FINAL LECTURE

End of Year Wrap Up

SECTION I

Circuits Review

Circuits Reflection

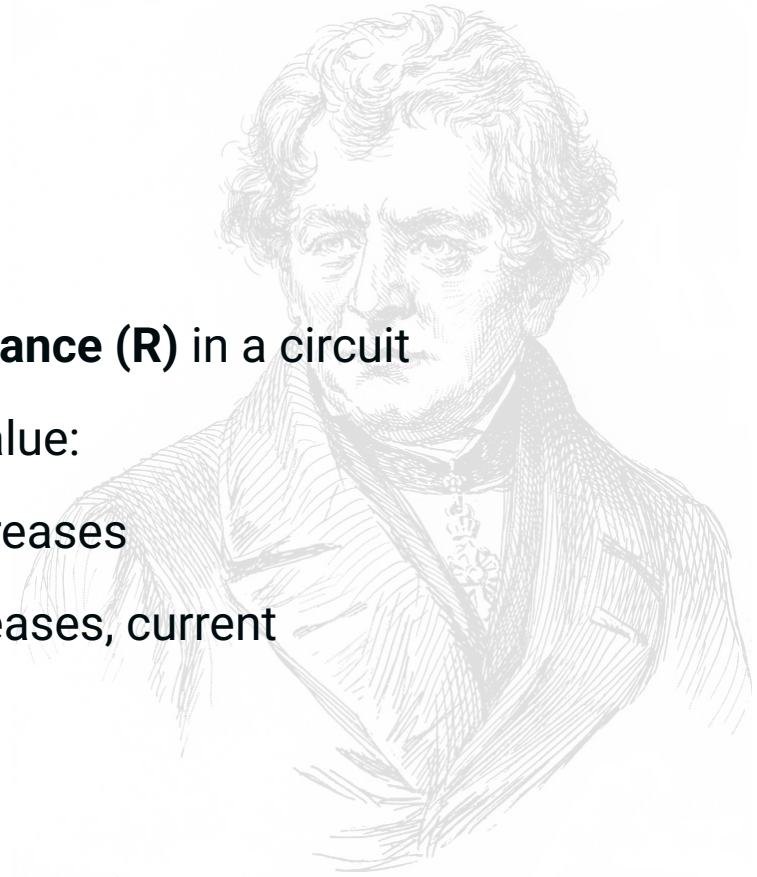
- What are the core concepts of circuits that you should take away from OPS?
- What pitfalls are important to look out for when trying to implement a circuit?

Voltage

- **Voltage** is the **electric potential difference**
  - Current can flow where **voltage** exists
  - Measured in **Volts, V**
  - Ex. **Batteries** are a voltage source
- **Requires a reference point** because it measures the difference in volts between two points

Ohm's Law

$$V = IR$$



- Relates the **voltage (V)**, **current (I)**, and **resistance (R)** in a circuit
- Suppose we hold the voltage at a constant value:
  - As the resistance increases, current decreases
  - In the opposite case, as resistance decreases, current increases

