Lecture 02
Microcontrollers

CE346 – Microcontroller System Design

Branden Ghena – Fall 2024

Some slides borrowed from:
Josiah Hester (Northwestern), Prabal Dutta (UC Berkeley)

Class Updates

- No “official” lab this Friday

- Personal Software Setup will be posted tonight
  - At some point
  - Gotta finish updating it

- Office hours will start sometime next week
  - If you need help with the software setup, always feel free to reach out on Piazza!

Today's Goals

- Explore microcontrollers
  - How do they compare to computers?
  - Purpose, capabilities, tradeoffs
- Describe history and state-of-the-art for microcontrollers
- Explore the microcontroller(s) on the Microbit

Outline

- **Microcontrollers and Computers**
- Microcontroller Design
- Microcontroller History
- Microbit microcontroller

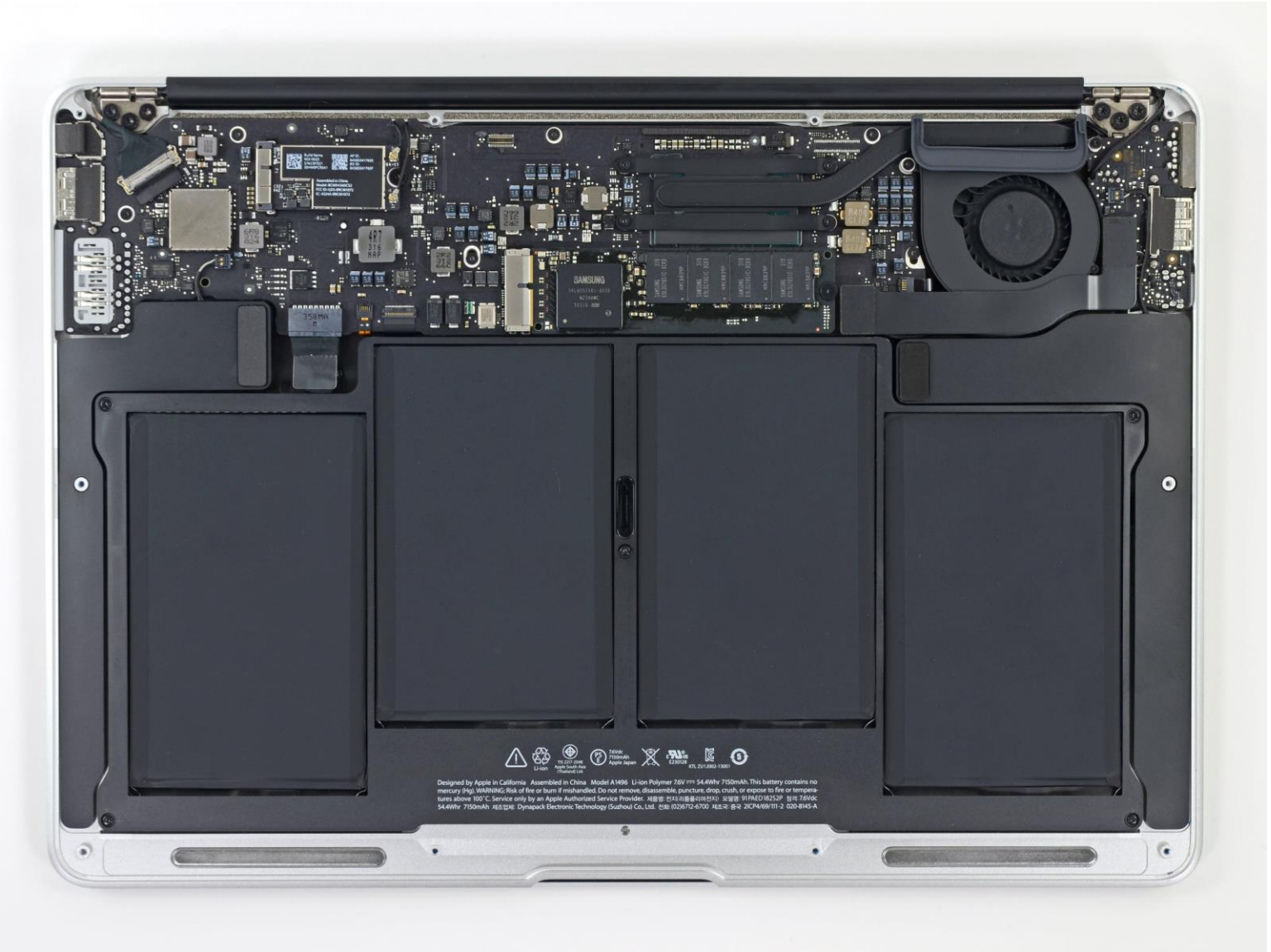
What's inside a computer?

- Macbook Air (circa 2013, 2nd gen)
  - Modern computers are mostly similar
  - Intel Core i5 processor
  - 128 GB Flash storage
  - 4 GB DDR3 RAM
  - 1440x900 pixel display
- Picked because there is a teardown I like of an embedded device from the same year

https://www.ifixit.com/Teardown/MacBook+Air+13-Inch+Mid+2013+Teardown/15042

Unscrewing the bottom cover

- Top half is the motherboard
  - Holds and connects all the parts of the computer
- Bottom half are battery packs



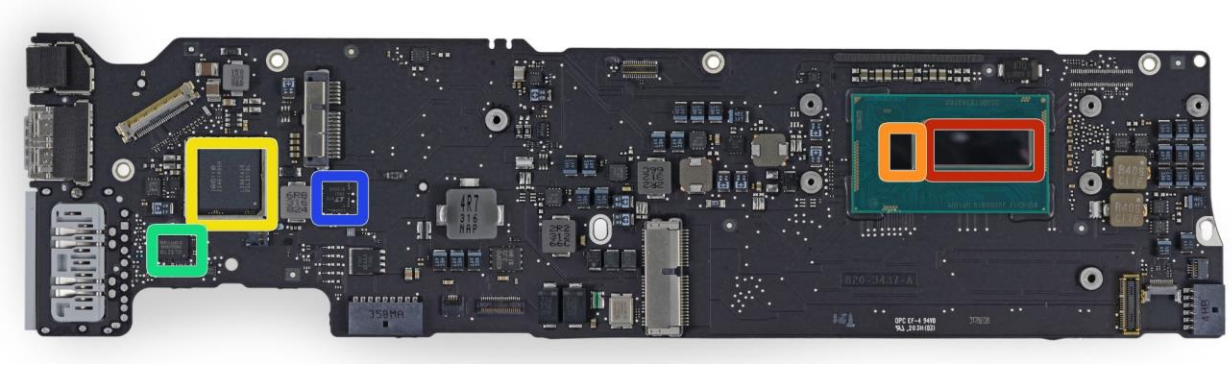
Non-volatile long-term storage: SSD

- The SSD is a module that connects through PCIe

- In modern laptops the SSD is often soldered directly onto the motherboard

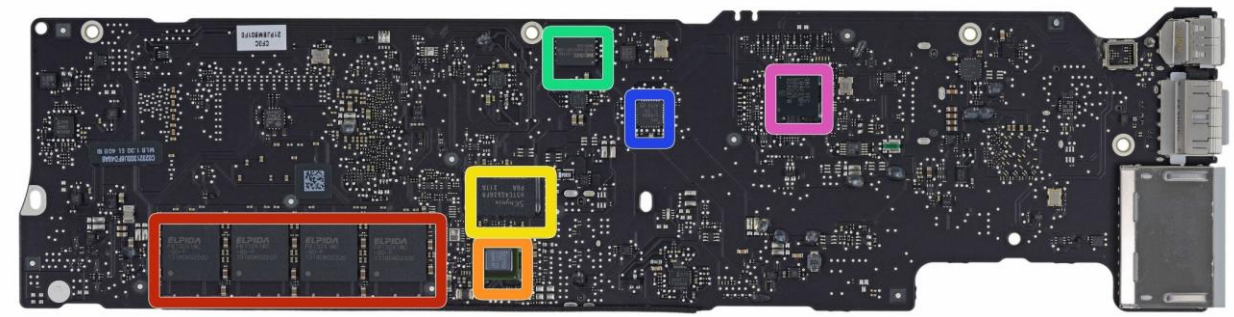
Investigating the motherboard

Front



- Red (front, right)
  - Intel core i5 processor
- Red (bottom, left)
  - Elpida LPDDR3 RAM, 4 GB

