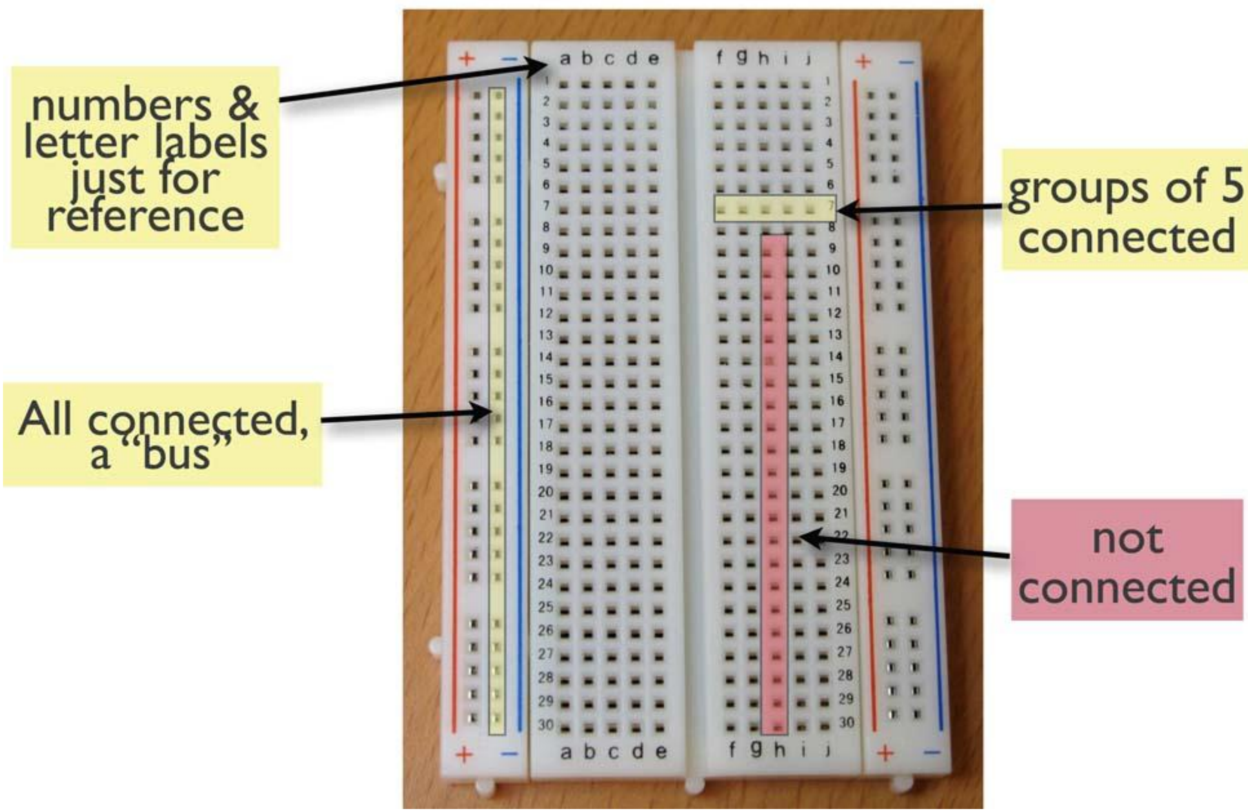
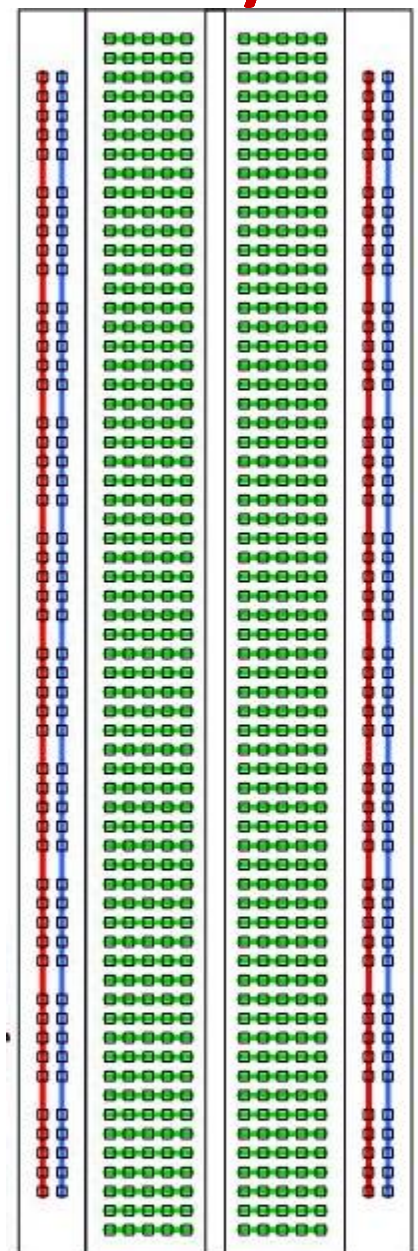
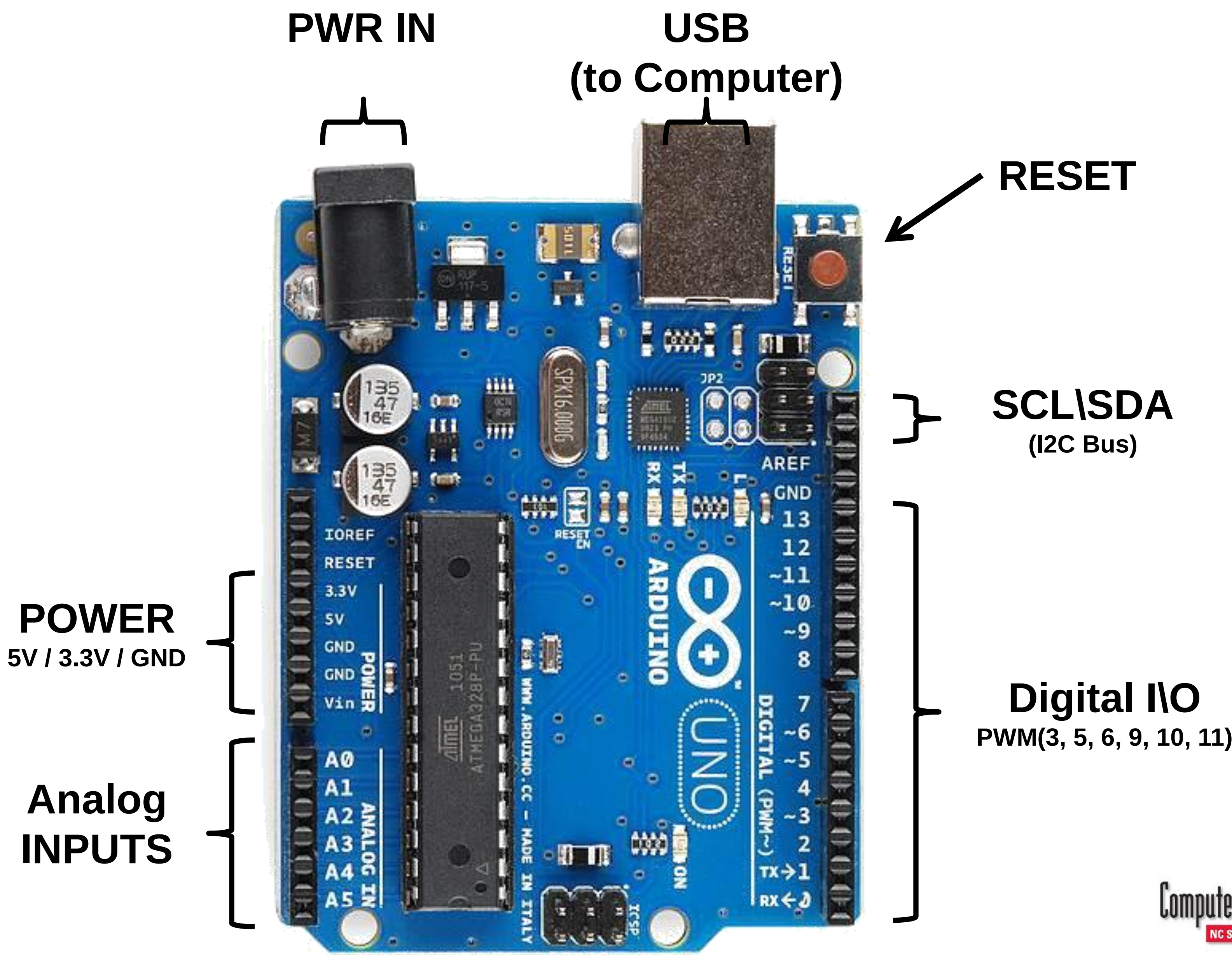
How to hook stuff together easily

Solderless Breadboards





Arduino Overview

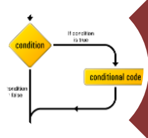


BIG 6 CONCEPTS

digitalWrite()

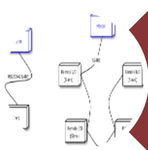
analogWrite()

digitalRead()



if() statements / Boolean

analogRead()



Serial communication

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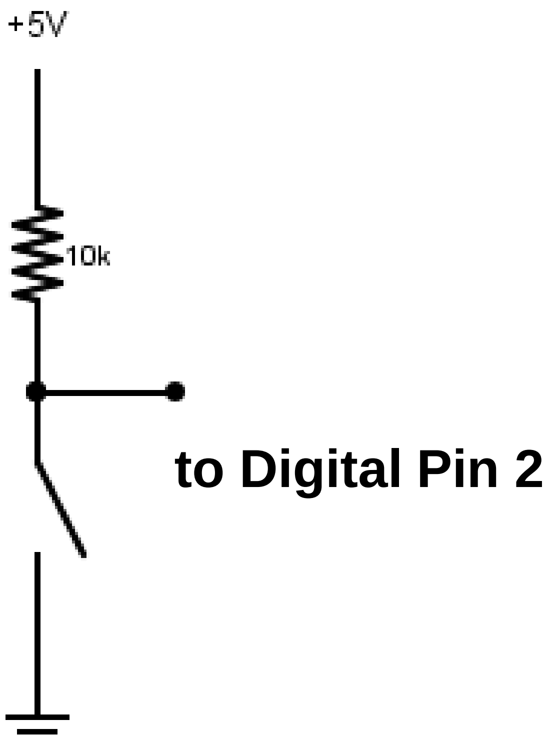
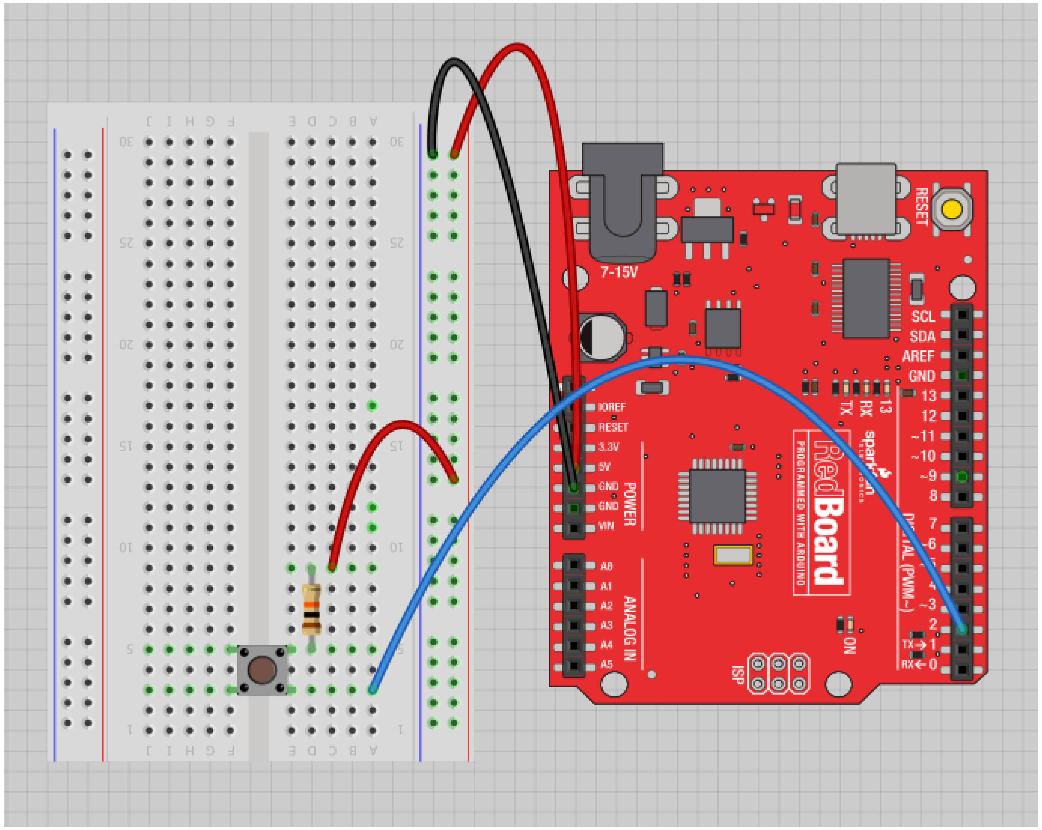
Project – Digital Input

- In Arduino, open up:
- File → Examples → 02.Digital → Button

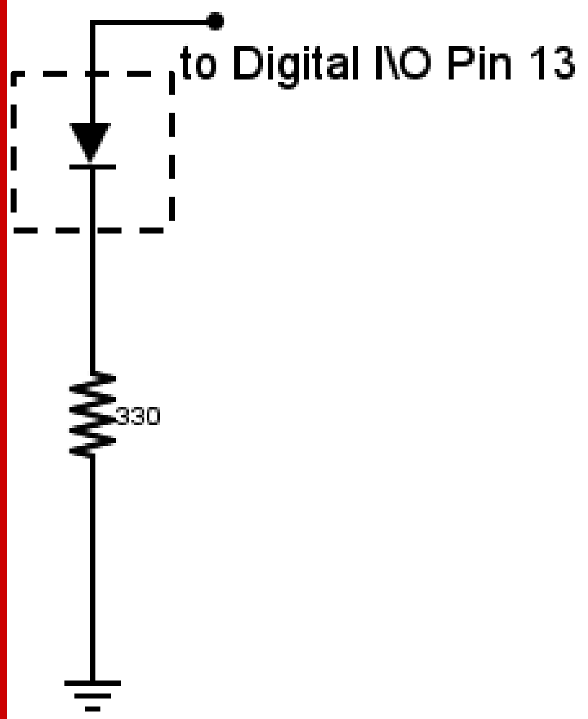
Digital Sensors (a.k.a. Switches)
Pull-up Resistor

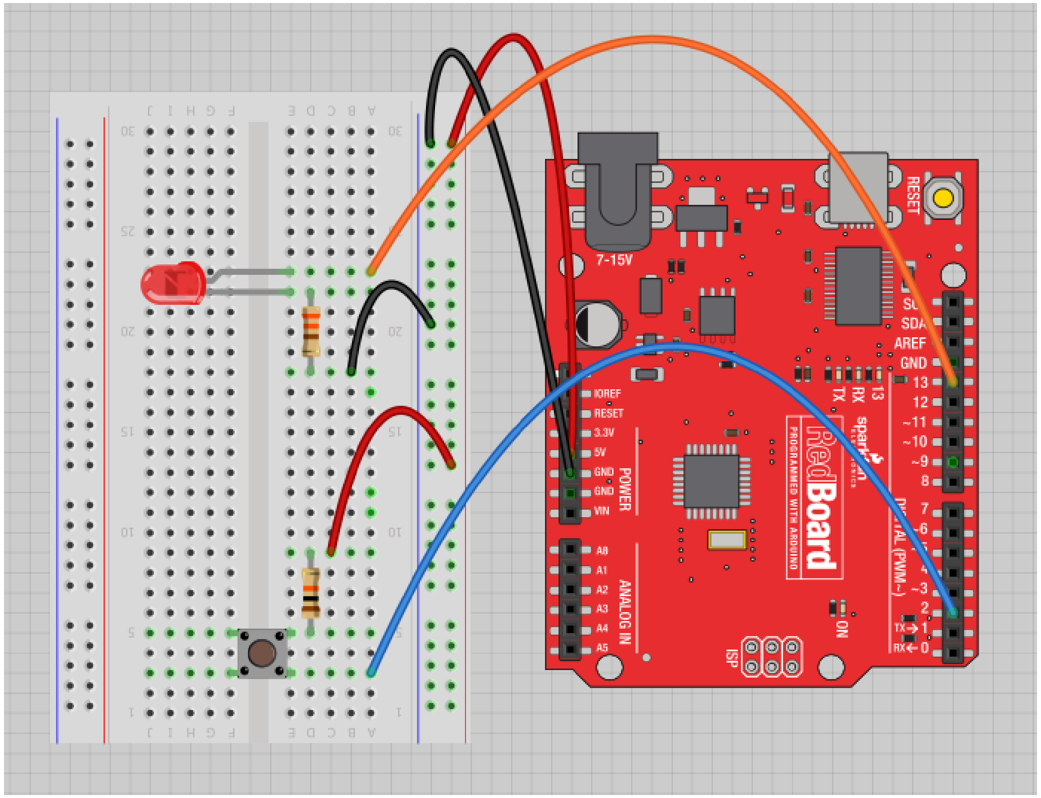




Digital Sensors (a.k.a. Switches)
Add an indicator LED to Pin 13

This is just like our 1st circuit!





Digital Input

- Connect digital input to your Arduino using Pins # 0 – 13 (Although pins # 0 & 1 are also used for programming)

- Digital Input needs a `pinMode` command:

  ```
  pinMode(pinNumber, INPUT);
  ```

  *Make sure to use ALL CAPS for **INPUT***

- To get a digital reading:

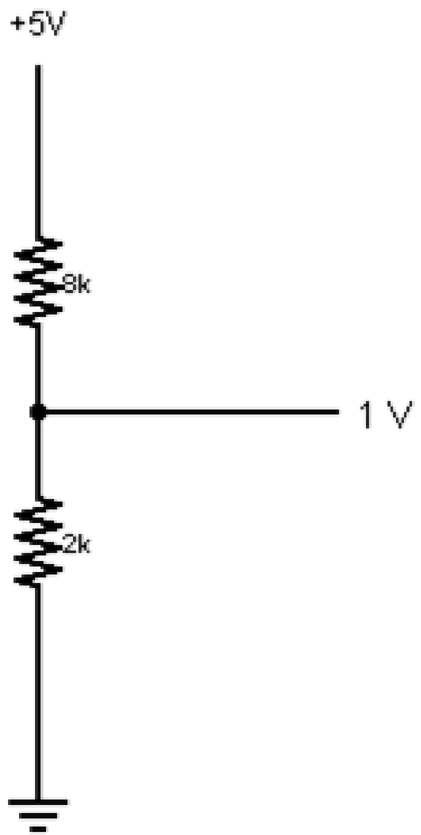
  ```
  int buttonState = digitalRead(pinNumber);
  ```

- Digital Input values are only **HIGH** (On) or **LOW** (Off)

Digital Sensors

- Digital sensors are more straight forward than Analog
- No matter what the sensor there are only two settings: On and Off
- Signal is always either HIGH (On) or LOW (Off)
- Voltage signal for HIGH will be a little less than 5V on your Uno
- Voltage signal for LOW will be 0V on most systems

Voltage dividers



- You get an in-between voltage based on the two resistances

$$V_{R1} = V_{CC} \cdot \left(\frac{R_1}{\mathrm{R}_{Total}} \right)$$

$$V_{R2} = V_{CC} \cdot \left(\frac{R_2}{\mathrm{R}_{Total}} \right)$$

$$R_{Total} = R_1 + R_2$$

analogRead()

Arduino uses a 10-bit A/D Converter:

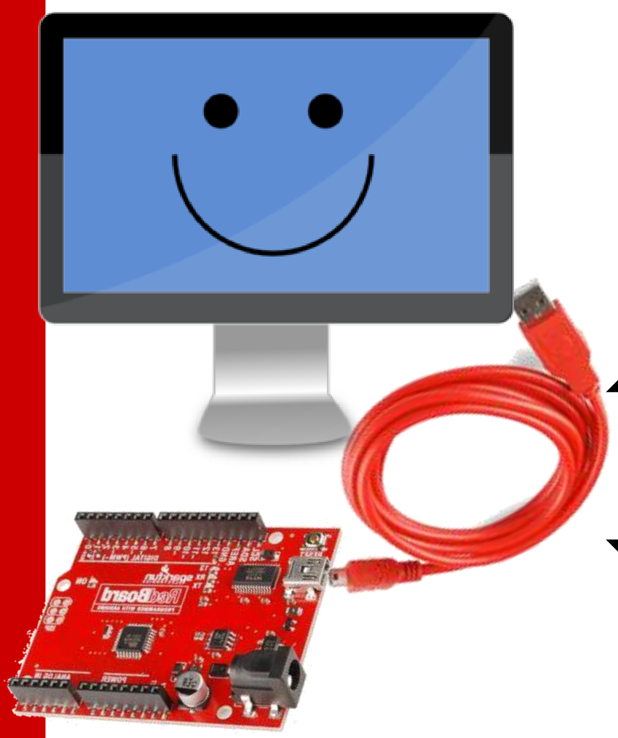
- This means that you get input values from 0 to 1023
  - 0 V → 0
  - 5 V → 1023

Ex:

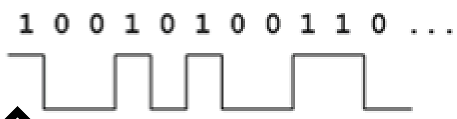
```
int sensorValue = analogRead(A0);
```

Using Serial Communication

Method used to transfer data between two devices.