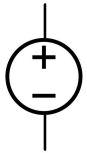
SECTION II

Circuit Analysis Review

Schematic Symbols

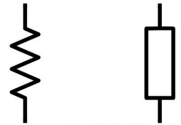
Battery

Voltage Source



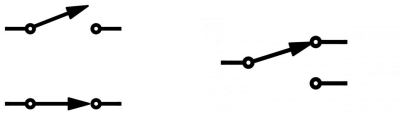
Ground

Resistor

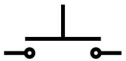


Potentiometer

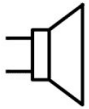
Switches



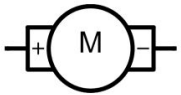
Pushbutton



Speaker



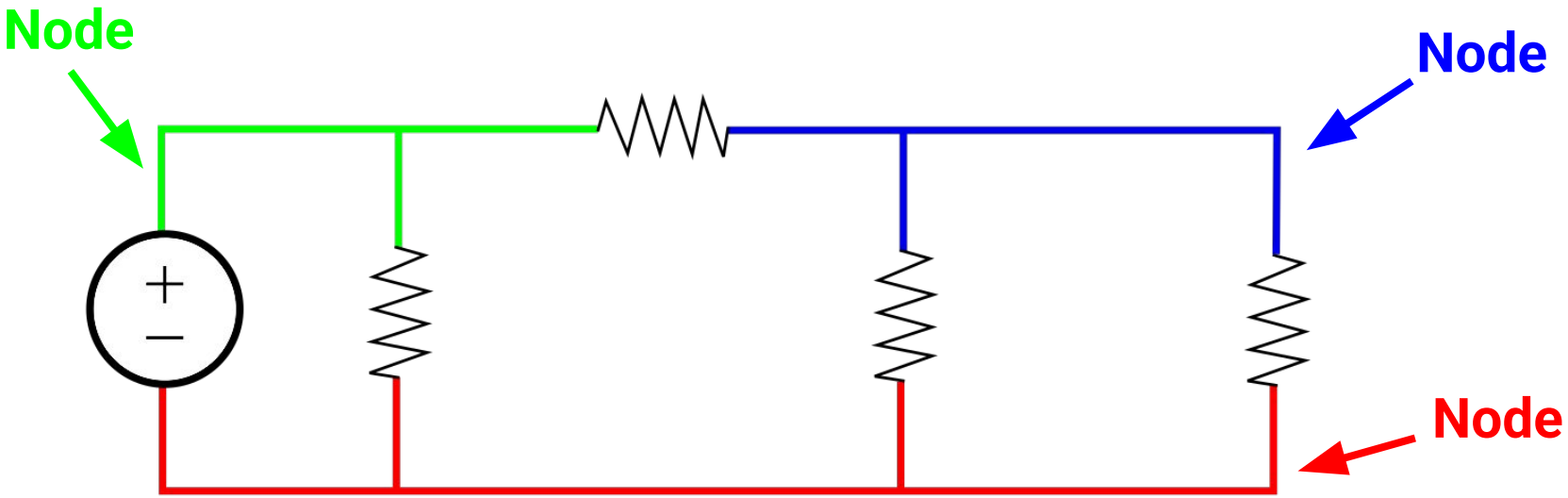
DC Motor



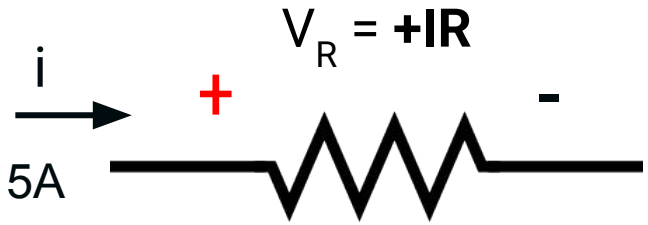
LED

Nodes

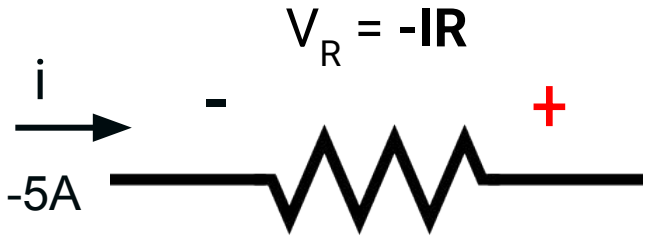
- A **node** is a **connection** between two or more **components**
- All points on the **same node** have the **same voltage**



Voltage Drop Sign Convention (Cont'd)



- The sign of the voltage drop is **positive** if current flows from **+** to **-** terminals
  - Conventional current flows from **+** to **-** terminals

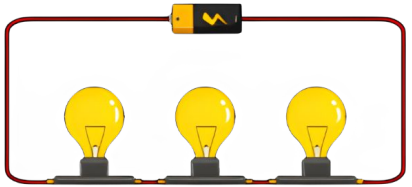


- The sign of the voltage drop is **negative** if current flows **-** to **+** terminals

Series and Parallel Circuits

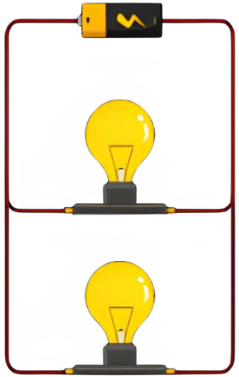
Series

- Two or more elements are in **series** if they exclusively are connected in one line
- Elements in series carry the **same current**



Parallel

- Two or more elements are in **parallel** if they are connected to they share the same two nodes
- Elements in parallel have the **same voltage** across them

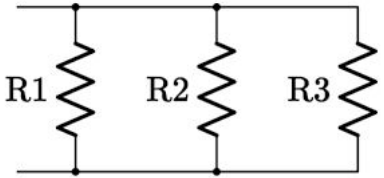


Series and Parallel Circuits

- If **multiple resistors** are arranged **in series or parallel**, we can treat them as having a **single equivalent resistance**

Parallel

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

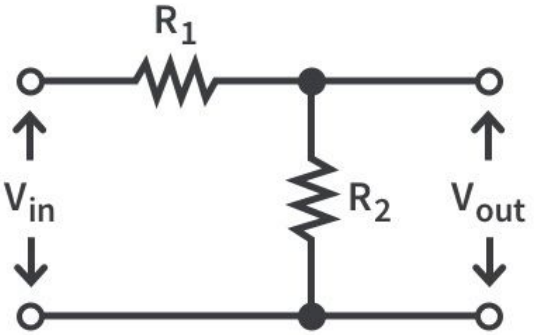


Series

$$R_{eq} = R_1 + R_2 + R_3$$

Resistor Divider

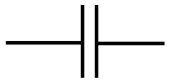
- A circuit configuration with **two resistors** that is used to scale down a voltage (**Vout**).
- Creates a ratio of two resistors to achieve a desired output voltage
  - **R1** and **R2** are connected in series
  - **Vin** is the input voltage
  - **Vout** is the output voltage across **R2**



