Introduction to Embedded Hardware for Machine Learning

Michael Stanley

http://sensip.asu.edu

Mike.Stanley@ieee.org

Lecture materials can be accessed at
https://github.com/mstanley103/SenSIP_RET_2021

Arizona State University

SenSIP INDUSTRY CONSORTIUM

Lecture Mission Statement

Platforms such as Arduino and Raspberry Pi make it their mission to provide easy to use development tools. This lecture provides some basic vocabulary to get you started and introduces you to some of the tradeoffs of choosing an embedded implementation.

Today's lecture is about embedded hardware for machine learning

- Vocabulary
- Options for Training & Deployment
  - Cloud
  - PC
  - Embedded
- MCU Architecture
- What you need to know about your embedded board
- Introduction to Sensors
  - Scalar sensors: Temperature, Pressure, Humidity, Microphone
  - Vector sensors: Accelerometer, Magnetometer, Gyroscope
  - Vision

Vocabulary

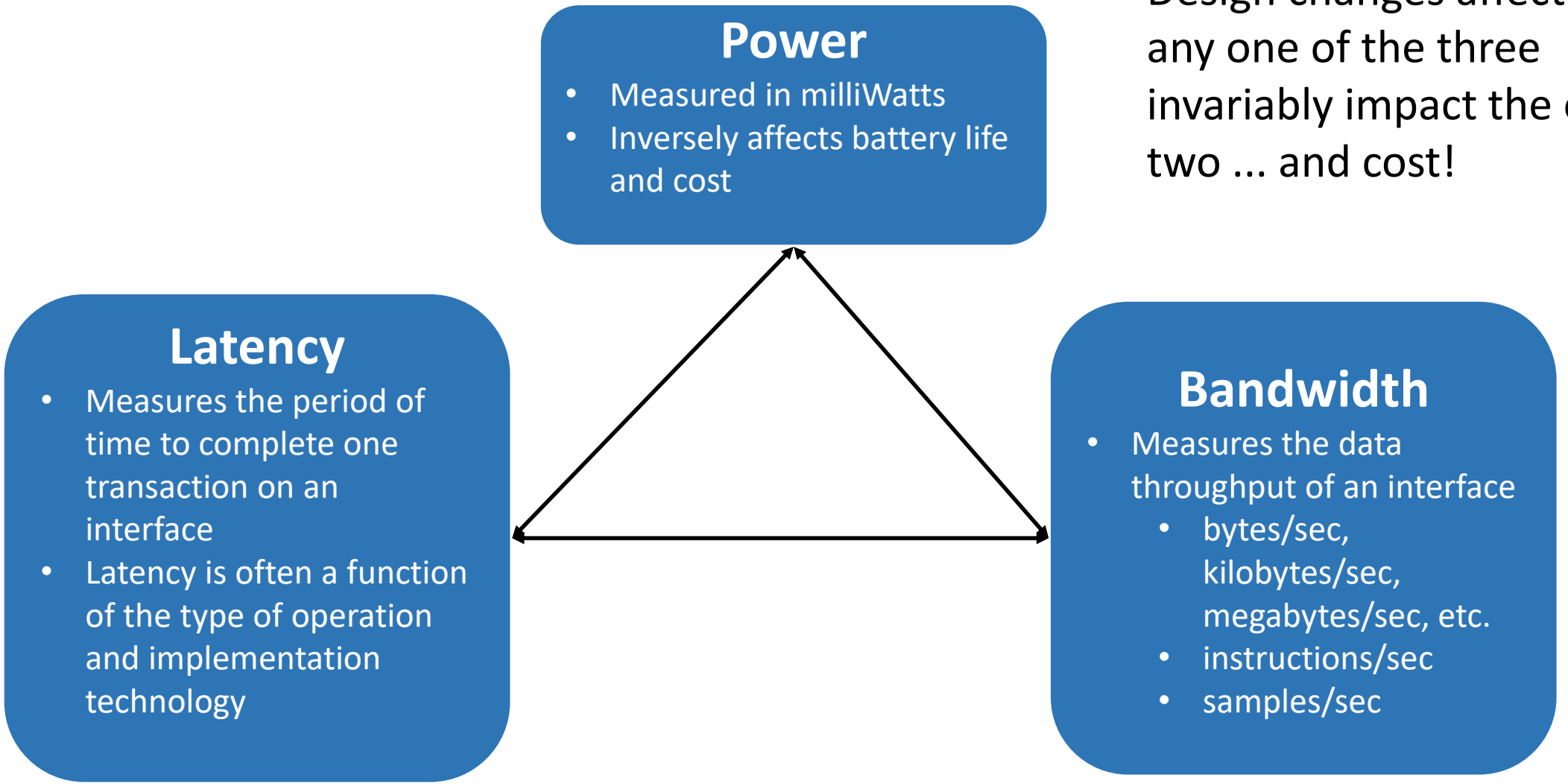
Metric Prefixes

Symbol	Prefix	Multiplication Factor	
T	tera	10^{12}	1,000,000,000,000
G	giga	10^{9}	1,000,000,000
M	mega	10^{6}	1,000,000
k	kilo	10^{3}	1,000
m	milli	10^{-3}	0.001
μ	micro	10^{-6}	0.000,0001

Name	Description
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
RTOS	Real Time Operating System
V_{DD}	3.3V or 5V logic supply