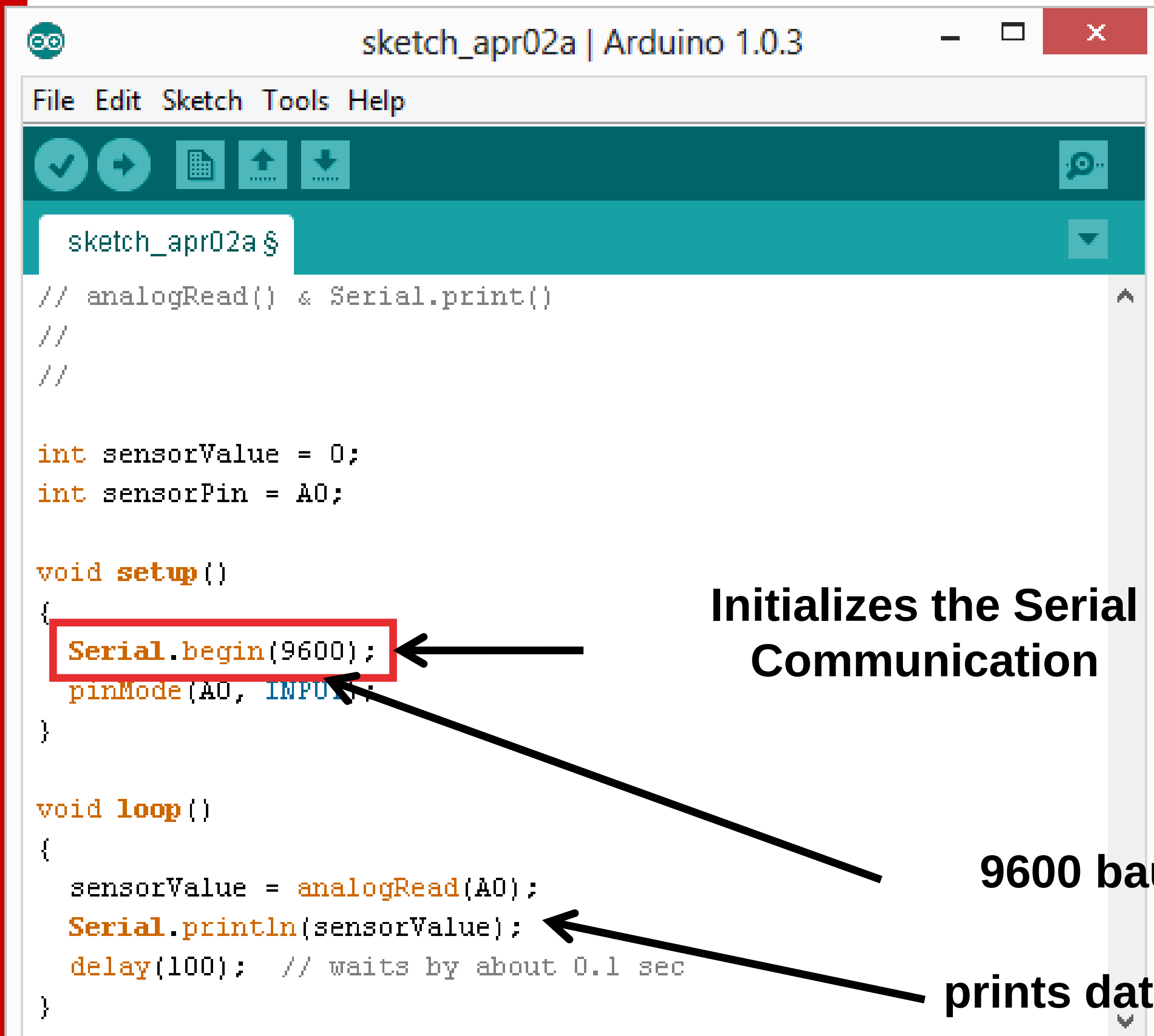


Data passes between the computer and Arduino through the USB cable. Data is transmitted as zeros (‘0’) and ones (‘1’) sequentially.



Arduino dedicates Digital I/O pin # 0 to receiving and Digital I/O pin #1 to transmit.

Serial Monitor & analogRead()

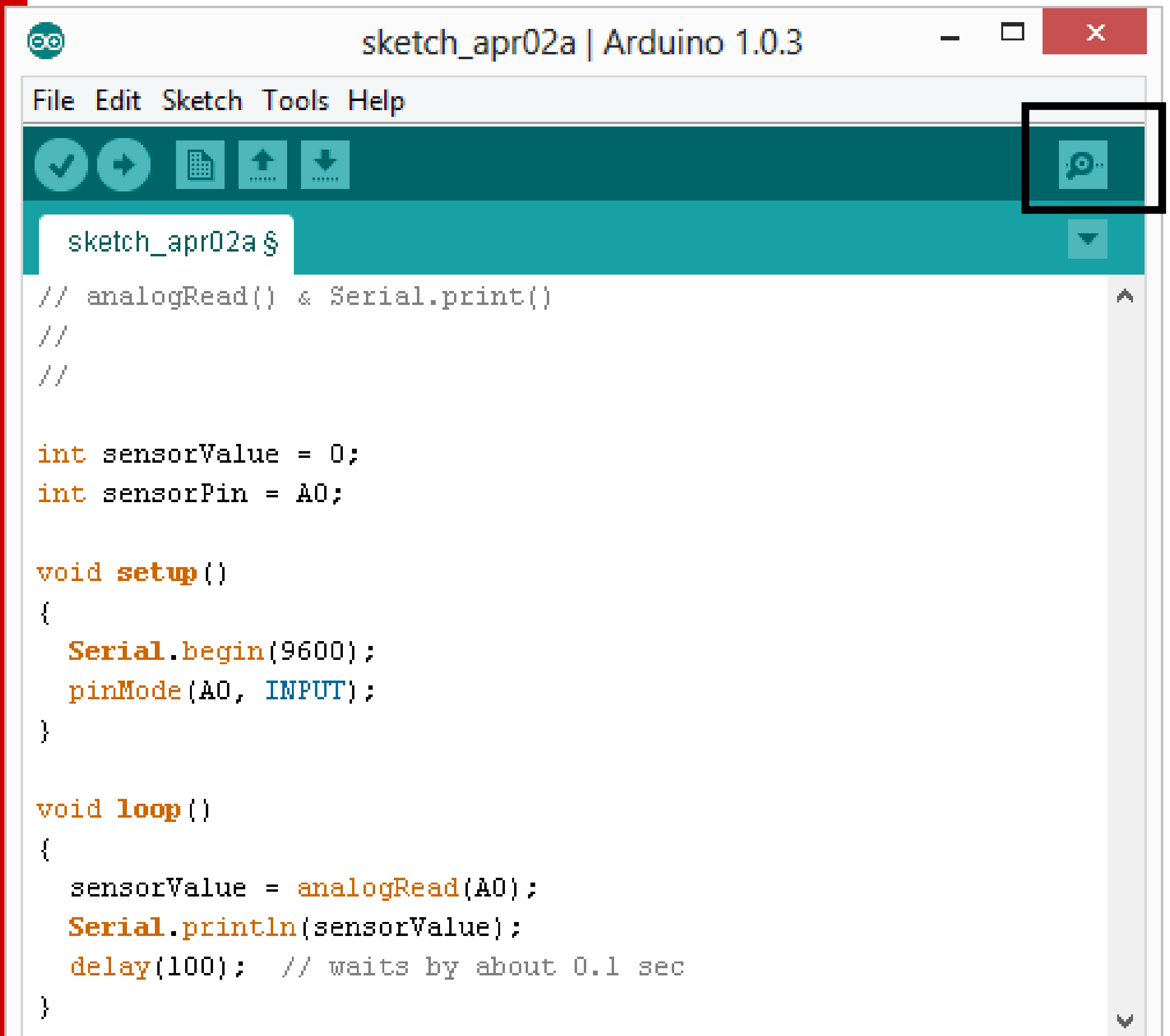


Initializes the Serial Communication

9600 baud data rate

prints data to serial bus

Serial Monitor & analogRead()



Opens up a Serial Terminal Window

The following slides comprise the entirety of the electronics workshop I put on with the TerrorBytes robotics team. It's aimed at a high school audience, so skip the basics as needed.

TERRORBYTES

FRC 4561

Introduction to Electronics and Custom Circuits

Tyler Bletsch

(Tyler.Bletsch@netapp.com)

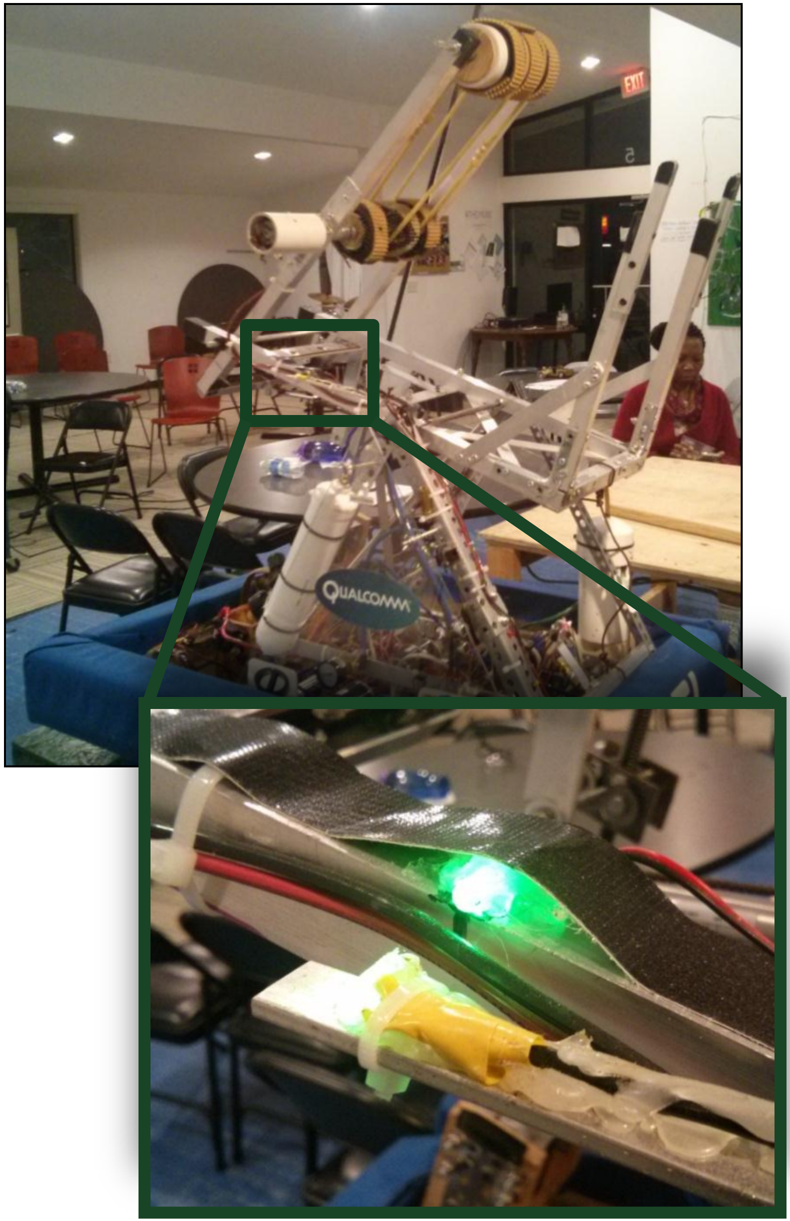
13 December 2014

FIRST

What can you do with this?

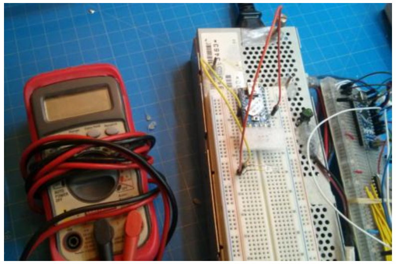
- We built an LED light sensor to act as a “middle limit switch” to find our shooting position.

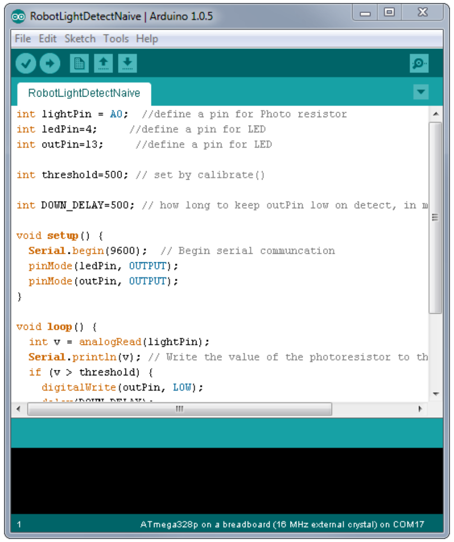
- Run by an Arduino; acts like a normal limit switch to the cRIO

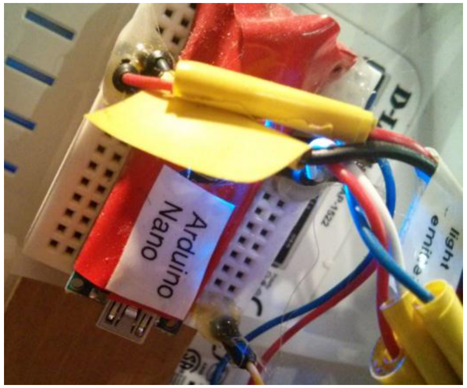


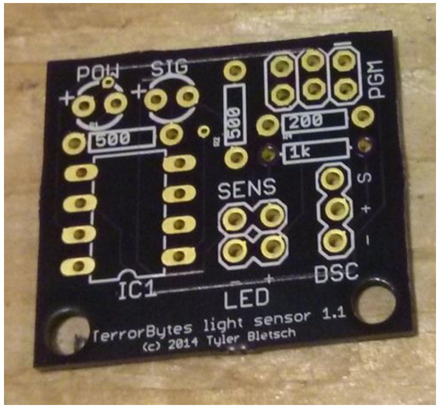
Process

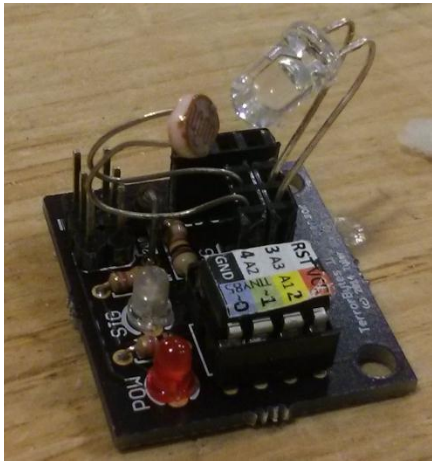
Prototype → Coding → Quick-and-dirty build → Custom PCB



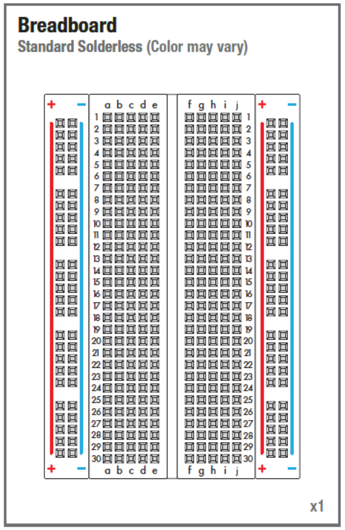


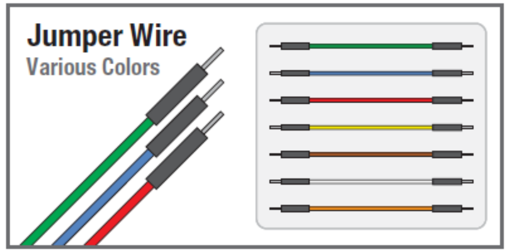


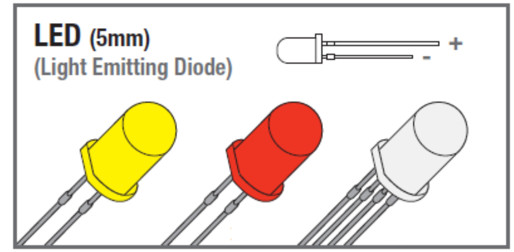


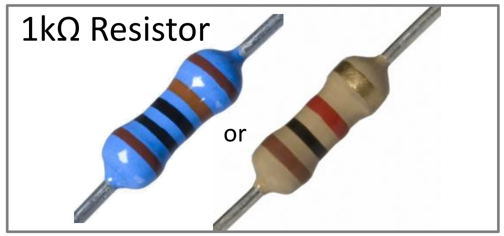


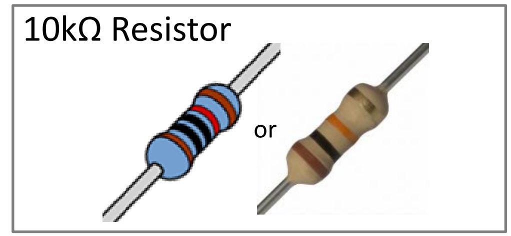
Your kit

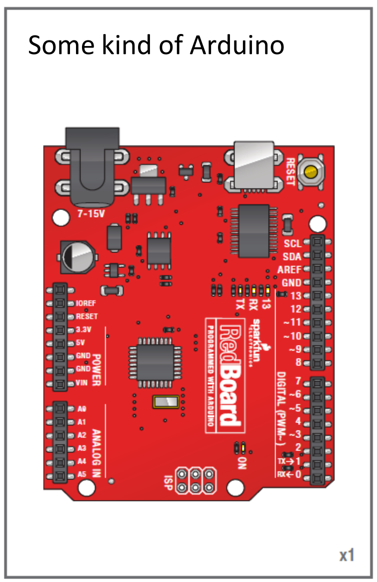

Breadboard
Standard Solderless (Color may vary)
x1


Jumper Wire
Various Colors


LED (5mm)
(Light Emitting Diode)
+
-


1kΩ Resistor
or


10kΩ Resistor
or


Some kind of Arduino
RedBoard
x1

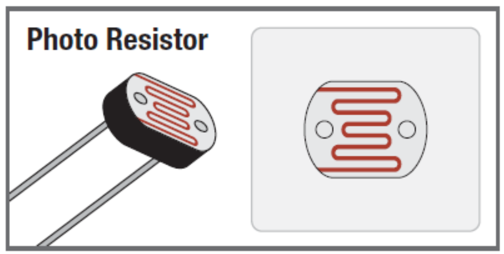
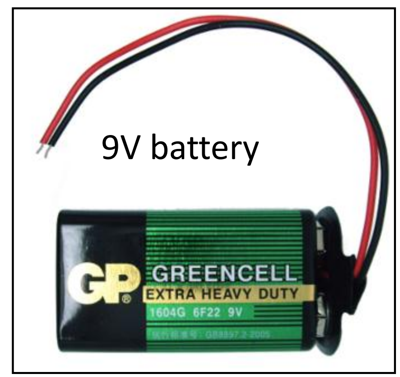
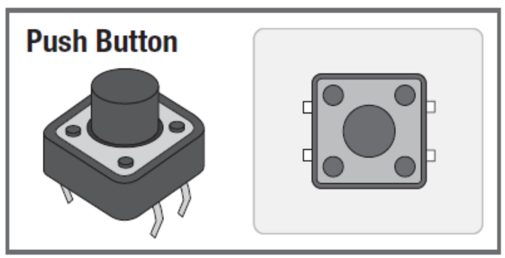


Photo Resistor


9V battery
GP
GREENCELL
EXTRA HEAVY DUTY
1604G 6F22 9V


Push Button

Sources used in this presentation

- This presentation includes material from:
  - Farzad Towhidkhah. Amirkabir University of Technology. Electrical Circuits, lecture 1. http://bme2.aut.ac.ir/~towhidkhah/Circuit/Circuit1/PPT/lec1.ppt
  - Jefferson Lab. Electrical Circuits. http://education.jlab.org/jsat/powerpoint/0708_electricity.ppt
  - Worldofteaching.com. Electric Circuits. http://www.worldofteaching.com/powerpoints/physics/electric%20circuits.ppt
  - Sparkfun. Introduction to Electronics and Breadboarding Circuits. http://create.coloradovirtuallibrary.org/sites/default/files/Curriculum/SparkFun/Beginner/IntrotoBasicElectronics.ppt
  - Sparkfun. Intro to Arduino. http://create.coloradovirtuallibrary.org/sites/default/files/Curriculum/SparkFun/Beginner/IntrotoArduino.ppt

PART 1: ELECTRICITY IS A THING!

Introduction to Electric Circuits

- Here we are going to remind what are:
  - Voltage
  - Current
  - Current flow
  - Voltage Sources
  - Voltmeter (Multimeter)

What is Voltage?

V = "Electrical pressure"   - measured in *volts.*

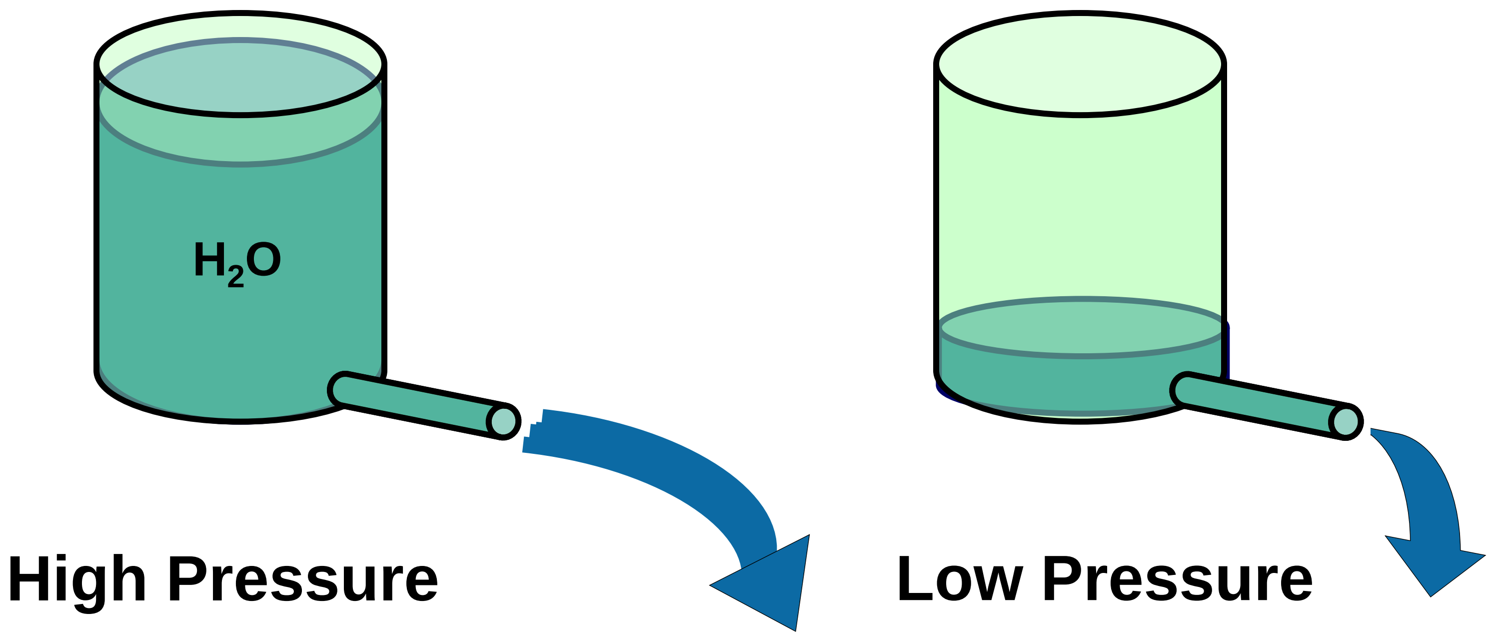
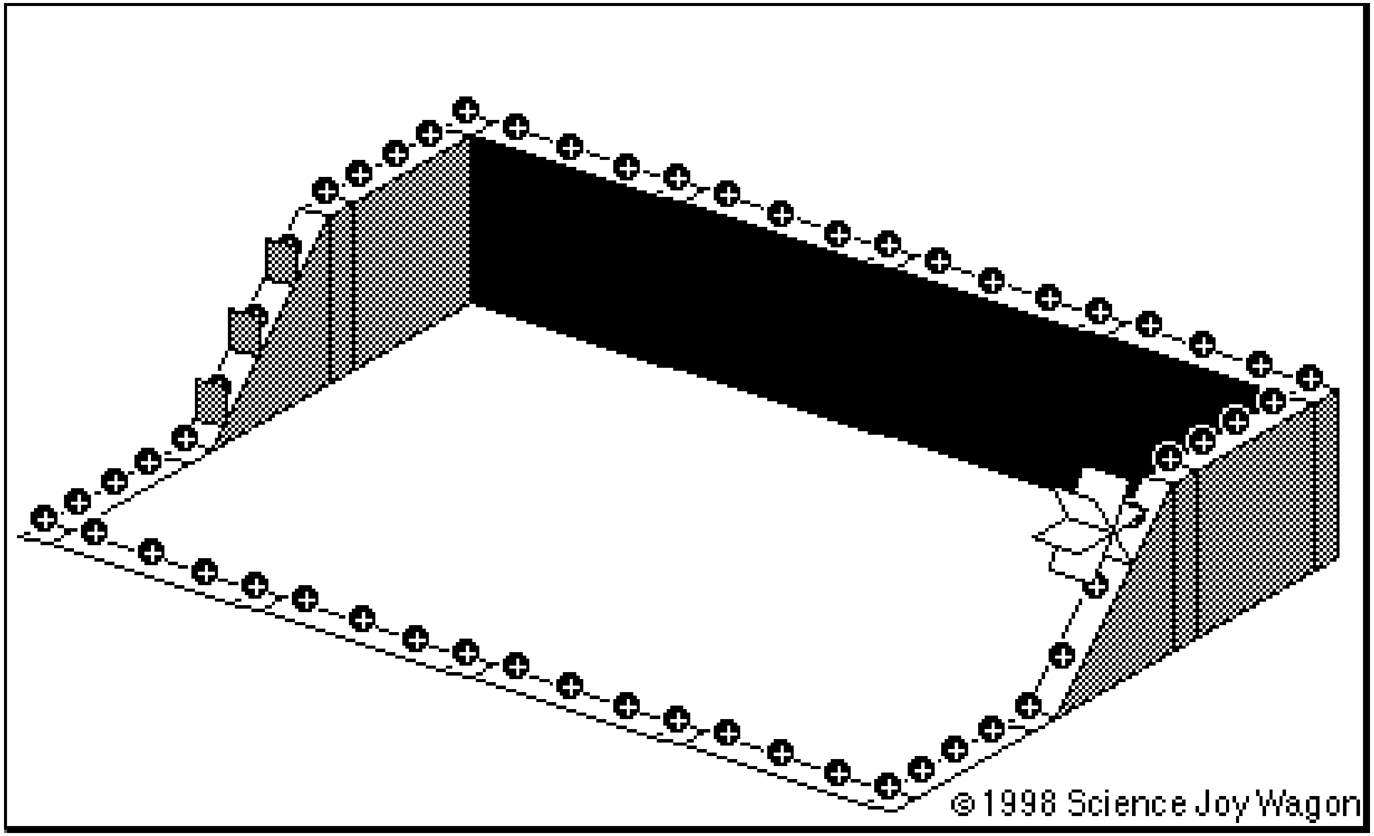


Figure 1.1

The water analogy

- A battery in an electrical circuit plays the same role as a pump in a water system.