$$V_{out} = \left(\frac{R_2}{R_1 + R_2}\right) V_{in}$$

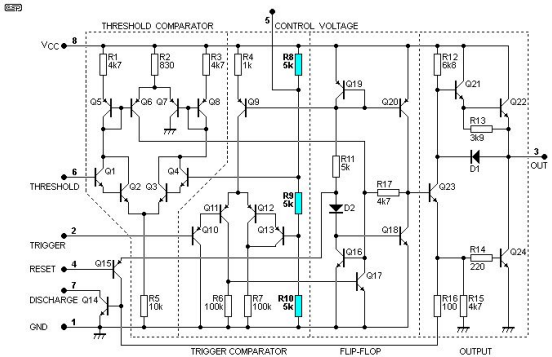
Capacitors

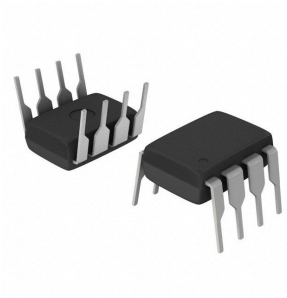
- A **capacitor** stores electrical energy which it charges and discharges
  - The ability of a capacitor to store energy is its **capacitance**, measured in **Farads** (**F**)
- Unlike a battery, a capacitor can only briefly store a small amount of energy
- When a capacitor is connected to a voltage source, it charges until it reaches the **same voltage** as the voltage source
- Used for filtering, storing a small amount of energy, and timing circuits



Integrated Circuits

- An **integrated circuit** (**IC, chip**, **microchip**) is a set of electronic circuits on one small flat piece of semiconductor material
  - Electronic components are **integrated** on the chip
  - Complex circuits can be **scaled down** and **mass-produced**
  - Used for a specific application





SECTION III

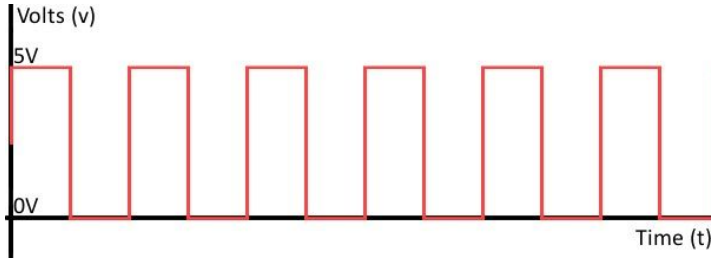
Microcontrollers

Microcontroller Reflection

- What does GPIO stand for?
- What are the main differences between digital and analog signals and when should you use one over the other?
- What is PWM and why is it important?

Digital Signals

- **Computers (and microcontrollers) 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

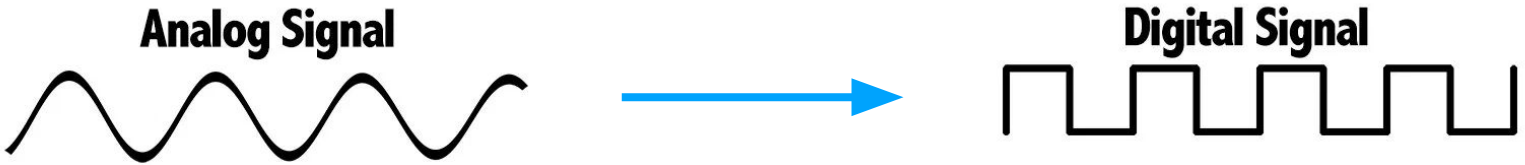


This is a **digital signal** where the waveform is either **5V** or **0V** (two *discrete* values)

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

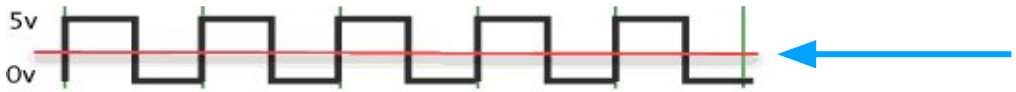
ADC and `analogRead`

- `analogRead` **utilizes the analog-to-digital converter** inside the 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`