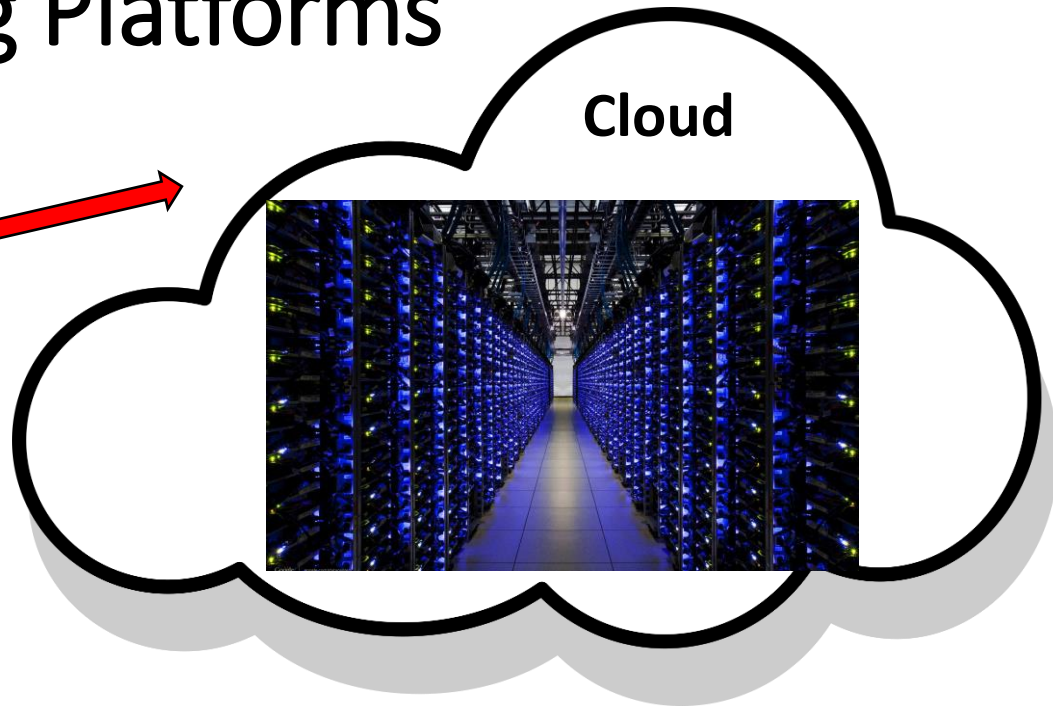
Name	Description
watts (W)	Power = voltage X current
bit	“0” or “1”
nibble	a 4 bit number
byte	an 8 bit number
word	a 16-bit number
long word	a 32-bit nmber
IMU	Inertial Measurement Unit
Tesla	a measure/unit of magnetic flux
Gauss	another measure of magnetic flux
Pascal	a measure/unit of pressure
RGB	Red-Green-Blue light breakdown

Vocabulary: Performance Metrics

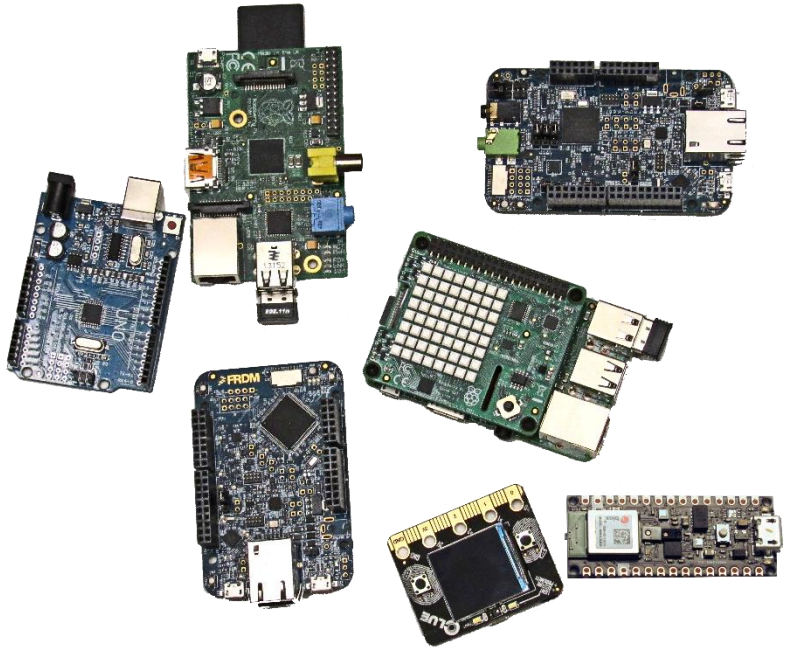


Design changes affecting any one of the three invariably impact the other two ... and cost!

Continuum of Machine Learning Platforms



Embedded



Consider also: Training vs Inferencing
Training takes considerably more resources