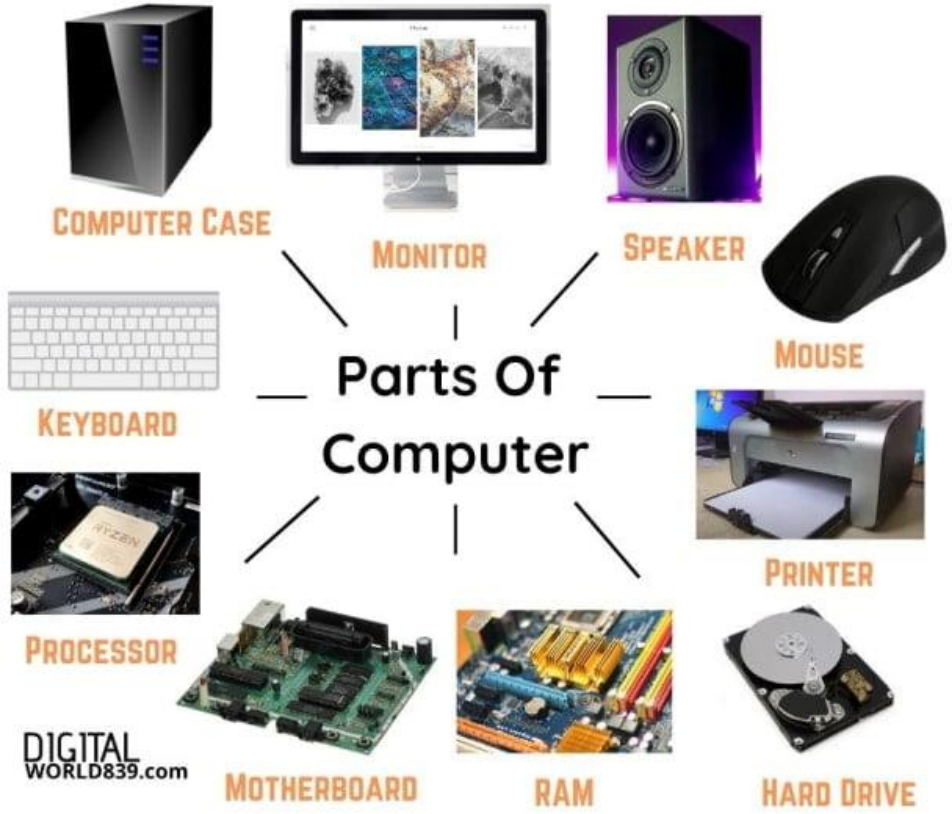
Back



- Other stuff are mostly radios, USB/Thunderbolt controllers, and power supply

Generalizing computer design

- Computers *usually* need
  - Processor
  - Memory (RAM)
  - Storage (Flash/SSD)
  - External communication
    - USB, Thunderbolt, SATA, HDMI, WiFi
  - Power management
    - Maybe batteries and charging
  - Something to connect it all: motherboard



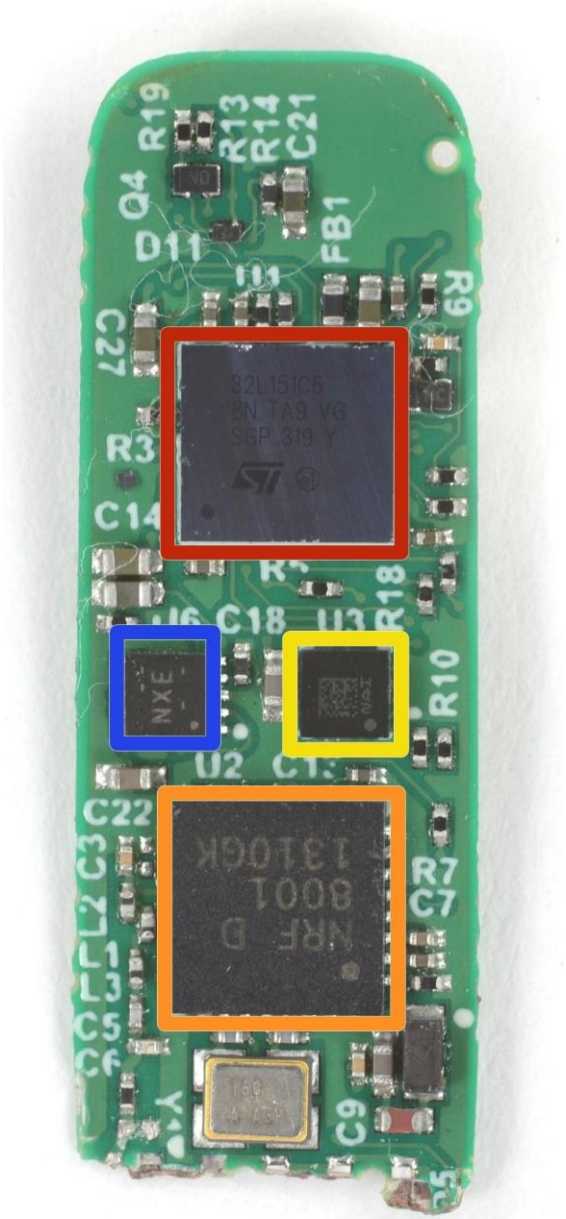
What's inside a Fitbit?

- Fitbit flex (circa 2013)
- Features
  - Counts your steps
  - Reports via Bluetooth Low Energy
  - Lights up some LEDs based on your goals
  - Vibrates when its battery is low

https://www.ifixit.com/Teardown/Fitbit+Flex+Teardown/16050

Fitbit teardown

Fitbit circuit board front



- Red (top)
  - STMicro 32L151C6 Microcontroller
- Blue (left)
  - TI BQ24040 Battery Charger
- Yellow (right)
  - STMicro LIS2DH Accelerometer
- Orange (bottom)
  - Nordic nRF8001 Bluetooth Low Energy Radio

The back is uninteresting

Fitbit as a computer

- Computers *usually* need
  - Processor
  - Memory (RAM)
  - Storage (Flash/SSD)
  - External communication
    - USB, Thunderbolt, SATA, HDMI, WiFi
  - Power management
    - Maybe batteries and charging
  - Something to connect it all: motherboard

- Microcontroller
- Bluetooth radio
- Vibratory motor
- Battery and power management
- Circuit board

Sidebar: you could make a Fitbit yourself

- All those parts are commercially available, so you could make your own Fitbit if you wanted to

1. Make a circuit board
2. Buy those parts and solder them on
3. Write some embedded software
4. Make a plastic case
5. … build a big software backend for everything
6. You've got a Fitbit!

Categories of computer chips

- Microprocessor (MPU or Processor)
  - CPU + Bus/Pins
  - No memory or peripherals
- Microcontroller (MCU)
  - CPU + Pins + Memory + Peripherals
  - Peripherals: separate hardware units within chip
    - Often I/O interfaces
- System on a Chip (SoC)
  - Microcontroller + Extensive Peripherals
  - Example: Radios or ML Accelerators
  - Essentially multiple chips combined
- Evolution of increased complexity over time

Break + Extend your thinking

- Microprocessor (MPU or Processor)
  - CPU + Bus/Pins
  - No memory or peripherals

- Microcontroller (MCU)
  - CPU + Pins + Memory + Peripherals
  - Peripherals: separate hardware units within chip
    - Often I/O interfaces

- **Why ever build a computer with a Microprocessor?**

Break + Extend your thinking

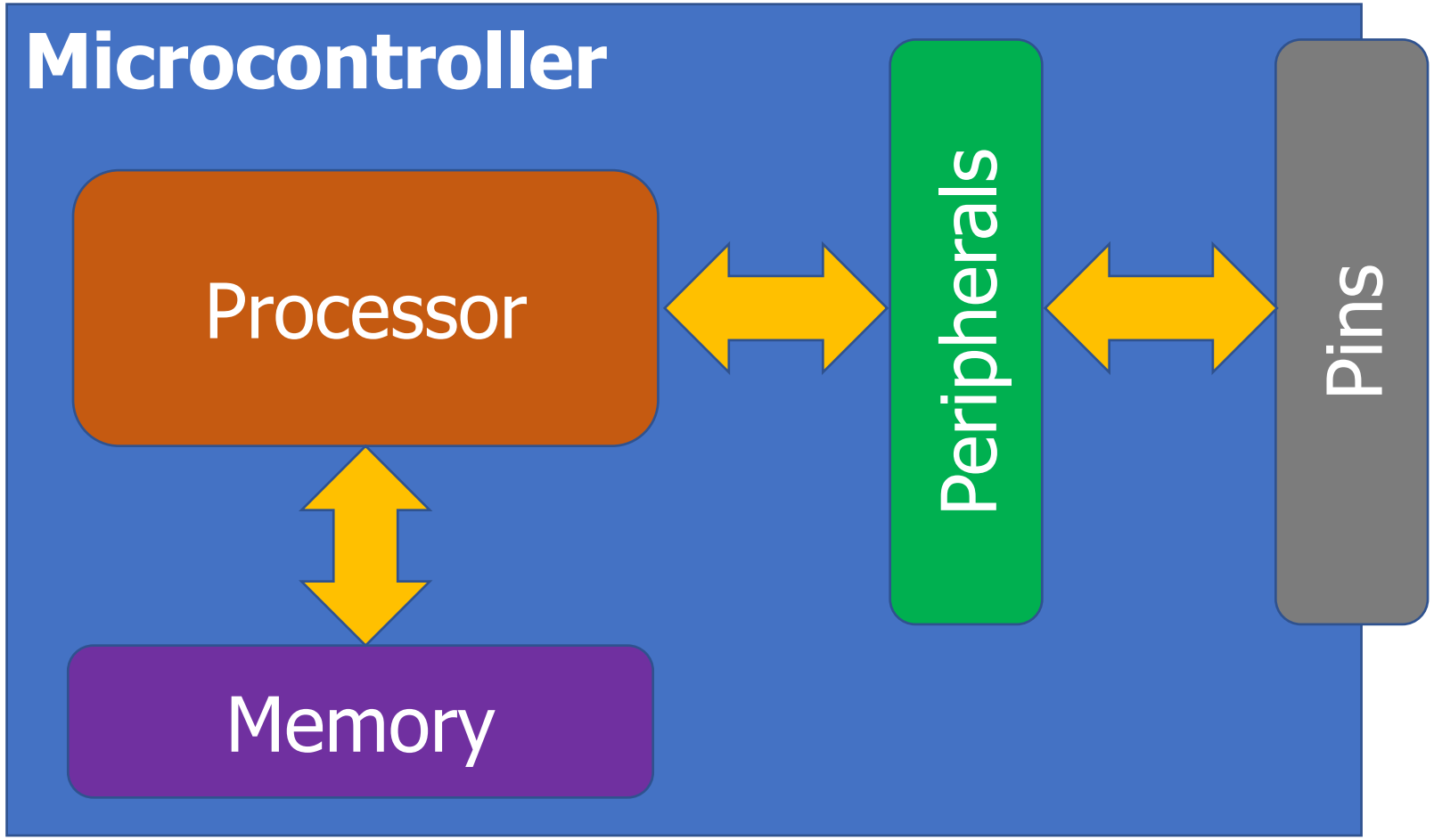
- Microprocessor (MPU or Processor)
  - CPU + Bus/Pins
  - No memory or peripherals
- Microcontroller (MCU)
  - CPU + Pins + Memory + Peripherals
  - Peripherals: separate hardware units within chip
    - Often I/O interfaces
- **Why ever build a computer with a Microprocessor?**
  - Microcontrollers have limited choice about memory or peripherals
  - Microcontroller memory/peripherals are more basic, because they have to fit together inside one chip