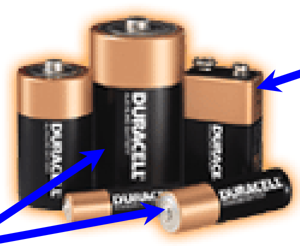


What produces voltage?

V = “Electrical pressure”

A Battery

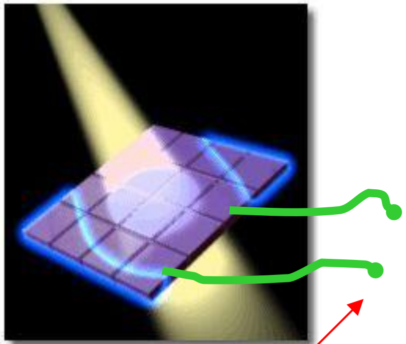
9 V



1.5 V

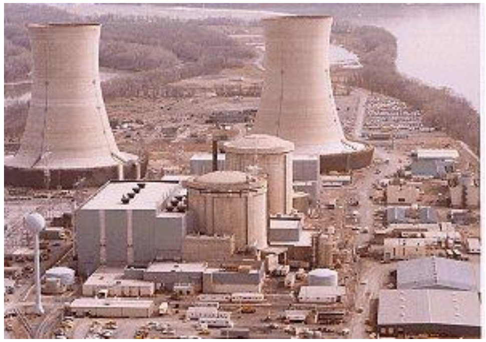
Lab Power Supply

Solar Cell



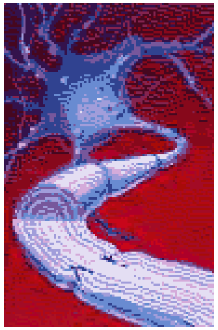
A few Volts

Electric Power Plant



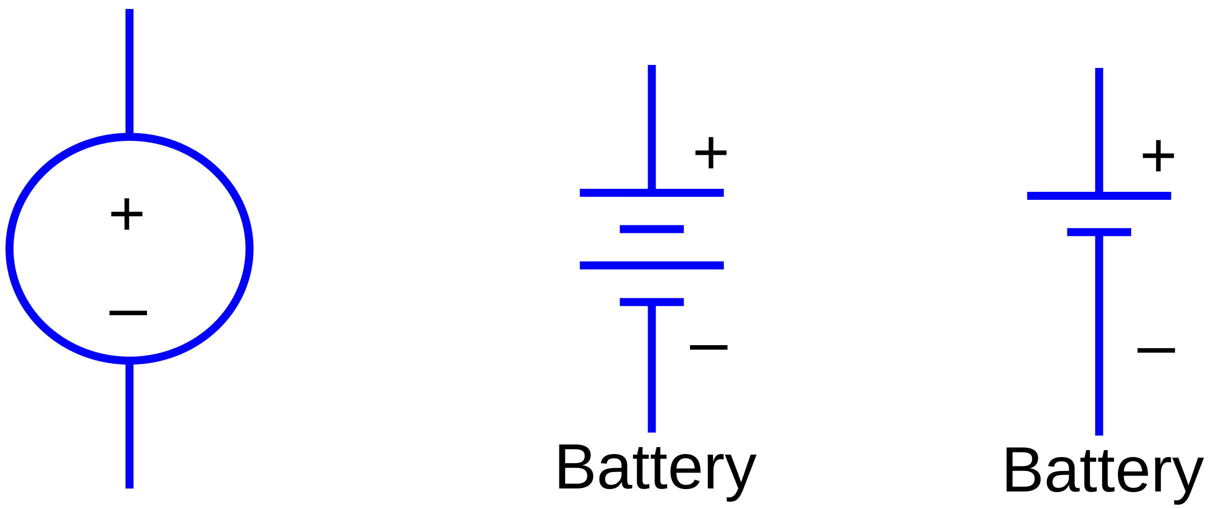
13,500 V

Nerve Cell



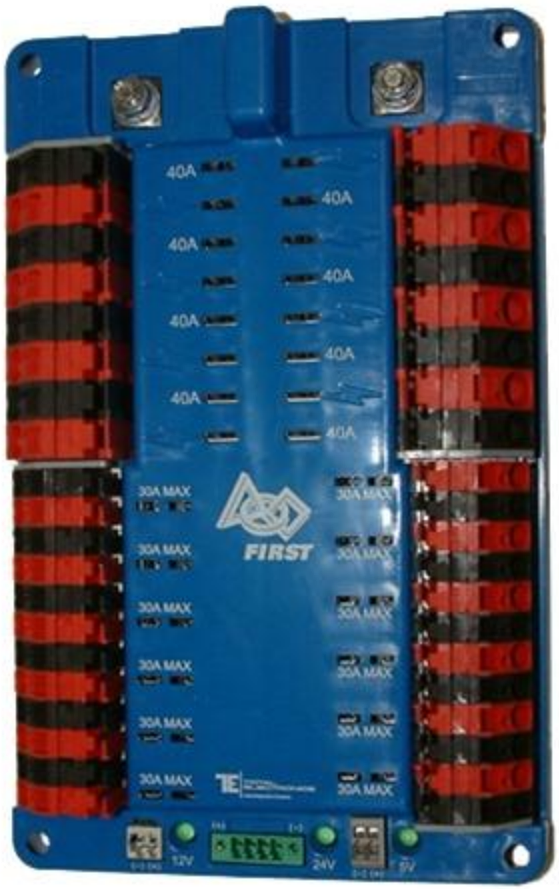
A few millivolts when activated by a synapse

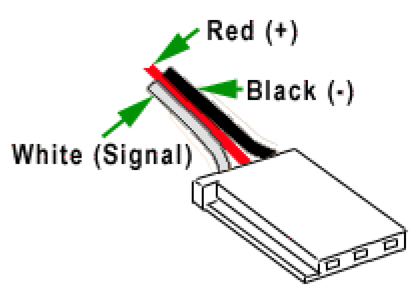
Symbols Used for Voltage Sources



All these symbols are interchangable.

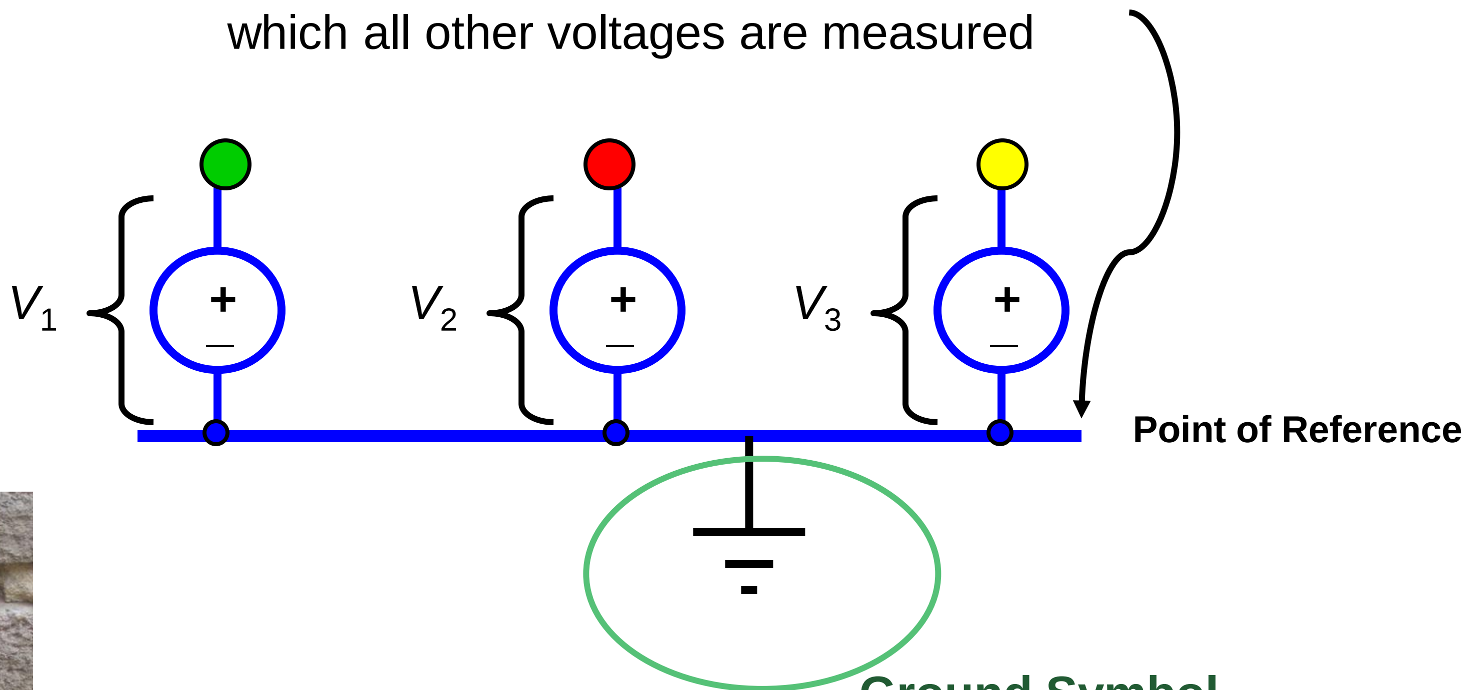
What voltages are used in FRC?





What is “Ground”?

“Ground” refers to the reference terminal to which all other voltages are measured



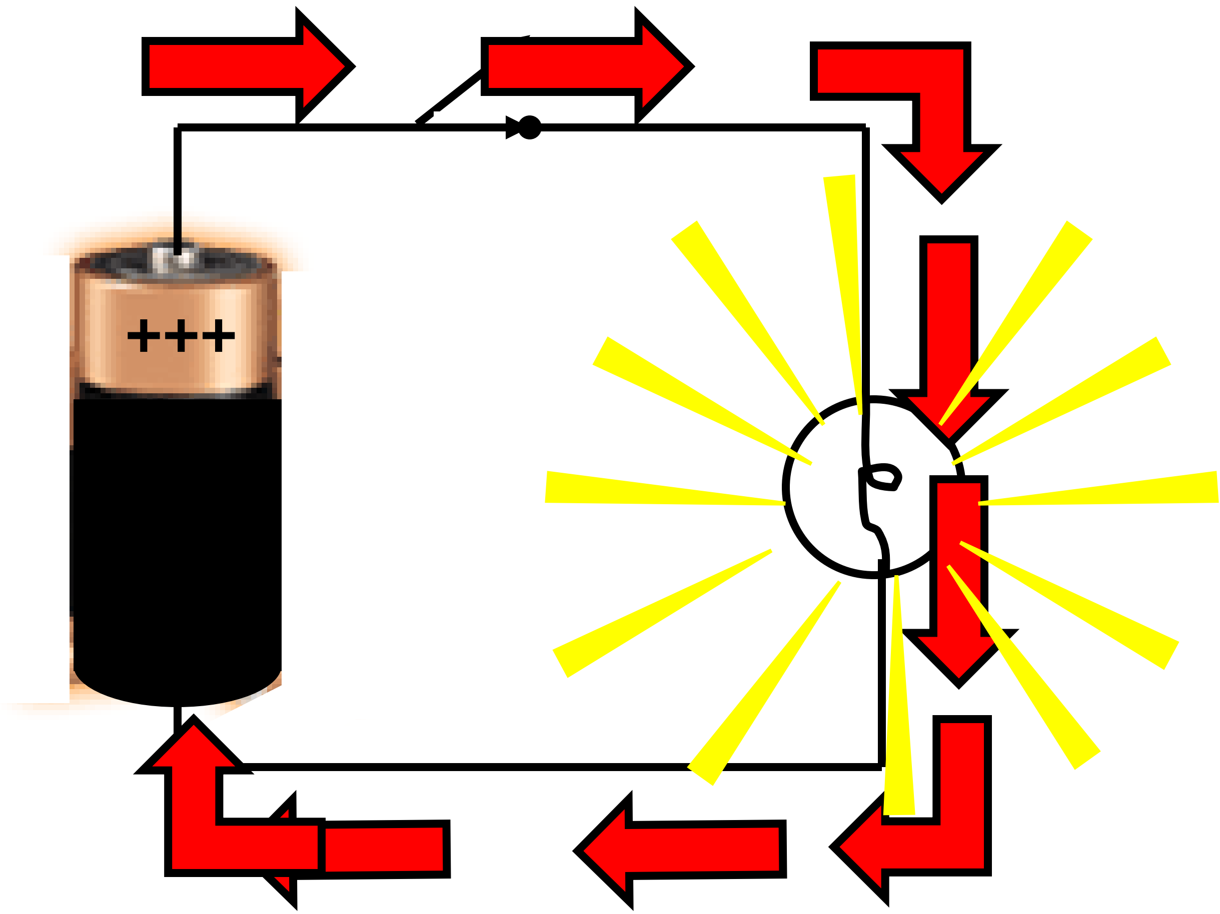
In non-battery-powered things,
ground is usually literally connected to a spike into the ground

Ground in robotics

- We call the negative of the battery “ground”

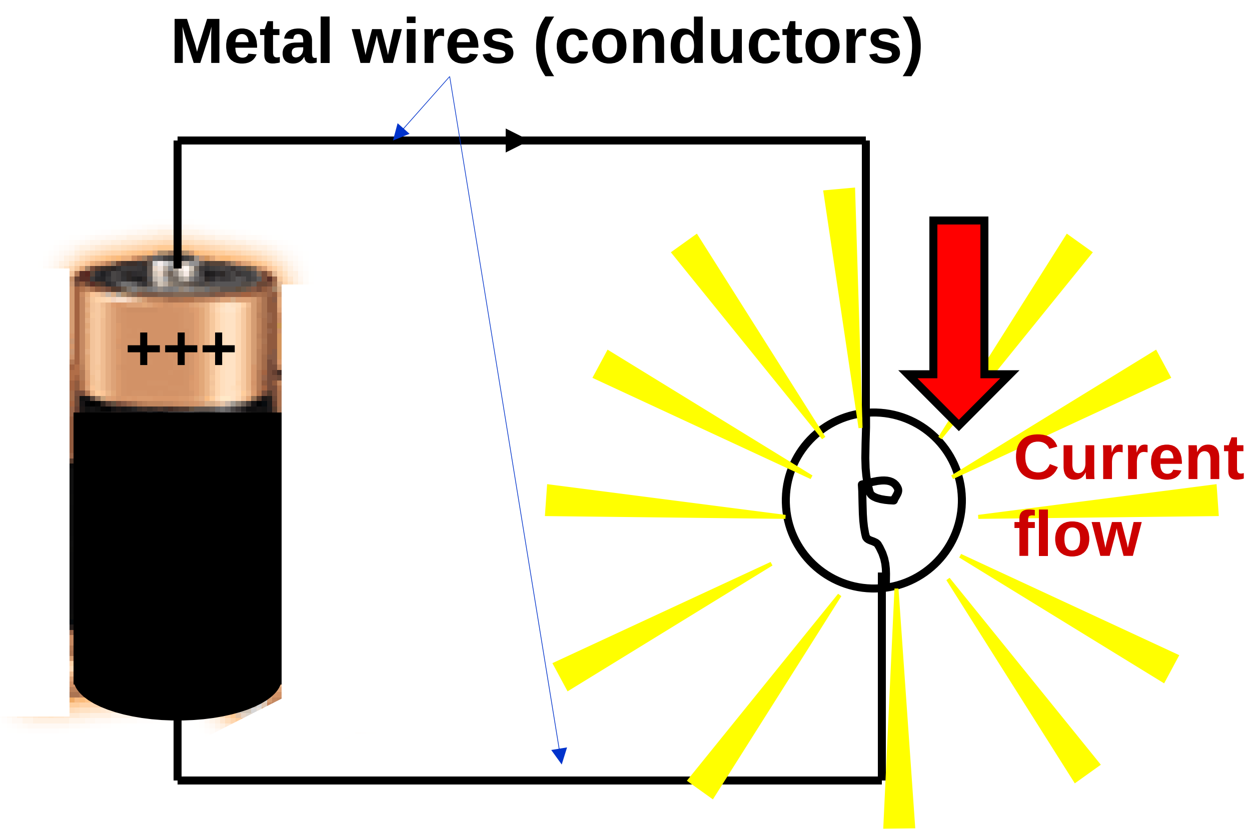
What is Current?

- Current is the **flow of charge** from a voltage source
- 1 Ampere (“Amp”) = Flow of 1 Coulomb/sec



How Does Current Flow?

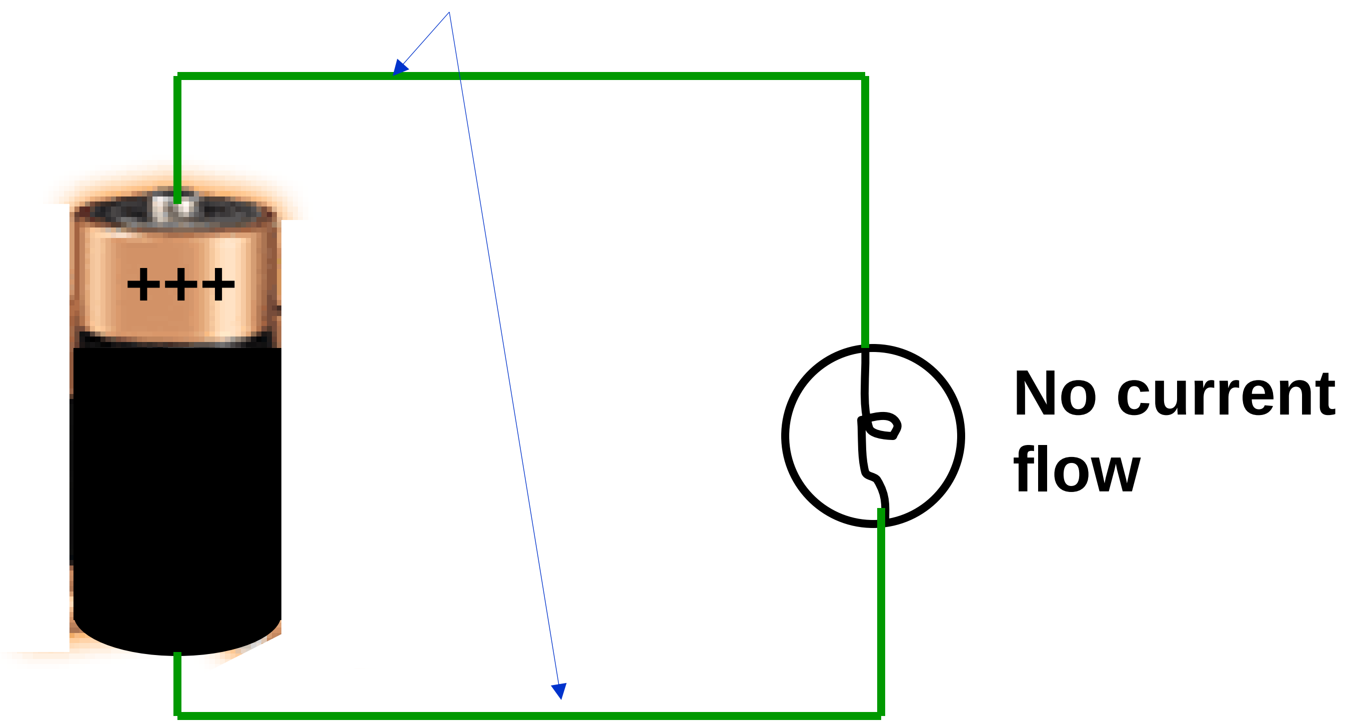
Current can only flow through conductors



When Does Current NOT Flow?

Current cannot flow through insulators

Plastic material (insulators)



Note that Air is an Insulator

Current cannot flow through insulators

No current flow

That's why a battery doesn't discharge if left on its own.