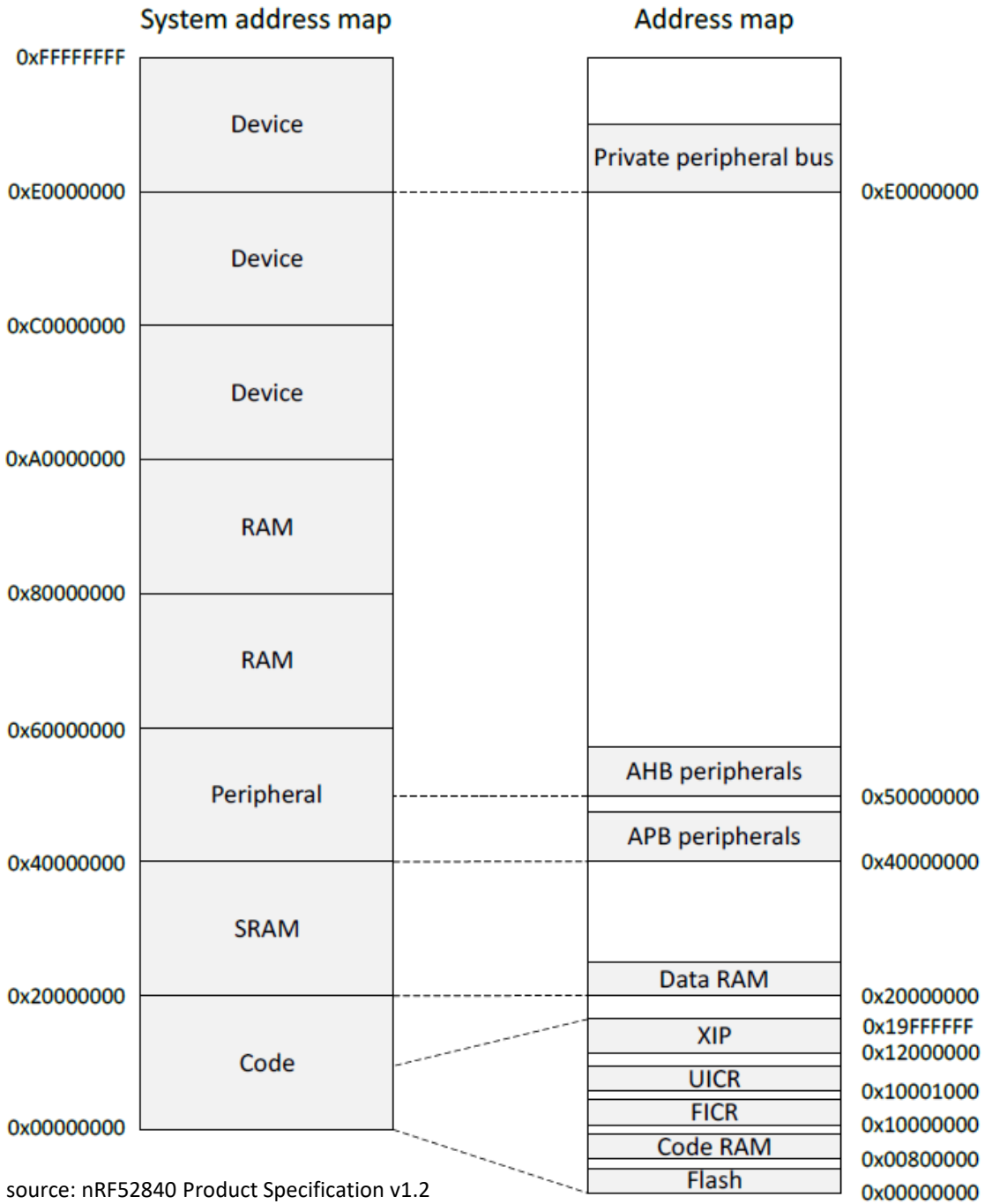
Some Terms: Microcontroller (MCU) vs Microprocessor (MPU)

Microcontroller **Arduino**

- On-chip memory
  - Flash memory limits tech node
  - Lower latency than off-chip
  - Limits on amount of memory
- Essentially self-contained
- Typically bare-metal or Real-Time Operating System (RTOS)
- Can be hard real-time
- Lower cost

Microprocessor **Raspberry Pi**

- Off-chip memory
  - Cutting edge technology support
  - Latencies vary, can be mitigated with on-chip cache
  - Larger memory blocks available
- Requires more support circuitry
- Typically Linux-based
- Not real-time
- Higher cost



source: nRF52840 Product Specification v1.2

All digital computers (including MCUs) have a memory map

Each system resource is assigned a range of addresses by which they can be accessed by the CPU.

Addresses are usually expressed in hexadecimal format (denoted by “0x” prefix).

decimal vs binary vs hexadecimal number formats

Decimal	Binary	Hex
0	00000000	00
1	00000001	01
2	00000010	02
3	00000011	03
4	00000100	04
5	00000101	05
6	00000110	06
7	00000111	07
8	00001000	08
9	00001001	09
10	00001010	0A
11	00001011	0B
12	00001100	0C
13	00001101	0D
14	00001110	0E
15	00001111	0F

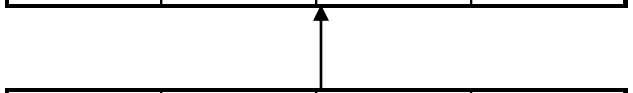
Decimal	Binary	Hex
16	00010000	10
17	00010001	11
18	00010010	12
19	00010011	13
20	00010100	14
21	00010101	15
22	00010110	16
23	00010111	17
24	00011000	18
25	00011001	19
26	00011010	1A
27	00011011	1B
28	00011100	1C
29	00011101	1D
30	00011110	1E
31	00011111	1F

Decimal	Binary	Hex
32	00100000	20
33	00100001	21
34	00100010	22
35	00100011	23
36	00100100	24
37	00100101	25
38	00100110	26
39	00100111	27
40	00101000	28
41	00101001	29
42	00101010	2A
43	00101011	2B
44	00101100	2C
45	00101101	2D
46	00101110	2E
47	00101111	2F

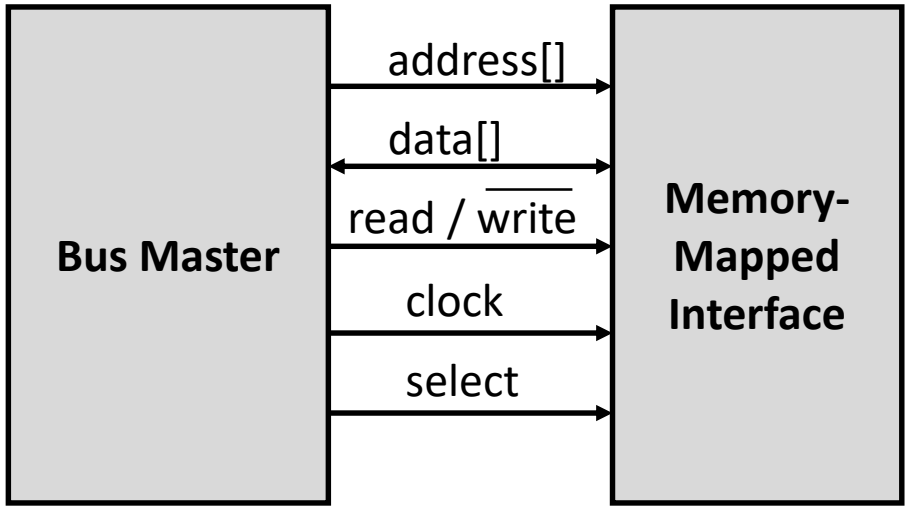
Decimal	Binary	Hex
48	00110000	30
49	00110001	31
50	00110010	32
51	00110011	33
52	00110100	34
53	00110101	35
54	00110110	36
55	00110111	37
56	00111000	38
57	00111001	39
58	00111010	3A
59	00111011	3B
60	00111100	3C
61	00111101	3D
62	00111110	3E
63	00111111	3F