Outline

- Microcontrollers and Computers
- **Microcontroller Design**
- Microcontroller History

- Microbit microcontroller

Generic microcontroller block diagram



Processor

- Microcontroller needs to execute software instructions
- Emphasis: simple and reliable
  - i.e. **not** x86 CISC
- Often simple, in-order, short-pipeline RISC architectures
  - Literally a three-stage pipeline you may have learned in CS361
- Many different ISAs are possible
  - Custom ISAs and ARM (ARMv7E-M) are both common

Background: Instruction Set Architecture

- ISA includes the actual instructions as well as the model for how the computer interacts with memory
  - Registers, reading/writing, etc.

- Does the ISA for a microcontroller matter if you're not programming in assembly? (and I promise we won't)

Background: Instruction Set Architecture

- ISA includes the actual instructions as well as the model for how the computer interacts with memory
  - Registers, reading/writing, etc.

- Does the ISA for a microcontroller matter if you're not programming in assembly? (and I promise we won't)
  - Yes
  - Differences in instruction efficiency and amount are important
  - Differences in compiler support are VERY important

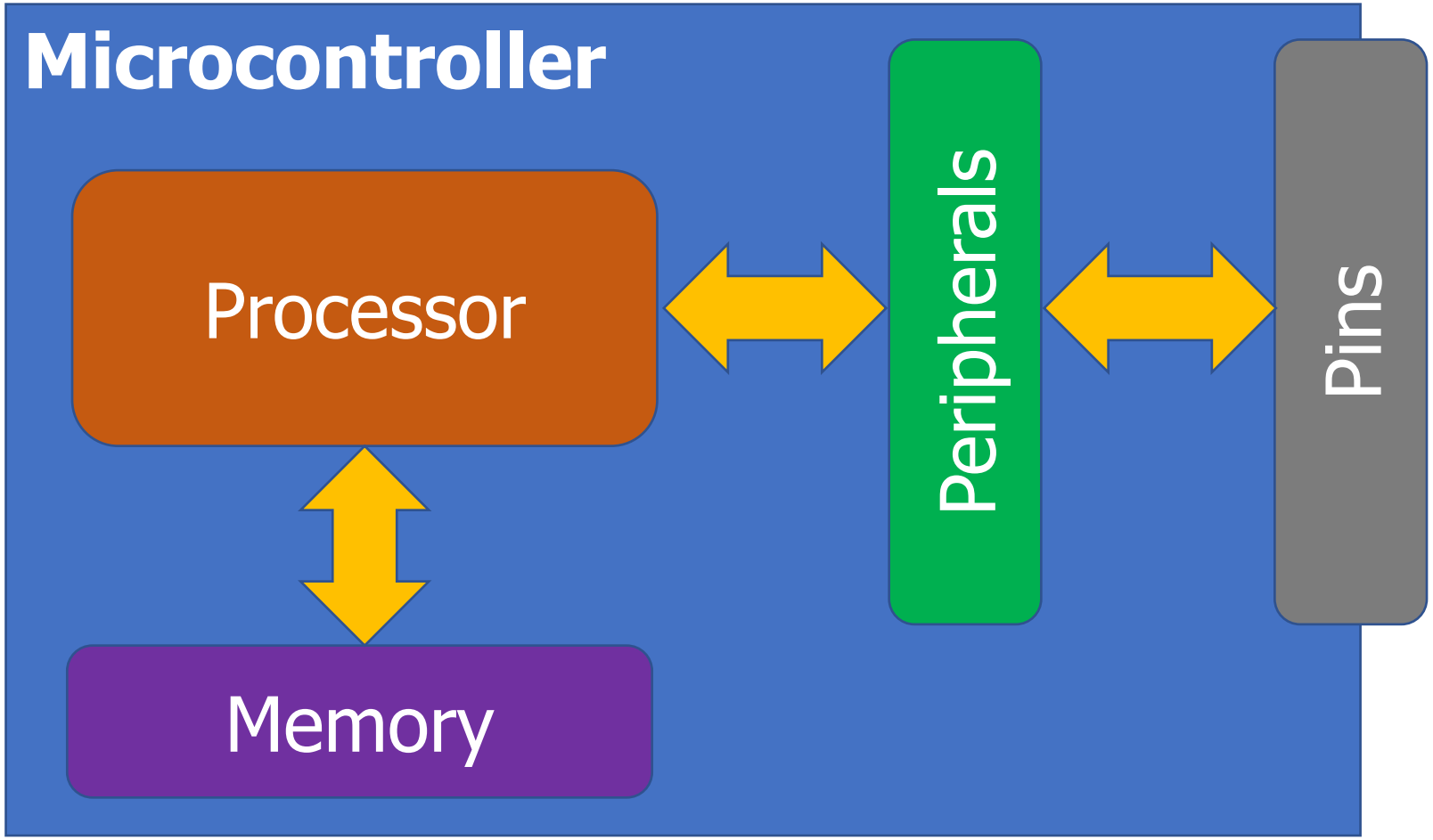
Processor design choices for embedded

- How many bits is the architecture?
  - 8-bit and 16-bit not uncommon
  - 64-bit is very rare (who has that much memory?)

- What instructions are supported?
  - Normal stuff yes
  - What about single-cycle multiply?
  - What about floating-point operations?
  - Vector instructions?

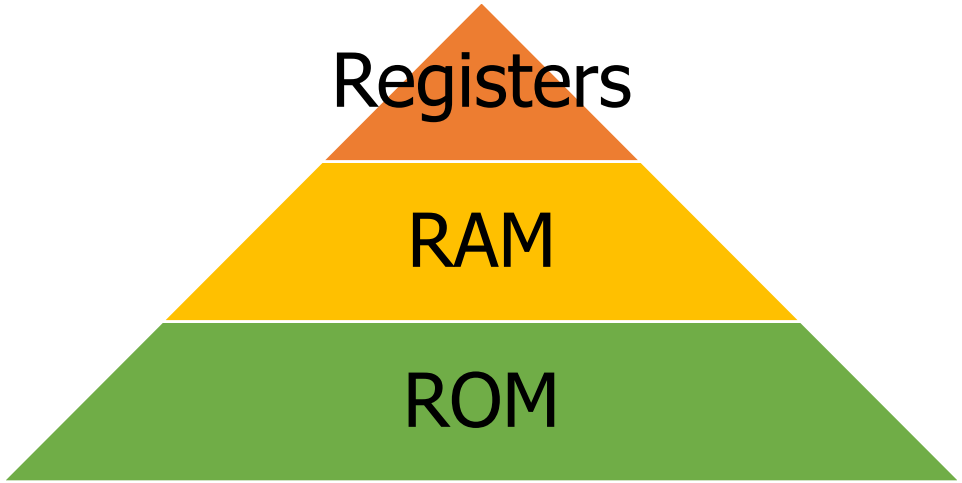
- How fast does it run?
  - 1-100 MHz is common on modern systems (faster is more energy cost)
  - Occasionally MUCH slower (think 32 kHz)

