LECTURE IV

# Microcontroller Architecture and Arduino

SECTION I

# Binary Numbers and Digital Signals

# Number Systems and Bases

- The **Decimal** number system contains the set of ten digits {0, 1, 2, 3, 4, 5, 6, 7, 8, 9}, making it a **Base-10** number system
- **There exist different bases** beyond the Decimal number system
  - For example, **Base-8** is the **Octal** number system with the set of only eight digits… {0, 1, 2, 3, 4, 5, 6, 7}
  - **Base-16**, or the **Hexadecimal** number system, has a whopping sixteen digits… {0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F}

# Number Systems and Bases (Cont'd)

- We can convert a number of a different base to Base-10 with the following method
- Ex) Convert Hex number $B32_{16}$ to Base-10

The base of a hexadecimal number is 16

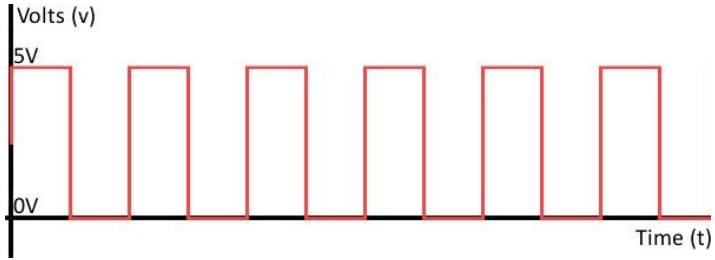
Each hexadecimal digit represents a power of 16

B is represented by the decimal number 11

$$
\begin{aligned}
&(B \cdot 16^2) + (3 \cdot 16^1) + (2 \cdot 16^0) \\
&= (B \cdot 16^2) + (3 \cdot 16^1) + 2 \\
&= (B \cdot 16^2) + 48 + 2 \\
&= (11 \cdot 16^2) + 48 + 2 \\
&= 2816 + 48 + 2 = 2866
\end{aligned}
$$

# Binary Signals

- **Computers transfer data** across wires/lines as **digital** (discrete) **voltage signals**
  - These signals are either a **HIGH** or **LOW** voltage
  - Contrasts from **analog signals** which can be values in a continuous range

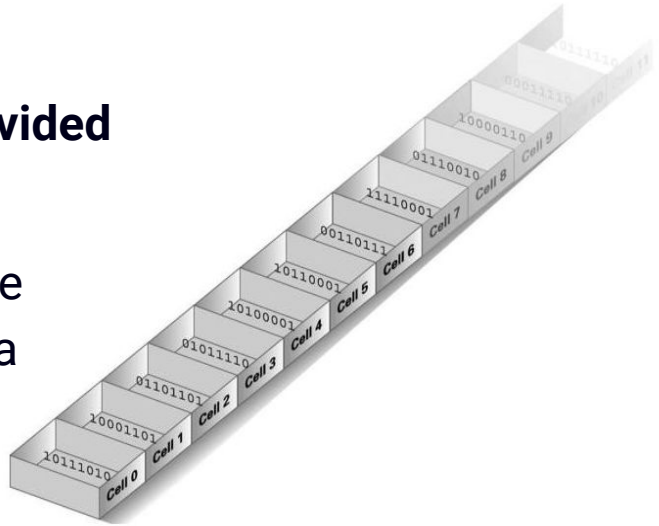



This is a **digital signal** where the waveform is either **5V** or **0V** (two *discrete* values)

- **Digital signals are translated** to the **Binary** number system or **Base-2** (1s and 0s)

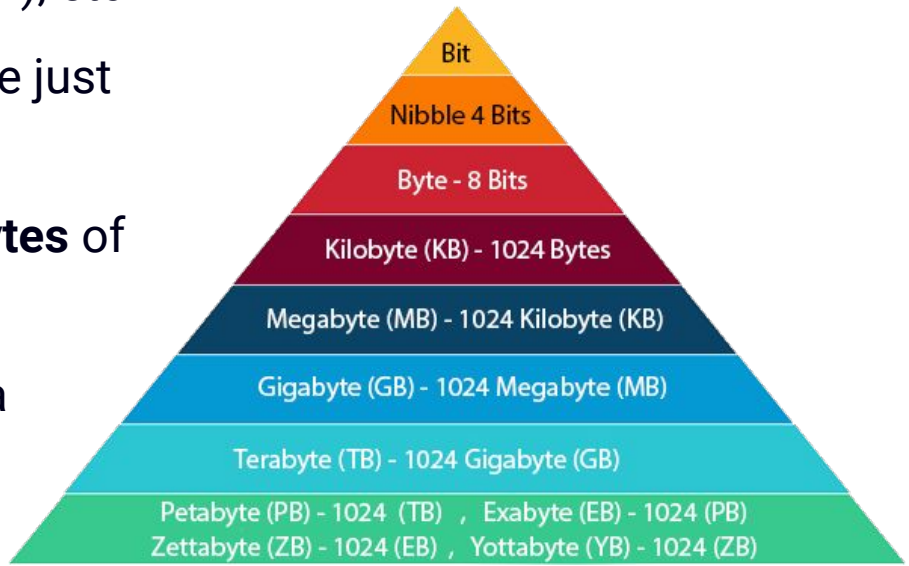
# Bits, Bytes, and Beyond

- **Single Binary digits** are called **bits**
  - Bits compose binary numbers like $10010_2$ $(18_{10})$
- **Eight bits** form a **byte**
  - For example… $10100010_2$ $01011111_2$
- Data in a computer is stored in **memory** which is **divided** into cells each a **byte** in width
  - This means that on many systems, a **byte** is the **smallest unit of data** that can be accessed by a computer



# Bits, Bytes, and Beyond (Cont'd)

- Decimal units are used to express the size of binary data
    - i.e. Kilobytes (KB), Megabytes (MB), etc.
- **Small embedded computers** may store just **kilobytes** or **megabytes** of data
- **Laptops** can store **gigabytes** or **terabytes** of information
- **Google servers** store **exabytes** of data
    - That's billions of gigabytes!

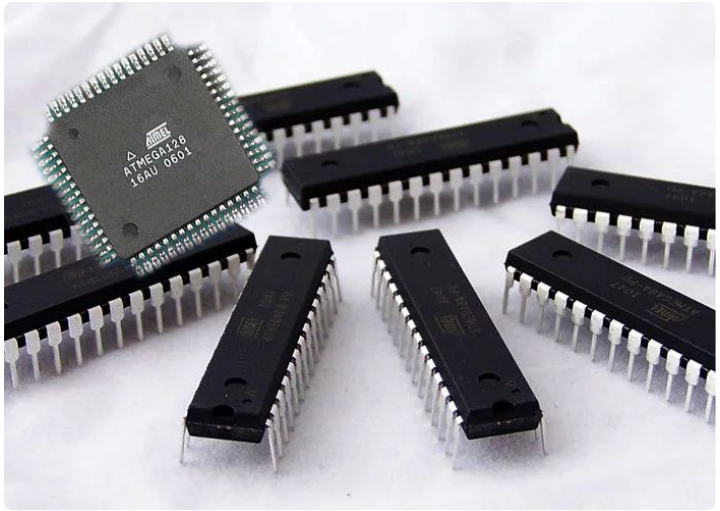


SECTION II

# Microcontrollers

# Microcontrollers

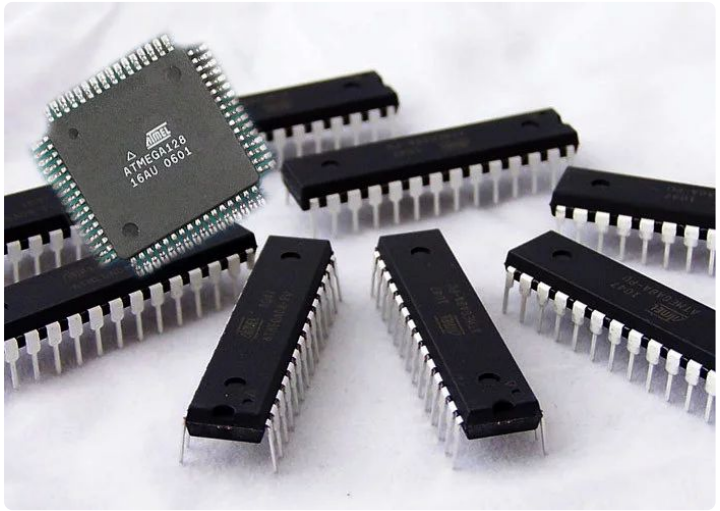
- A **microcontroller** (or **MCU**) is a **small computer** on a single integrated circuit
  - It is quite literally a computer, complete with everything needed to run and store programs
- An **architecture** defines the organization of hardware within the computer
  - **MCUs have different architectures**
    - Sometimes we say they “belong to different families”




**AVR Microcontroller Family**

# Microcontrollers (Cont'd)

- We will focus on a microcontroller which adheres to the **AVR architecture**
    - It runs programs made with the **AVR instruction set**
- To better understand how an AVR microcontroller works, we will examine its key components…