32-bit MCUs can access up to 4 bytes at a time

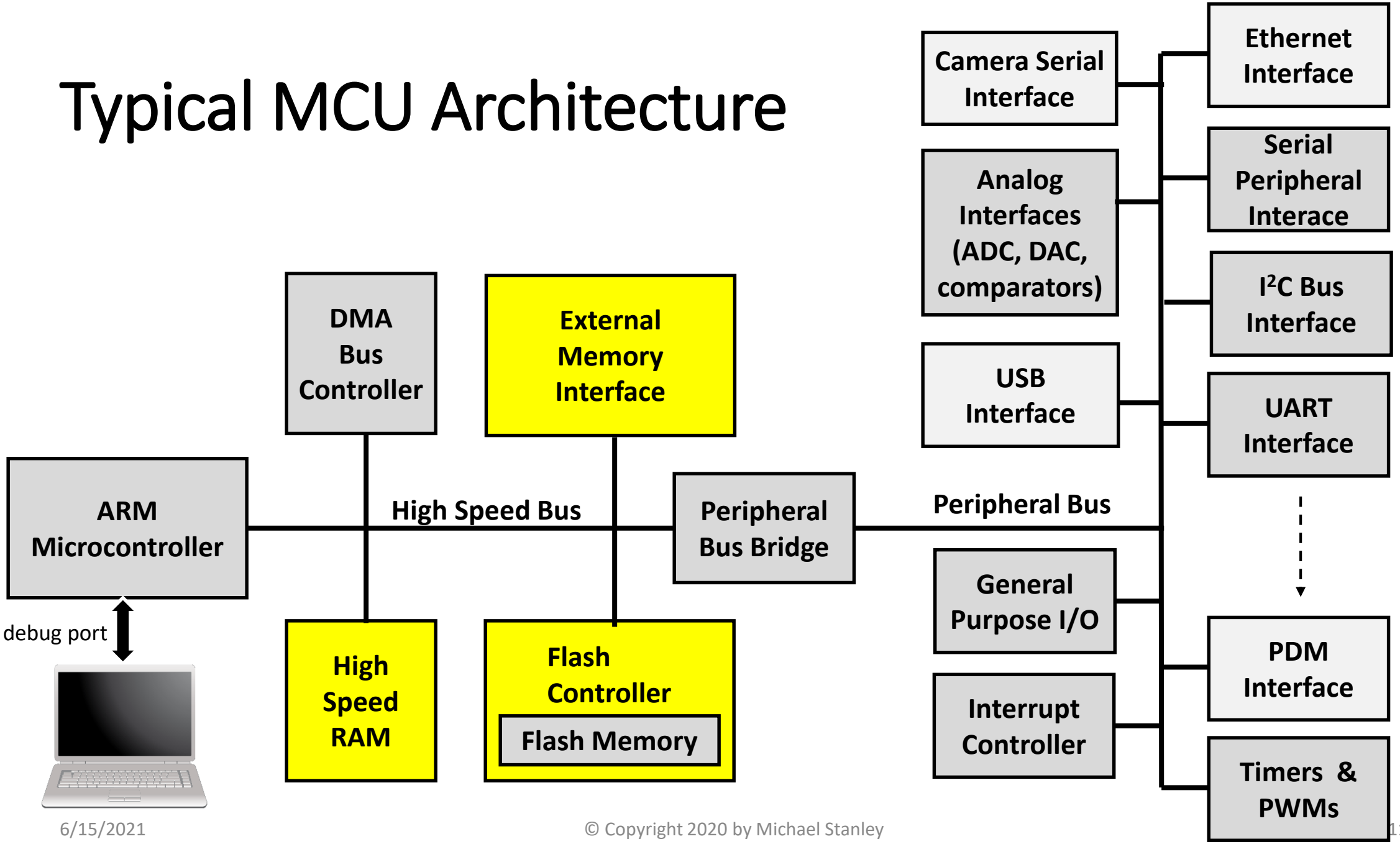
00FF	00FE	00FD	00FC
00FB	00FA	00F9	00F8
00F7	00F6	00F5	00F4
00F3	00F2	00F1	00F0
00EF	00EE	00ED	00EC
00EB	00EA	00E9	00E8
00E7	00E6	00E5	00E4
00E3	00E2	00E1	00E0
00DF	00DE	00DD	00DC
00DB	00DA	00D9	00D8
00D7	00D6	00D5	00D4
00D3	00D2	00D1	00D0
00CF	00CE	00CD	00CC
00CB	00CA	00C9	00C8
00C7	00C6	00C5	00C4
00C3	00C2	00C1	00C0



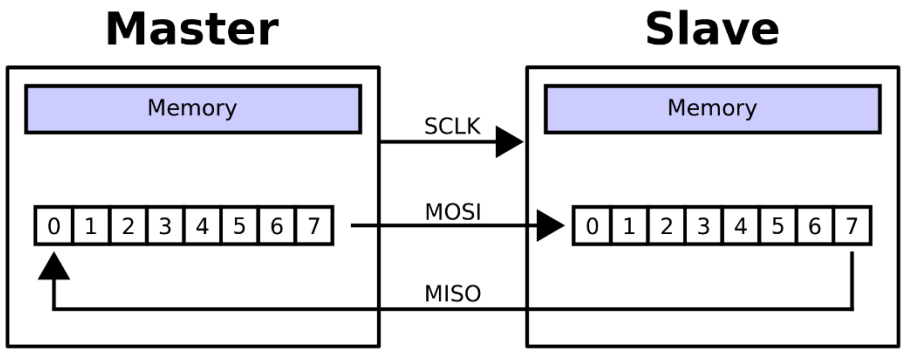
000B	000A	0009	0008
0007	0006	0005	0004
0003	0002	0001	0000