Generic microcontroller block diagram



Memory

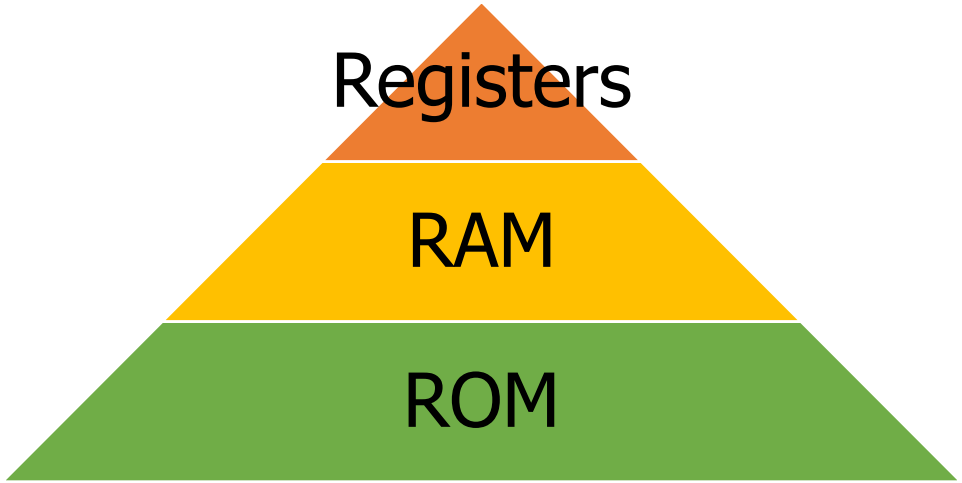
- Embedded memory hierarchy



- **What's missing? Why?**

Memory

- Embedded memory hierarchy



- **What's missing? Why?**
  - **Cache**
  - **Makes timing unreliable**

More modern microcontrollers often have optional instruction caches

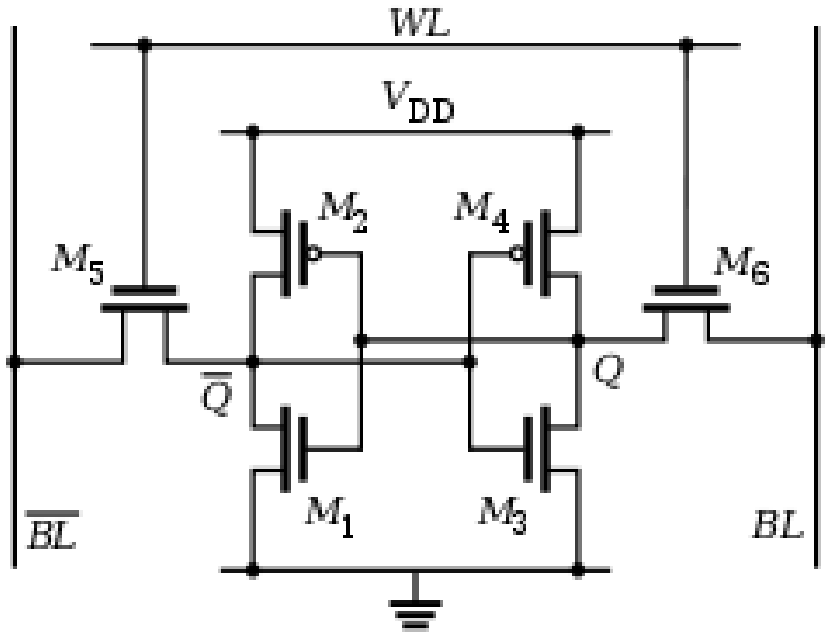
Can be enabled by software

Volatile memory: SRAM

- Same design as registers in traditional computer systems
  - No need to refresh it -> lower energy costs

- Embedded systems use SRAM for all of their memory (no DRAM)

- Tradeoffs:
  - Way less energy cost
  - Faster to access
  - More expensive
  - Physically larger



Non-Volatile memory: Flash (usually)

- Same design as SSDs and Flash drives

- Memory is stored with no energy costs
  - Reading is lowish energy and quick
  - Writing is high energy and very slow
    - Writing also has to occur in blocks (e.g. 512 bytes)

- Concern: Flash has a limited lifetime ~10,000 writes
  - Only writing to Flash when you load code? Essentially forever
  - Recording data to Flash every second? 2.8 hours

SRAM (RAM) versus Flash (ROM) memory

- Size and time difference between non-volatile and volatile memory is *significantly* reduced from traditional computing
  - Non-volatile store 2-10x larger than volatile
  - Single-cycle RAM. Maybe two-cycles to Flash (to read)

- Major difference: energy and writability
  - SRAM is low-energy to read and write (no refresh needed)
  - Flash is lowish-energy to read, but very high energy to write

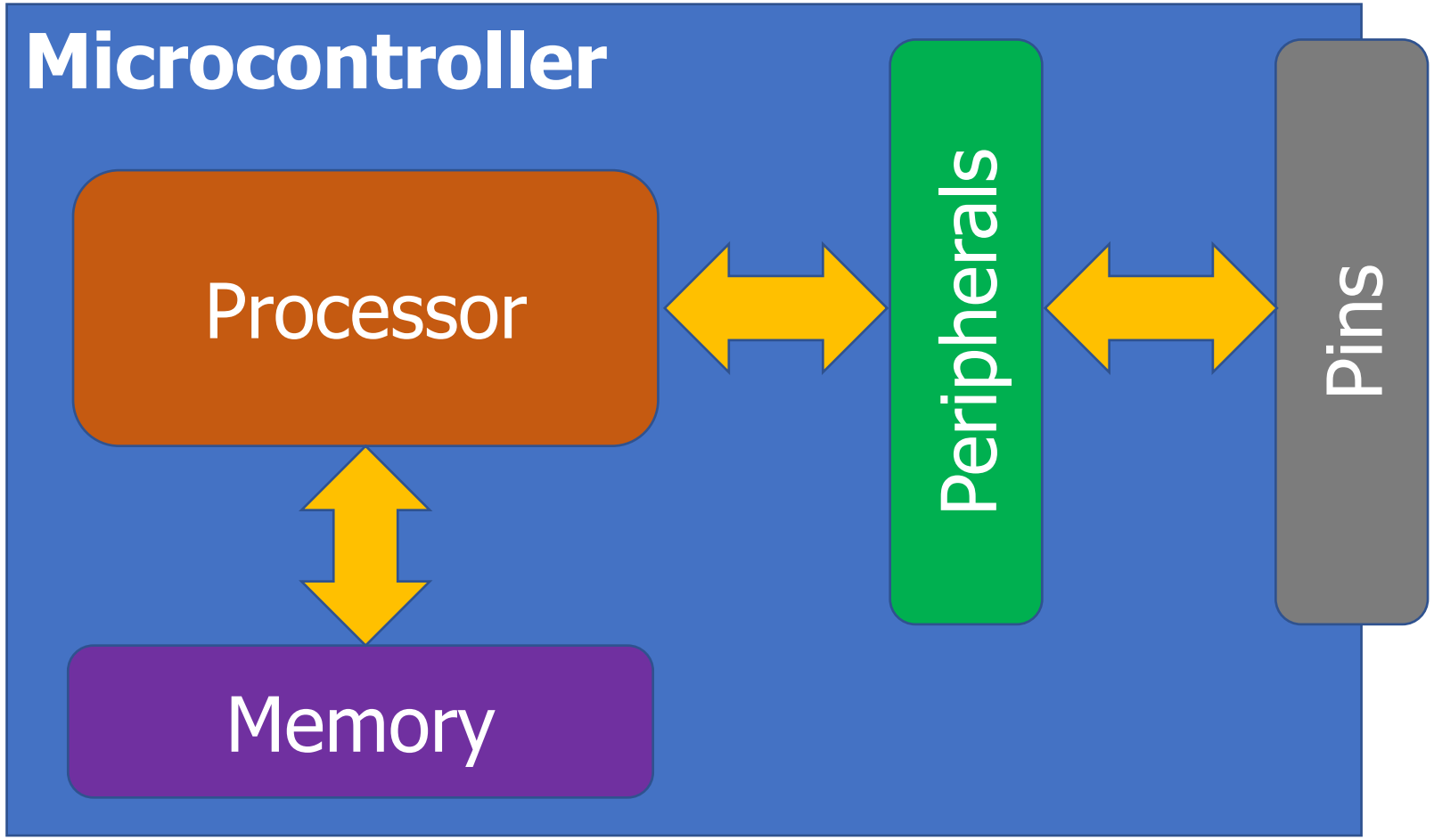
- Hierarchical structure is not enforced
  - Same address space for RAM and Flash (very different from traditional)
  - Run instructions right inside of Flash
  - Keep variables in RAM (or `const` variables in Flash)

Memory design choices

- How much memory can we fit without making it too high cost or too high power?
  - The answer has slowly increased over time
  - 15 years ago: 2 KB RAM – 32 KB Flash
  - Today: 256 KB RAM – 1 MB Flash

- How to provide memory safety?
  - Usually no virtual memory (all addresses are real addresses)
  - Nothing stops arbitrary memory overwriting
  - Modern systems: Memory Protection Unit
    - Specify a small number of ranges and permissions