**AVR Microcontroller Family**

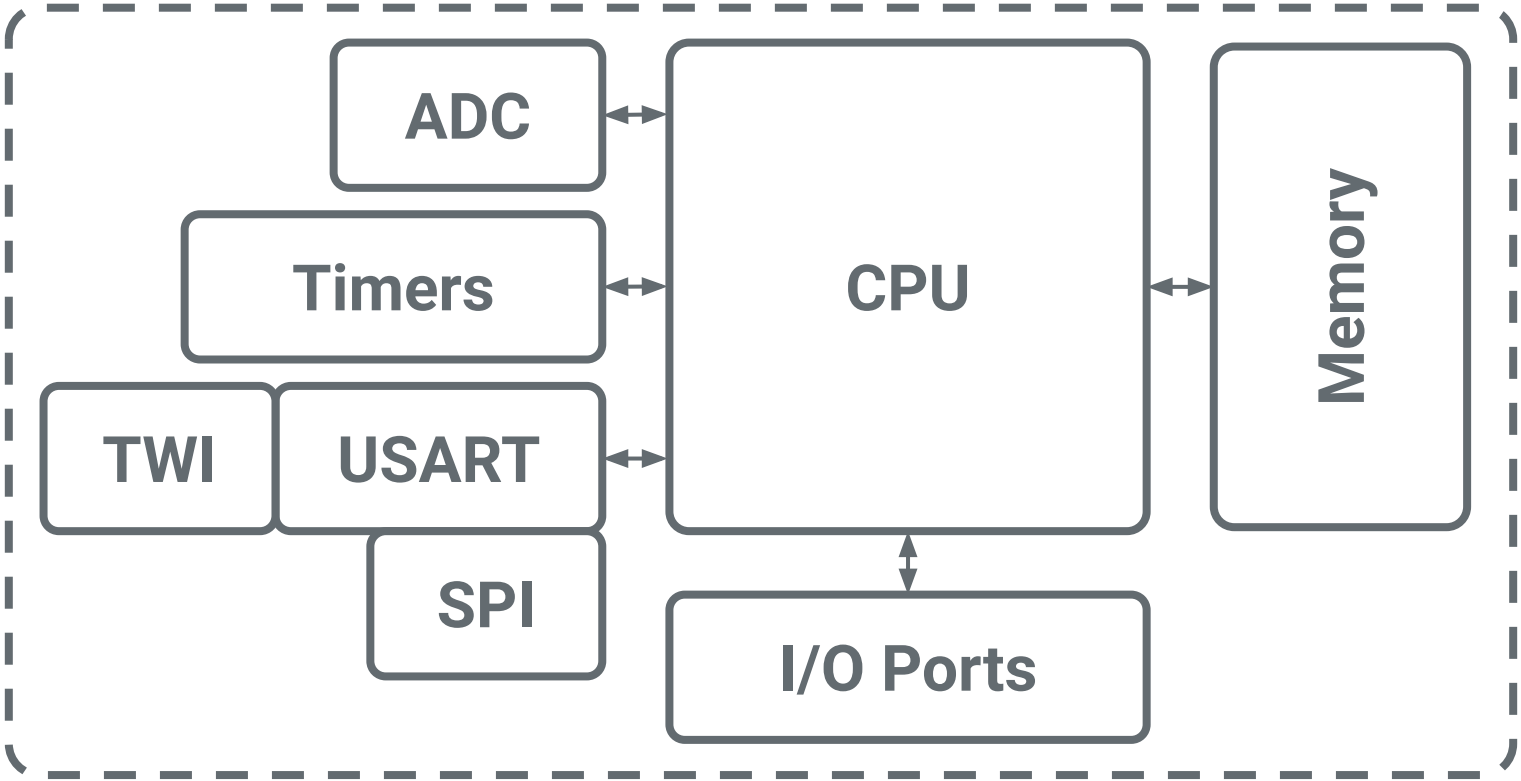
SECTION III

# AVR Microcontroller Architecture

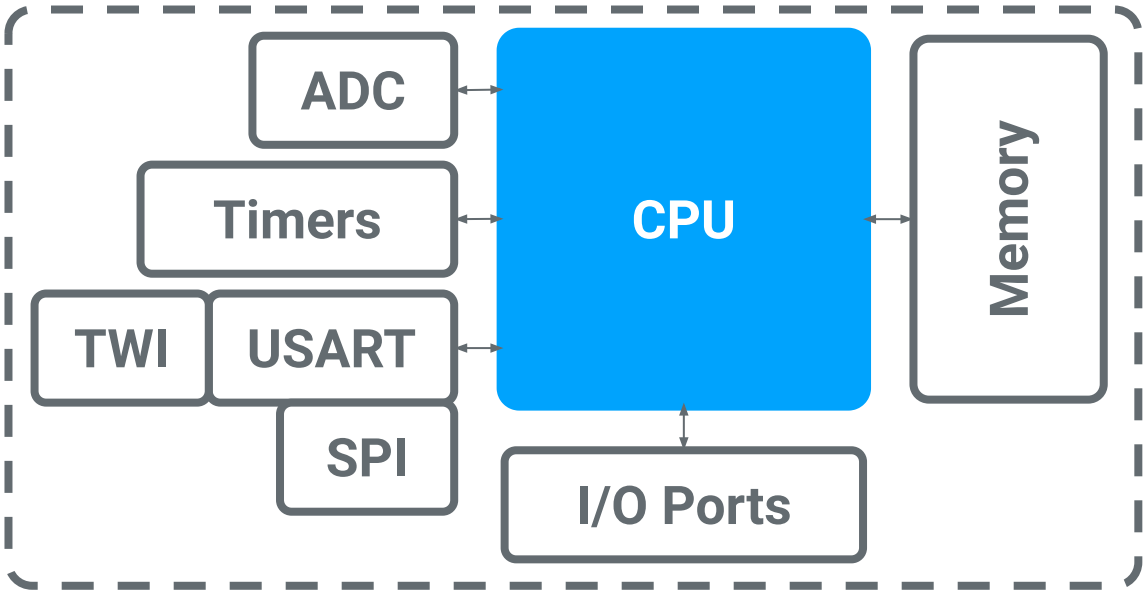
# AVR Architecture

- Main units of an AVR microcontroller:
  - **Central Processing Unit (CPU)**
  - **Memory**
  - **Analog-to-Digital Converter**
  - **Timers**
  - **Input/Output Ports**
  - **Serial Communication Units**

# AVR Architecture (Cont'd)

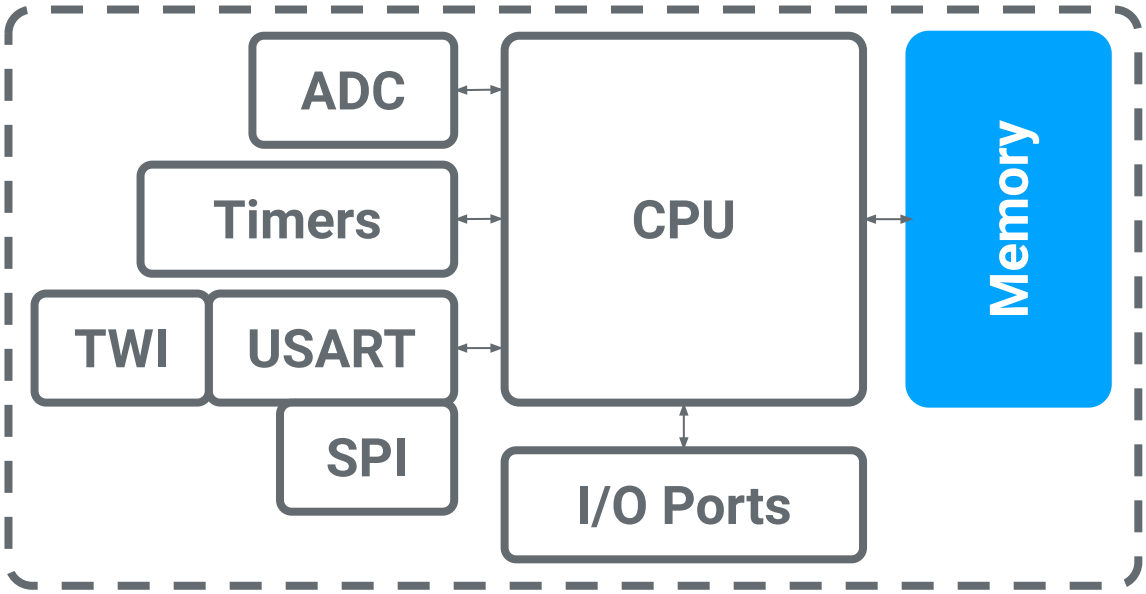


# Central Processing Unit (CPU)



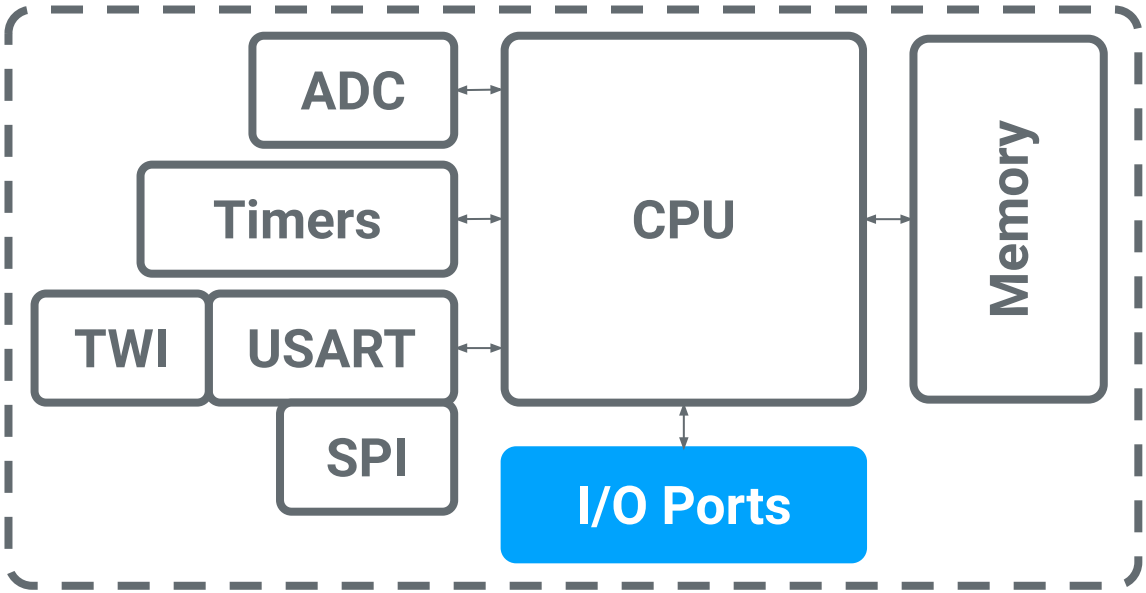

A **CPU** **executes instructions** provided by a memory unit. These instructions may be mathematical **computations**, memory **data transfer**, or signals to **input and output** ports.