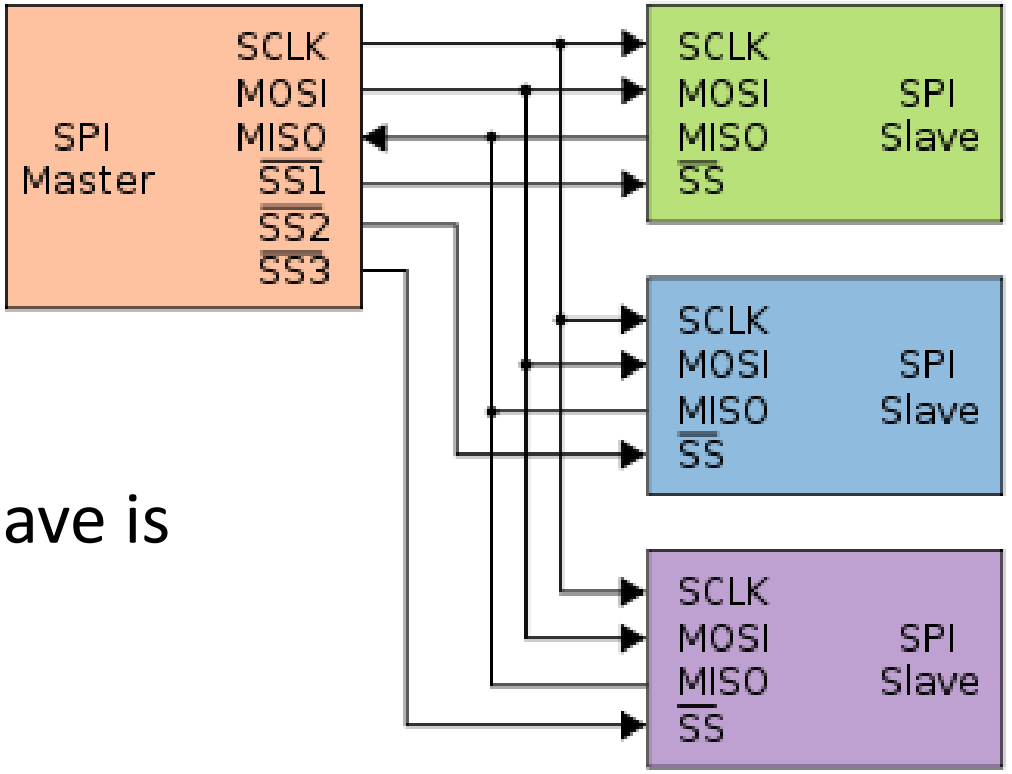


Typical MCU Architecture



Some sensors use a Serial Peripheral Bus (SPI) Interface

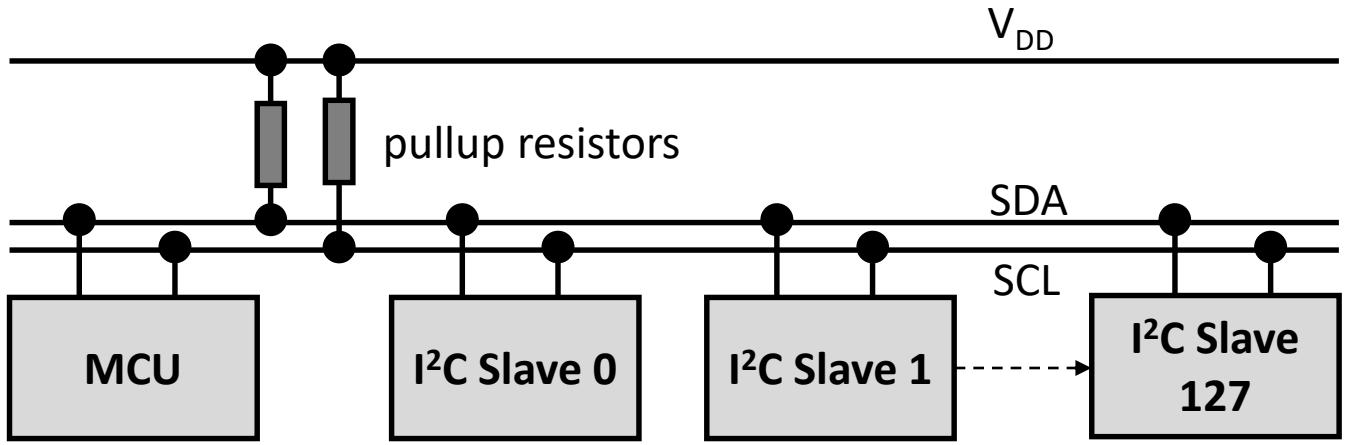


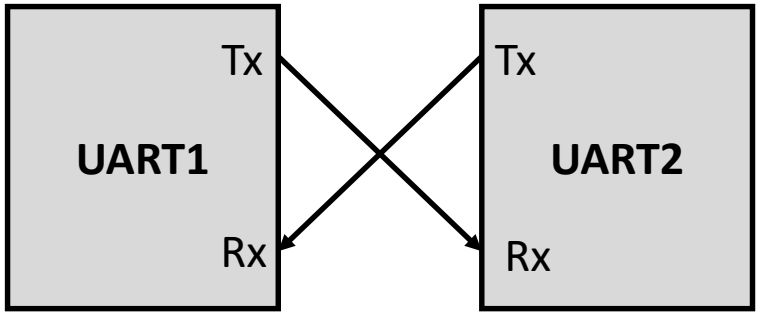


In the context of this course, a bus slave is typically a sensor of some type.