Generic microcontroller block diagram

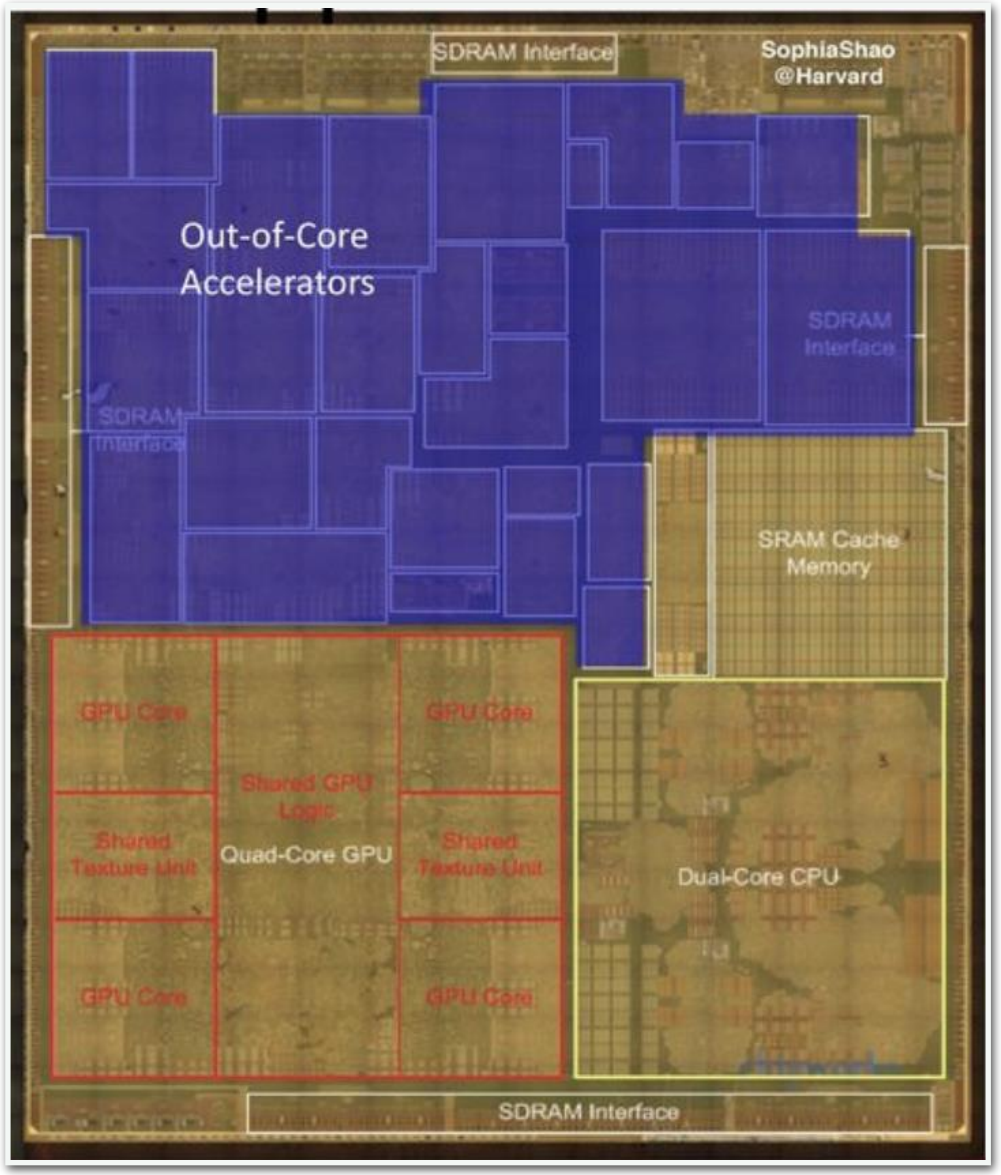


Peripherals

- Hardware modules that perform some action
- Common examples
  - Control digital input and output pins
  - Read analog inputs
  - Send messages over various simple wire protocols (UART, SPI, I2C)
  - Set and check timers
- Less common examples
  - Cryptography accelerators
  - Complicated wire protocols (USB, CAN)
  - Wireless radios (BLE, 802.15.4, WiFi)
- We'll spend most of class learning various peripherals

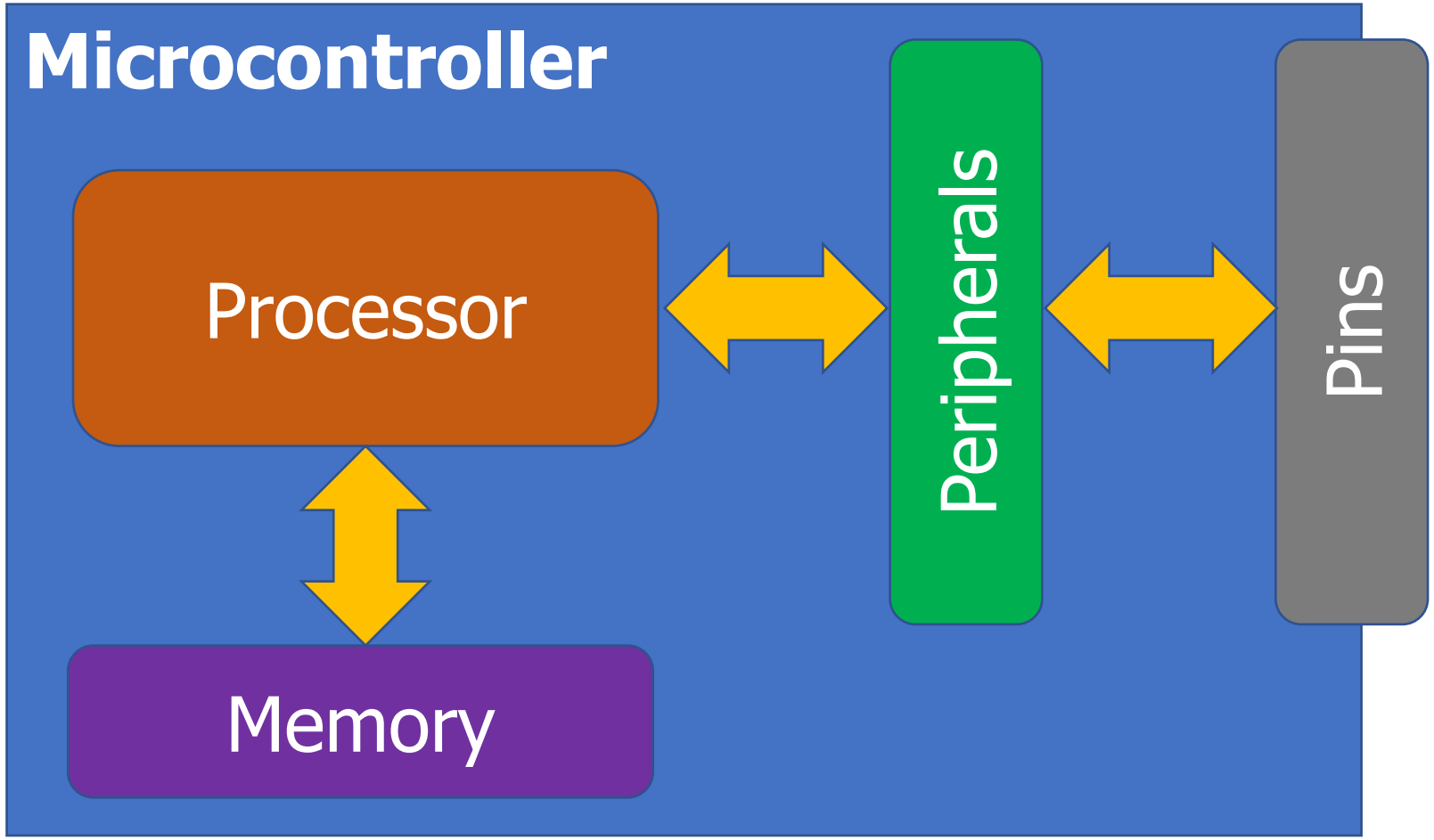
Peripheral design choices

- More peripherals mean more use cases
  - But also means more cost for the chip
  - Peripherals occupy silicon
  - Most peripherals will go unused for a given application…
- Flexibility tradeoffs within a given peripheral
  - One capability is easier to use
  - Many capabilities are more useful



Apple A8 SoC

Generic microcontroller block diagram

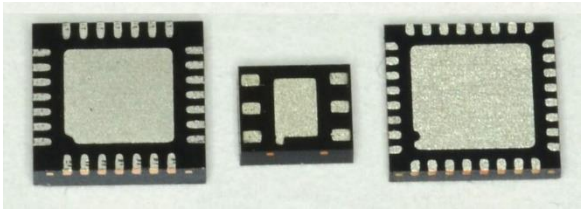


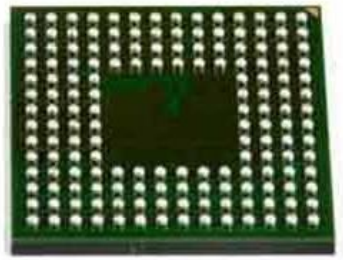
Pins

- Peripherals need to electrically connect to outside world
  - Attach to pins on the exterior of the chip

- More pins allow for more connections
  - At increased cost and size

- Pin layouts can add more pins for cheaper
  - But make soldering and debugging difficult