# Memory



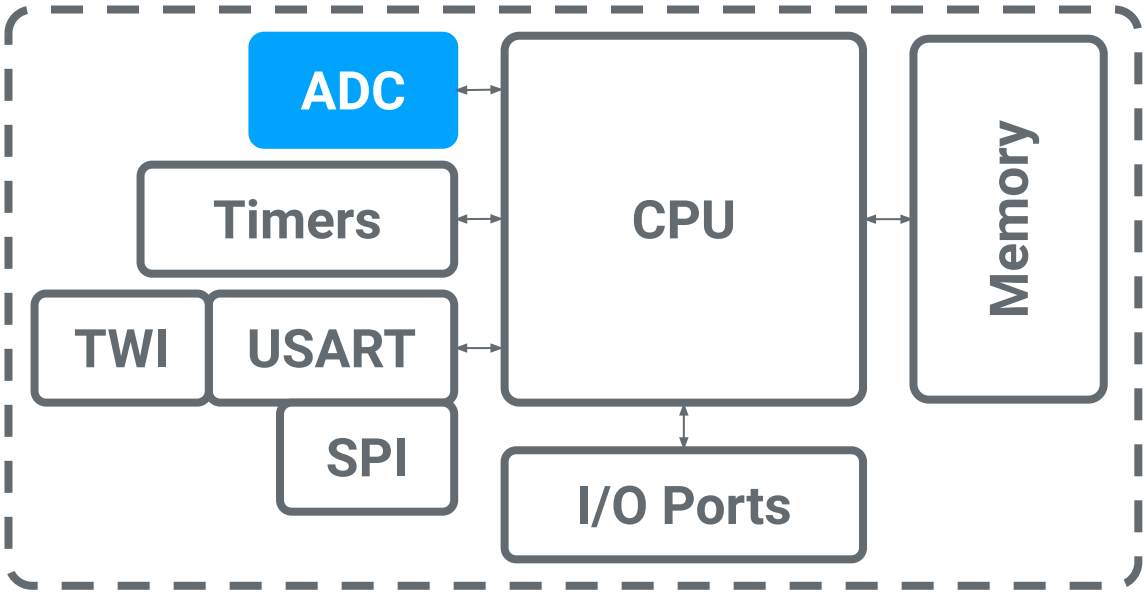

**A memory unit stores data and instructions.** There are subunits of memory, some of which are for short-term storage, erased when the microcontroller is disconnected from its power supply, while others are long-term.

# Input/Output (I/O) Ports



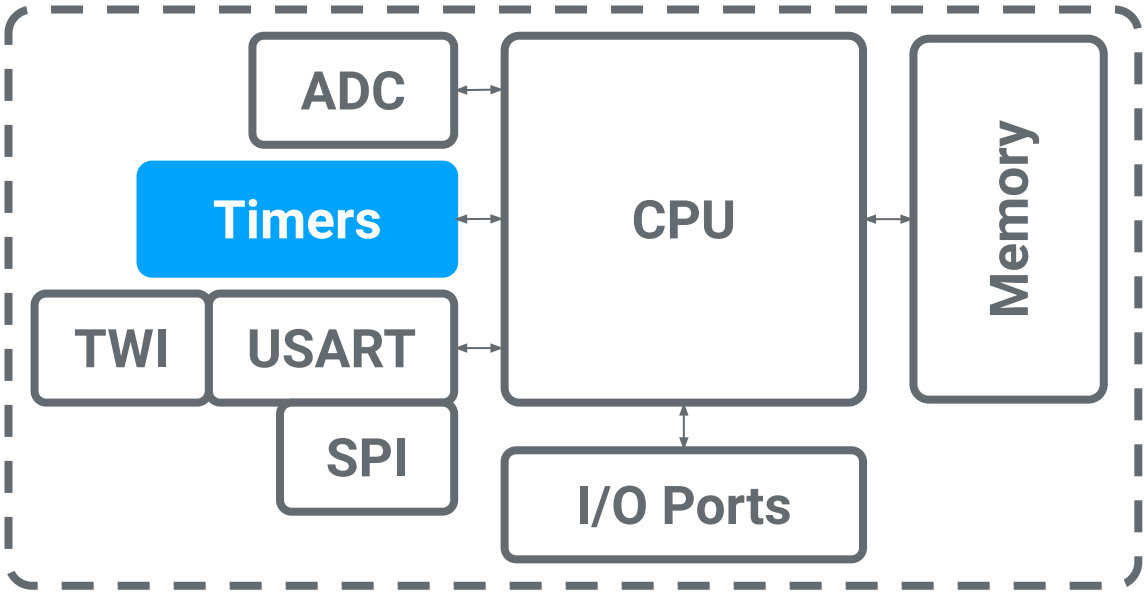

**Input/Output Ports (I/O Ports) connect the microcontroller to peripheral devices** that transfer data to and from the microcontroller. This data may be stored in memory or interpreted by the CPU. The I/O Ports are wired to **physical leads on the IC** called **I/O pins**.

# Analog-To-Digital Converter (ADC)



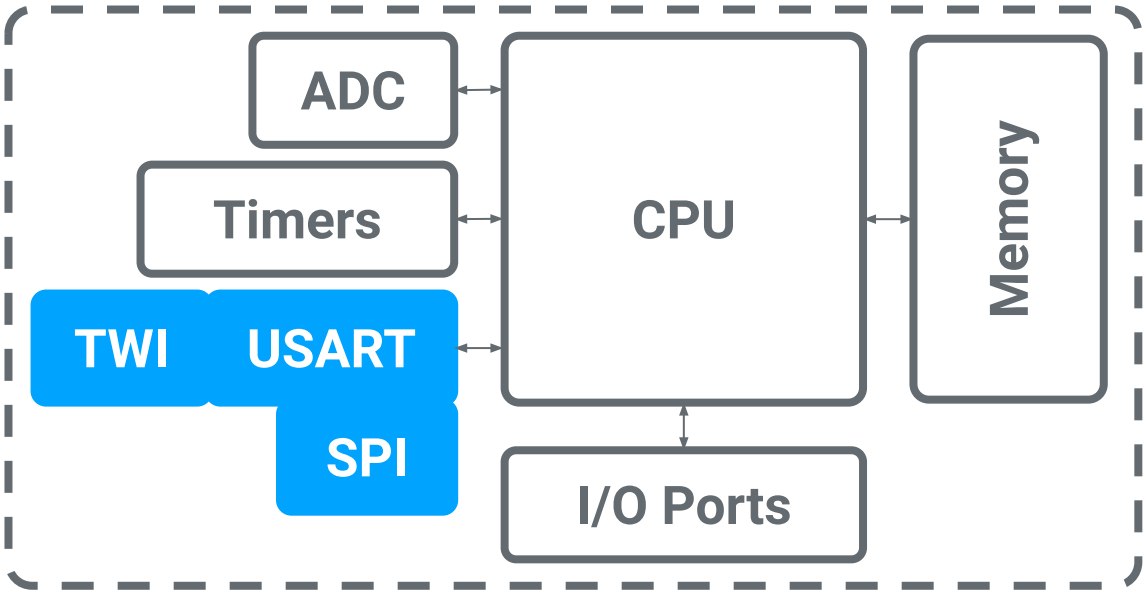

The **analog-to-digital converter** **(ADC) measures real-world, analog signals** from the I/O pins (i.e. temperature, pressure, acceleration) and **converts them into digital signals** that the microcontroller can interpret.

# Timers




**Timers** are used by the microcontroller to **control the timing** of program execution or output signals and **measure time**.

# Serial Communication Units




The **TWI**, **USART**, and **SPI** are all units that **generate and interpret serial communication signals** between the microcontroller and I/O peripherals. This facilitates data transfer across devices. We will expand on these terms in a future lecture on communication.

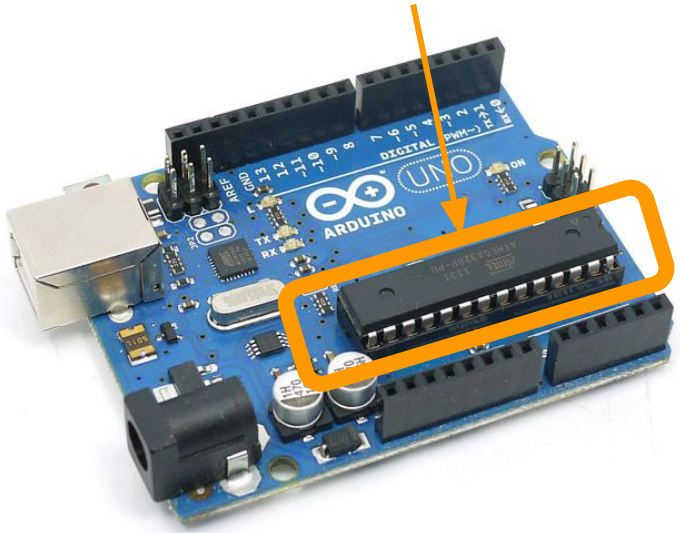
SECTION IV

# Arduino Boards

# Arduino Boards

- The Arduino company designed **microcontroller boards** to make several AVR microcontrollers **hobbyist-friendly**
  - Added a USB port, input voltage regulator, onboard LEDs, among other things
  - This family of boards includes the **Arduino Uno**, **Arduino Nano**, and many, many more!