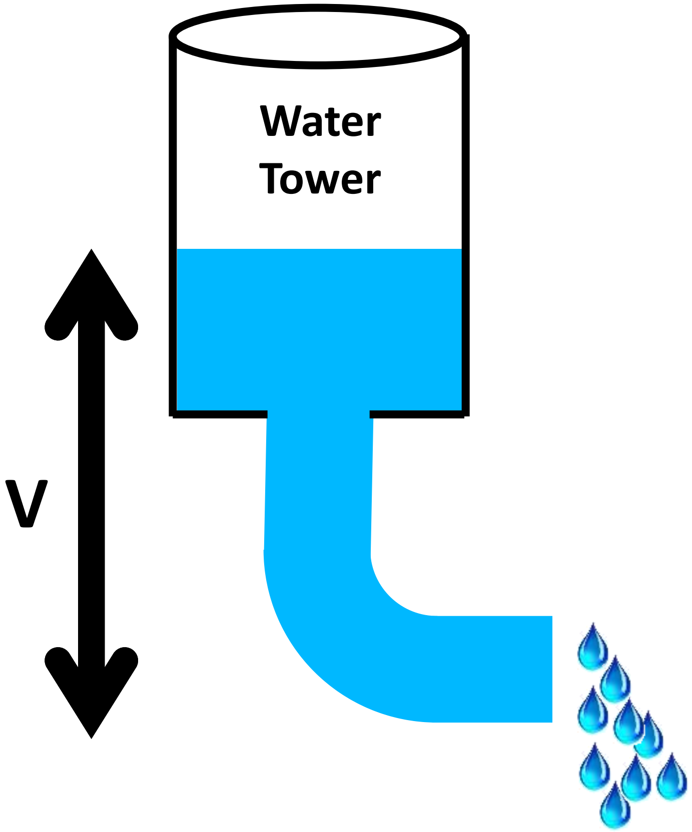
Current Flow Analogy

High Current

Low Current

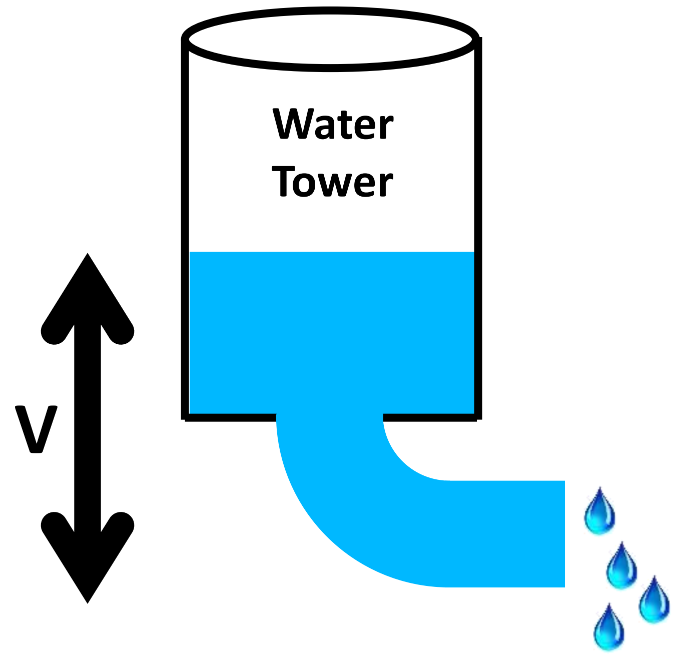
Voltage Analogy

V = I R



More Energy == Higher Voltage

V=I R

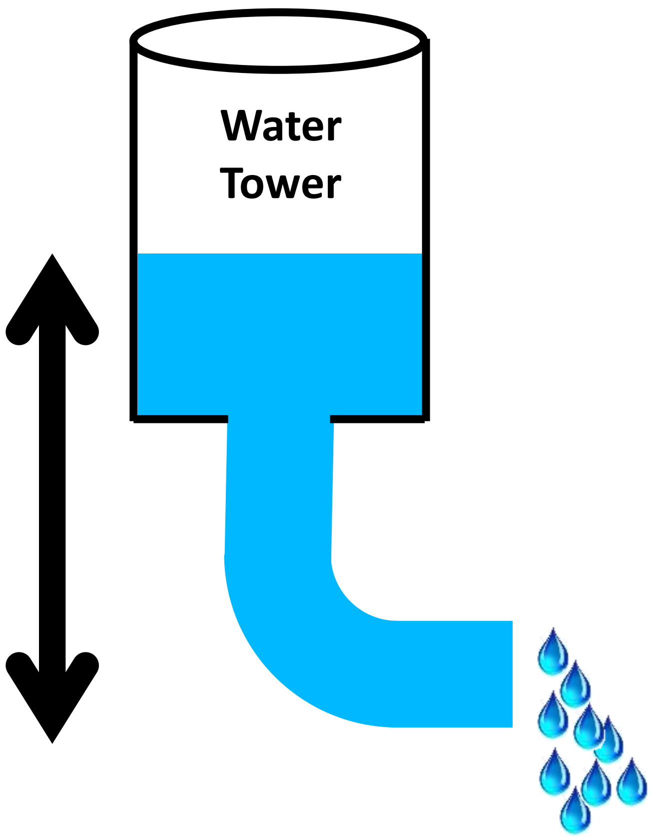


Less Energy == Lower Voltage

V = I R

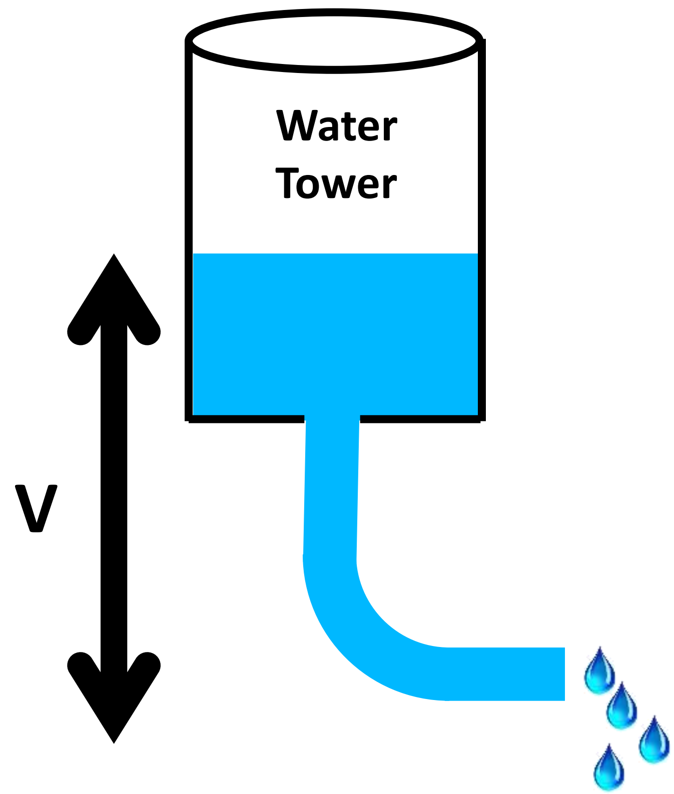
Resistance Analogy

V = IR



Big Pipe == Lower Resistance

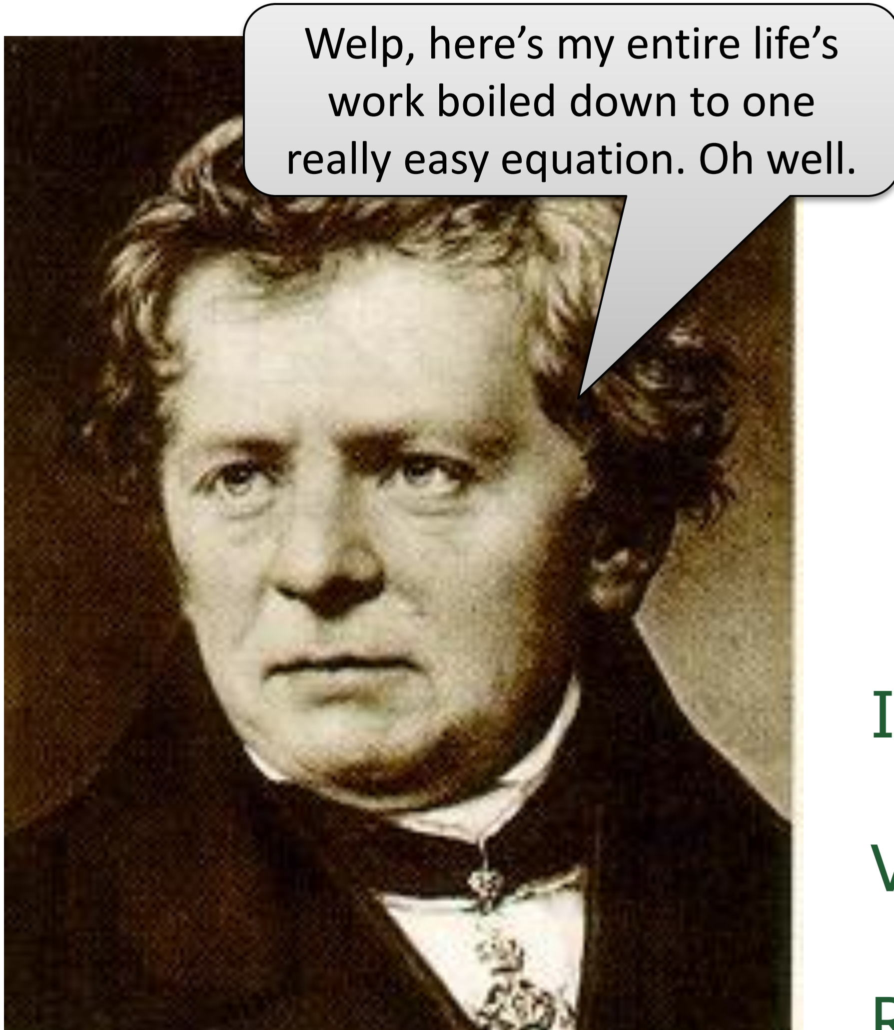
V=IR



Small Pipe == Higher Resistance

V= IR

Ohm's Law



Georg Simon Ohm (1787-1854)

Describes the relationship between voltage, current, and resistance.

$$V = I R$$

or

$$I = V / R$$

I = Current (Amperes) (amps, A)

V = Voltage (Volts, V)

R = Resistance (ohms, Ω)

Electrical Properties

Voltage V	Current I	Resistance R
• Defined as the amount of potential energy in a circuit. • Units: Volts (V)	• The rate of charge flow in a circuit. • Units: Amperes (A)	• Opposition to charge flow. • Units: Ohms (Ω)

$$[\boldsymbol{V} = \boldsymbol{I} \cdot \boldsymbol{R}]$$

Resistance

- Anything that isn't a PERFECT conductor has resistance (and nothing's perfect).

- 20 ft. of 18AWG wire: 0.128 Ω

- 60W incandescent lightbulb: 240 Ω

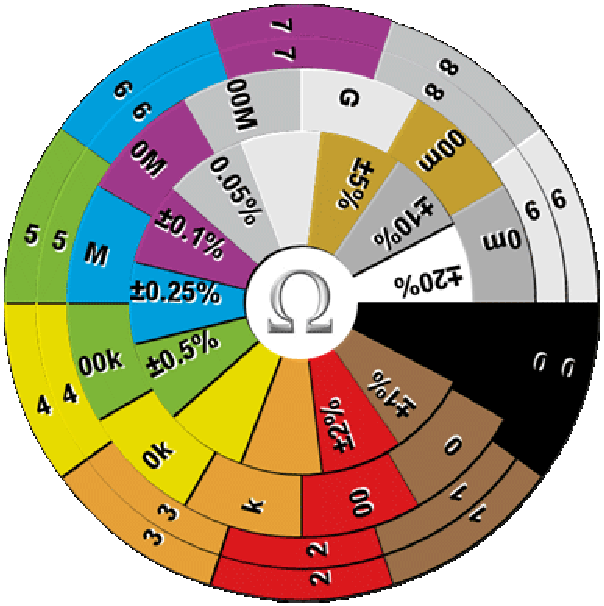
- My face: ~30 MΩ

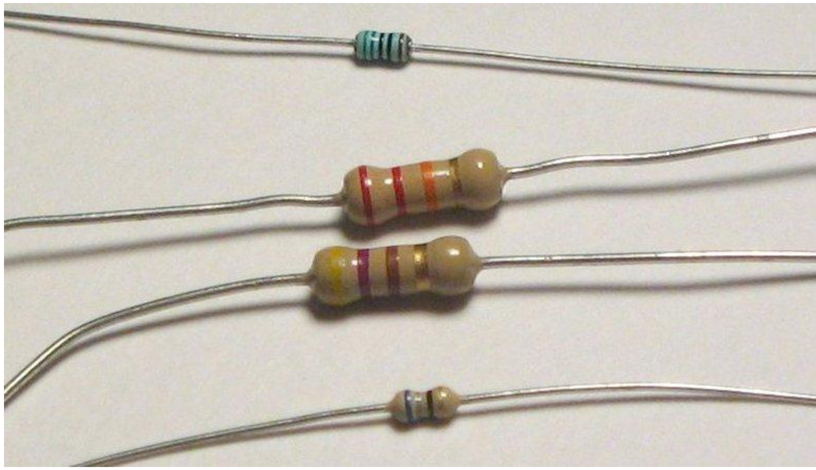
Resistors

- Resistors provide a specific amount of resistance to a path in a circuit or wire.

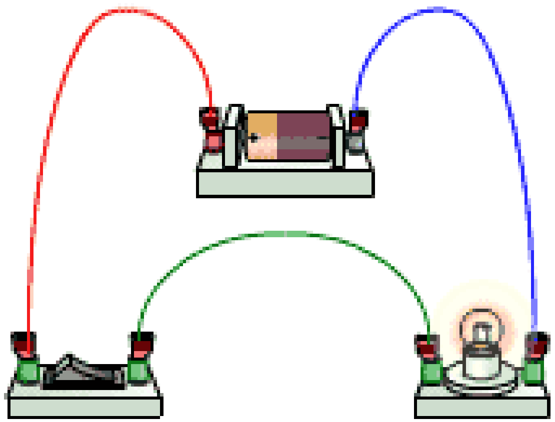
- Resistors are color coded.

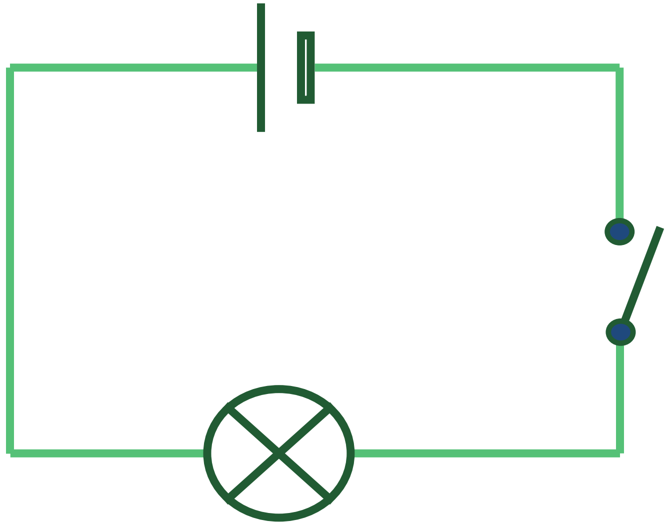
Circuit symbol for a resistor



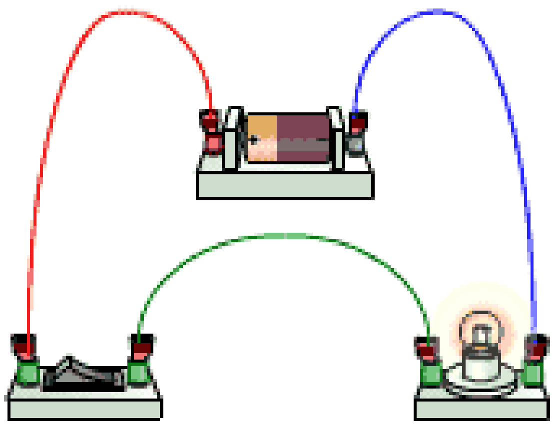


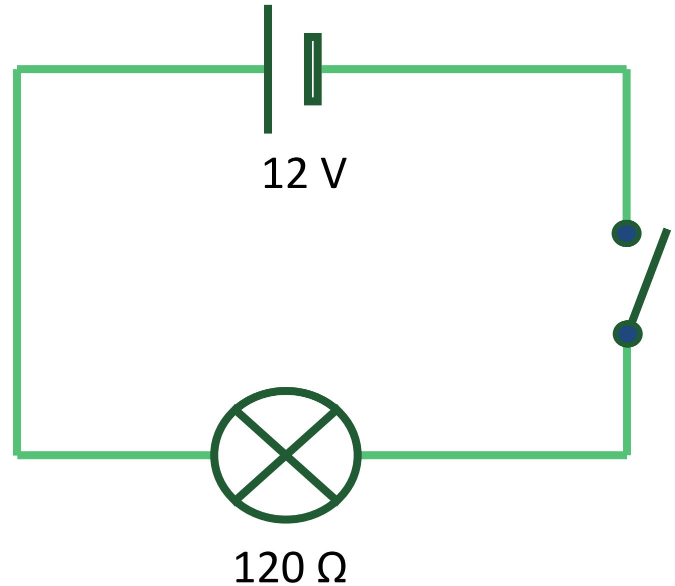
Exercise





Exercise





What's the CURRENT?

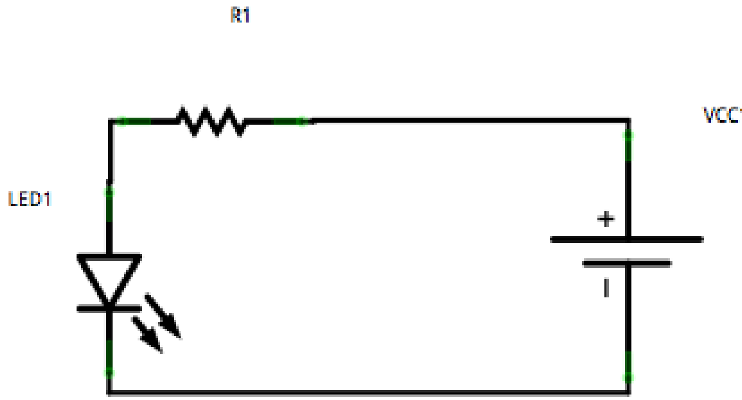
Get with it, grandma

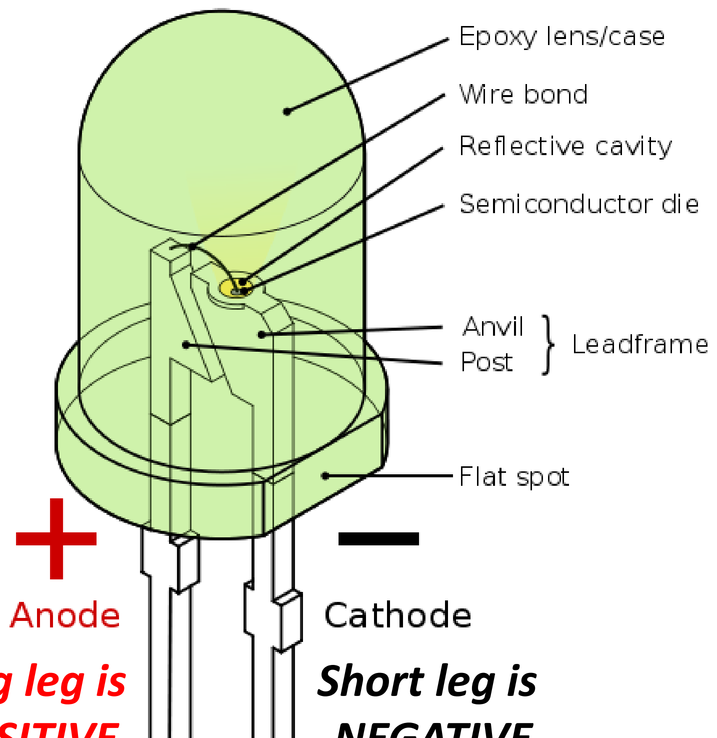
- Lightbulbs are for old people

- Light Emitting Diodes (LEDs) are where it's at!

What are LEDs?

- Light Emitting Diodes
- Diode Symbol + Arrows
- Points to ground





Long leg is POSITIVE

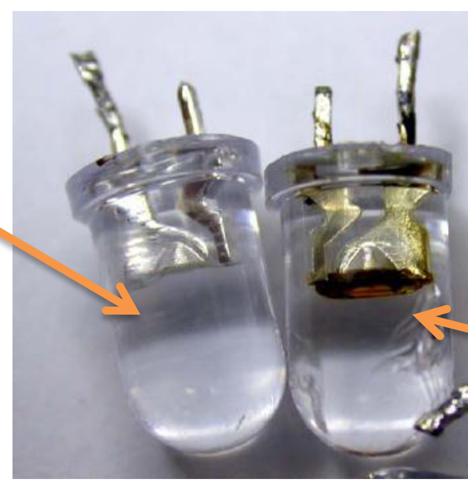
Short leg is NEGATIVE

Can emit a variety of colors

Rules of LEDs

- They need above a certain voltage to turn on (the *forward voltage drop*)
  - Typically 1.5 – 3 V
- They need less than a certain current to not burn up
  - Typically 5 – 20 mA (milli-amps)

This is your LED…

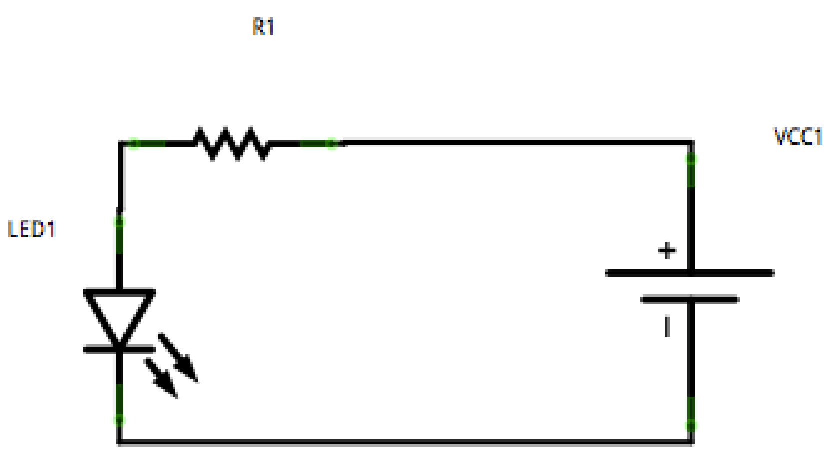


This is your LED
on too much current.
Any questions?

How to limit current?

- I have a 12V source
- I have an LED
- How can I limit the current?????

Resistors!

