MCU Architecture

1. MCU Packages

- Every microcontroller unit (MCU) comes in a **package** – the physical form with pins that connect to a circuit board.
- Package names follow **industry standards**. The number at the end of the name tells you how many pins it has.
    - Example: a package ending in *64* has **64 pins** (16 pins per side on a square chip).
- On an **STM32 Nucleo board**, the MCU sits on the **main board**, but there's also a smaller **ST-Link sub-board**.
    - ST-Link = used only for **debugging and programming**.
    - Main board = runs your software.
- Different package options exist for the same MCU:
    - **Mounting scheme**: how the part is soldered (surface mount vs through-hole).
    - **Pin count**: ranges from ~48 to 100 pins.
    - **Physical size**: from ~3 mm to ~14 mm per side.
    - **Resources**: some packages even differ in the number of timers or peripherals inside.
- **Why package choice matters**:
    - More pins = more peripheral options.
    - Larger package = takes more PCB space.
    - Manufacturing process may limit mounting schemes.
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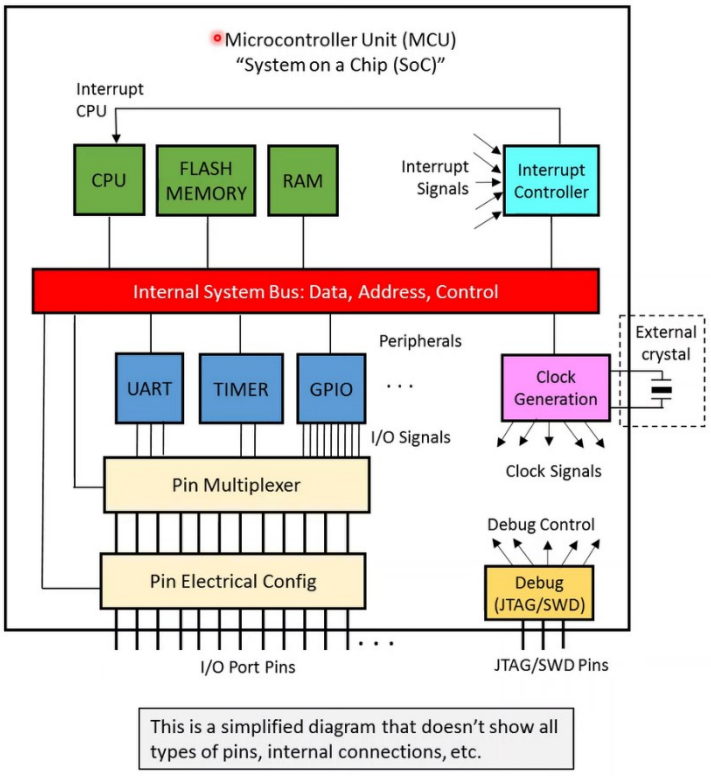
2. System-on-a-Chip (SoC)

- An MCU is a **System-on-a-Chip**.
    - This means CPU, memory, and peripherals are integrated into one silicon die.
- **Advantages**: smaller, cheaper, uses less power.
- **Disadvantages**: harder to expand — you can't just "add RAM" like in a PC.
- **Solution**: manufacturers sell many versions of the same MCU family with different memory sizes and peripheral options.

- Historical note: decades ago, all these blocks were **separate chips** on a board. Today, they're merged into one part.



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3. CPU and Memory

- **CPU** = heart of the MCU, executes your software.
- **Flash memory**:
  - Stores **machine code (software instructions)**.
  - **Persistent**: keeps data even when powered off.
  - **Limitations**:
    - Slow to write.
    - Can "wear out" after many writes.
  - Best use: program storage or configuration data that changes rarely.
  - Example: product settings stored once during installation.
- **RAM**:
  - Stores **dynamic data** (variables, stack, buffers).
  - **Fast** and doesn't wear out.
  - **Volatile**: data is lost when power is off.
  - Some MCUs allow **battery backup RAM**, so it survives short power losses.
- **Example sizes (STM32 Nucleo)**:

    - 512 KB Flash
    - 96 KB RAM
- Compared to a laptop or phone, this is tiny. But for MCU tasks (like reading sensors, controlling motors, handling communication), it's often plenty.
- If **internal memory isn't enough**, you can connect **external memory chips**. This is slower but sometimes necessary.

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4. System Bus

- Inside the MCU, all parts must communicate → this is handled by the **system bus**.
- Think of it like a **city bus system**: passengers (data) move between different stops (CPU, RAM, Flash, peripherals).
- **Parallel bus**: moves many bits at once, very fast, but requires lots of internal wires.
- Larger systems (PCs) also use buses, but often external.
- Real MCUs usually have **several buses** connected together to avoid bottlenecks.
- You usually don't worry about buses directly, except with **DMA controllers**, which rely on bus efficiency.