The MCU is **an IC that sits in a DIP socket** on the board

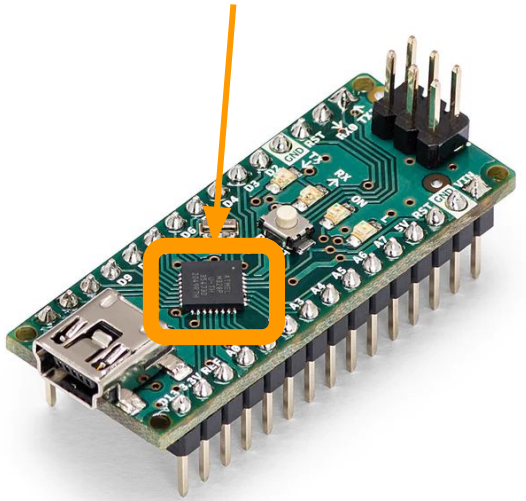



**Arduino Uno**

# Arduino Nano

- The current and future lectures use the **Arduino Nano** (based on the **ATmega328P** microcontroller)
  - The ATmega328P belongs to the AVR family
  - The **Arduino Uno uses the same microcontroller**
  - Almost all code written for the Arduino Nano is directly transferable to the Arduino Uno

The MCU is **an SOIC** soldered to the board



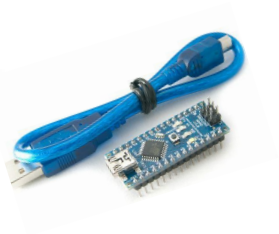
**Arduino Nano**

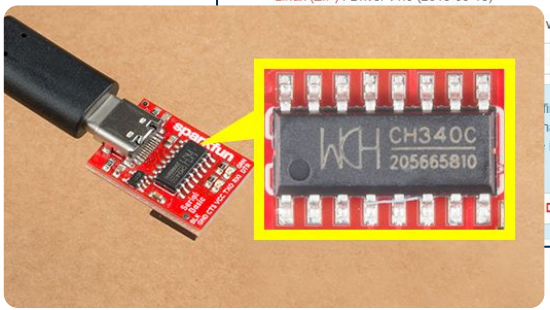
SECTION V

# Arduino IDE

# CH340 Driver

- We will use the CH340 driver so that our personal computers understand how to communicate with the Arduino board
- Download the CH340 installer here






## Drivers (If You Need Them)

The CH340 has been tested on:

- Windows 7/10
- Mac OSX
  - v10.10.5 (Yosemite)
  - v10.11.6 (El Capitan)
  - v10.13.0 (High Sierra)
  - v10.14.5 (Mojave)
- Linux
  - Raspbian Stretch (11-13-2018 release) for the Raspberry Pi
  - Raspbian Buster (2019-07-10 release) for the Raspberry Pi
  - Ubuntu v18.04.2, 64-bit

These operating systems have the CDC drivers pre-installed, which means you shouldn't need to install any extra software. However, there are a wide range of operating systems out there, so if you run into driver problems, you can get the archived drivers linked below:

- Windows (EXE) -- Driver executable
- Windows (ZIP) : Driver v3.4 (2016-09-27)
- Mac (ZIP) : Driver v1.5 (2018-07-04)
- Linux (ZIP) : Driver v1.5 (2018-03-18)

version of their drivers in their English translated website.

DRIVERS (ENGLISH PAGE)

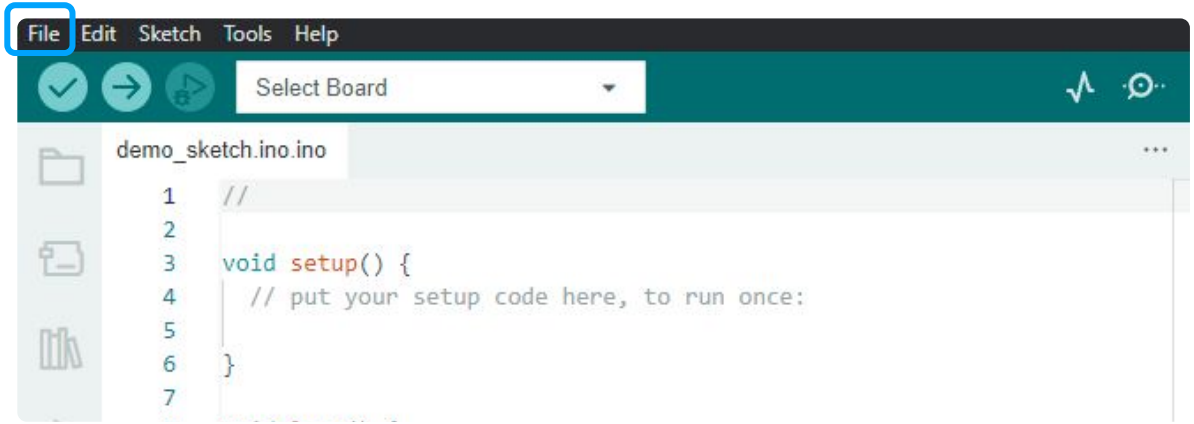
find the latest version of their drivers from their website in had the option to have the web page translated. However, you in either language. For those interested in heading to the

DRIVERS (MANDIRIN PAGE)

# Arduino IDE

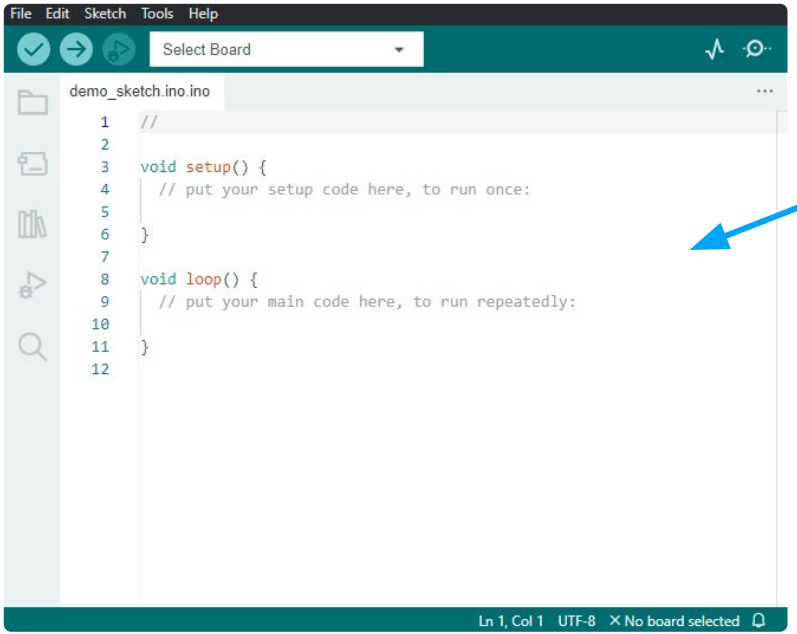
- We will write code, compile, and upload it to the Arduino board from our personal computers using the **Arduino IDE** software kit
- Download the IDE installer here

# Creating a Sketch



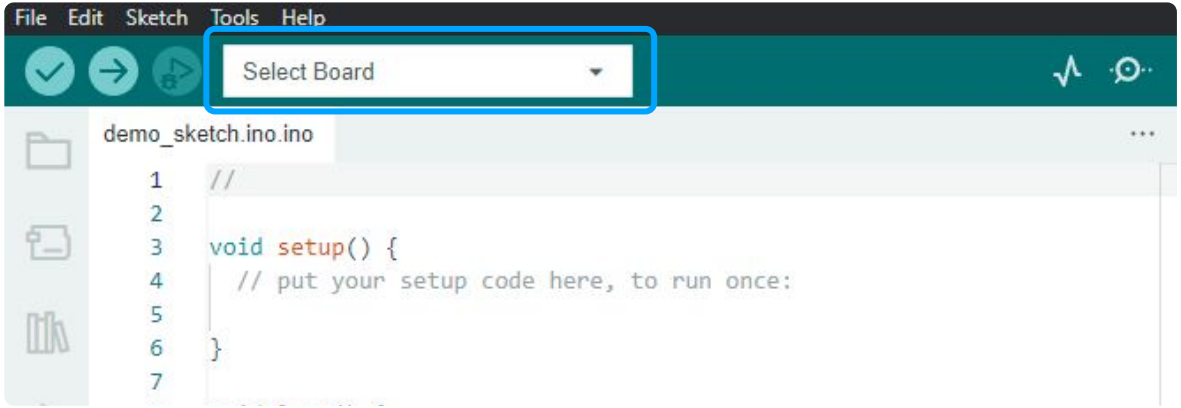

- An Arduino source code file is called a **sketch** and has the **.ino** extension
- When the IDE opens, a new sketch will be created automatically or a previous sketch will open
    - To create a new sketch, select **File** → **New Sketch** from the menu