figure source: Wikipedia

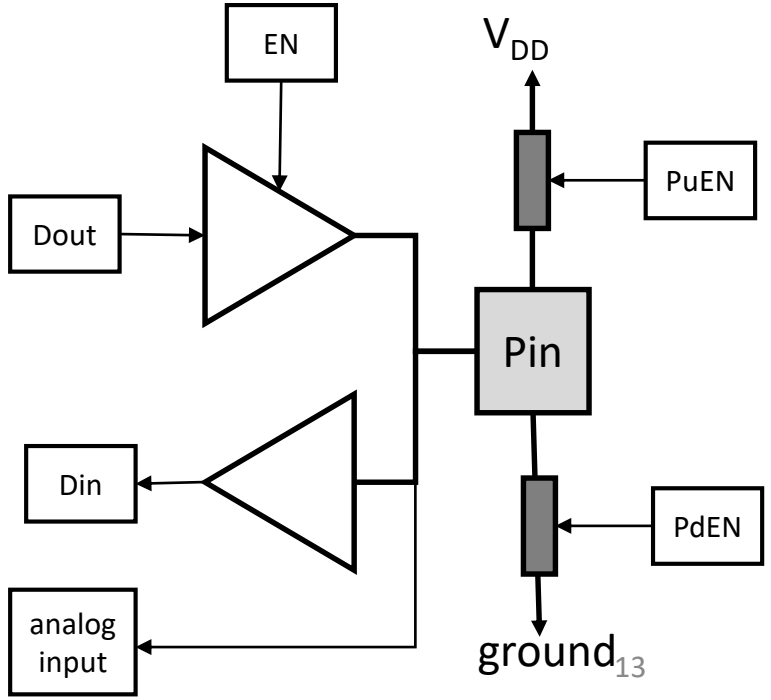
Others may use I²C, UART, ...





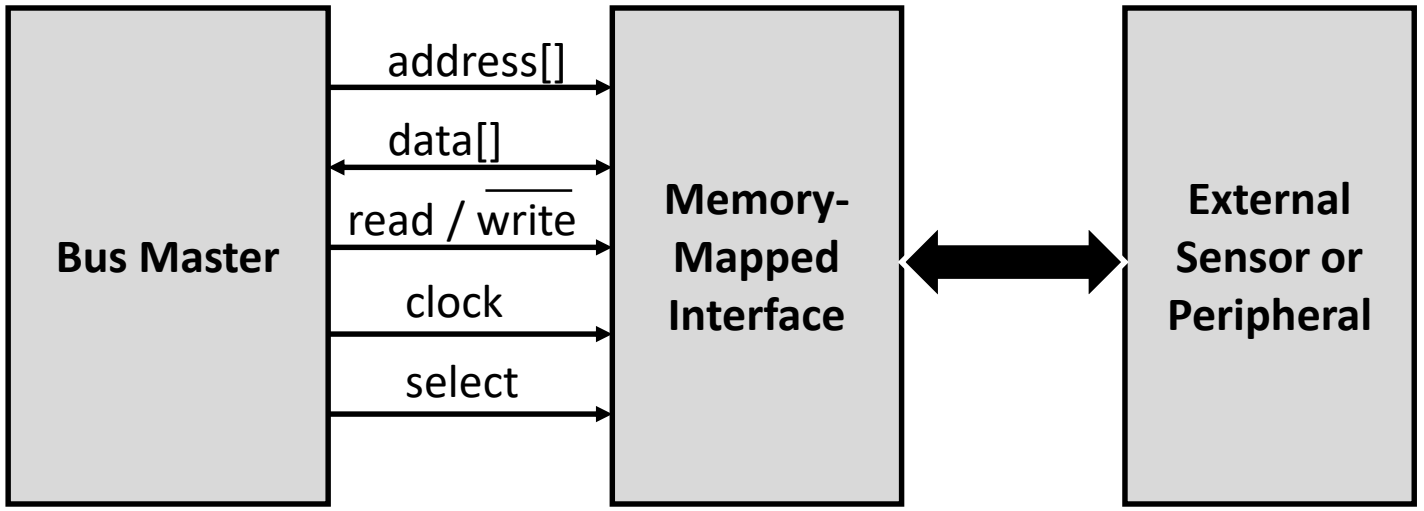
UART = Universal asynchronous receiver-transmitter

General Purpose I/O



Why are there so many types of communications interfaces?

- Each one is optimized for a different cost/latency/bandwidth/power tradeoff
- History and avoidance of patent and trademark infringement also play a role, although this is less an issue now than in the past