Internal connections to pins

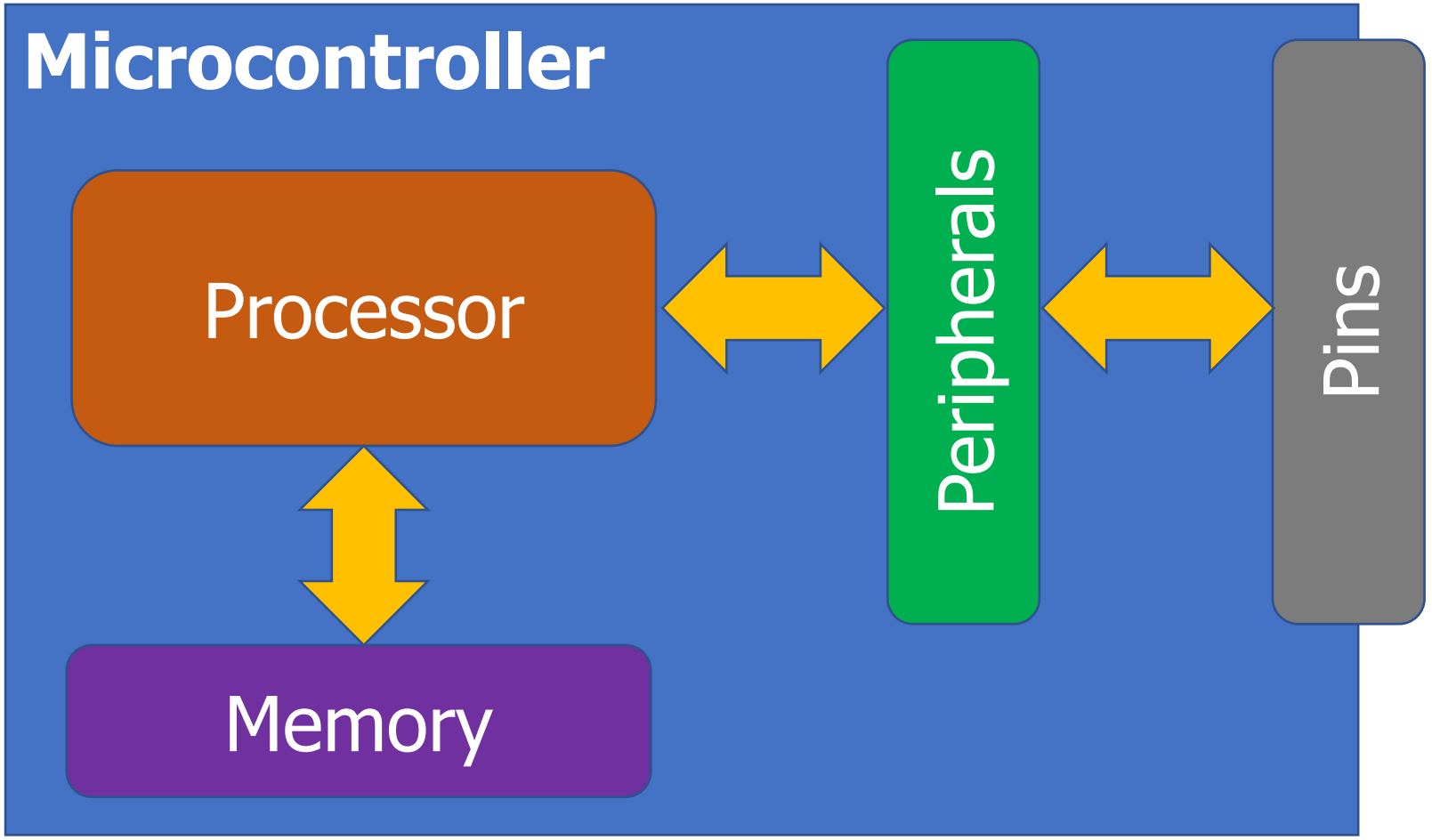
- Peripherals need to connect to external pins
  - Can any peripheral connect to any pin, or are there limited mappings?
  - Modern microcontrollers allow any-to-any connections

- Older MCUs had mapping tables and pin selection was more challenging

Table 3-1. 100-pin GPIO Controller Function Multiplexing (Sheet 1 of 4)

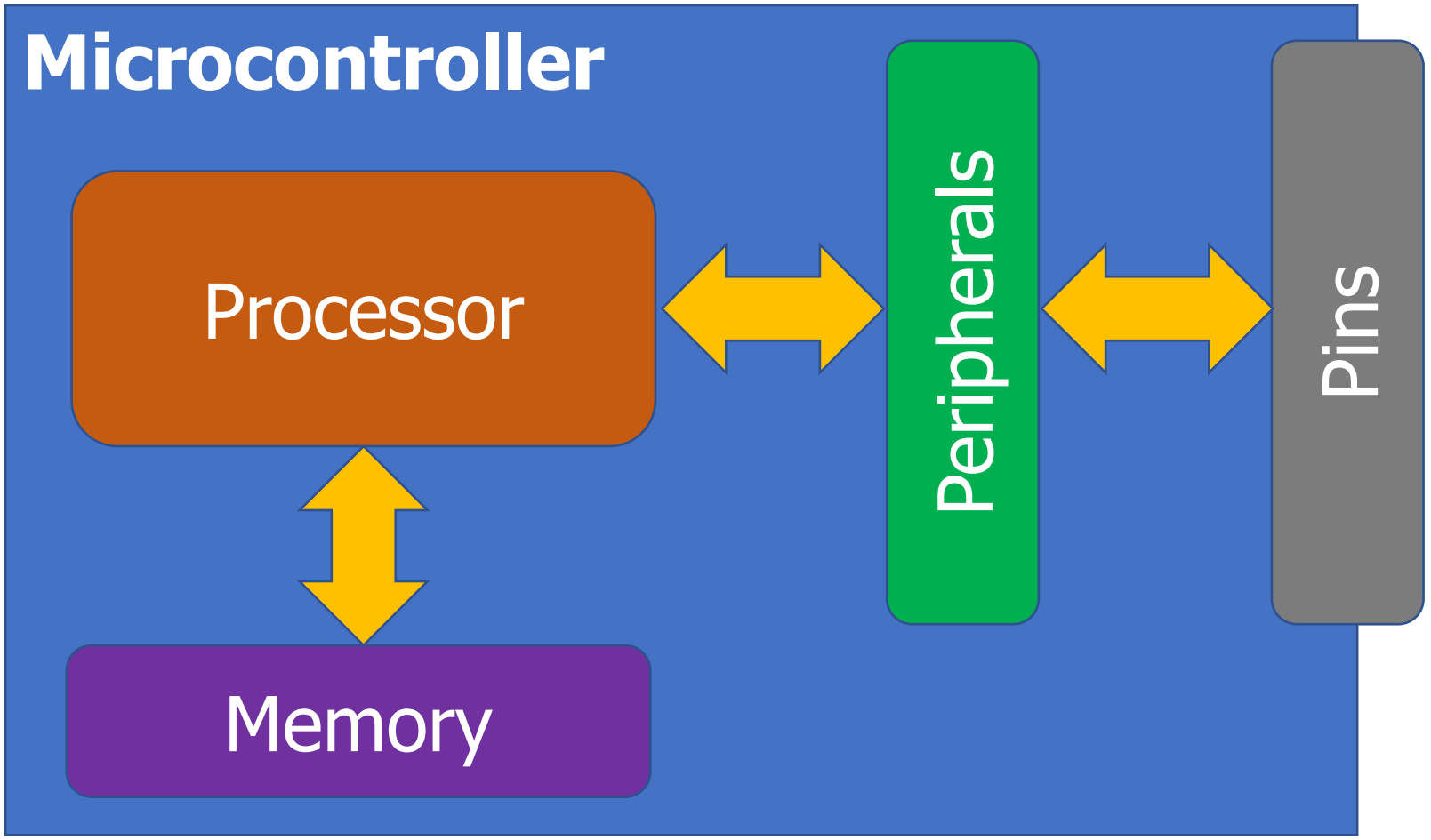
ATSAM4LC		ATSAM4LS		Pin	GPIO	Supply	GPIO Functions						
QFN	VFBGA	QFN	VFBGA				A	B	C	D	E	F	G
5	B9	5	B9	PA00	0	VDDIO							
6	B8	6	B8	PA01	1	VDDIO							
12	A7	12	A7	PA02	2	VDDIN	SCIF GCLK0	SPI NPCS0					CATB DIS
19	B3	19	B3	PA03	3	VDDIN		SPI MISO					
24	A2	24	A2	PA04	4	VDDANA	ADCIFE AD0	USART0 CLK	EIC EXTINT2	GLOC IN1			CATB SENSE0
25	A1	25	A1	PA05	5	VDDANA	ADCIFE AD1	USART0 RXD	EIC EXTINT3	GLOC IN2	ADCIFE TRIGGER		CATB SENSE1
30	C3	30	C3	PA06	6	VDDANA	DACC VOUT	USART0 RTS	EIC EXTINT1	GLOC IN0	ACIFC ACAN0		CATB SENSE2

What haven’t we talked about?



What haven’t we talked about?

- **Power**
- **Programming**
- **Others?**
  - Clocks
  - Antennas



Powering microcontrollers

- Usually require a specific voltage
  - E.g. 5 volts, 3.3 volts, 1.8 volts
  - Must be stable and supply enough current (or MCU “browns out”)
  - Noisy power supply can be an issue

- Some microcontrollers have wider ranges of acceptable voltages
  - Need to pay attention to acceptable range on I/O though

Programming microcontrollers

- JTAG (Joint Test Action Group)
  - Hardware built into the microcontroller for testing purposes
  - Can arbitrarily read/write memory
  - Can single step process too, at runtime!
    - GDB can connect to it! (sort of)

- Bootloaders
  - Software runs on the microcontroller at boot that waits a short time for someone to contact it and upload code
    - Via I/O pins
  - Convenient, but sometimes unreliable

Break + Open Question

- How little memory (RAM and/or ROM) can a computer have and still be useful?