# Editing a Sketch



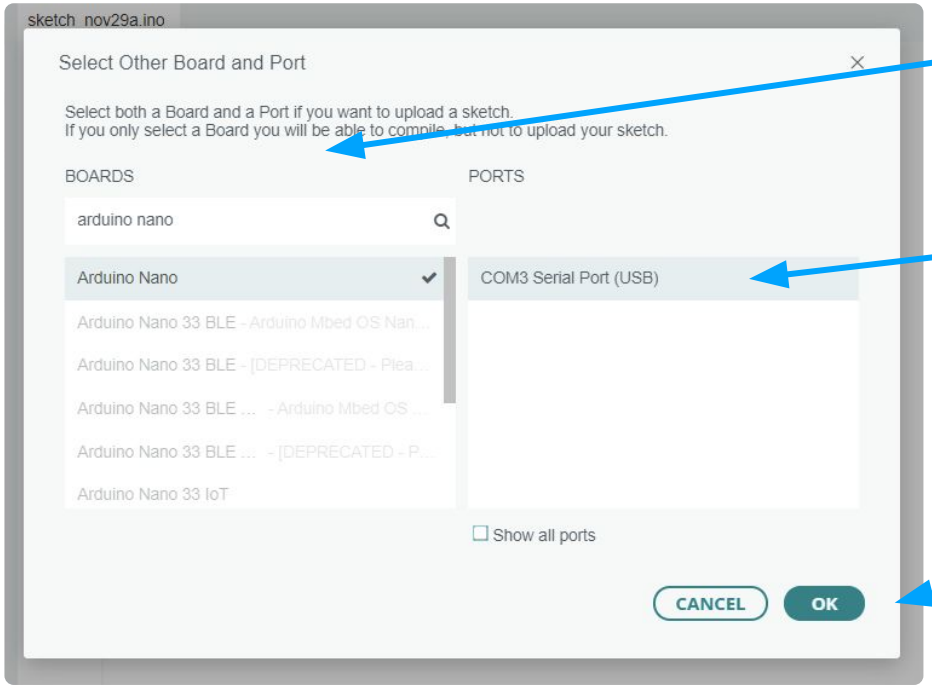

- Sketches can be modified from the **code editor**, which appears just below the menu
- New sketches opened in the editor come with **template code**
- The editor is also enhanced with text **autocompletion**

# Setting the Target Board



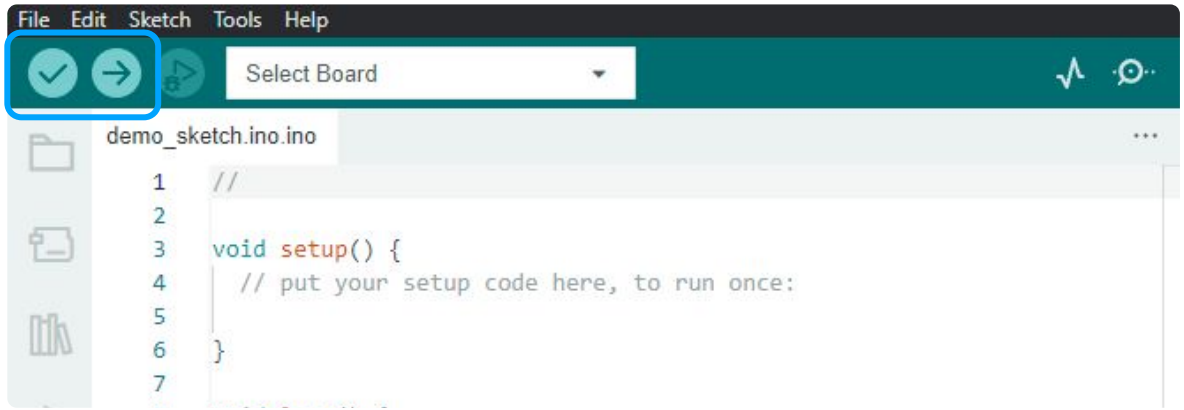

- Before we can upload a sketch, we must **connect the Arduino board via USB to the computer** and configure the IDE to the correct board and USB port
- Open the **Select Board** dropdown and select an available Arduino Nano board
    - If no option appears, click **Select other board and port…**

# Setting the Target Board (Cont'd)




- In the popup window, search **Boards** and select **Arduino Nano**
- From the available items under **Port**, select the USB port to which the board is currently connected
- Confirm the selections by clicking **OK**

# Verifying and Uploading a Sketch




- Before uploading the sketch, select **Verify** (the **checkmark** icon) to compile the sketch
- Once the sketch compiles successfully, select **Upload** (the **right arrow** icon) to upload the compiled sketch to the Arduino board

# Troubleshooting Ports

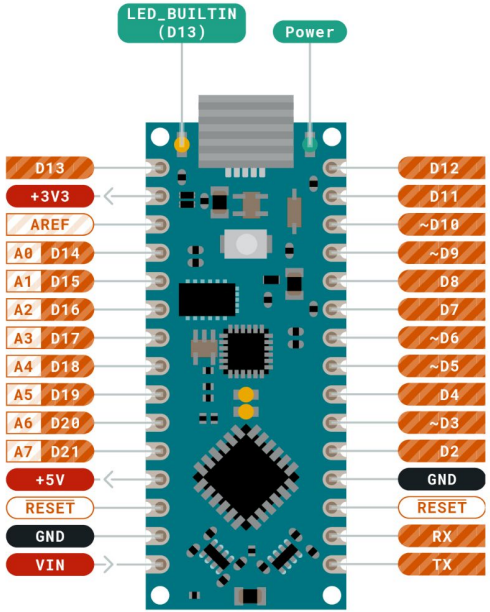
Did the upload time out? Are active ports missing from the dropdown?
**Here's what to do**:

1) Check your USB connection
    - Check your system's device manager to verify the Arduino is connected
    - Replace the USB cable or switch to a different USB port
2) Verify your CH340 driver installation
3) Restart the IDE and/or the personal computer
4) Give up and phone a friend

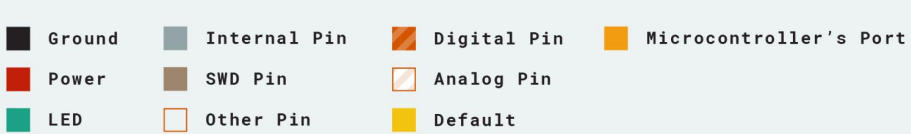
SECTION VI

# Basic Arduino Pins and Functions

# Arduino Pinout Diagram




- A pinout diagram is included in the Arduino Nano datasheet
- **General Purpose Input/Output** (**GPIO**) pins are pins with no predefined purpose
  - These are the **analog** and **digital pins** marked by the pinout diagram
  - We will design an Arduino sketch to control these pins



# Sketch Structure

- Sketches are written in the **Arduino language**, which is much like C++
- **Assign pins as global variables** at the beginning of the sketch:
  `const int pinName = pin#;`
  - Each GPIO pin is associated with an integer
- Just like the C++ **`main`** function, Arduino has built-in functions **`setup`** and **`loop`**, which must be defined by the programmer

```
const int RECEIVER = 14;
const int LED = 7;

void setup()
{
   pinMode(LED, OUTPUT);
   pinMode(RECEIVER, INPUT);
   Serial.begin(9600);
}

void loop()
{
   Serial.println(analogRead(RECEIVER));
   digitalWrite(LED, HIGH);
}
```

# Sketch Structure (Cont'd)

- `setup()` runs once at the beginning of program execution
  - Used to initialize pin modes and global variables
- `loop()` runs repeatedly in an infinite loop
  - This is where you implement the "main" code
- **Do not define the `main` function.** Arduino does this for you

```
const int RECEIVER = 14;
const int LED = 7;

void setup()
{
    pinMode(LED, OUTPUT);
    pinMode(RECEIVER, INPUT);
    Serial.begin(9600);
}

void loop()
{
    Serial.println(analogRead(RECEIVER));
    digitalWrite(LED, HIGH);
}
```

# Things to do in `setup`

- `void pinMode(int pin, int mode)`
  - Call this function for each digital pin you want to use
  - Pass the global variable assigned to each pin to the `pin` param
  - Specify if your pin is `INPUT` or `OUTPUT` mode
    - We **read data from input pins** and **send data to output pins**

```
void setup()
{
   pinMode(LED, OUTPUT);
   pinMode(RECEIVER, INPUT);
   Serial.begin(9600);
}
```