PWM

- The ESP32 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**

SECTION IV

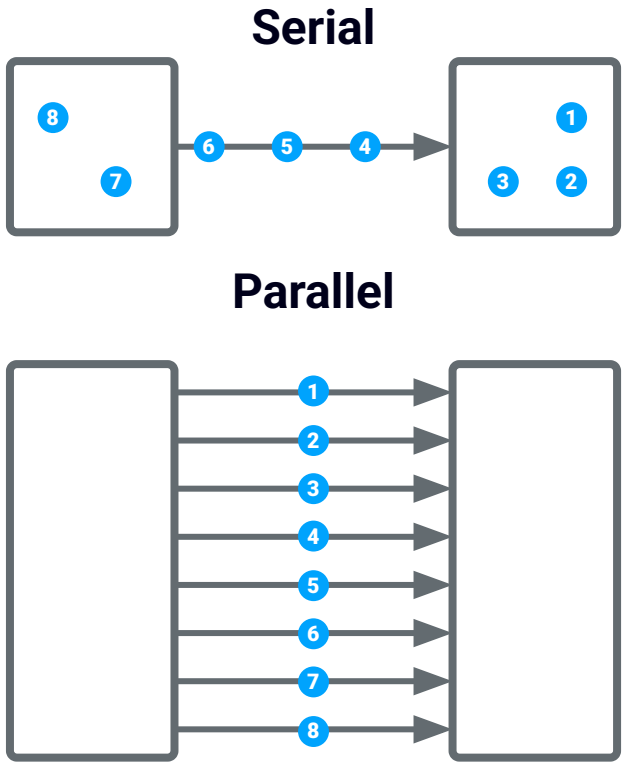
Communication Protocols

Communication Protocols Reflection

- What's the difference between synchronous and asynchronous protocols?
  - What synchronous protocols did we learn?
  - What asynchronous protocols did we learn?
- Why are clock signals important for SPI and I2C?

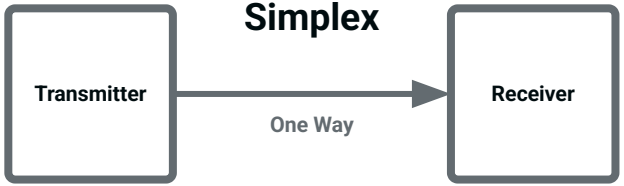
Serial vs Parallel Protocols

- **Serial** - bits are sent over a connection one by one to a device
  - Bits are sent in a specific order
  - The most common protocols are serial
- **Parallel** - multiple bits (often one byte) are sent simultaneously over a connection
  - This connection requires more wires, which takes up more space
  - Higher transmission rate

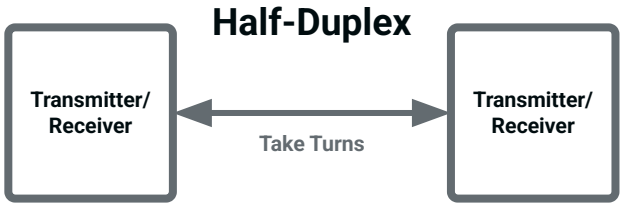


Transmission Modes

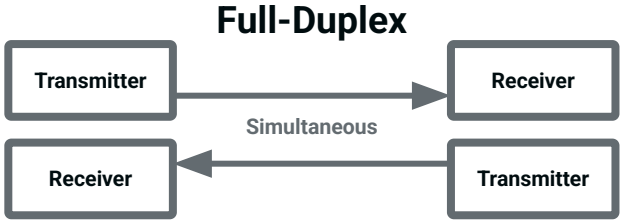
- **Simplex** protocols allow communication in only one direction



- **Half-Duplex** protocols allow communication in both directions but only in one direction at a time



- **Full-Duplex** protocols allow communication in both directions simultaneously

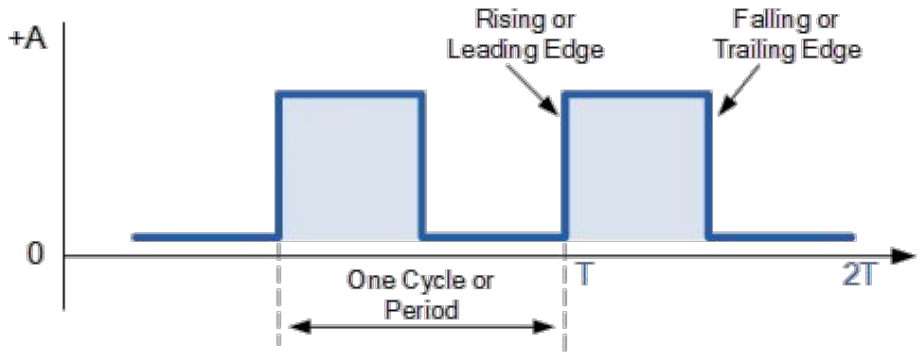


UART Protocol

- UART is a **communication protocol with certain characteristics**. It has rules for data transmission.
  - UART can be configured to **full-duplex, half-duplex,** and **simplex modes**
  - There are only **two lines** (electrical connections)
  - There is **no clock signal**/line hence the “asynchronous” part of the title
  - The data transmission speed is determined by a **baud rate**
    - It is quite **slow compared to other protocols**

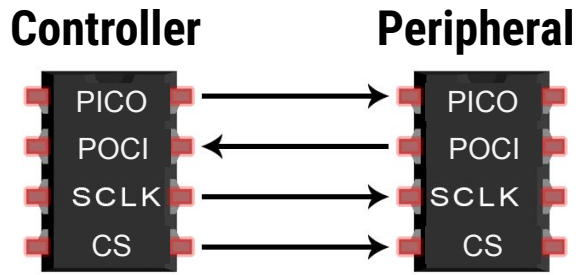
Clock Signals

- **Digital signals** are timed to a **clock signal** - most often, a square wave with a 50% duty cycle
  - For example, in a serial signal, one bit of data is sent per clock cycle
    - The bit might be timed to the rising or falling edge of the clock signal
- **Clock speed** determines the rate at which data is transmitted
  - measured as **frequency (Hz)**
  - inversely proportional to cycle (or period)