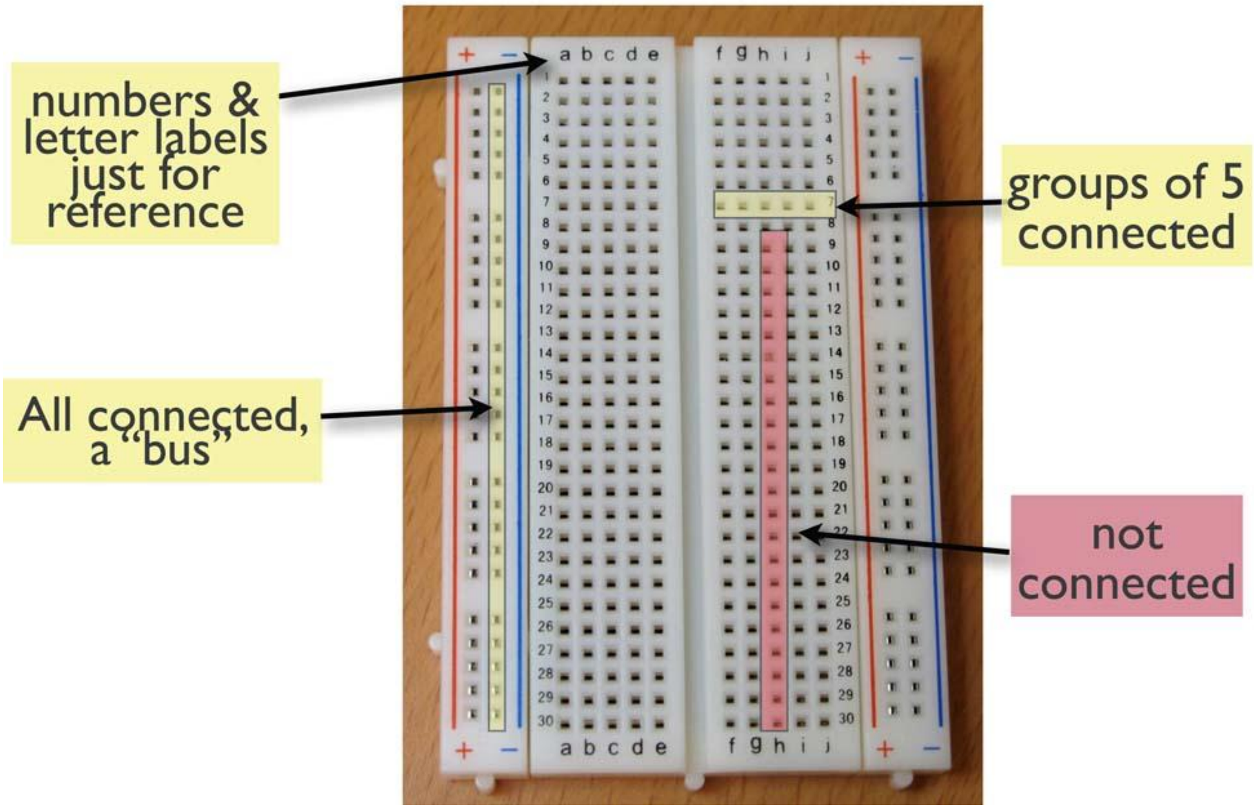


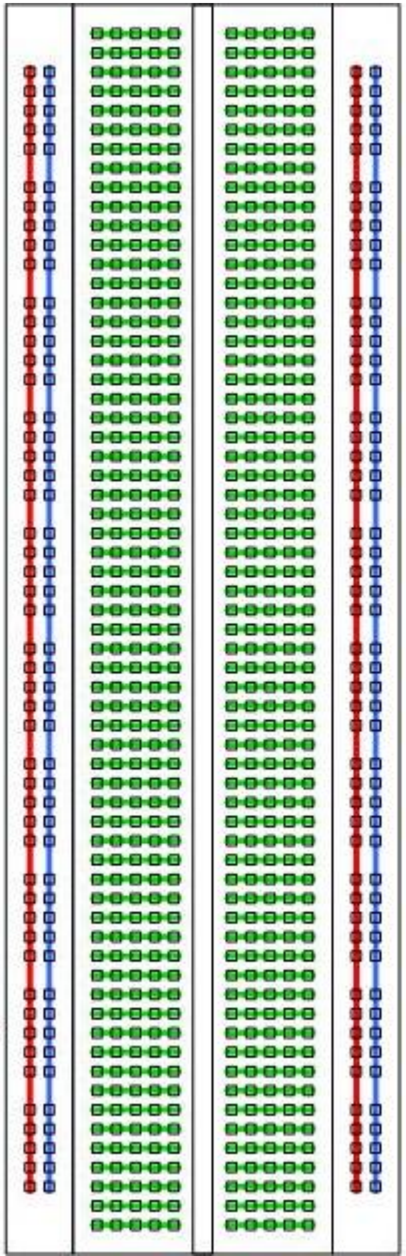
- I'm going to give it 12V
- The LED will eat 2V
- That leaves 10V left
- What resistor will limit the extra 10V to 10mA (0.01 A)?

- V = I * R
- 10 = 0.01 * R
- R = 10 / 0.01
- R = 1000
- **1000 Ohms!**

How to hook stuff together easily

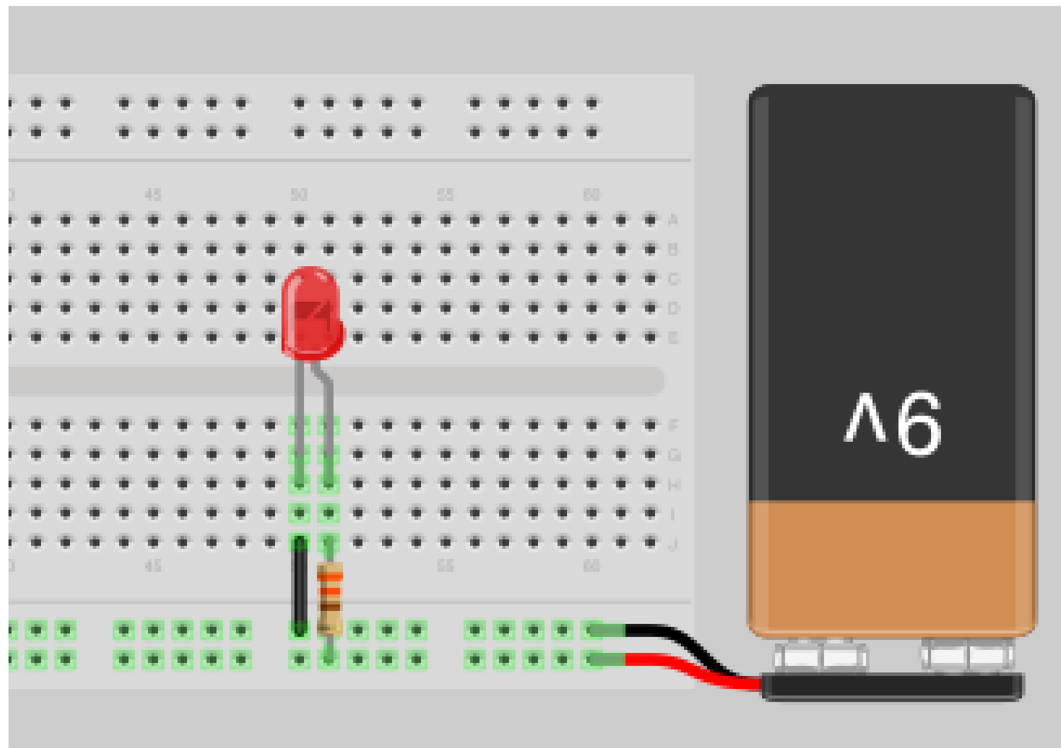
Solderless Breadboards





LET’S ACTUALLY DO A THING!!!

- Make that LED turn on!!



PART 2: ARDUINO DOES STUFF!

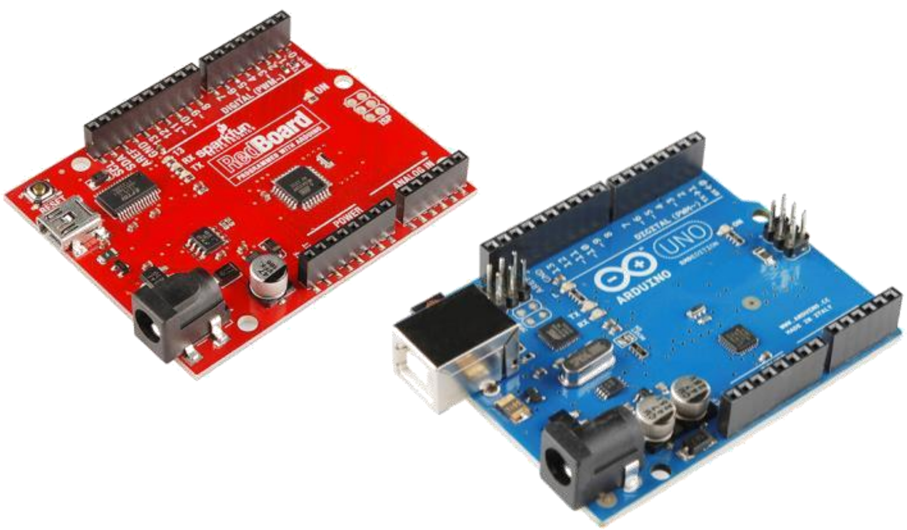
Add computing to your circuit

- All this electronics stuff is cool, but I want to DO STUFF, not make a light turn on
- Enter Arduino
  - Tiny little computer that's really cheap
  - Designed to talk to electronics

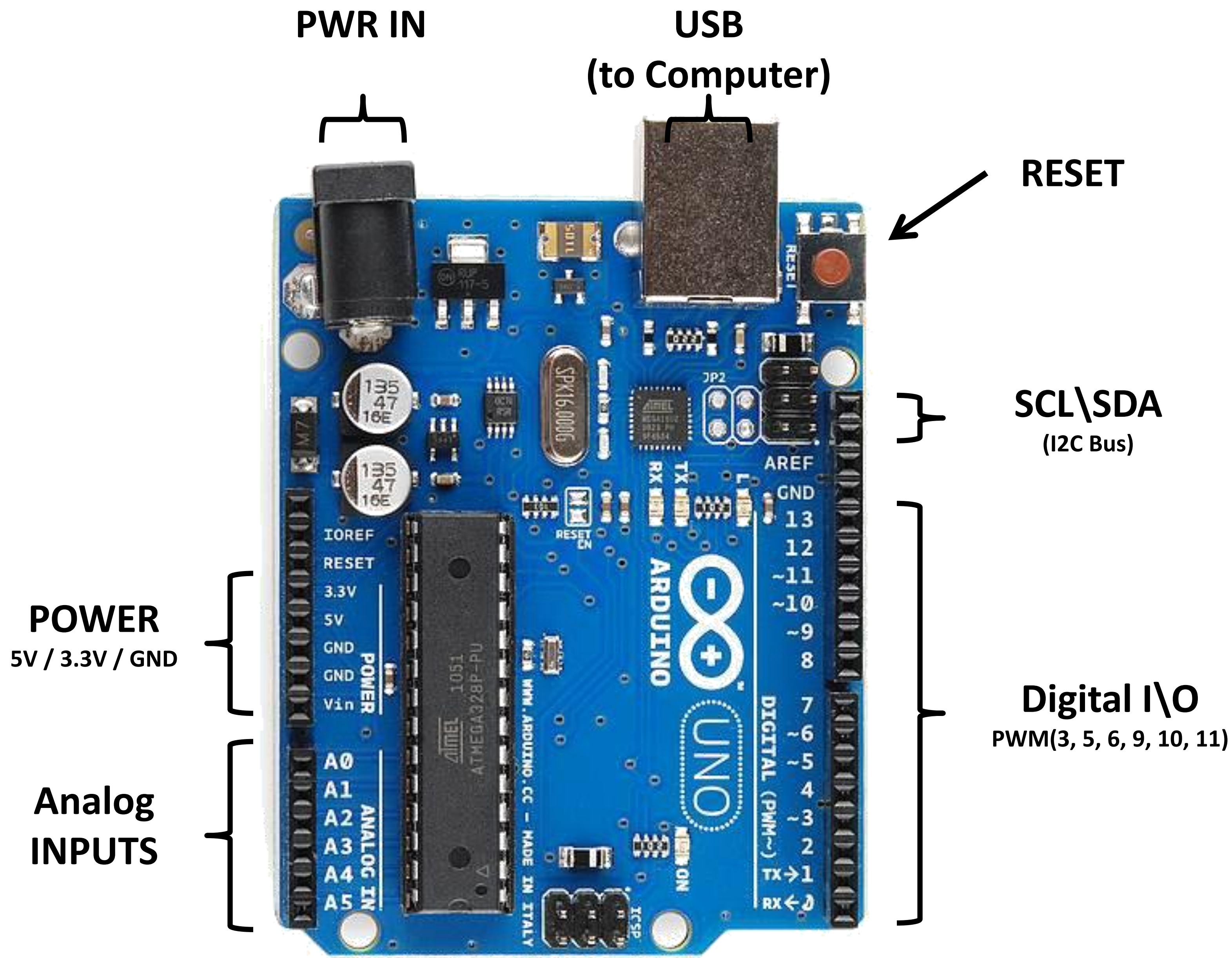
Arduino Board

- "Strong Friend" Created in Ivrea, Italy
- in 2005 by Massimo Banzi & David Cuartielles
- Open Source Hardware
- ATMEL Processor
- Coding is accessible & transferrable → (C++, Processing, java)

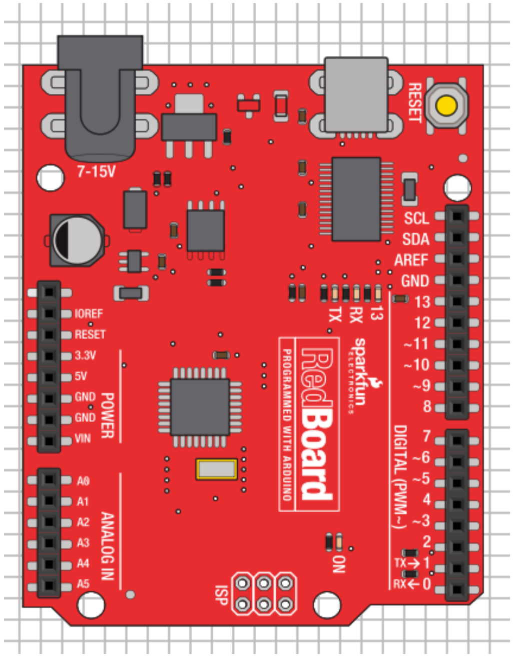
open source hardware



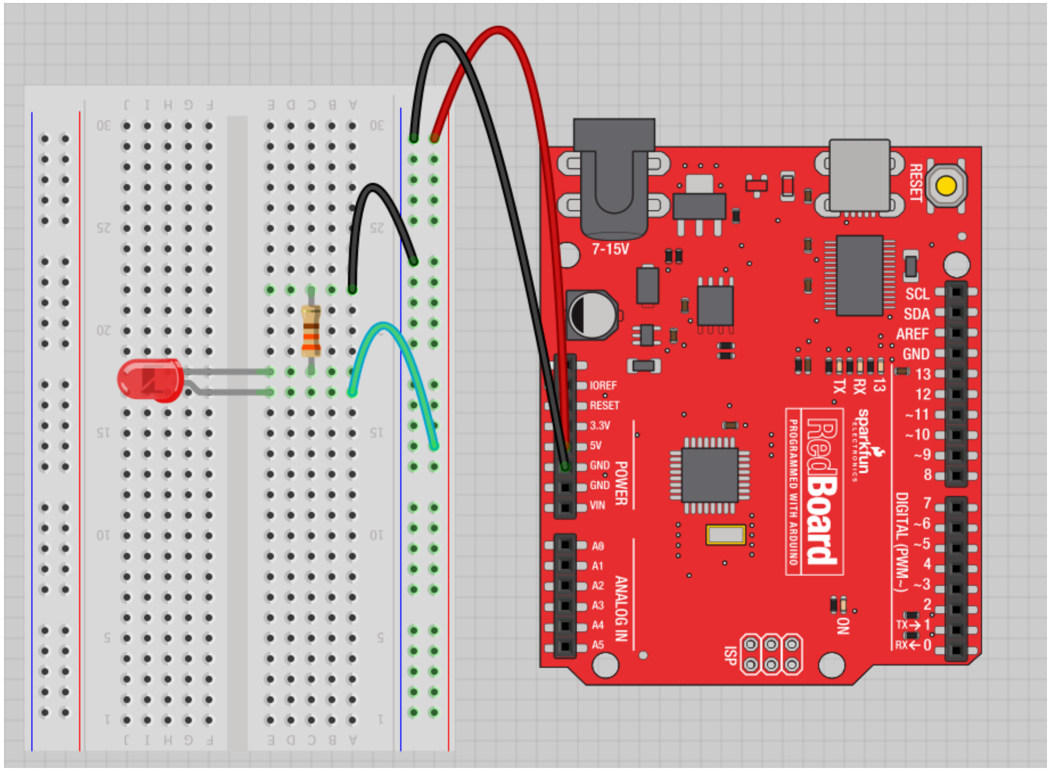
Arduino Overview



Go ahead and plug your board in!

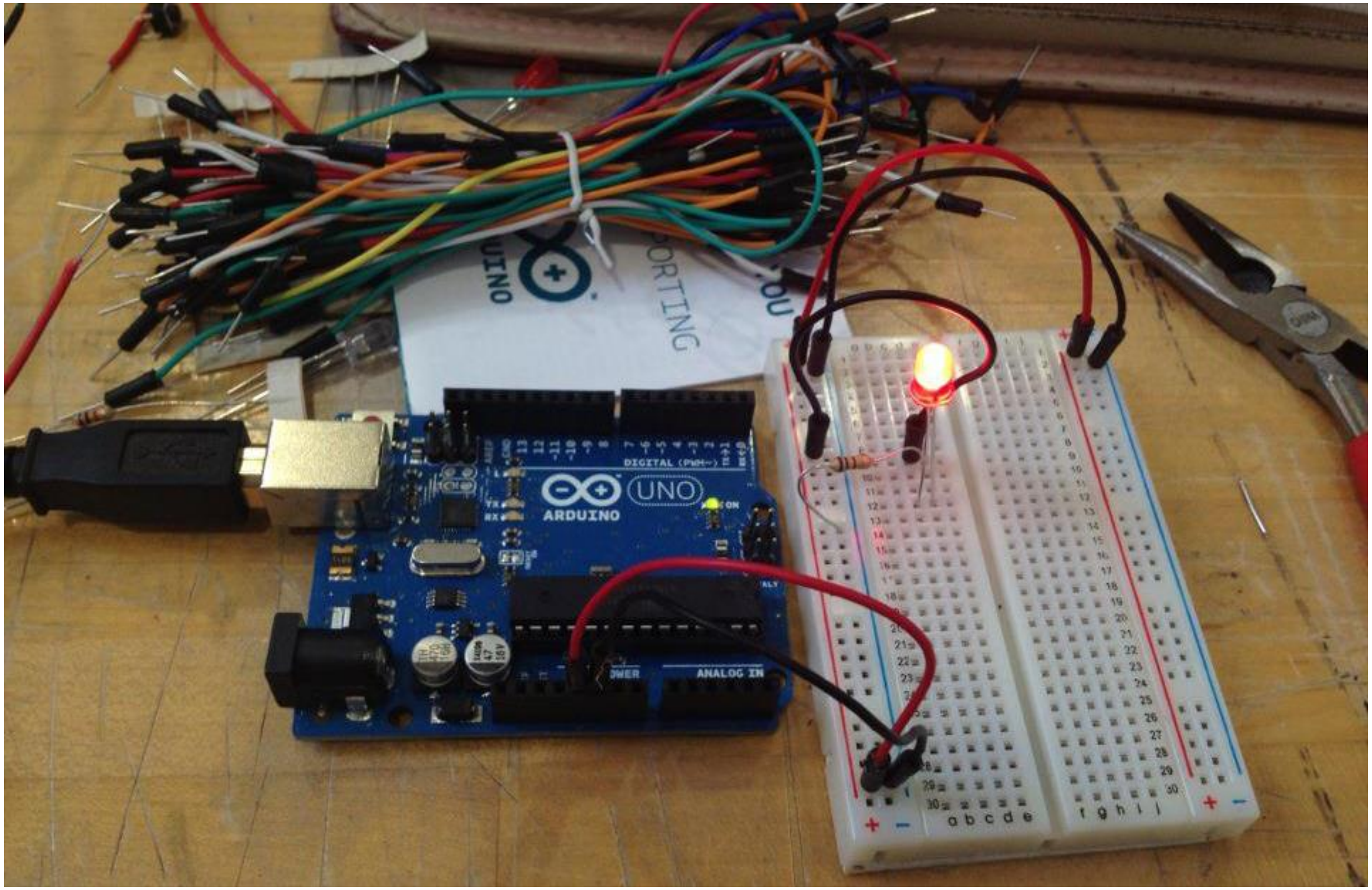


Replace the 9V with the Arduino



Adding control

- Let's use the Arduino and start programming!!!

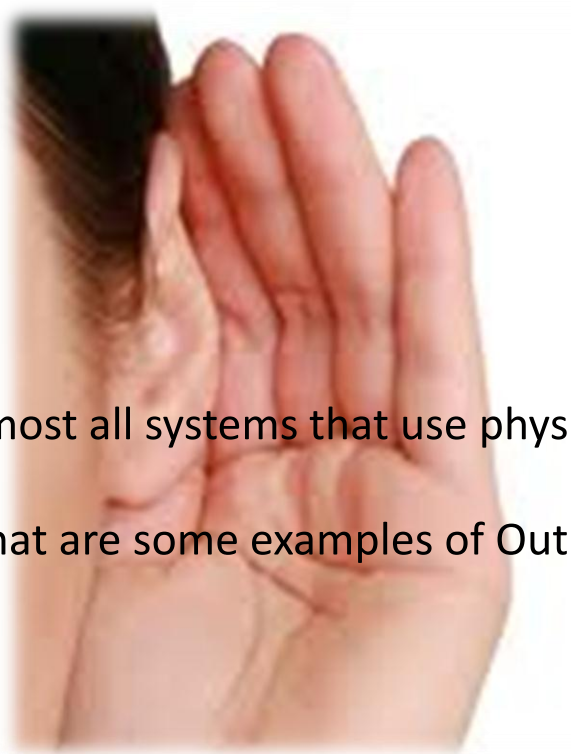


Concepts: INPUT vs. OUTPUT

- Referenced from the perspective of the microcontroller (electrical board).

Inputs is a signal / information going into the board.

Output is any signal exiting the board.



Almost all systems that use physical computing will have some form of output

What are some examples of Outputs?

Concepts: INPUT vs. OUTPUT

- Referenced from the perspective of the microcontroller (electrical board).

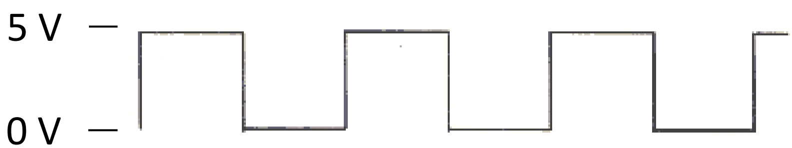
Inputs is a signal / information going into the board.

Output is any signal exiting the board.