# Things to do in `setup` (Cont'd)

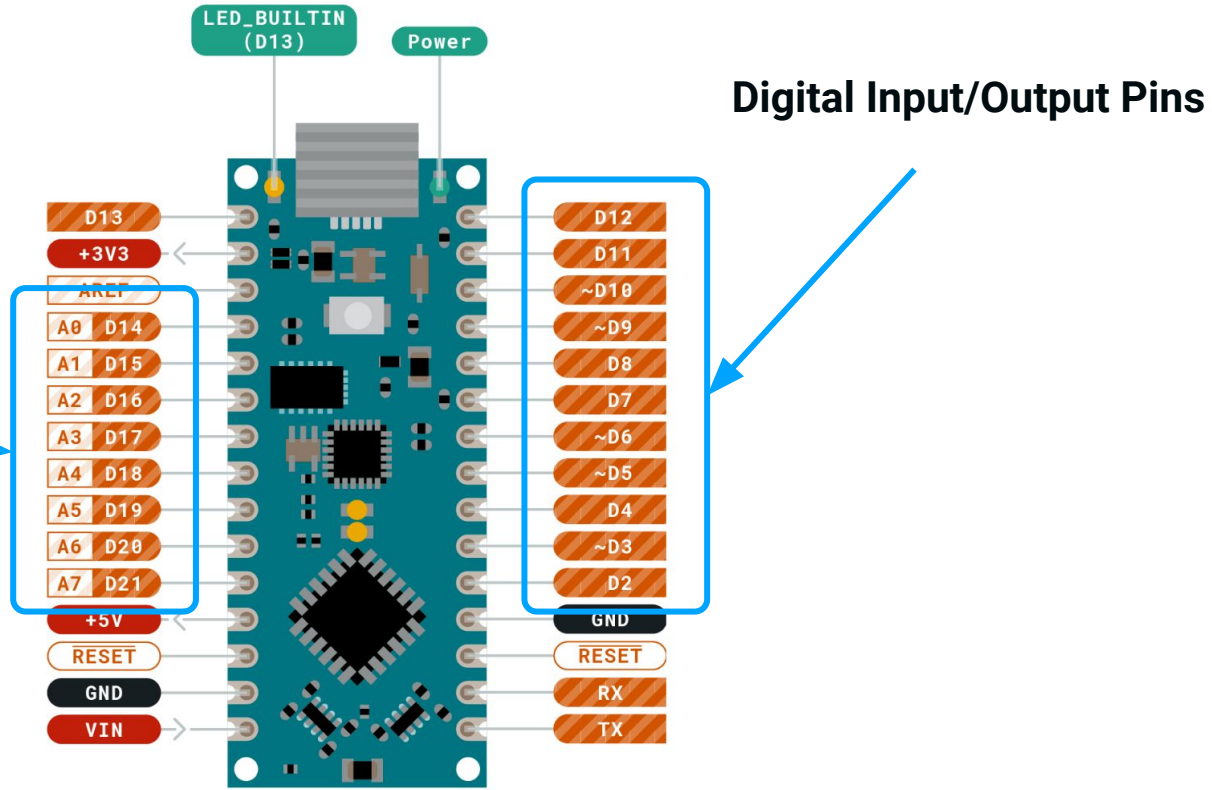
- `Serial.begin(int baud_rate)`
  - `Serial` is an object that facilitates communication between the Arduino board and the computer connected to it via USB
  - Pass `9600` bits per second as the argument for this member function
    - To be elaborated in future lectures

```
void setup()
{
    pinMode(LED, OUTPUT);
    pinMode(RECEIVER, INPUT);
    Serial.begin(9600);
}
```

# Digital Pins

**Digital Output Pins**

These pins are numbered as `2, 3, 4… 20, 21`



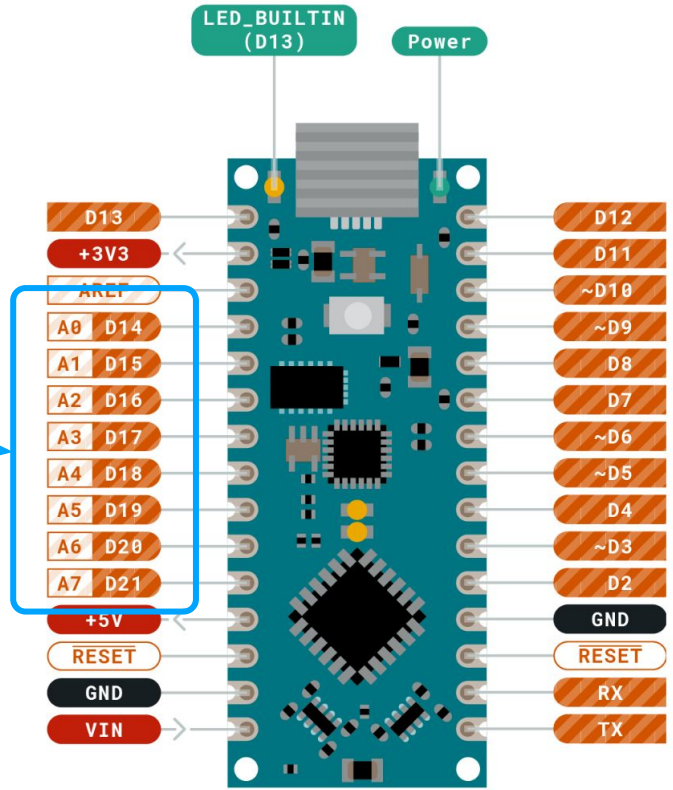
# Digital Pin Functions


- `int digitalRead(int pin)`
  - **Reads the voltage** at the input pin, returning `HIGH` (5V) or `LOW` (0V) as an integer (1 or 0)
- `void digitalWrite(int pin, int value)`
  - **Sets the voltage** at the output pin to either a `HIGH` (5V) or `LOW` (0V) value
- Analogy - light switch and light bulb:
  - You use the switch to set the bulb to either MAX brightness or MIN brightness

# Analog Pins

**Analog Input Pins**

These pins have the aliases `A0`, `A1`, `A2`, and so on… instead of `0`, `1`, `2`




**PWM-Capable Digital Output Pins**

These pins are marked with ~ on the pinout diagram

# Analog Pin Functions


- `int analogRead(int pin)`
  - **Reads the voltage** at the input pin, maps it to a value in the **discrete range** `0-1023` (0V to 5V) and returns that value
  - Use the aliases `A0, A1, A2…` for the pin number
- `void analogWrite(int pin, int value)`
  - **Sets the average voltage** on digital output pin to a value in the **discrete range** `0-255` (0V to 5V)
  - This is a function for **~ PWM pins only**
- Analogy - light dimmer:
  - You use the slide to set the bulb to anywhere *between* MAX brightness or MIN brightness

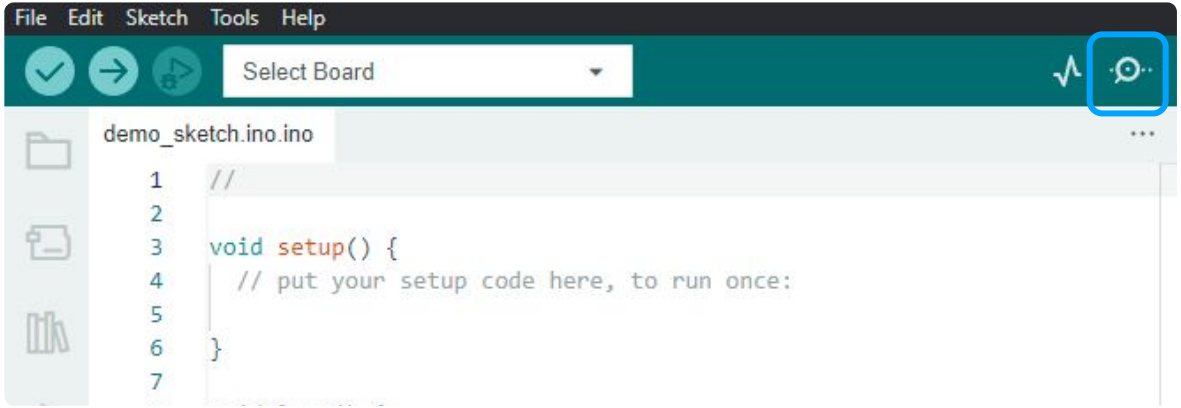
# ADC and `analogRead`

- `analogRead` **utilizes the analog-to-digital converter** inside the Arduino's AVR microcontroller to **measure the real-world, analog signal** and **convert it to a digital signal**
    - The measurement resolution is 10 bits, which is why the function returns values from `0-1023`

# More Basic Functions

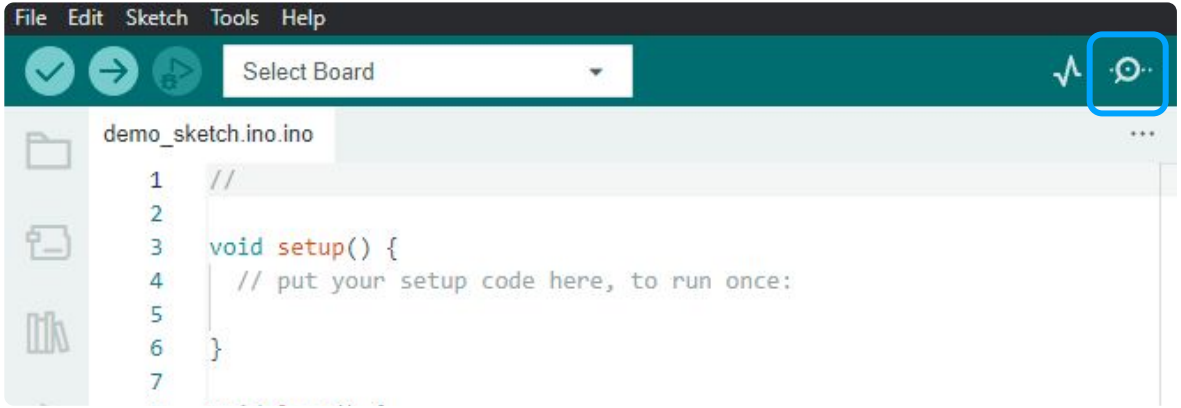
- `void delay(int ms)`
  - **Pauses the program execution** by `ms` milliseconds
- `Serial.print(val)`
  - Sends `val` to the computer connected via USB and **displays `val` on the Serial Monitor** in the IDE
- `Serial.println(val)`
  - Sends `val` to the computer connected via USB and **displays `val` on the Serial Monitor** in the IDE, **followed by a newline**