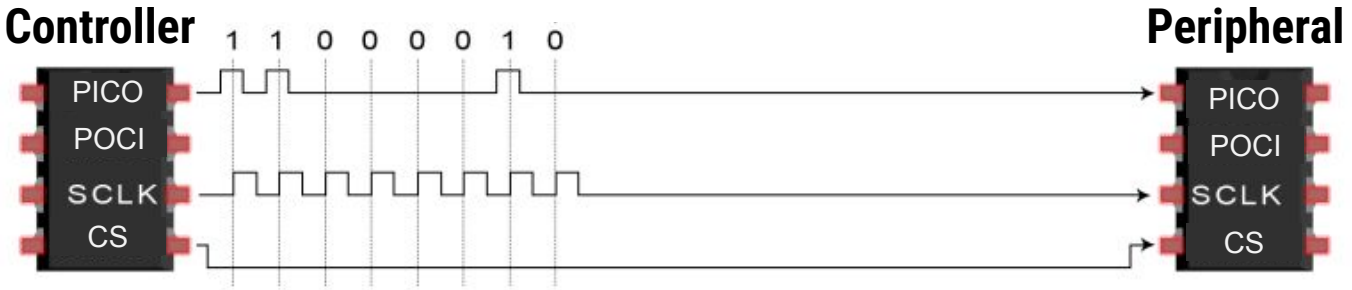


SPI Protocol

- **Serial Peripheral Interface** or **SPI** is a serial communication protocol which is **synchronized with a clock**
- Unlike UART, **data is transferred continuously** in SPI
  - There are no packets, start bits, stop bits, parity bits, or anything else
- One device acts as a **controller** to one or more **peripheral** devices
- Supports **full-duplex** communication
  - Bi-directional communication



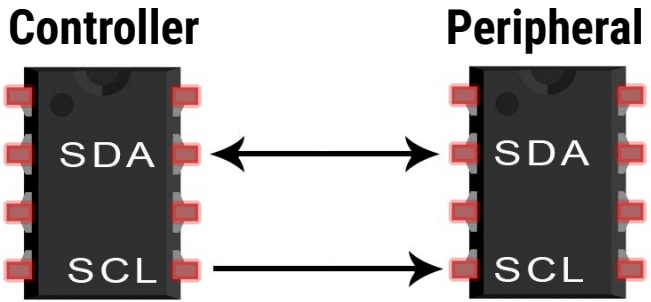
SPI Transmission



1. The controller first **selects a peripheral** by pulling a HIGH signal to LOW along the Chip Select (CS) line
2. The controller **sends data** to the selected peripheral along the Peripheral-In/Controller-Out (PICO) line
    - Bits in the PICO signal are **synchronized with the rising edge** of the oscillating clock signal
    - Alternatively, the peripheral sends data along the Peripheral-Out/Controller-In (POCI) line

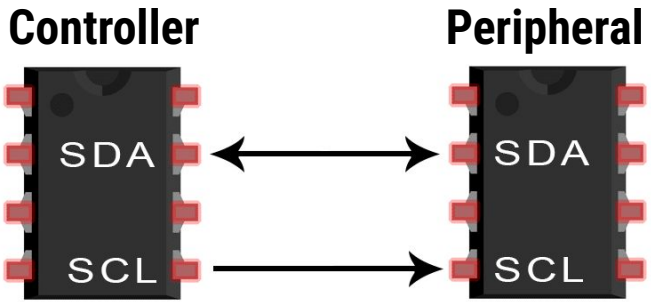
I²C Protocol

- **Inter Integrated Circuit** or **I²C** is another synchronized, serial protocol
- Unlike UART and SPI, I²C supports **multiple controllers**
- I²C features **acknowledgements** to confirm if messages are received and addressing for peripherals
- Supports **half-duplex** communication
    - One way communication



I²C Layout

- SDA (**Serial Data**) - the line for the controller and peripheral to send and receive data
- SCL (**Serial Clock**) - the line that carries the clock signal
- All peripherals can share the same two SDA and SCL lines



UART vs SPI vs I^2C

Protocol	UART	SPI	I^2C
# of Lines	2	4+	2
# of Controllers	1	1	1+
# of Peripherals	1	1+	1+
Transmission Type	Full-Duplex	Full-Duplex	Half-Duplex
Error-Checking	✅	❌	✅
Speed	Slowest	Fastest	Slower