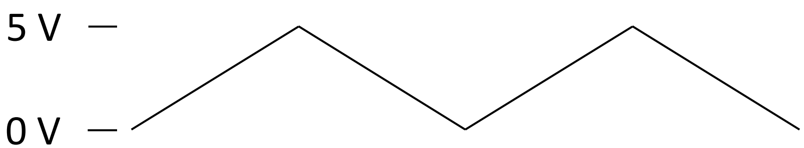
Examples: Buttons Switches, Light Sensors, Flex Sensors, Humidity Sensors, Temperature Sensors…	Examples: LEDs, DC motor, servo motor, a piezo buzzer, relay, an RGB LED

Concepts: Analog vs. Digital

- Microcontrollers are digital devices – ON or OFF. Also called – discrete.
- analog signals are anything that can be a full range of values. What are some examples? More on this later…



Digital Signal



Analog Signal

Open up Arduino

- Hints:
- For PC Users →
- Run the installer copy and move the files to the appropriate locations, or

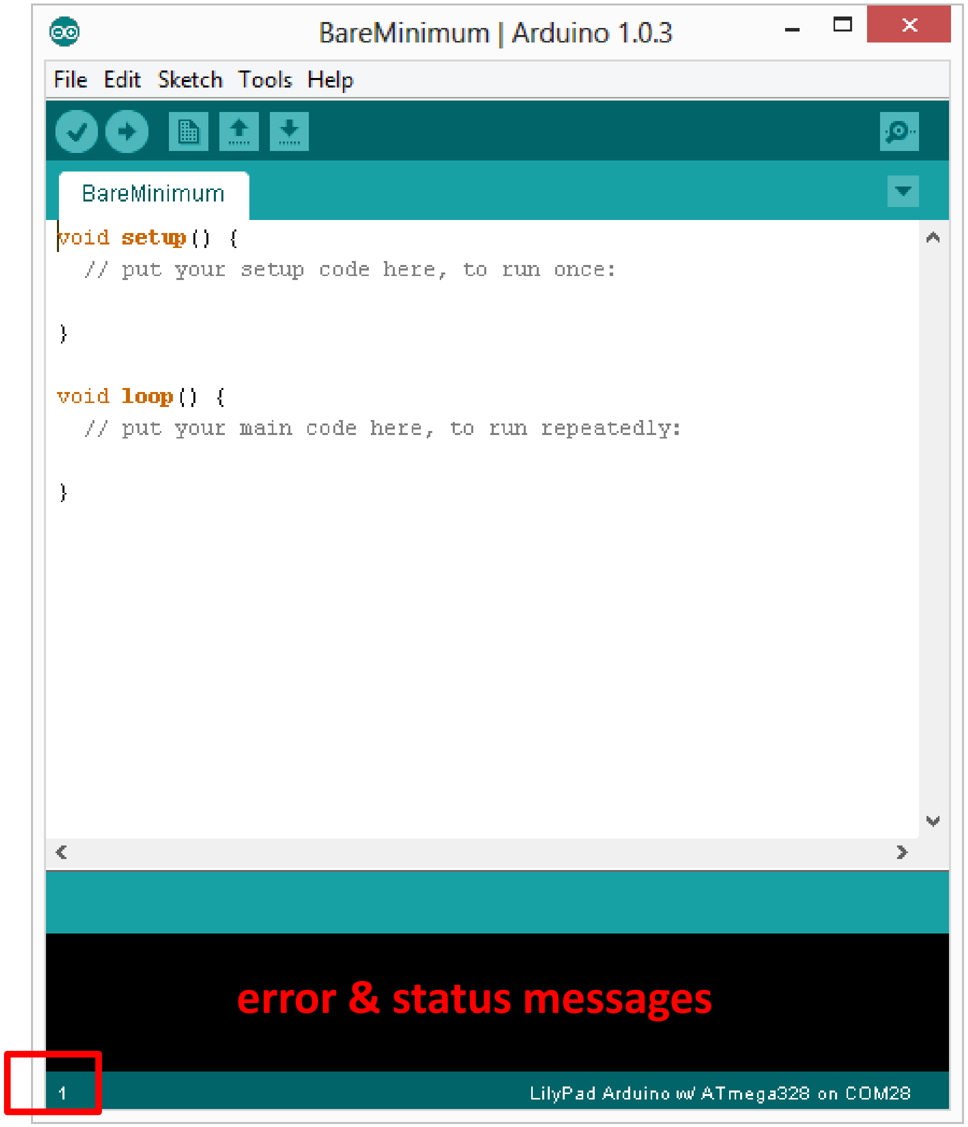
- For Mac Users →

1. Move the Arduino executable to the dock for ease of access.
2. Resist the temptation to run these from your desktop.

ARDUINO

Arduino

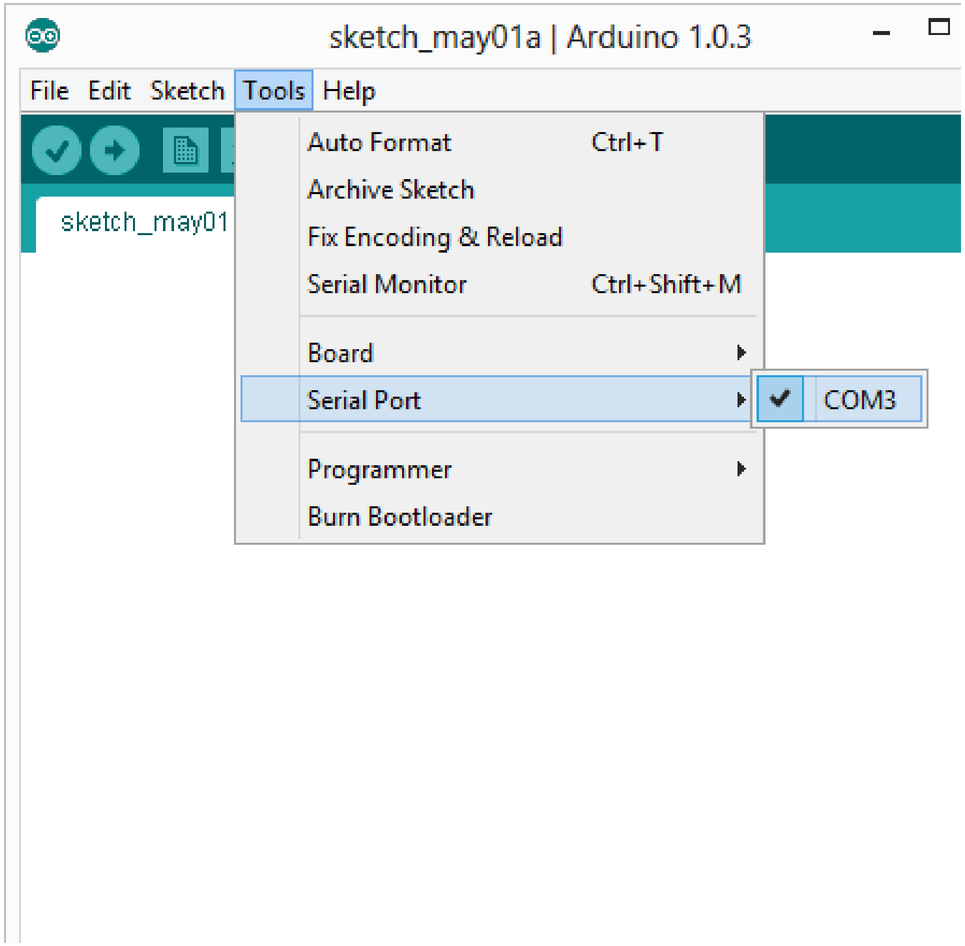
Integrated Development Environment (IDE)



Two required functions / methods / routines:

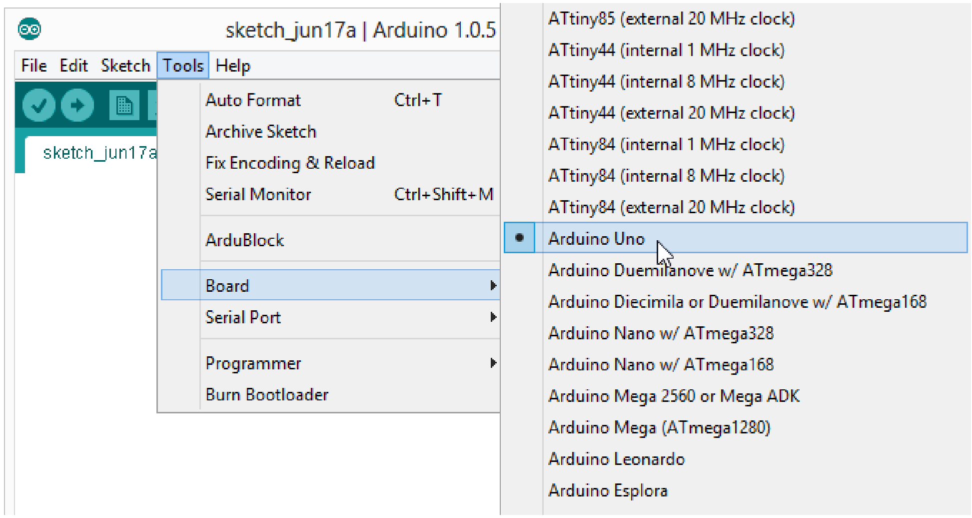
```
void setup() {
      // runs once
}

void loop() {
      // repeats
}
```

Settings: Tools → Serial Port



- Your computer communicates to the Arduino microcontroller via a serial port → through a USB-Serial adapter.
- Check to make sure that the drivers are properly installed.

Settings: Tools → Board



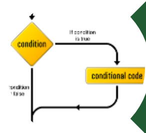
- Next, double-check that the proper board is selected under the Tools→Board menu.

BIG 6 CONCEPTS

digitalWrite()

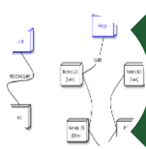
analogWrite()

digitalRead()



if() statements / Boolean

analogRead()



Serial communication

Let’s get to coding…

- Project #1 – Blink
  - “Hello World” of Physical Computing
- Psuedo-code – how should this work?

Comments, Comments, Comments

- Comments are for you – the programmer and your friends…or anyone else human that might read your code.

```
// this is for single line comments

// it's good to put a description at the
// top and before anything 'tricky'

/* this is for multi-line comments
   Like this…
   And this….
*/
```

BareMinimum | Arduino 1.0.5

File Edit Sketch Tools Help

BareMinimum §

```
// Name of sketch
// Brief Description
// Date:
//

void setup()
{
  // put your setup code here, to run once:

}

void loop()
{
  // put your main code here, to run repeatedly:

}
```

comments

Three commands to know…

```
pinMode(pin, INPUT/OUTPUT);
      ex: pinMode(13, OUTPUT);

digitalWrite(pin, HIGH/LOW);
      ex: digitalWrite(13, HIGH);

delay(time_ms);
      ex: delay(2500); // delay of 2.5 sec.

// NOTE: -> commands are CASE-sensitive
```

Project #1: Wiring Diagram

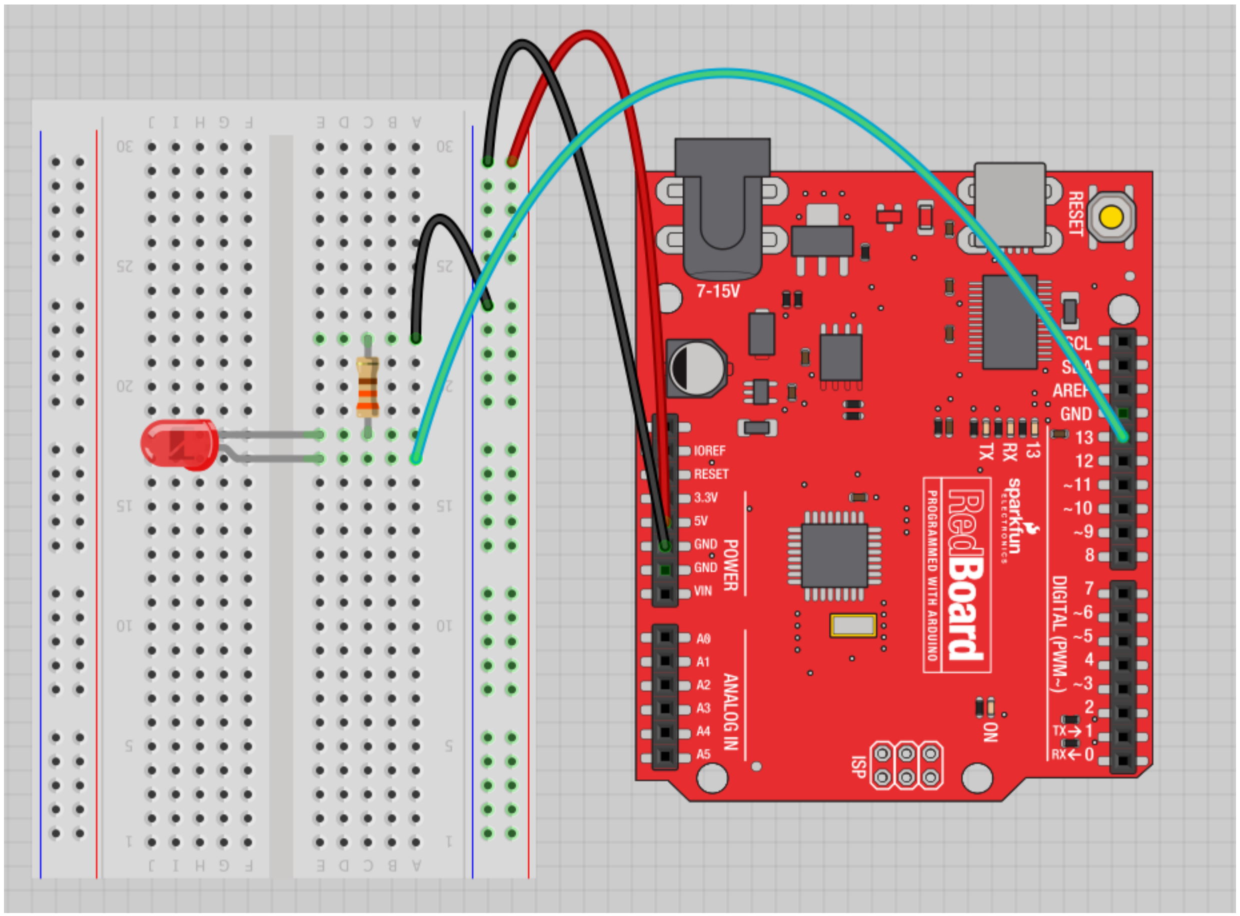


Image created in Fritzing

Move the green wire from the power bus to pin 13 (or any other Digital I/O pin on the Arduino board.

A few simple challenges

- Let’s make LED#13 blink!
  - Challenge 1a – blink with a 200 ms second interval.
  - Challenge 1b – blink to mimic a heartbeat
  - Challenge 1c – find the fastest blink that the human eye can still detect…

    1 ms delay? 2 ms delay? 3 ms delay???

Programming Concepts: Variables

ProtosnapProMiniExample2 §

```
// Comments go here
// Written by:  Joesephine Jones
// Date:  April 12, 2013

int sensorValue;
int ledPin;

void setup()
{
  // put your setup code here, to run once:
  int setupVariable;

}

void loop()
{
  // put your main code here, to run repeatedly:
  int loopScopeVariable
}
```

Variable Scope

Global

Function-level

Programming Concepts: Variable Types

- Variable Types:

8 bits	16 bits	32 bits
byte char	int unsigned int	long unsigned long float

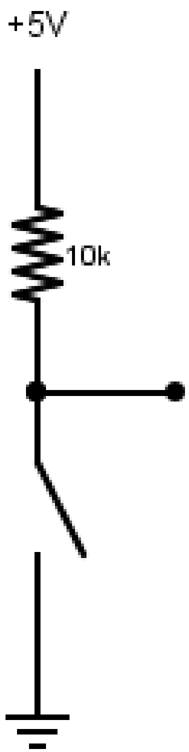
Input

- Input is any signal entering an electrical system.
  - Both digital and analog sensors are forms of input
  - Input can also take many other forms: Keyboards, a mouse, infrared sensors, biometric sensors, or just plain voltage from a circuit

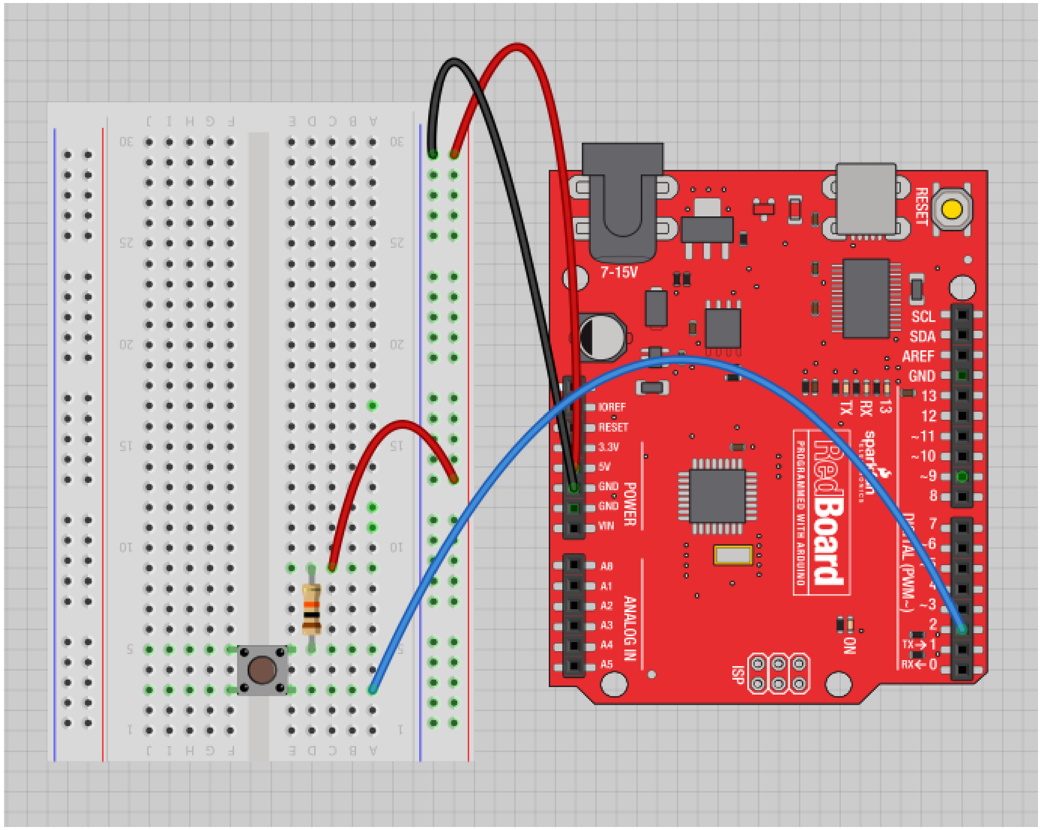
Project – Digital Input

- In Arduino, open up:
- File → Examples → 02.Digital → Button

Digital Sensors (a.k.a. Switches)
Pull-up Resistor

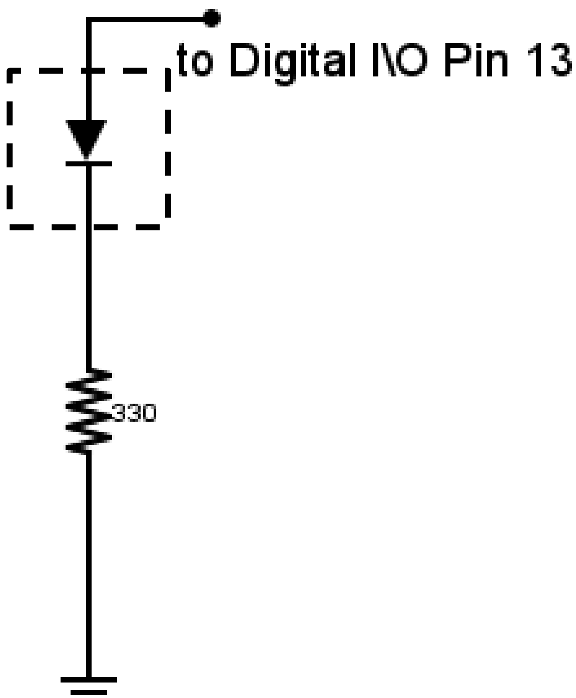


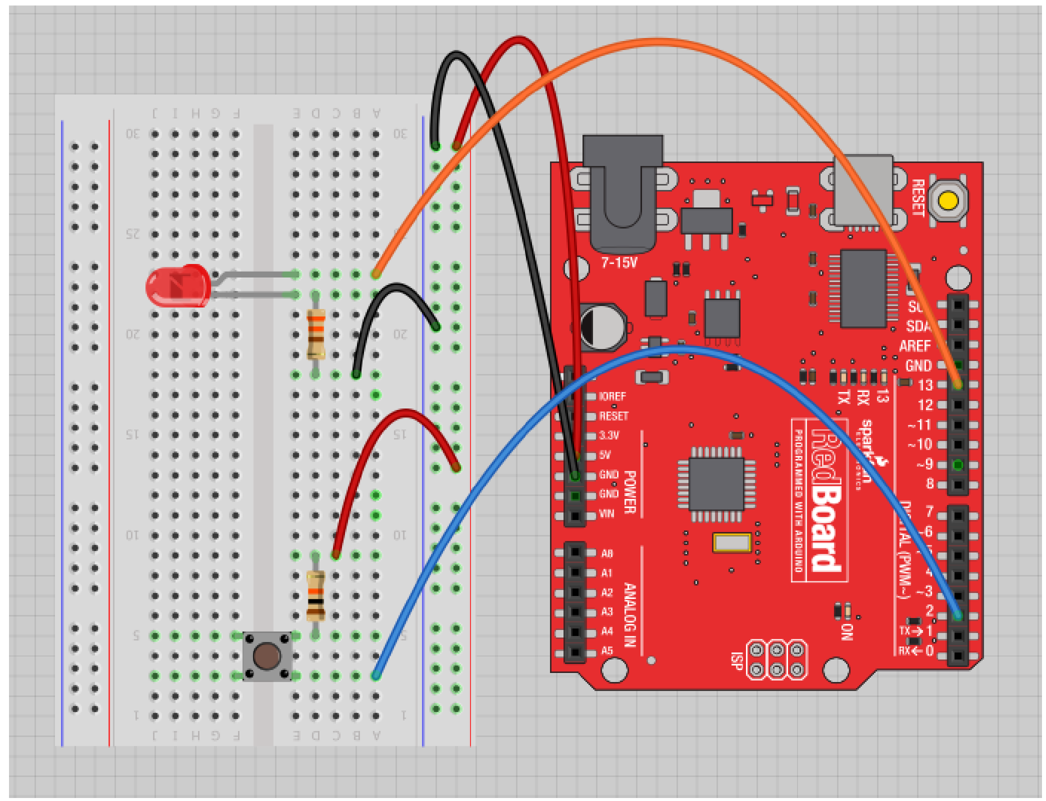
to Digital Pin 2



Digital Sensors (a.k.a. Switches)
Add an indicator LED to Pin 13

This is just like our 1st circuit!





Digital Input

- Connect digital input to your Arduino using Pins # 0 – 13 (Although pins # 0 & 1 are also used for programming)

- Digital Input needs a `pinMode` command:

```
pinMode(pinNumber, INPUT);
```

  Make sure to use ALL CAPS for ***INPUT***

- To get a digital reading:

```
int buttonState = digitalRead(pinNumber);
```

- Digital Input values are only **HIGH** (On) or **LOW** (Off)

Digital Sensors

- Digital sensors are more straight forward than Analog
- No matter what the sensor there are only two settings: On and Off
- Signal is always either HIGH (On) or LOW (Off)
- Voltage signal for HIGH will be a little less than 5V on your Uno
- Voltage signal for LOW will be 0V on most systems

Anatomy of a statement

We set it equal to the function digitalRead(pushButton)

The function digitalRead() will return the value 1 or 0, depending on whether the button is being pressed or not being pressed.