# Using the Serial Monitor



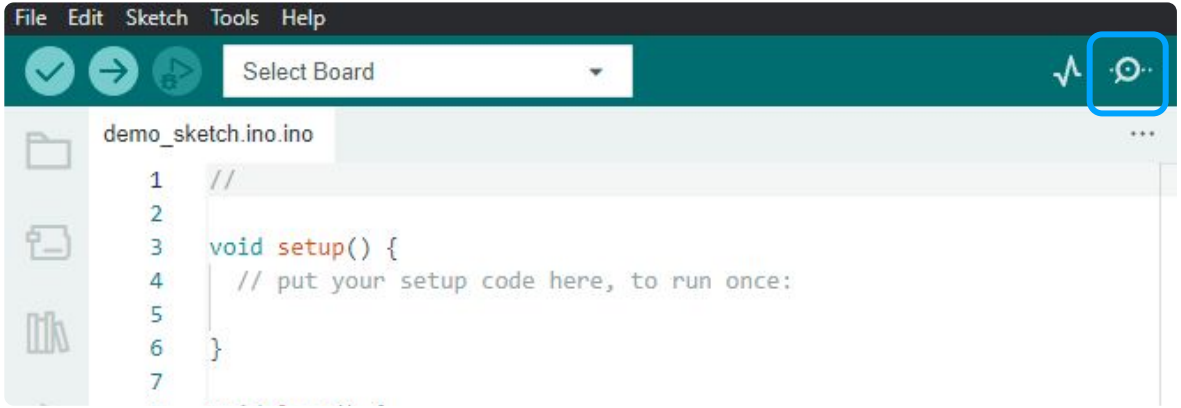

- While the Arduino board is connected to the personal computer via USB, select **Serial Monitor** (the **magnifying glass** icon) in the IDE
    - A pane will appear at the bottom of the IDE window which displays all data sent by the Arduino board using `Serial.print`

# Using the Serial Monitor (Cont'd)



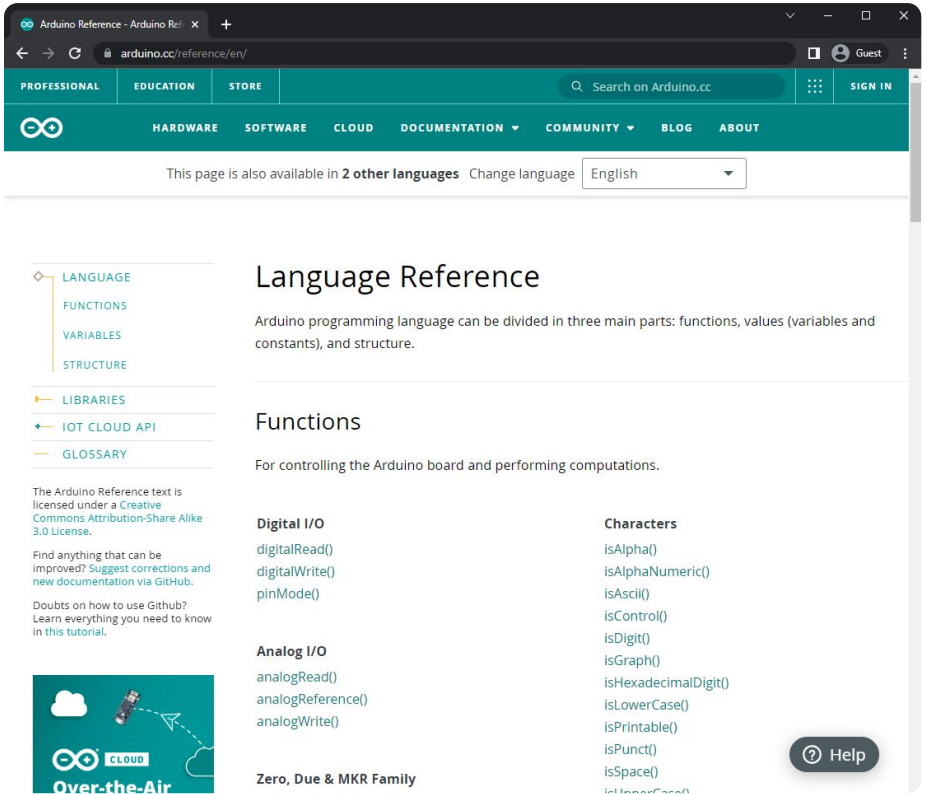

- In the absence of a debugger (the Arduino Nano is not capable of using one), `Serial.print` is an excellent tool to **help debug programs**
  - Print values to track across parts of your program
    - Unexpected values displayed to the Serial Monitor indicates an error

# Using the Serial Monitor (Cont'd)




- The C++ **iostream library is not compatible with Arduino**
  - Do not use **`cin`** or **`cout`** to print text
- **`Serial.print`** is the primary way to print text to the Serial Monitor

# Arduino Reference Library



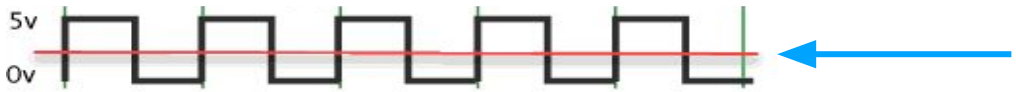

- Learn more about Arduino functions and libraries here
- The **Arduino Reference Library** includes support for devices like LCDs, Sensors, and WiFi modules

SECTION VII

# Pulse Width Modulation

# PWM

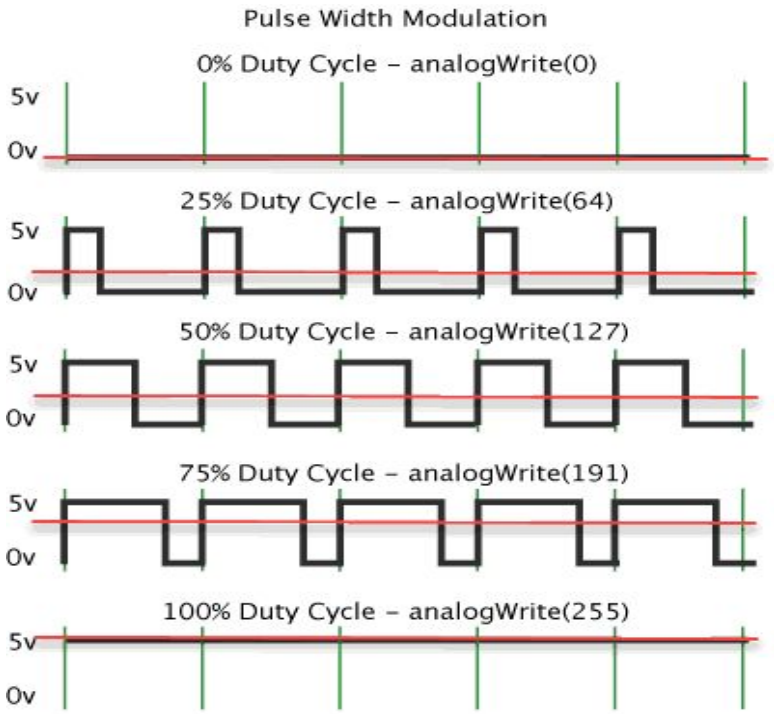
- The Arduino board (the underlying AVR microcontroller) is a **digital source**, meaning it can only output a `HIGH` (5V) or `LOW` (0V) voltage
  - Then how does `analogWrite` output analog signals?
- **Pulse Width Modulation** (**PWM**) is an oscillating digital waveform that emulates an analog output
  - By oscillating a signal from `HIGH` to `LOW` quickly, the average voltage over time will be *between* `HIGH` and `LOW` - an analog value




The average value, the *analog value,* of this waveform is **2.5V**

# PWM Duty Cycle

- The **duty cycle** of the PWM wave is the percentage of time where the signal is `HIGH`
  - For example, a 50% duty cycle translates to an average value of 2.5V (50% of 5V)
  - Allows us to output a continuous range of voltages between `HIGH` and `LOW`
  - Duty cycle is **controlled by a timer** inside the AVR microcontroller

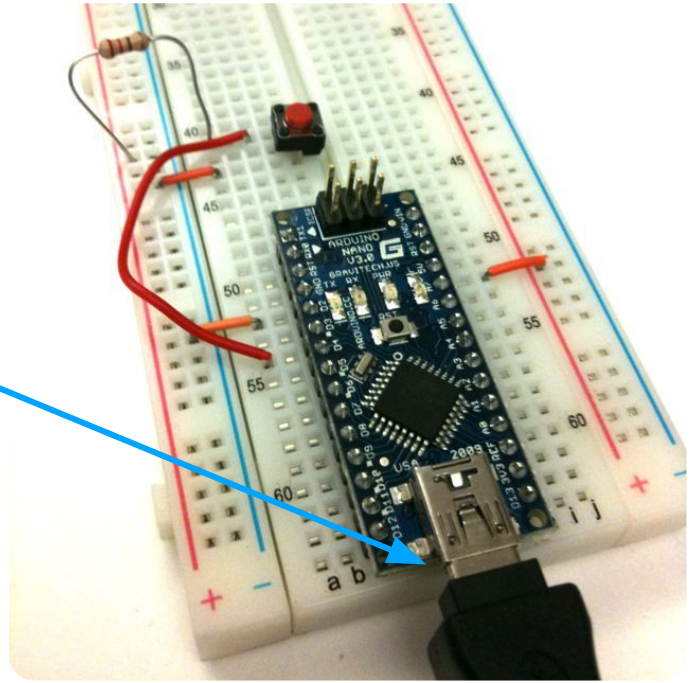


SECTION VIII

# Digital LED Circuit Exercises

# Prototyping with the Arduino Nano

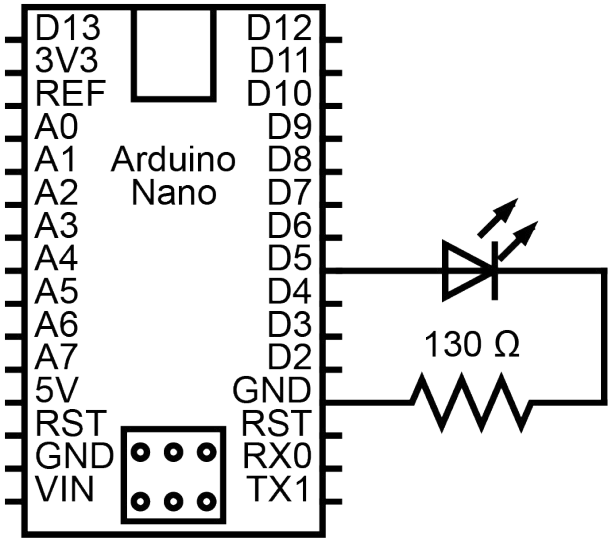
- The Arduino Nano can be **seated along the DIP channel** of a standard breadboard just like a DIP IC
- The **Arduino Nano's USB port should be oriented away from the board**, so the connected cable doesn't obstruct the breadboard
- Circuits that interface with the Arduino board must **share a common ground with the GND pin of the board**



# Digital LED Circuit

I/A

Build the circuit below from the schematic. Then, complete the template code, flash it to the Arduino board, and verify the circuit.