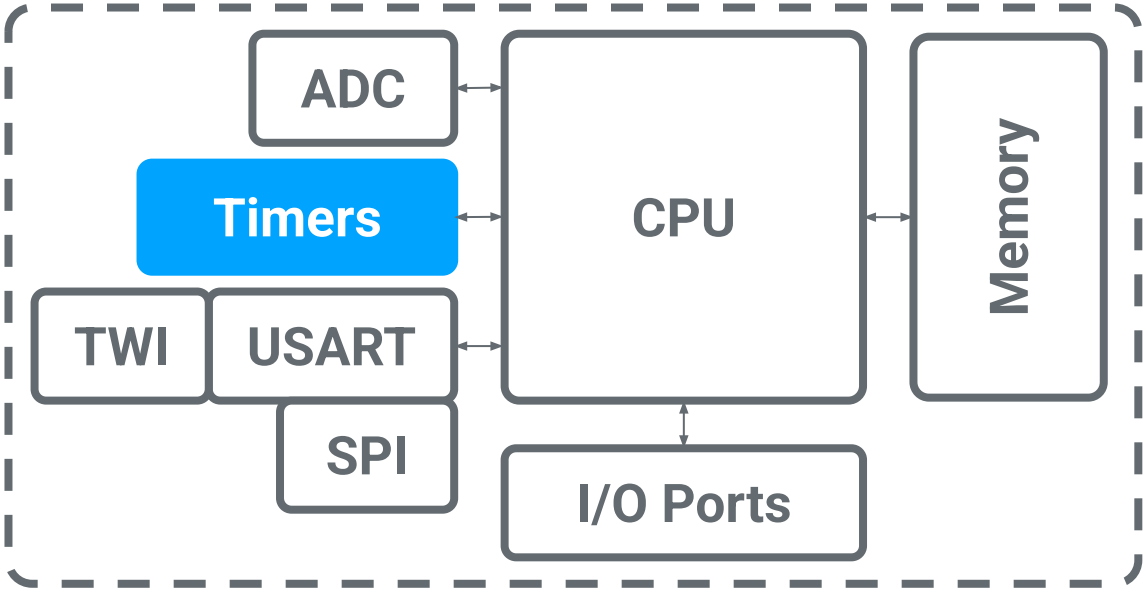
SECTION V

Timers & Interrupts

Timers & Interrupts Reflection

- What do timers do and what applications could they have?
- Why do we use interrupts and why can they be useful?
- What's the difference between hardware and software interrupts?

Timers



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

Types of Timers

- Timer types can be distinguished by when the **timeout** triggers
  - A **timeout** is an event that occurs after a preset period of time
- A **one-shot timer** has a single timeout
  - For the timer to be run again, it must be **reloaded manually**
  - Ex) A countdown timer runs just once, stopping when it reaches zero
- A **periodic** (or **auto-reload**) **timer** has *periodic* timeouts that occur at a fixed interval
  - The timer **reloads automatically**
  - Ex) An alarm clock rings once every morning

Interrupts

- An **interrupt** is a request for the CPU to **halt the currently executing code** when an event occurs
  - The CPU suspends the current program to *handle* the event by executing a function called an **interrupt handler** or **interrupt service routine** (**ISR**)
  - When an interrupt halts the current code, a separate program / function can be called and run.
  - When the interrupt handler finishes execution, the CPU returns to the old program

Polling

- **Polling** is a method of periodically checking the status of a device
  - Ex) A person checking their phone for new messages every 10 minutes
    - We have been using polling in the `void loop()`
  - Polling loops cost additional CPU time
- Should we use interrupts instead of polling?
  - Interrupts signal *when* an event occurs whereas polling *checks* to see if an event occured
    - Ex) A person reading their phone upon receiving a push notification
  - **Use interrupts when an event is urgent and/or infrequent**

Types of Interrupts

- A **software interrupt** is triggered by an instruction
  - Also called a **trap** or **exception**
  - Often caused by an illegal operation
    - Ex) Dividing by zero, Accessing memory without permission
- A **hardware interrupt** is triggered by devices external to the CPU
  - Also called an **external interrupt**
  - Caused when a devices sends an **interrupt request** (**IRQ**) signal to the CPU
    - Ex) Timer timeout, button press, power failure