We declare a variable as an integer.

```
int buttonState = digitalRead(pushButton);
```

We name it buttonState

The value 1 or 0 will be saved in the variable buttonState.

Recall that the pushButton variable stores the number 2

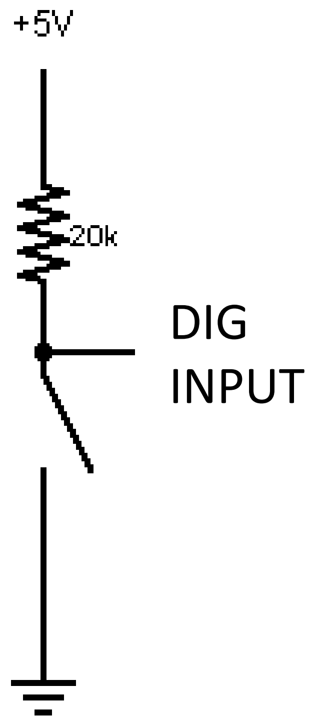
Programming: Conditional Statements - `if()`

```
if (analogValue > threshold) {

  digitalWrite(ledPin, HIGH);

}
else {

  digitalWrite(ledPin, LOW);

}
```

- If this is TRUE...
- Do this.
- Otherwise, do this.

Programming: Conditional Statements - `if()`

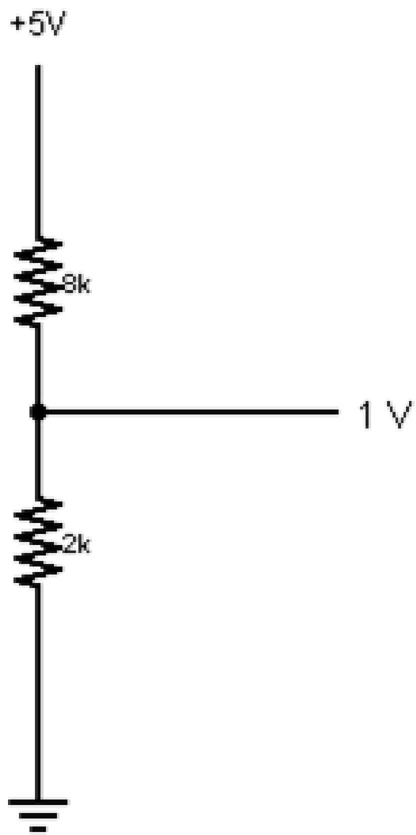
```
void loop()
{
        int buttonState = digitalRead(5);
        if(buttonState == LOW)
        {       // do something
        }
        else
        {  // do something else
        }
}
```



Boolean Operators

<Boolean>	Description
( ) == ( )	is equal?
( ) != ( )	is not equal?
( ) > ( )	greater than
( ) >= ( )	greater than or equal
( ) < ( )	less than
( ) <= ( )	less than or equal

Voltage dividers



- You get an in-between voltage based on the two resistances

$$V_{R1} = V_{CC} \cdot \left(\frac{R_1}{\mathrm{R}_{Total}}\right)$$

$$V_{R2} = V_{CC} \cdot \left(\frac{R_2}{\mathrm{R}_{Total}}\right)$$

$$R_{Total} = R_1 + R_2$$

analogRead()

Arduino uses a 10-bit A/D Converter:

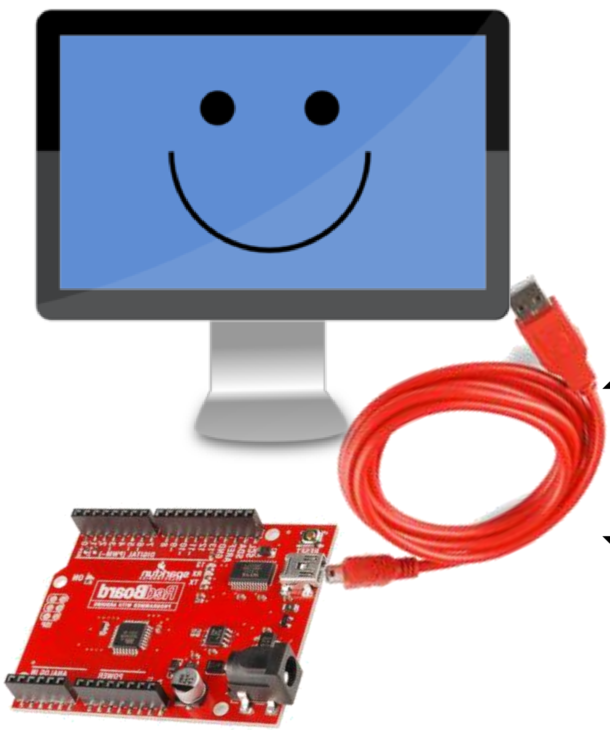
- This means that you get input values from 0 to 1023
  - 0 V → 0
  - 5 V → 1023

Ex:

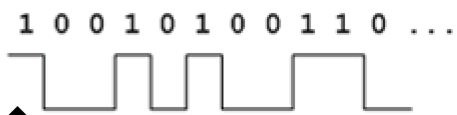
```
int sensorValue = analogRead(A0);
```

Using Serial Communication

Method used to transfer data between two devices.



Data passes between the computer and Arduino through the USB cable. Data is transmitted as zeros ('0') and ones ('1') sequentially.



Arduino dedicates Digital I/O pin # 0 to receiving and Digital I/O pin #1 to transmit.

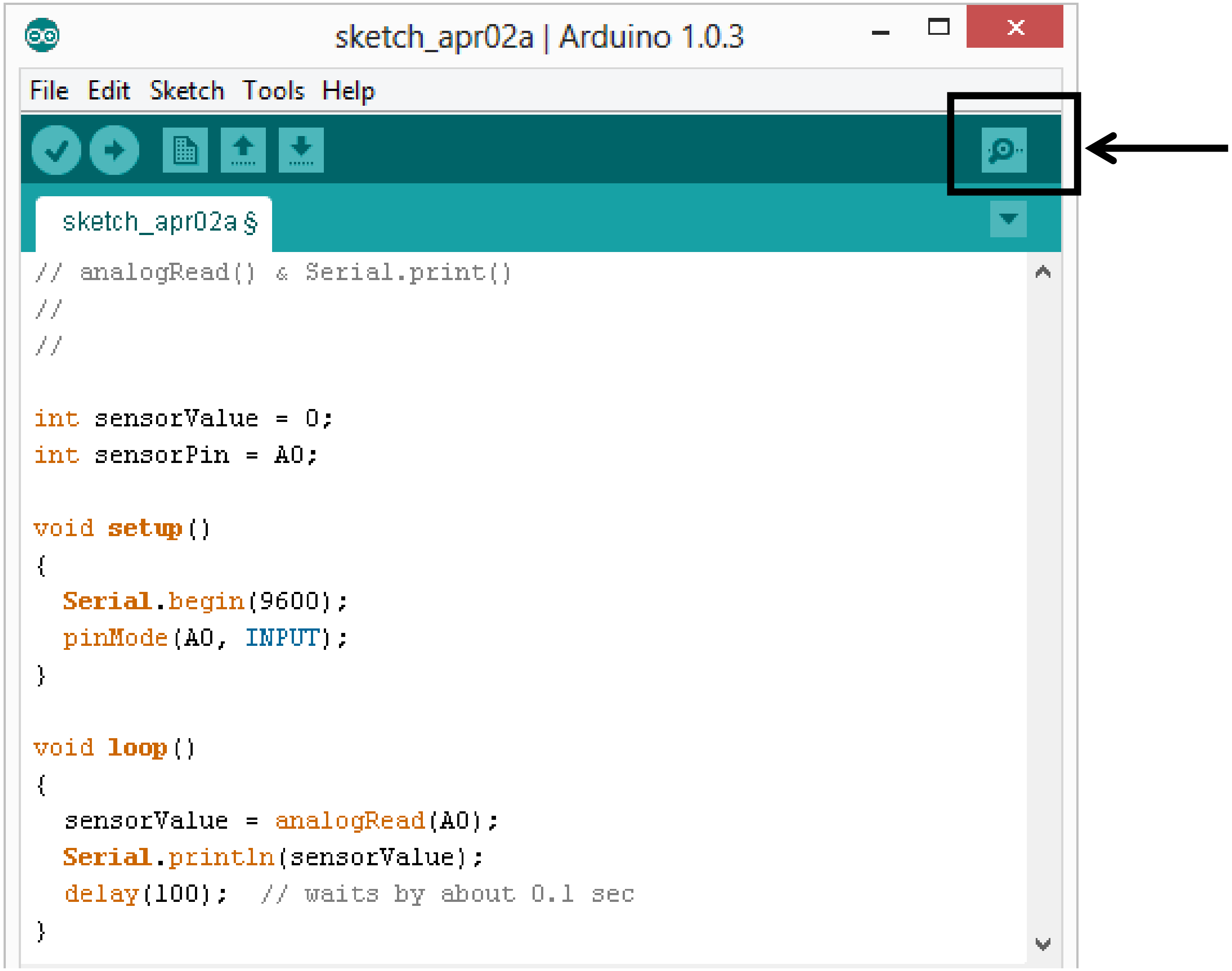
Serial Monitor & analogRead()

Initializes the Serial Communication

9600 baud data rate

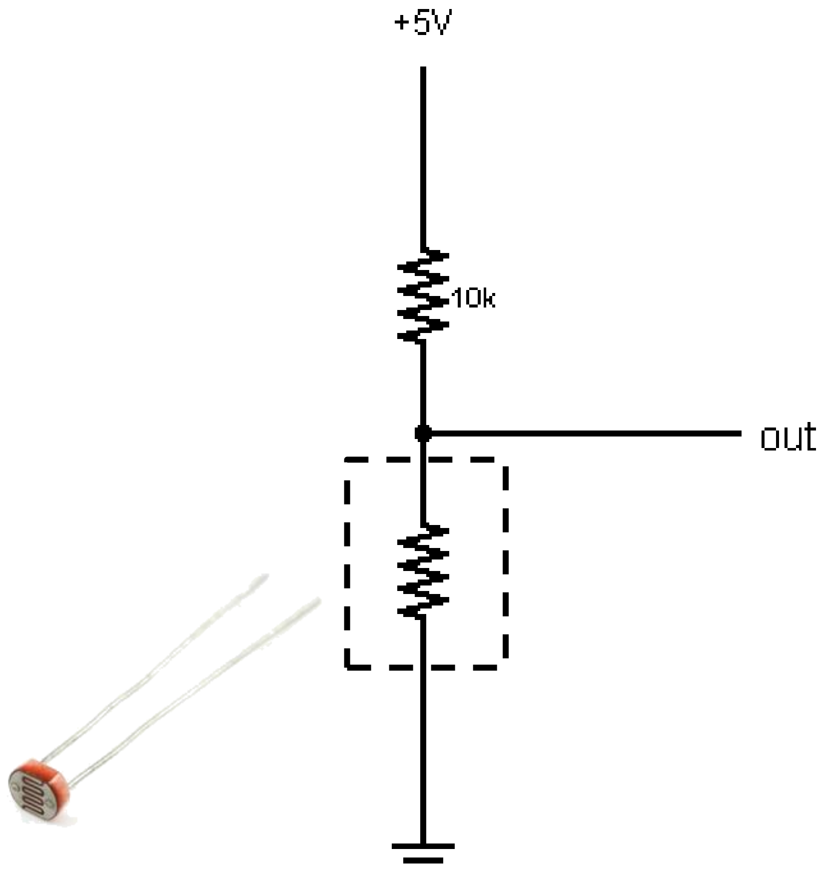
prints data to serial bus

Serial Monitor & analogRead()



Opens up a Serial Terminal Window

Analog Sensors
2 Pin Analog Sensors = var. resistor



- Take two sensors -- Use the Serial Monitor and find the range of input values you get for each sensor.

- MaxAnalogRead = __________

- MinAnalogRead = __________

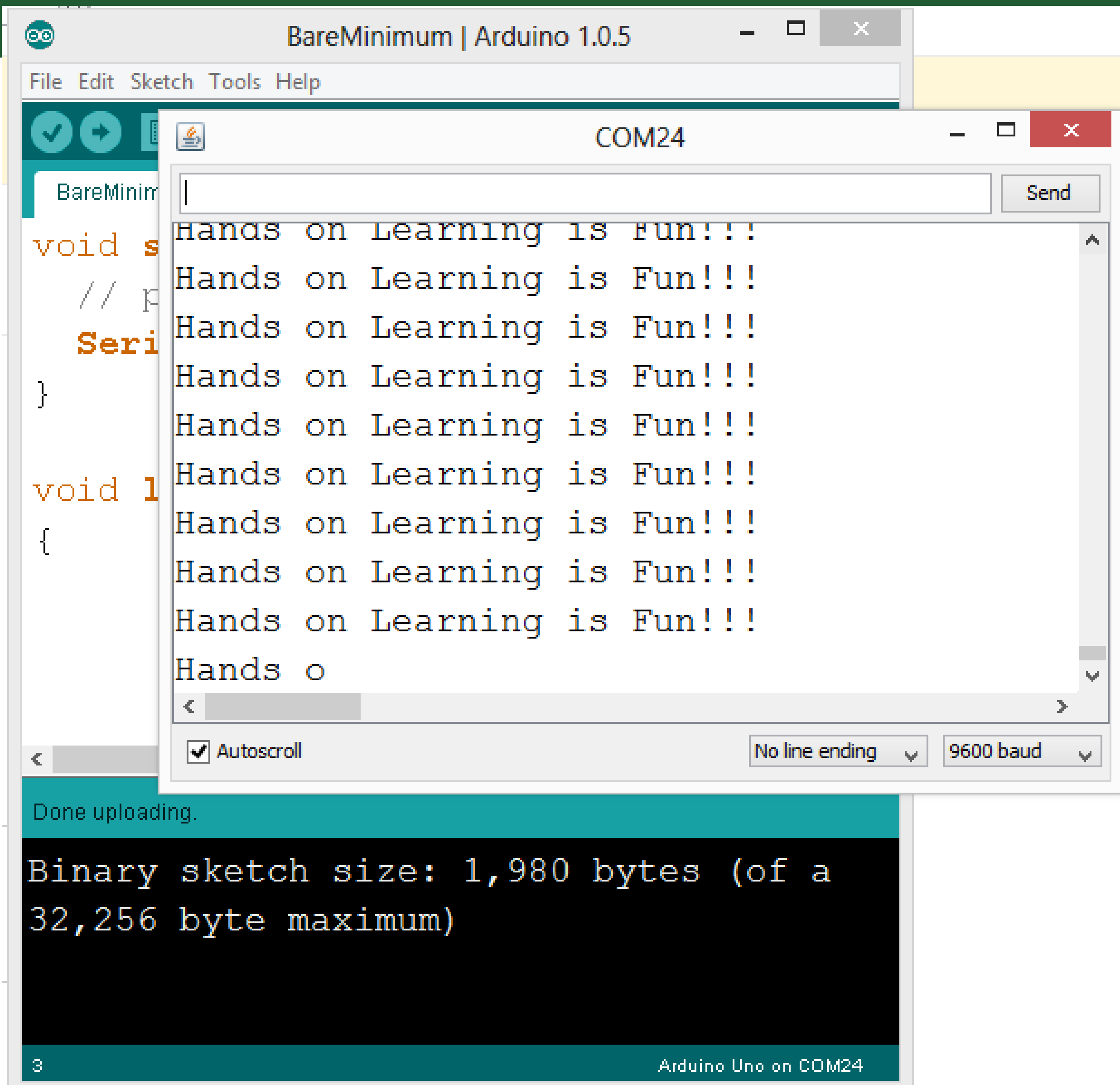
Analog Sensors

Examples:

Sensors	Variables
Mic	soundVolume
Photoresistor	lightLevel
Potentiometer	dialPosition
Temp Sensor	temperature
Flex Sensor	bend
Accelerometer	tilt/acceleration

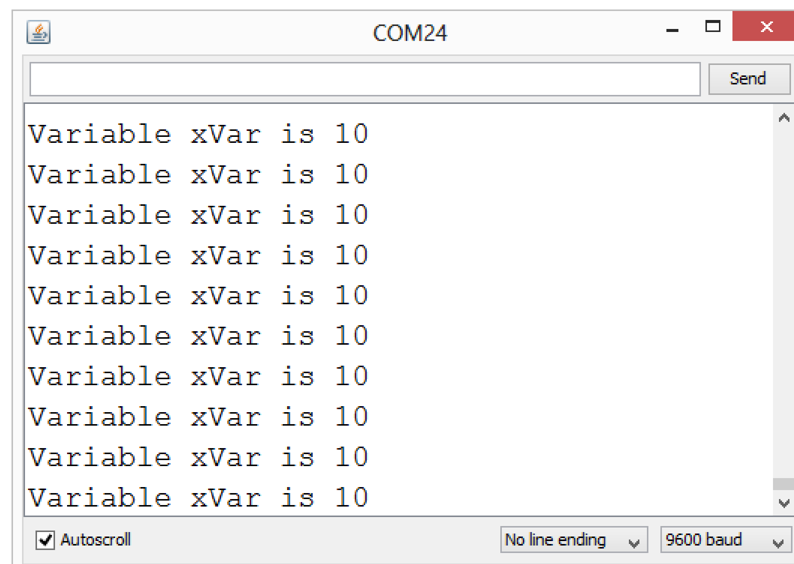
Additional Serial Communication
Sending a Message

```
void loop ( )
{
      Serial.print(“Hands on “) ;
      Serial.print(“Learning ”) ;
      Serial.println(“is Fun!!!”) ;

}
```


BareMinimum | Arduino 1.0.5
File Edit Sketch Tools Help
BareMinim
void s
// p
Seri
}
void l
{
COM24
Send
Hands on Learning is Fun!!!
Hands on Learning is Fun!!!
Hands on Learning is Fun!!!
Hands on Learning is Fun!!!
Hands on Learning is Fun!!!
Hands on Learning is Fun!!!
Hands on Learning is Fun!!!
Hands on Learning is Fun!!!
Hands on Learning is Fun!!!
Hands o
Autoscroll
No line ending
9600 baud
Done uploading.
Binary sketch size: 1,980 bytes (of a 32,256 byte maximum)
3
Arduino Uno on COM24

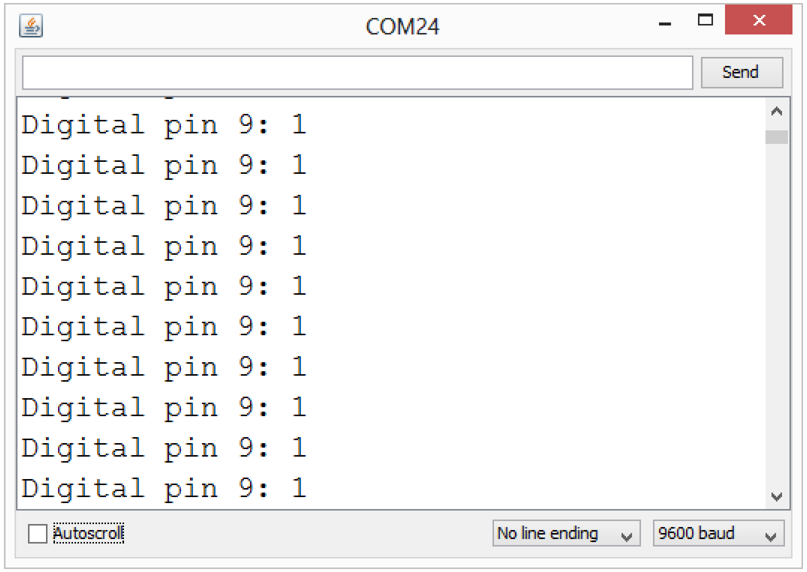
Serial Communication: Serial Debugging

```
void loop()
{
    int xVar = 10;
    Serial.print ( "Variable xVar is " ) ;
    Serial.println ( xVar ) ;
}
```



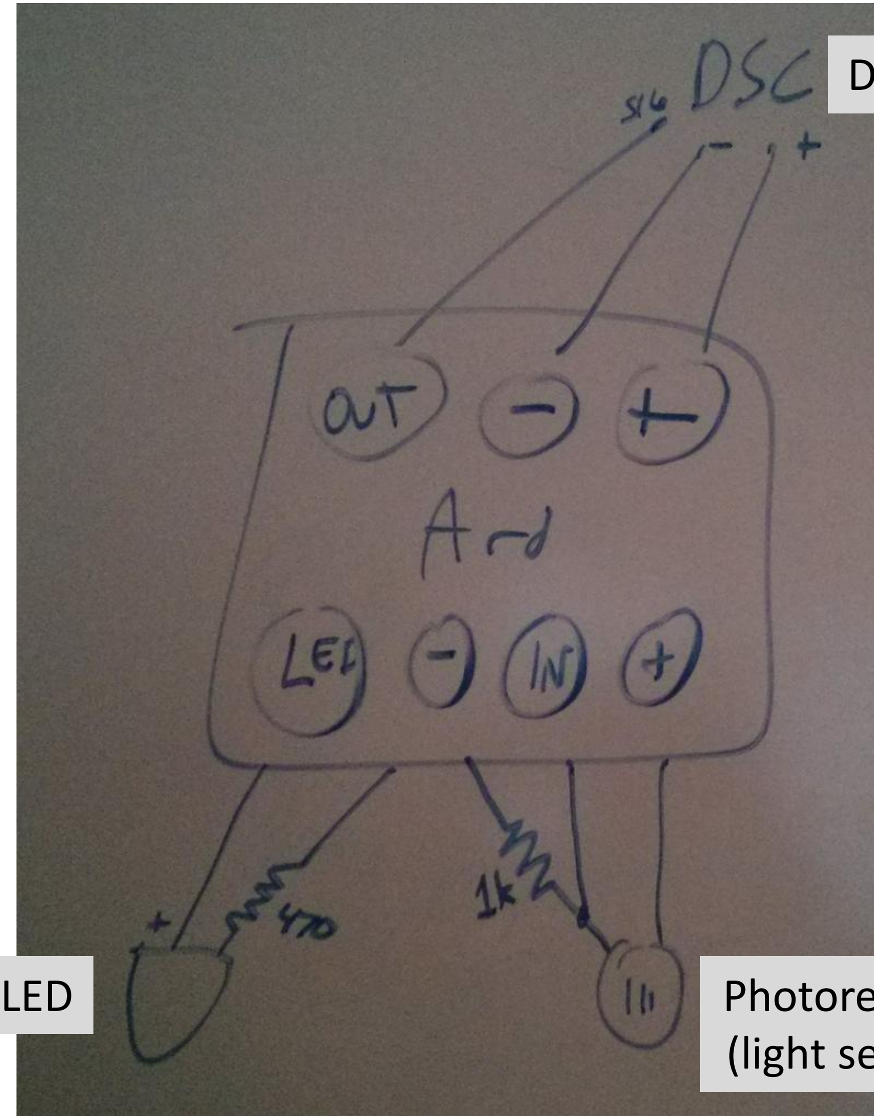
Serial Communication:
Serial Troubleshooting

```
void loop ( )
{
      Serial.print (“Digital pin 9: “);
      Serial.println (digitalRead(9));
}
```



PART 3: THE LIGHT SENSOR SYSTEM

Our actual light sensor schematic from build season



- What pins are outputs?
- What pins are inputs? Analog or digital?