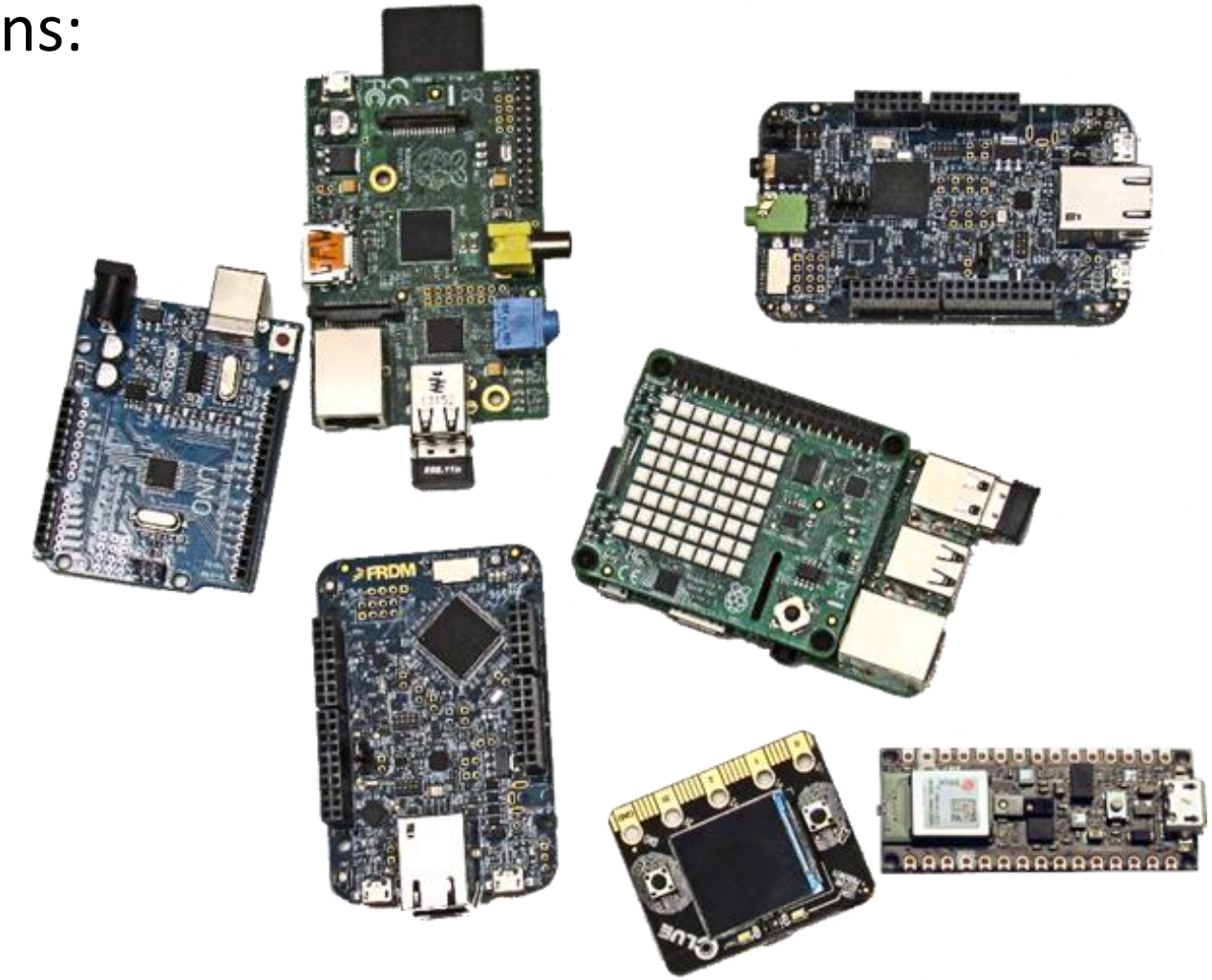


Software drivers for external sensors must understand both the sensor interface, as well as the bus architecture encapsulated by the memory-mapped interface.

Arduino and Raspberry Pi software libraries often provide these for you.

Questions to ask when selecting an embedded target

- What are my primary concerns:
  - Development environment?
  - Ease of use?
  - Size?
  - Means of Communications?
  - Power?
  - Application? Education?
  - Sensor selection? Drivers?
  - Sampling Frequencies?
  - Cost?
  - Availability
  - Expansion options