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5. Peripherals

- **Peripherals** are hardware modules that extend the CPU's basic capabilities.
- They connect to the **system bus** (for configuration by the CPU) and to **I/O pins** (to interact with the outside world).
- Examples:
    - **UART (Universal Asynchronous Receiver/Transmitter)**
        - Sends and receives data serially (1 bit at a time).
        - Example: talking to a PC console or GPS module.
        - USART adds synchronous mode (rarely used).
    - **Timers**
        - *System timer*: provides a tick (e.g., 1 ms).
        - *General-purpose timers*: measure time, count events, or generate PWM.
    - **GPIO (General Purpose I/O)**
        - Digital pins you can configure as input (switch) or output (LED).
    - **ADC (Analog to Digital Converter)**
        - Converts analog voltage (e.g., microphone signal) into a digital value.
    - **I^2C (Inter-Integrated Circuit)**
        - Serial bus for communication with sensors, displays, or other chips.
    - **SPI (Serial Peripheral Interface)**

        - Another serial bus, often faster than I²C. Example: external flash memory.
    - **DMA (Direct Memory Access)**
        - Moves data automatically without CPU involvement.
        - Example: sending data from RAM to SPI buffer.
        - Frees CPU to do "smarter" work.

👉 An MCU often has **multiple instances** of each peripheral. Example: 3 UARTs, 4 timers, several ADC channels.

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6. Pin Multiplexer and Electrical Config

- **Problem**: MCU has more peripheral signals than pins available.
- **Solution**: Pin multiplexer → maps internal signals to external pins.
- Not fully flexible: each pin can only support a limited set of functions.
- IDE tools help avoid conflicts.
- **GPIO exception**: any pin can always be used as GPIO.
- **Electrical configuration**: each pin can also be set as input or output, with optional pull-up/pull-down resistors.
- **Package choice**:
    - More pins = more mapping options.
    - Example: 100-pin package makes it easier to use multiple peripherals simultaneously.

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7. Interrupt Controller

- An **interrupt** is a way for hardware to get the CPU's attention quickly.
- CPU has limited interrupt inputs (e.g., 1–2).
- MCU might have **50+ interrupt sources** (UART, GPIO, timers).
- **Interrupt controller**:
    - Collects all interrupt requests.
    - Tells CPU which source triggered.
    - Supports **priorities**, so urgent events (like emergency stop) can override less urgent ones.
- Example: UART receives a character → raises interrupt → CPU runs "UART handler code" → then goes back to its previous work.

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8. Clocks

- **Digital hardware runs step by step** → the clock signal sets the speed.
- MCUs often have **multiple clocks** for different modules (CPU, bus, peripherals).
- **External crystal**: provides very accurate timing (good for precise time measurement).
- **Internal oscillator**: cheaper, less accurate, sometimes "good enough."
- **Power trade-off**:
  - Higher frequency = faster, but uses more power.
  - Lower frequency = slower, but saves power.
- **Trick**: Turn off clocks to unused modules to save power.
- **RTC (Real Time Clock)**:
  - Keeps calendar time (hours, minutes, seconds).
  - Often has battery backup so it runs even when the MCU is off.

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9. Debug Interface

- Essential for software development.
- Functions:
  - Control MCU from debugger (step, pause, inspect).
  - Read/write memory.
  - Program flash with your code.
- Standards:
  - **JTAG**: uses 5 signals.
  - **SWD (Serial Wire Debug)**: ARM standard, uses only 2 signals (common in STM32).
  - **SWIM**: single-wire debug (other MCU families).
- By default, **debug pins are reserved** on startup so you can always connect a debugger.
- Later, you can reassign those pins for other functions if needed.

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10. Software Setup

- When MCU powers on, CPU starts executing code from **flash**.
- First steps of your software: **configure hardware** (clocks, peripherals, pins, interrupts).
- IDE can help by generating setup code, but ultimately **you are responsible**.
- If code misbehaves, people blame you, not the IDE.

✅ **Key Takeaway**:
An MCU is like a **mini-computer in a single chip**.

- CPU runs your code.
- Flash holds the program, RAM holds the data.
- A system bus ties everything together.
- Peripherals handle communication, timing, analog signals, etc.
- The pin multiplexer decides what each pin does.
- Interrupts make the CPU responsive.
- Clocks set speed and power usage.
- Debug interfaces make programming possible.