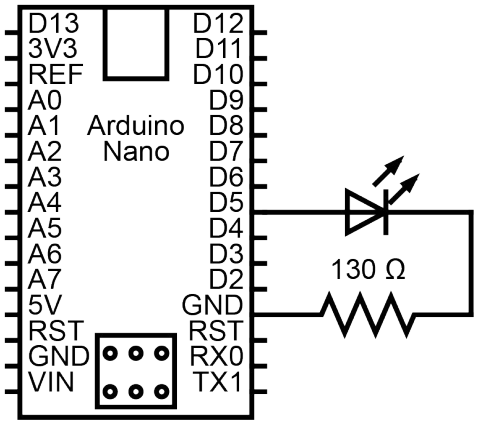



```
// Assign variable to pin number for LED

void setup() {
    // Configure LED pin's behavior to OUTPUT
    // Configure the Serial baud rate
}

void loop() {
    // Set LED pin to HIGH
}
```

# Digital Blinking LED Circuit

I/A

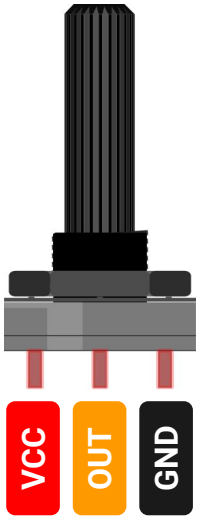
Build the circuit below from the schematic. Then, complete the template code, flash it to the Arduino board, and verify the circuit.



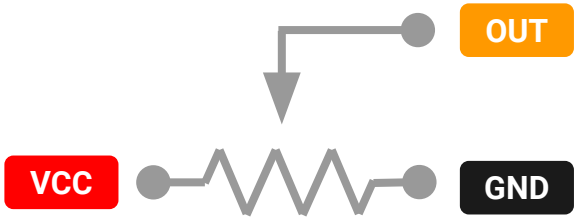

```
// Assign variable to pin number for LED

void setup() {
      // Configure LED pin's behavior to OUTPUT
      // Configure the Serial baud rate
}

void loop() {
      // Set LED pin to HIGH
      // Delay
      // Set LED pin to LOW
      // Delay
}
```

# Potentiometers

- A **potentiometer** is a **three-terminal variable resistor**
- We will use the potentiometer as a **voltage divider** - a circuit which accepts a supply voltage and outputs a voltage which is a fraction of the supply voltage
- The voltage of the potentiometer's output pin ranges between the VCC and GND pin voltages

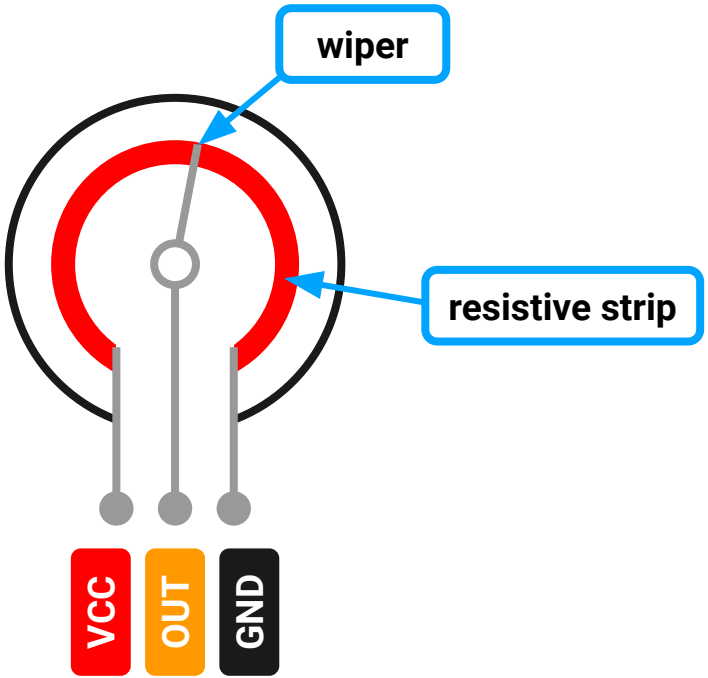



The positions of **VCC** and **GND** can be swapped



# Potentiometers (Cont'd)

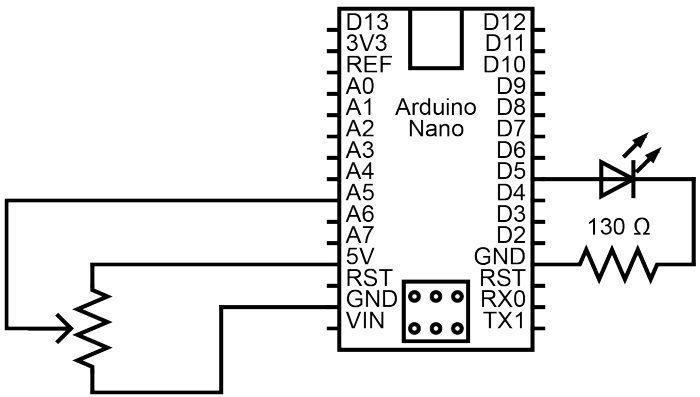
- Internally, a **resistive strip** connects its VCC and GND pins
    - A rotating **wiper** connects the output pin to the strip
- **The greater the distance** along the strip between the wiper and the VCC pin, **the greater the resistance** between the wiper and VCC
- The wiper **reduces the voltage** at the output pin the further it is **turned clockwise** (toward GND)



# Digital Dimmable LED Circuit

I/A

Build the circuit below from the schematic. Then, complete the template code, flash it to the Arduino board, and verify the circuit.

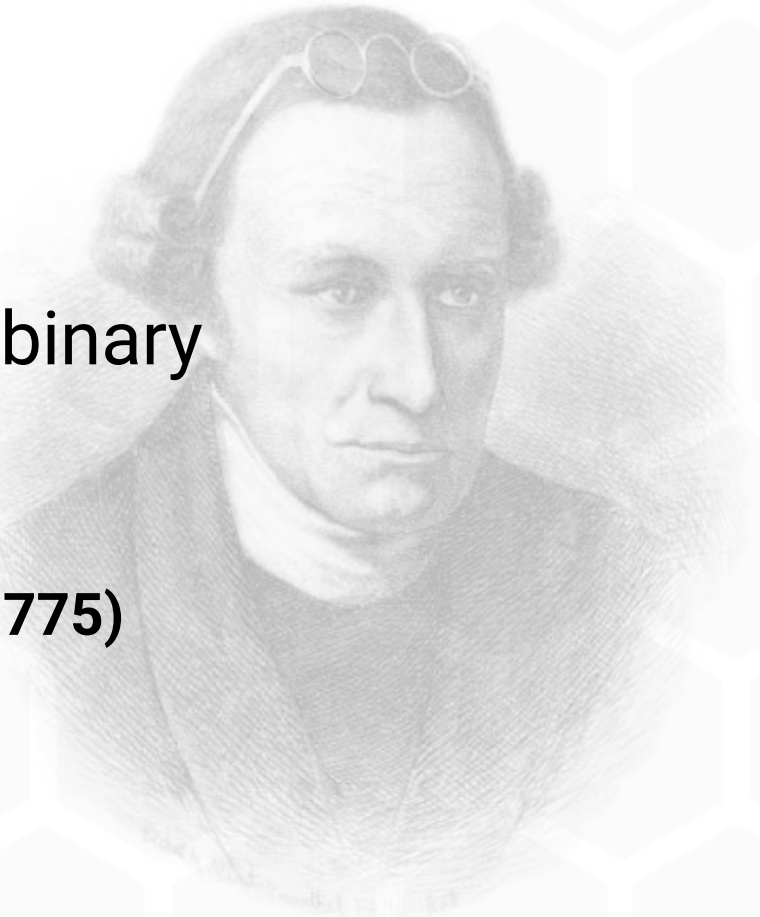



```
// Assign variable to pin number for LED
// Assign variable to pin number for Pot

void setup() {
  // Configure the LED pin's behavior to OUTPUT
  // Configure the Pot pin behavior to INPUT
  // Configure the Serial baud rate
}

void loop() {
      // Read pot pin value
      // Set LED pin to the pot pin value
}
```

“Give me **PWM** or give me a **binary state** of existence!”

**Patrick Henry (circa 1775)**

Famous Misquotes



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