SECTION VI

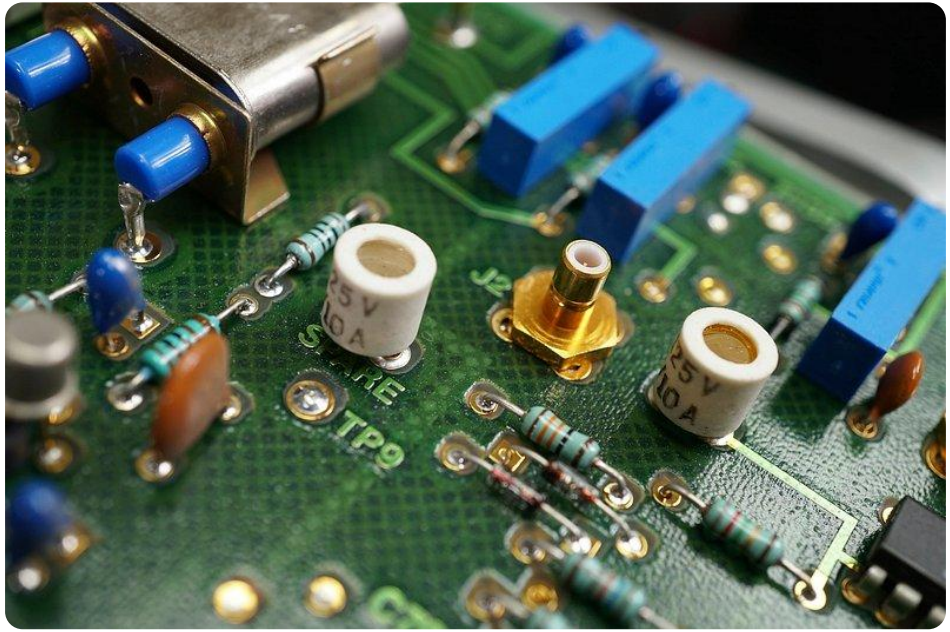
PCB Design

PCB Design Reflection

- Why do we use PCBs instead of breadboards?
- What are common issues that can occur when creating/assembling a PCB?

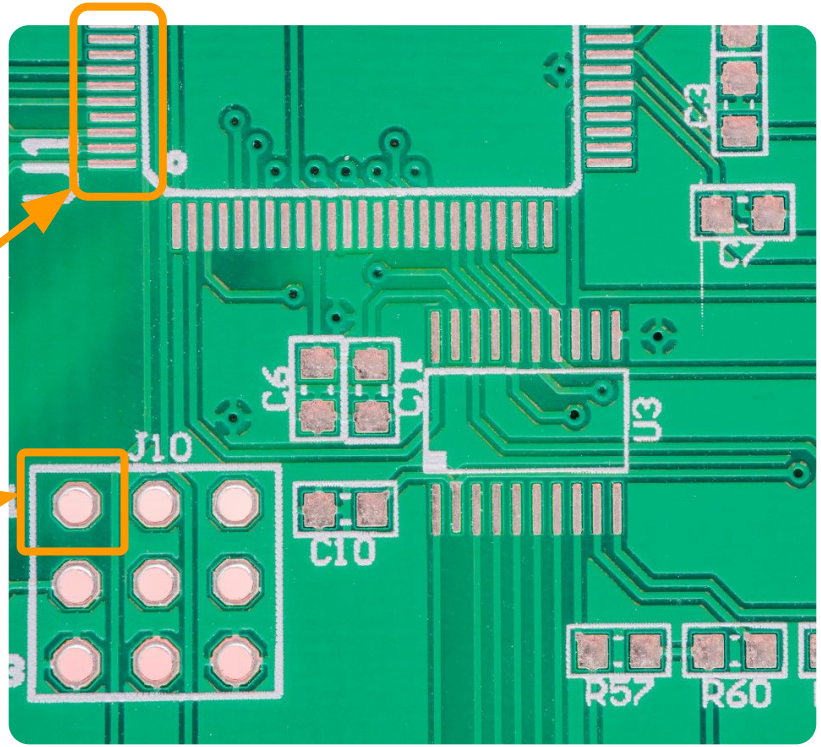
Printed Circuit Boards (PCBs)

- A **printed circuit board** (**PCB**) is an electronic assembly that uses copper conductors to **connect components**
  - It acts as a permanent map in placing and connecting electronic components
  - Made from **multiple**, **alternating layers** of **conductive** (usually copper) and **insulating material**



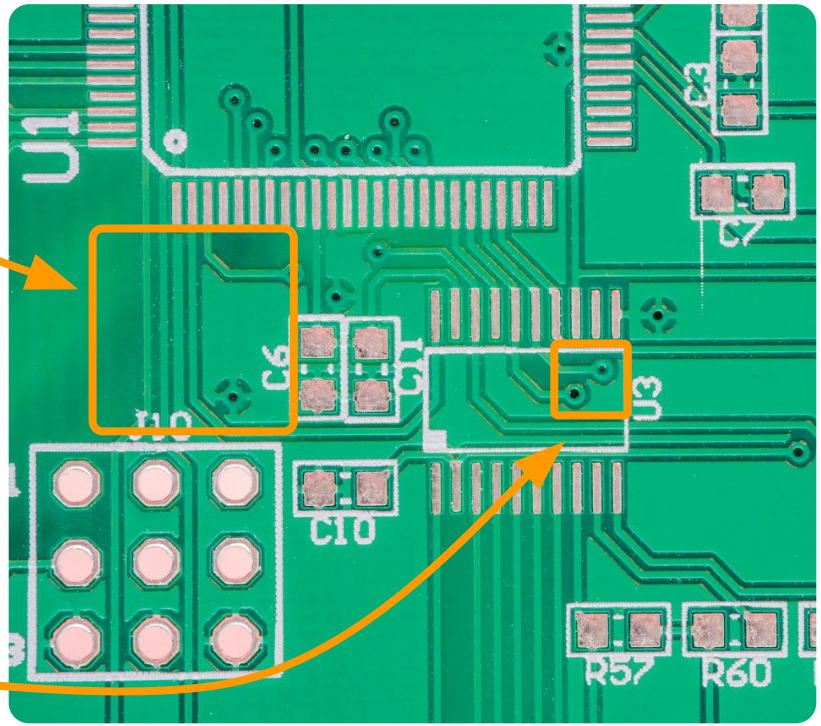
How are Components Connected?