Break + Open Question

- How little memory (RAM and/or ROM) can a computer have and still be useful?
  - If we want to run C code, we need a stack and a global data section
  - Function calls may require local variables to be placed in the stack

  - To use less memory, we'd need to write applications in registers
  - Most variables could *probably* fit in registers?
  - So the limit could get *very* low
    - Enough ROM space for some useful code + a tiny bit of RAM

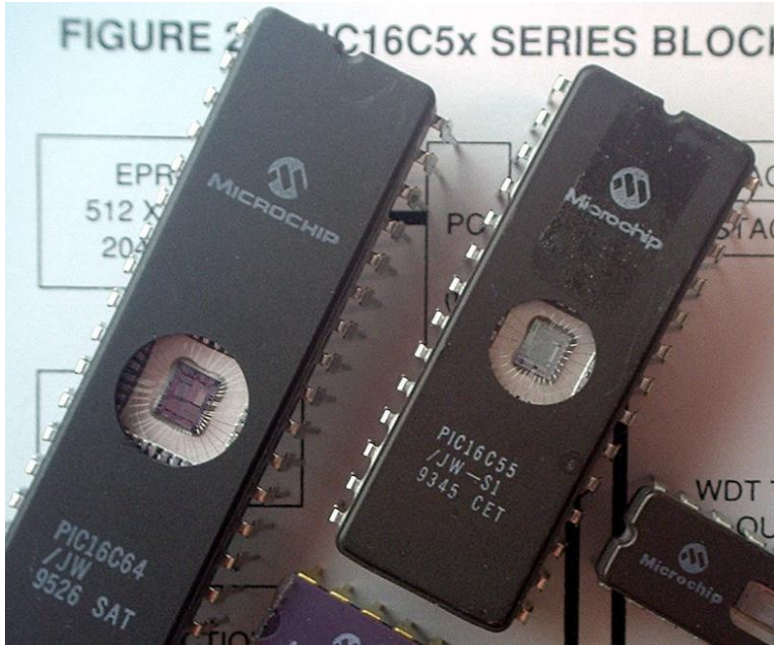
  - Real-world answer coming on the next slide

Outline

- Microcontrollers and Computers
- Microcontroller Design
- **Microcontroller History**
- Microbit microcontroller

Older microcontrollers (90s-00s)

- Focus: cheap, small computer systems



- PIC
  - 8, 16, and 24-bit MIPs architecture
  - PICAXE available with Basic interpreter

- AVR
  - 8-bit custom architecture (AVR architecture)
  - Used in Arduinos
  - AT Tiny 4: $0.30 per unit
    - 4 I/O pins, 32 Bytes RAM, 512 Bytes ROM

More capable microcontrollers (00s-10s)

- Focus: diversify into extreme low power and more capable systems

- MSP430
  - 16-bit custom architecture (MSP430 architecture)
  - Capable, but also extremely low power
    - <1 μA sleep current

- STM32, Atmel SAM series (Cortex-M0, M3, M4, M4F)
  - 32-bit ARM architecture (ARMv7)
    - Leverage success of ARM on smartphones
  - Every peripheral under the sun. Plus a variety of memory choices

Cortex M Series

- A number of options for increasing capabilities

- In practice:
  - Cortex-M0+ for low-end systems
  - Coretx-M4 for high capability systems

ARM Cortex-M instruction variations

Arm Core	Cortex M0[2]	Cortex M0+[3]	Cortex M1[4]	Cortex M3[5]	Cortex M4[6]	Cortex M7[7]
ARM architecture	ARMv6-M[9]	ARMv6-M[9]	ARMv6-M[9]	ARMv7-M[10]	ARMv7E-M[10]	ARMv7E-M[10]
Computer architecture	Von Neumann	Von Neumann	Von Neumann	Harvard	Harvard	Harvard
Instruction pipeline	3 stages	2 stages	3 stages	3 stages	3 stages	6 stages
Thumb-1 instructions	Most	Most	Most	Entire	Entire	Entire
Thumb-2 instructions	Some	Some	Some	Entire	Entire	Entire
Multiply instructions 32x32 = 32-bit result	Yes	Yes	Yes	Yes	Yes	Yes
Multiply instructions 32x32 = 64-bit result	No	No	No	Yes	Yes	Yes
Divide instructions 32/32 = 32-bit quotient	No	No	No	Yes	Yes	Yes
Saturated instructions	No	No	No	Some	Yes	Yes
DSP instructions	No	No	No	No	Yes	Yes
Single-Precision (SP) Floating-point instructions	No	No	No	No	Optional	Optional
Double-Precision (DP) Floating-point instructions	No	No	No	No	No	Optional

Modern system-on-chips (10s-?)

- Focus: increase memory and capability
  - Include radios in the same chip

- nRF51 and nRF52 series
  - 32-bit ARM microcontrollers (Cortex M)
  - Include 2.4 GHz radio: Bluetooth Low Energy and 802.15.4/Thread

- Others have followed this same path
  - TI CC26XX
  - Apollo3
  - STM32WL

Future microcontrollers

- Multi-core systems
  - Not for performance, but for separation of concerns
    - Run radio code on one core
    - Application code goes on the other core
  - Also allows BIG.little architecture
    - Higher performance core when interpreting data
    - Lower performance core for sampling sensors
  - nRF54 series really emphasizes this
    - Multiple BIG ARM processors and little RISC-V processors

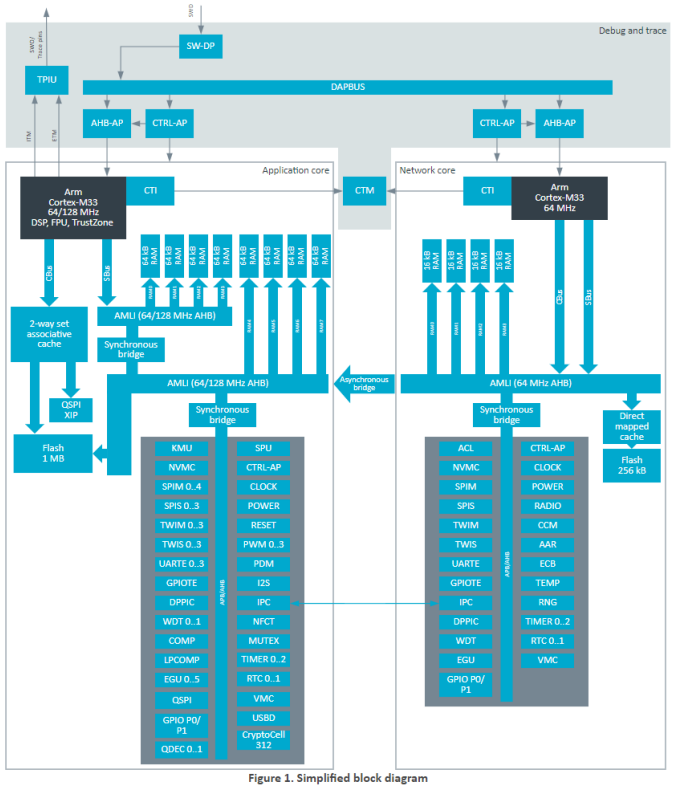


Figure 1. Simplified block diagram

Break + Open Question

- Consider the lifecycles of computer systems
  - i.e., how long are people still actively using them for?

  - **How long does a processor generation need to be supported?**
    - **Think Intel Core i7-7500U or Apple M1**

  - **How long does a microcontroller chip need to be supported?**
    - **Think nRF52833 or MSP430**

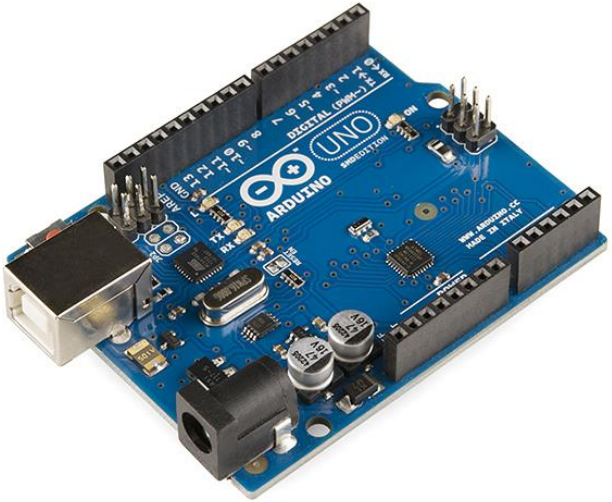
Break + Open Question

- Consider the lifecycles of computer systems
  - i.e., how long are people still actively using them for?