Our first-gen code

```
int lightPin = A0;  //define a pin for Photo resistor
int ledPin=4;      //define a pin for LED
int outPin=13;     //define a pin for output to DSC

int threshold=150; // set experimentally

int DOWN_DELAY=500; // how long to keep outPin low on detect, in ms

void setup() {
  Serial.begin(9600);  // Begin serial communcation
  pinMode(ledPin, OUTPUT);
  pinMode(outPin, OUTPUT);
}

void loop() {
  int v = analogRead(lightPin);
  Serial.println(v); // Write the value of the photoresistor to the serial monitor.
  if (v > threshold) {
    digitalWrite(outPin, LOW);
    delay(DOWN_DELAY);
  } else {
    digitalWrite(outPin, HIGH);
  }
}
```

Problems

- What do you think went wrong?
  - Would malfunction if light levels changed from where we tested it

- What to do?

Our second-gen code

```
// <some variable declarations omitted>
int threshold=-1; // set by calibrate()
int CALIBRATE_NUM_SAMPLES=10;

void calibrate() {
  digitalWrite(ledPin, LOW);

  int avg=0;
  for (int i=0; i<CALIBRATE_NUM_SAMPLES; i++) {
    avg += analogRead(lightPin);
  }
  avg /= CALIBRATE_NUM_SAMPLES;

  threshold = avg*1.75;

  digitalWrite(ledPin, HIGH);
}

void setup() {
  Serial.begin(9600);
  pinMode(ledPin, OUTPUT);
  pinMode(outPin, OUTPUT);
  calibrate();
}
```

```
void loop() {
  int v = analogRead(lightPin);
  Serial.println(v);
  if (v > threshold) {
    digitalWrite(outPin, LOW);
    delay(DOWN_DELAY);
  } else {
    digitalWrite(outPin, HIGH);
  }
}
```

How does it work?

- On start-up, measure the light levels with the LED off, and call 75% more than that the threshold

Problems

- What do you think this did wrong?
  - Would malfunction if light levels changed after power-on (such as moving it to a brightly lit competition field…)

- What to do?

Our final code

```
// <some variable declarations omitted>
int threshold = 40; // derived experimentally

int downTime = 6; // time to wait with led off before measuring (ms)
int upTime   = 6; // time to wait with led on before measuring (ms)

void setup() {
  Serial.begin(9600);  //Begin serial communcation
  pinMode(ledPin, OUTPUT);
  pinMode(outPin, OUTPUT);
}

void loop() {
  int v = measureLight();
  if (DEBUG) Serial.println(v);

  if (v > threshold) {
    digitalWrite(outPin, LOW);
    delay(DOWN_DELAY);
  } else {
    digitalWrite(outPin, HIGH);
  }

  if (DEBUG) delay(20);
}
```

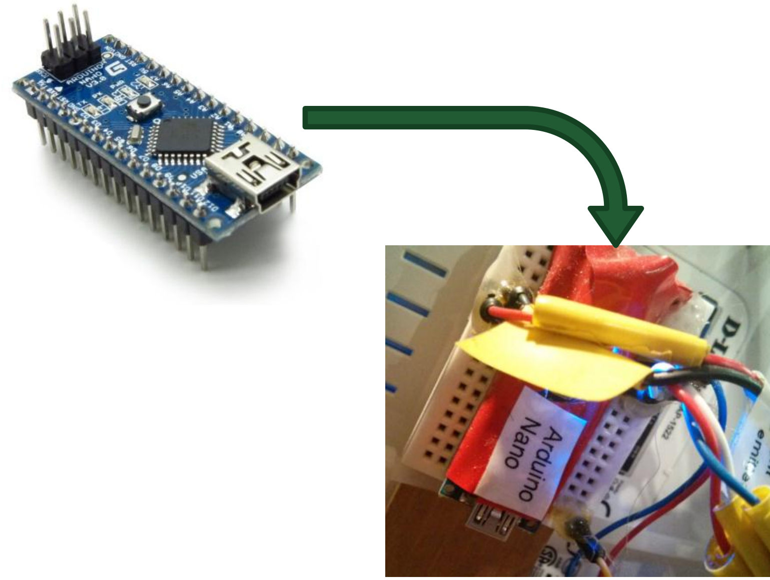
```
int measureLight() {
  // measure with LED off
  digitalWrite(ledPin,LOW);
  delay(downTime);
  int v_off = analogRead(lightPin);

  // measure with LED on
  digitalWrite(ledPin,HIGH);
  delay(upTime);
  int v_on = analogRead(lightPin);

  // debug output of raw values
  if (DEBUG>=2) {
    Serial.print(v_off);
    Serial.print("  ");
    Serial.print(v_on);
    Serial.print("  ");
  }

  // return difference
  return v_on - v_off;
}
```

How does it work?

- Turn the LED off
- Measure
- Turn the LED on
- Measure
- Calculate difference and use *that*

Physical mounting

- Used an Arduino Nano, which jams into a breadboard



- How to keep wires in breadboard?
  - Lots and lots of hot glue

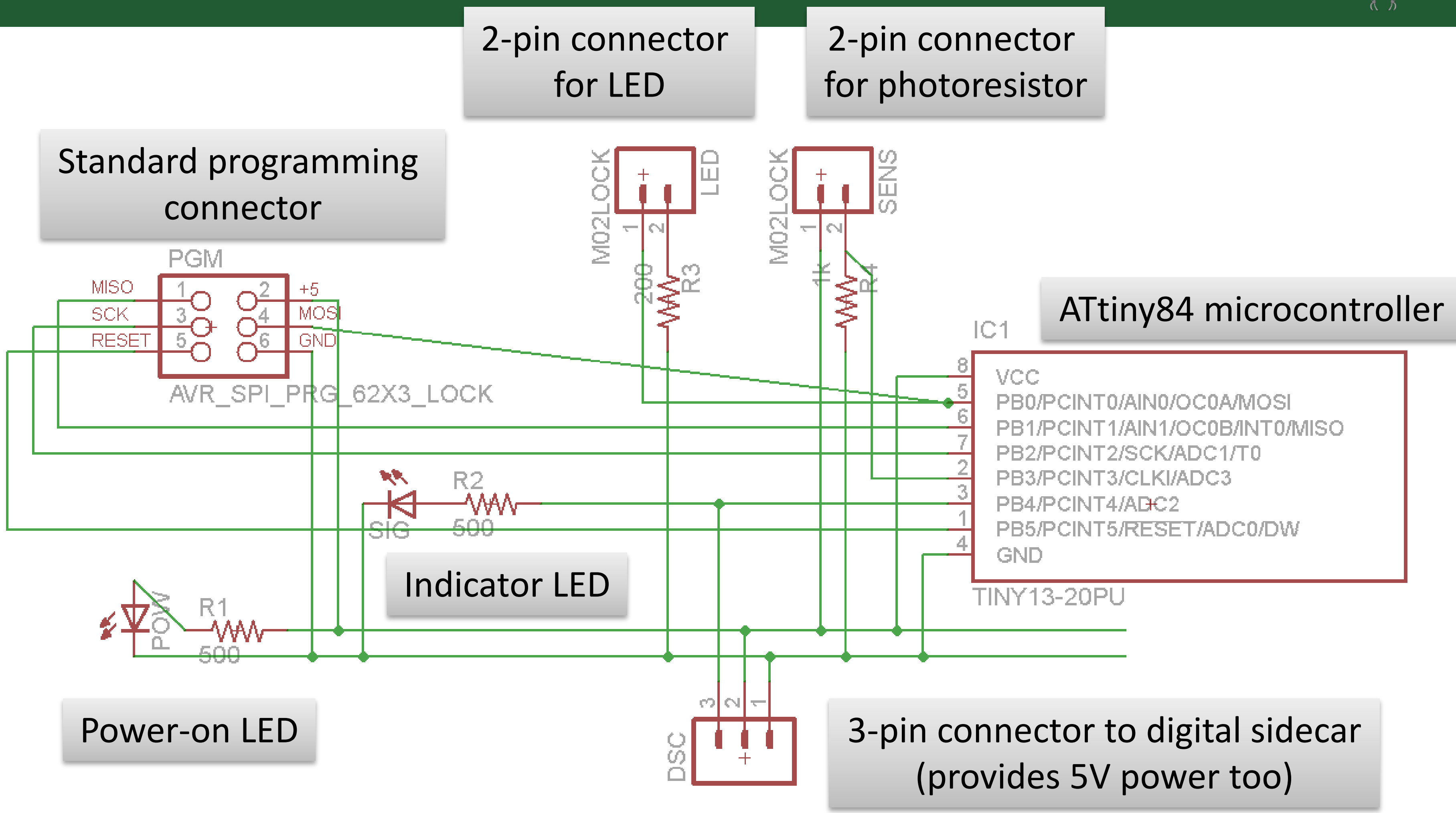
- Result was 100% stable and reliable light sensor
- Robot stopped at the firing position every single time

PART 4: CUSTOM CIRCUIT BOARD

The short story

- Get EAGLE (it's free)
- Lay out all the components and connect them just like we did before
  - For the Arduino, replace it with a an Arduino-compatible chip (like the ATtiny84 or the ATmega328)

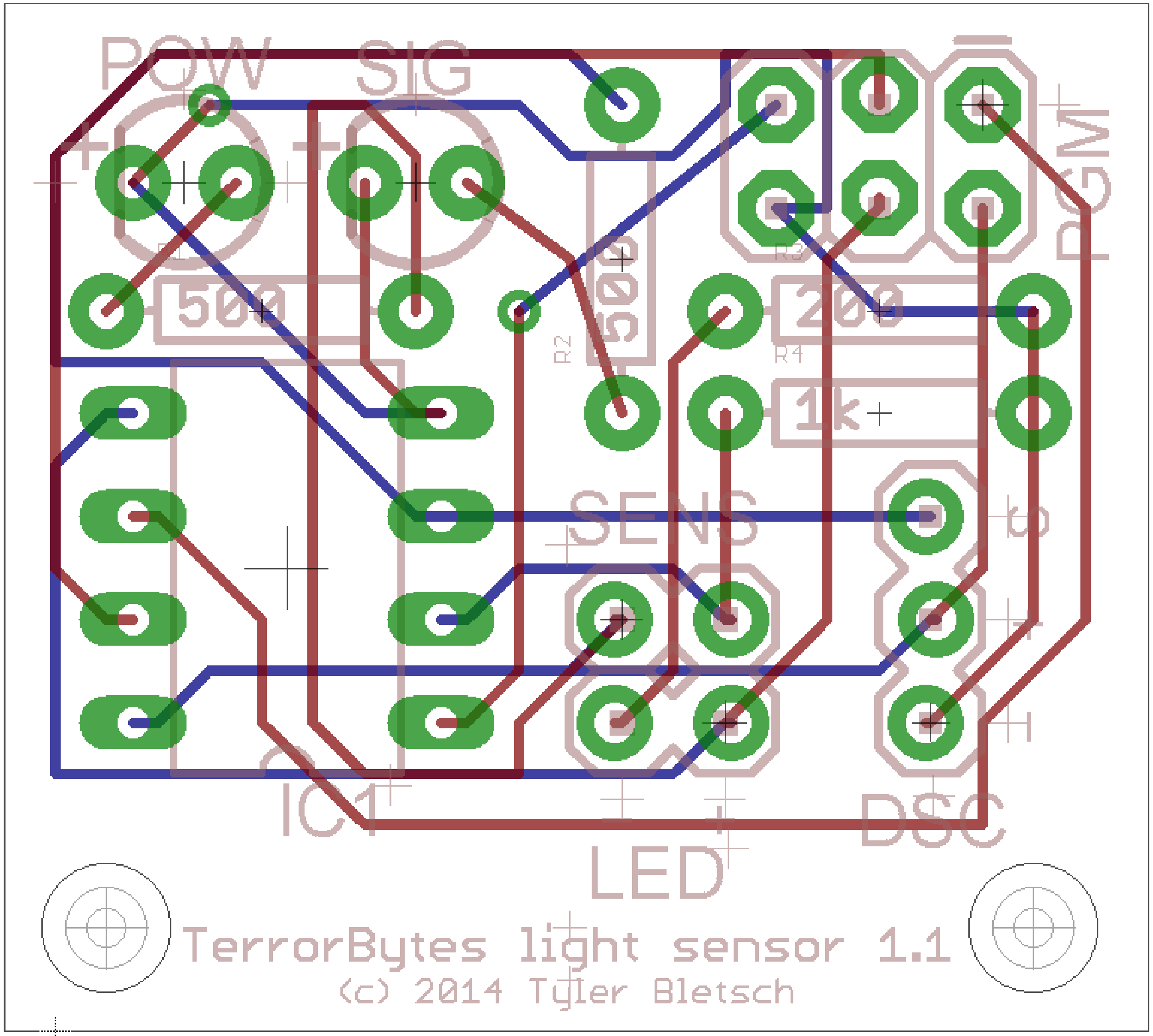
The schematic



Board design

- EAGLE helps you translate the schematic to a board layout
- You position all the components where you want, run the connection ‘wires’, and put printed labels on stuff

Board layout

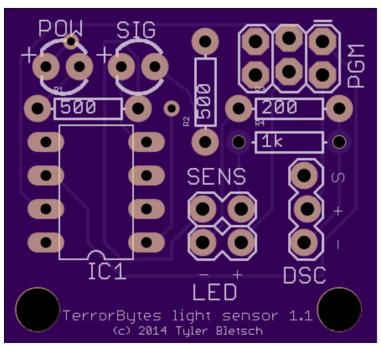


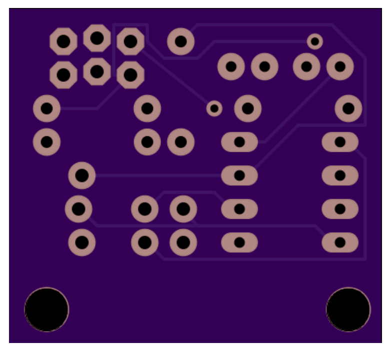
- Red = wire running on top
- Blue = wire running on bottom
- Green = Copper pad and hole to put a component through
- Pink = Labels printed on board

Making it real

- Send the board to a fabricator company like OSH Park and they make it for a fee
  - OSH Park is $5 per square inch.
    This board was about a square inch,
    so we got three boards for $5. *Cheap!*
- OSH Park mockup of our board:

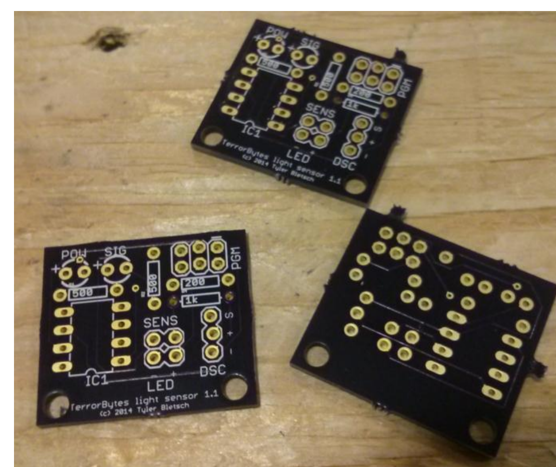
Top





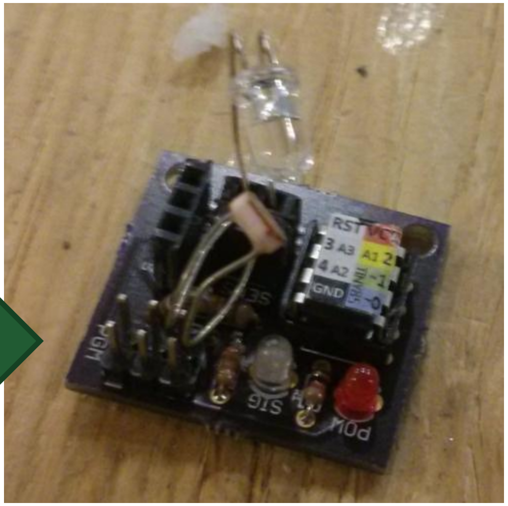
Bottom

- Actual boards, straight from the factory:

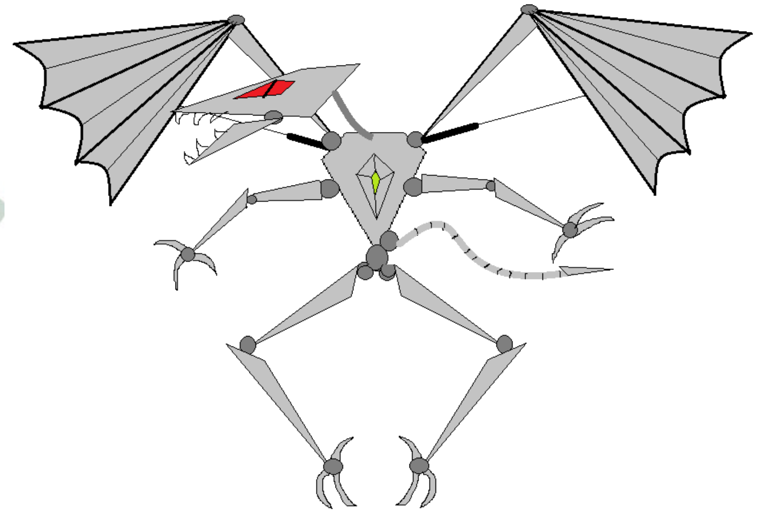


Solder it up

- Bam, done



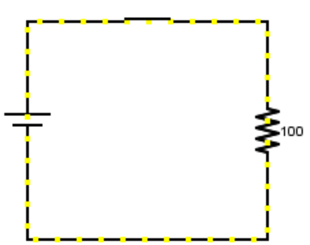
Thank You!



Continuity – Is it a Circuit?

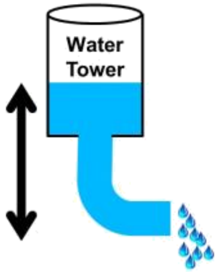
The word “circuit” is derived from the circle. An Electrical Circuit must have a continuous LOOP from Power (V_{cc}) to Ground (GND).

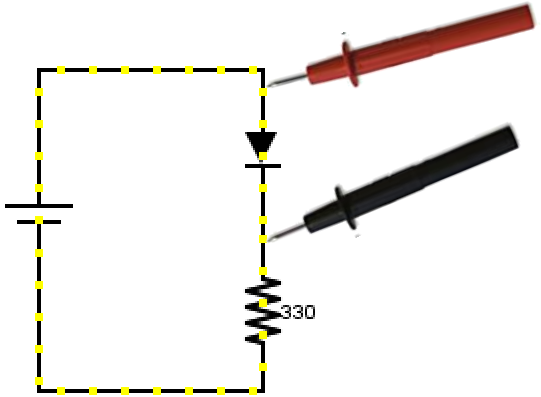
Continuity is important to make portions of circuits are connect. Continuity is the simplest and possibly the most important setting on your multi-meter. Sometimes we call this “ringing out” a circuit.

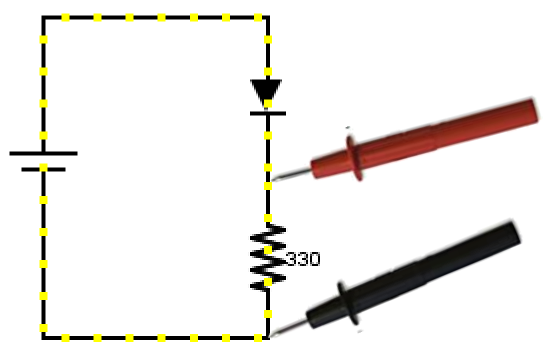


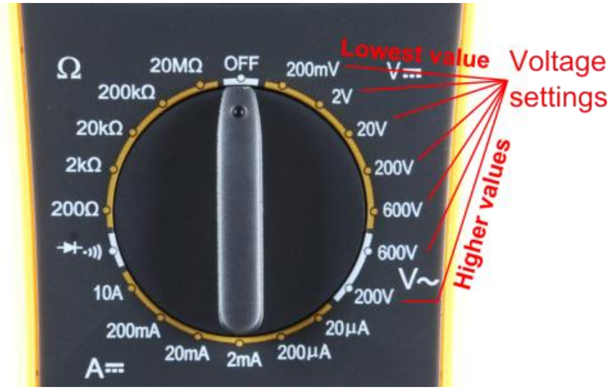
Measuring Electricity – Voltage

Voltage is a measure of potential electrical energy. A voltage is also called a potential difference – it is measured between two points in a circuit – across a device.



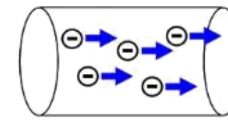




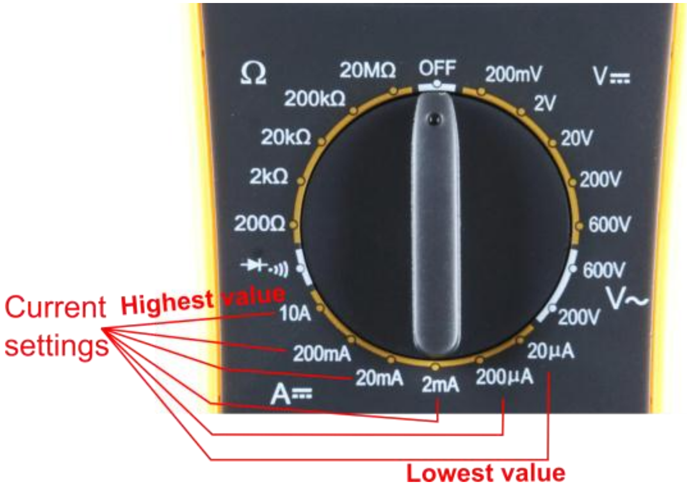


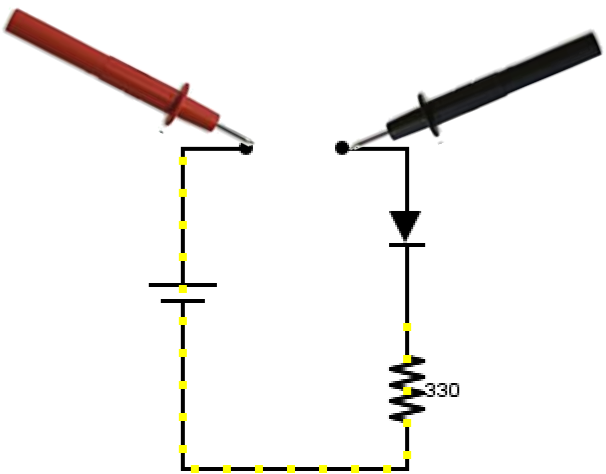
Measuring Electricity -- Current

Current is the measure of the rate of charge flow. For Electrical Engineers – we consider this to be the movement of electrons.



In order to measure this – you must break the circuit or insert the meter in-line (series).





Measuring Electricity -- Resistance

Resistance is the measure of how much opposition to current flow is in a circuit.

Components should be removed entirely from the circuit to measure resistance. Note the settings on the multi-meter. Make sure that you are set for the appropriate range.