- **Pads** are exposed copper surfaces which connect the leads of the electronic components to the board
  - Some pads are designed for **surface-mounted** (**SMD**) leads while others are for **through-hole** (**THT**) leads
  - Component **leads are soldered to the pads**



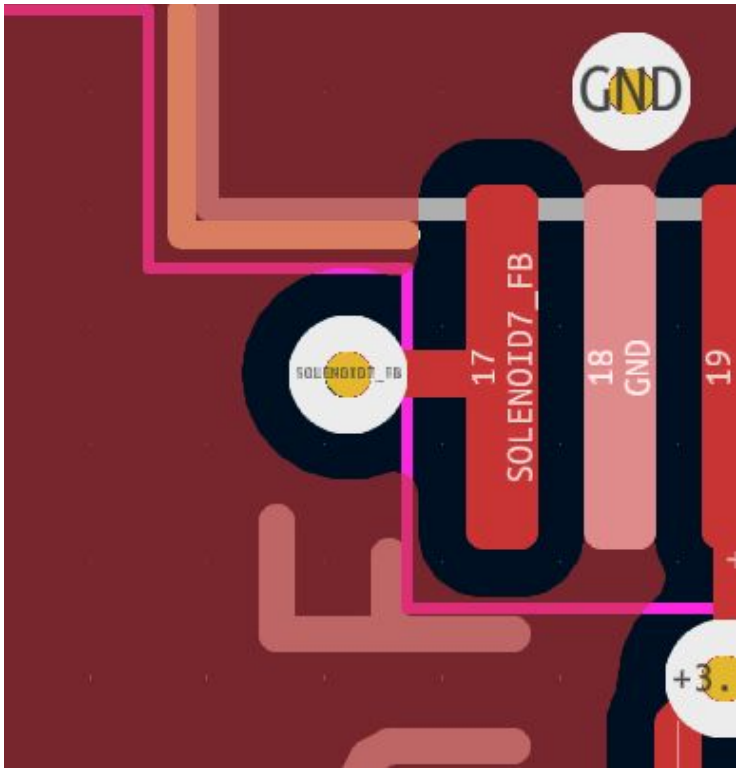
How are Components Connected? (Cont'd)

- **Traces** are **copper tracks** which connect pads
  - They are covered by a layer called the **solder mask** (colored green in the image)
- **Vias** are **conductive holes** drilled into the board to **connect different copper layers**



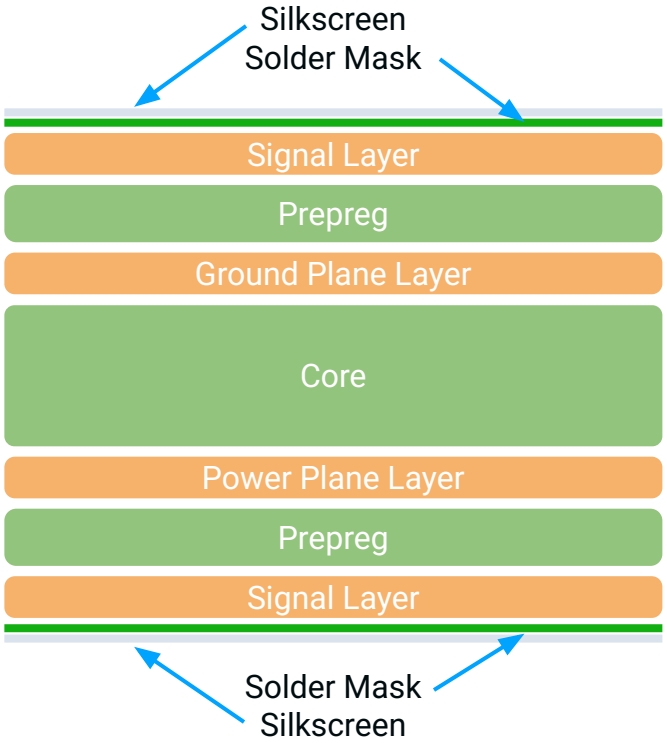
How are Components Connected? (Cont'd)

- A **plane** is an **inner conductive layer**
  - Used to create a ground point
- **Fills** are **large areas of copper** used for the same purpose as planes but can be integrated into the **same layer as traces**
  - The transparent shape surrounding the vias and the pads on the right is a Fill, that is used to ground the ground pad



PCB Stack-Up

- The **PCB Stack-Up** is the **arrangement** of PCB layers
- Most PCBs have multiple of the following layers:
  - **Copper layer**
    - Signal or routing layer
    - Ground/Power plane layer
  - **Insulation layer**
    - Core
    - Prepreg
  - **Solder mask layer**
  - **Silkscreen layer**



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