  - **How long does a processor generation need to be supported?**
    - **Think Intel Core i7-7500U or Apple M1**
    - After some number of years, new products no longer use it
    - Old products eventually wear out or are unsupported

  - **How long does a microcontroller chip need to be supported?**
    - **Think nRF52833 or MSP430**
    - New products might still use them years later, because redesigning embedded systems is hard and new chips aren’t that much better

Popular components rarely die



- Majority of popular older options still exist
  - Designers can trade off cost, capability, and efficiency alongside "modern features"
- Upgrading for an existing product is unlikely
  - Large cost, little benefit

- Example: Arduino still primarily uses AVR
  - Works just fine for its needs
  - Also releases new boards with nRF52s (Arduino Nano 33 BLE)

Fall 2024: cheapest microcontroller

- ATTINY10-TSHR
  - 8-bit custom architecture
  - 32 bytes of RAM
  - 1 kB of Flash
  - 4 I/O pins

  - $0.44 per microcontroller
    - Still an “active” chip being manufactured

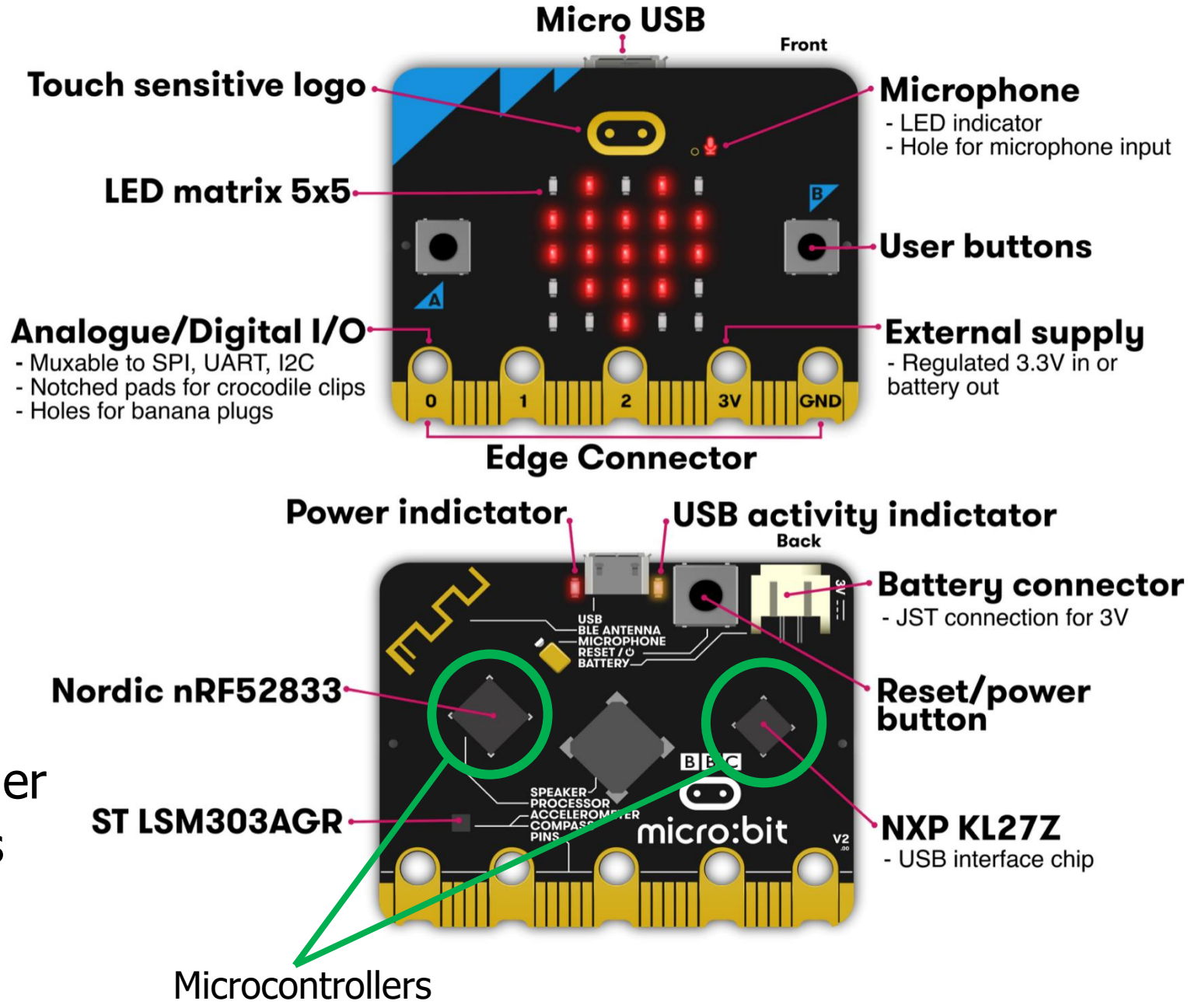
Outline

- Microcontrollers and Computers
- Microcontroller Design
- Microcontroller History

- **Microbit microcontroller**

Micro:bit v2

- Circuit board
  - Entire thing
  - a.k.a “Dev Board”
  - a.k.a PCB (Printed Circuit Board)
- Microcontroller
  - The computer on it
  - Microbit has two
    - One as a programmer
    - One for applications

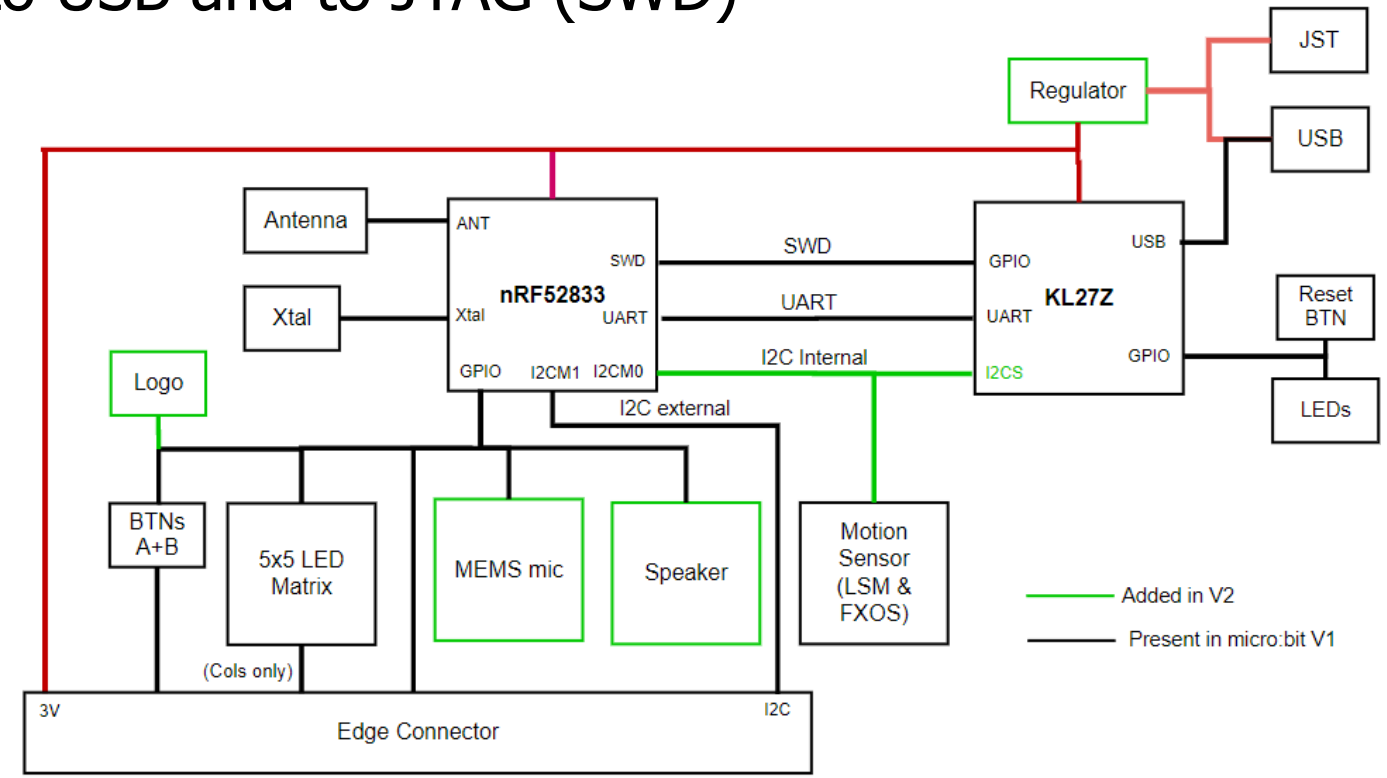


nRF52833 – Microcontroller on the Micro:bit v2

- 32-bit ARM Cortex-M4F microcontroller
  - 64 MHz core, 128 KB RAM, 512 KB Flash
  - Floating point support
  - 2.4 GHz Radio: Bluetooth Low energy / 802.15.4
  - Various peripherals
    - ADC, PWM
    - I2C, UART, SPI, USB
    - RNG, 32-bit Timers, Watchdog, Temperature
    - Up to 42 I/O pins

KL27Z – Programmer on the Micro:bit v2

- 32-bit ARM Cortex-M0+ microcontroller
  - 48 MHz core, 16 KB RAM, 256 KB Flash
- Acts as a programming interface to nRF52833
  - Connects to USB and to JTAG (SWD)



Microbit version 2.2

- Starting in 2020 there was a global chip shortage
  - Lots of demand for electronics
  - Reduced supply due partly to pandemic
- Microbit had to come out with a revision
  - Replaced KL27Z (the programmer chip) with a WAY more capable nRF52820
- This has caused some annoyances for lab that I needed to fix
  - The programming interface changed a little

To the datasheet!

- nRF52833 Product Specification
  - Online: https://docs.nordicsemi.com/bundle/ps_nrf52833/page/keyfeatures_html5.html
  - PDF: https://docs-be.nordicsemi.com/bundle/ps_nrf52833/attach/nRF52833_PS_v1.7.pdf

Outline

- Microcontrollers and Computers
- Microcontroller Design
- Microcontroller History

- Microbit microcontroller(s)