Example Hardware: The Arduino Nano 33 BLE Sense

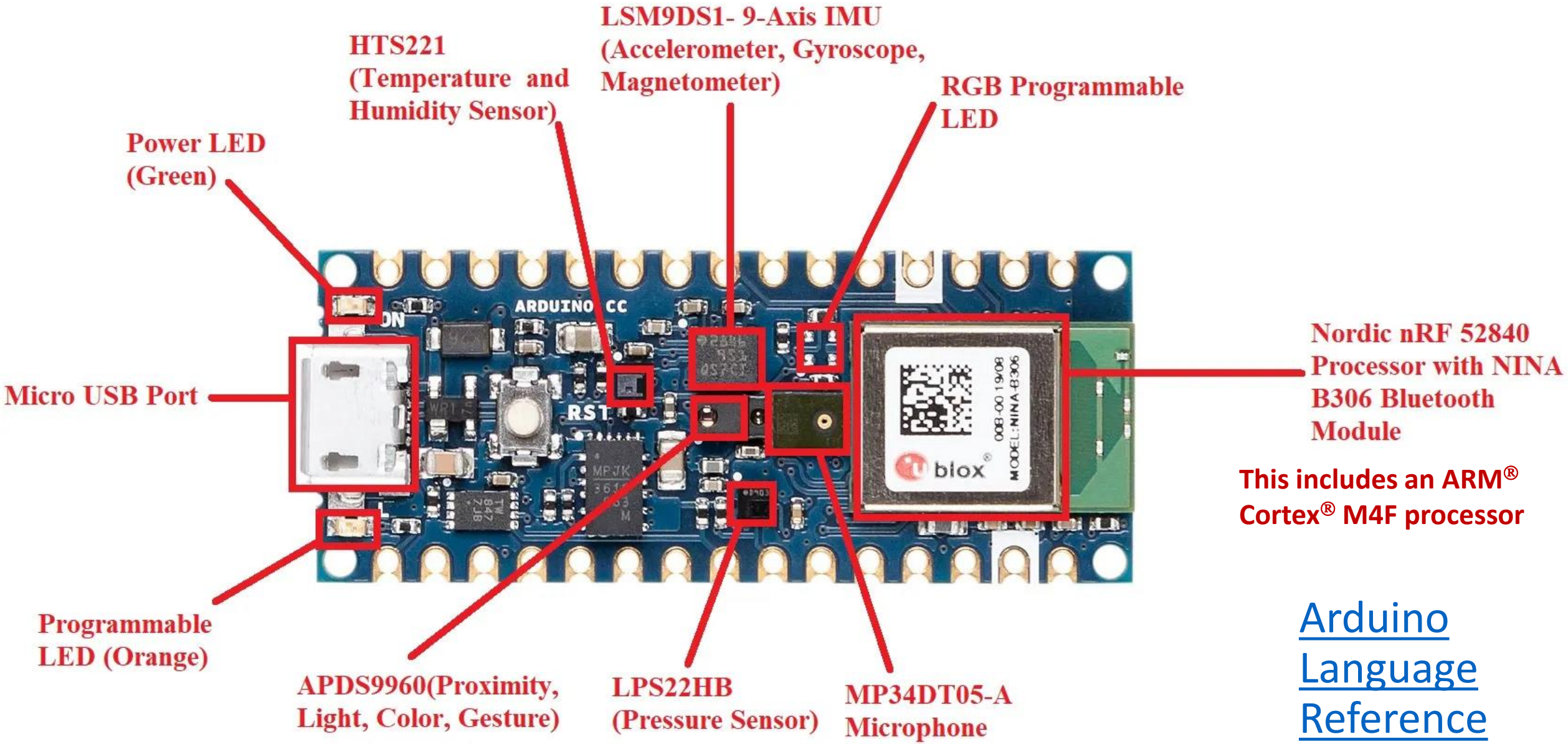


Image source: https://www.etechnophiles.com/arduino-nano-33-ble-sense-pinout-introduction-specifications/

Arduino Language Reference

From the Nano 33 BLE Sense Datasheet

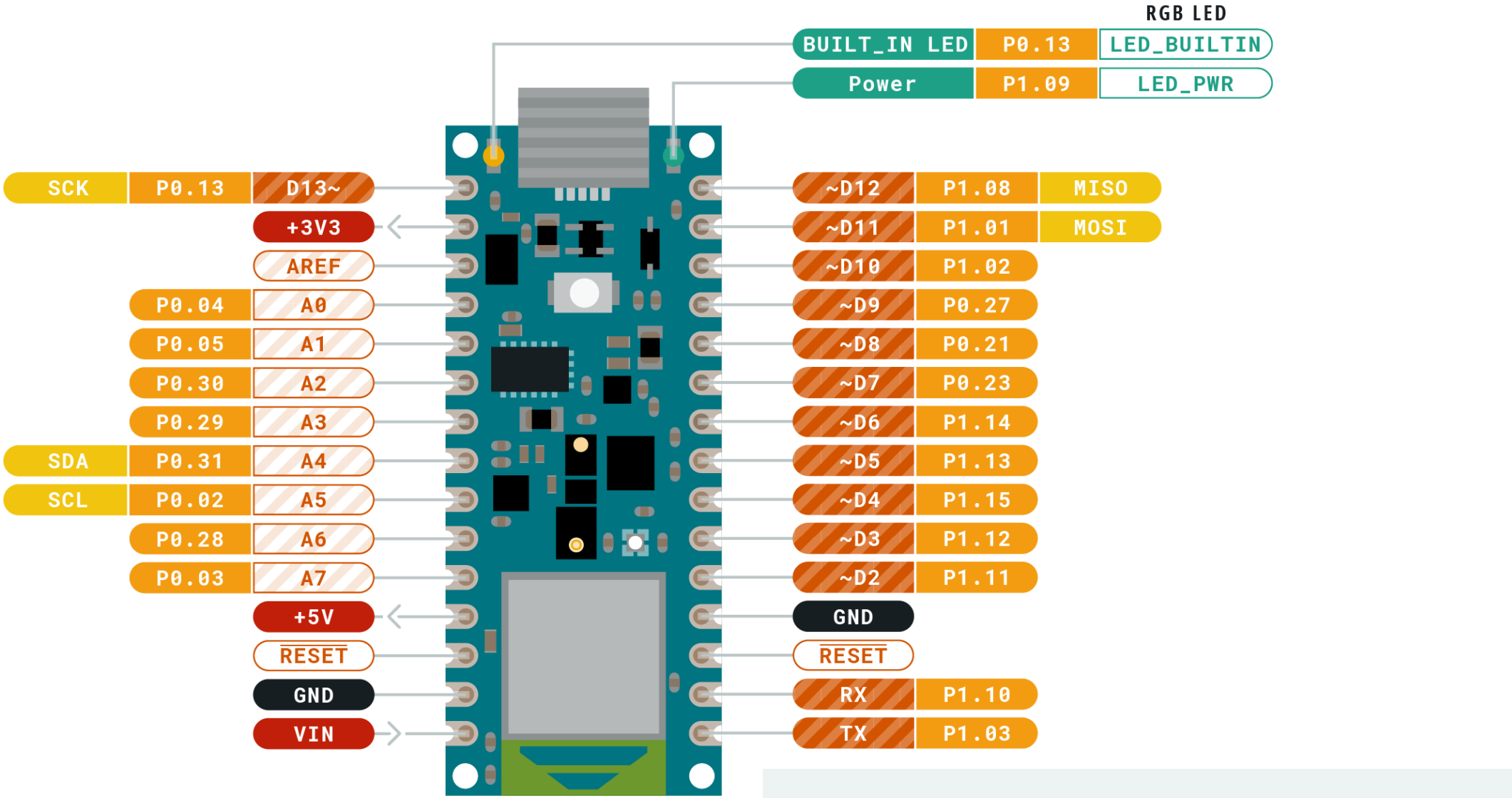
This board is based on the nRF 52840 microcontroller.

64MHz ARM ® Cortex®-M4 Processor with floating point unit

Clock	64MHz
Flash	1MB
RAM	256KB

Please note: Arduino Nano 33 BLE Sense only supports 3.3V I/Os and is **NOT** 5V tolerant so please make sure you are not directly connecting 5V signals to this board or it will be damaged. Also, as opposed to Arduino Nano boards that support 5V operation, the 5V pin does NOT supply voltage but is rather connected, through a jumper, to the USB power input.

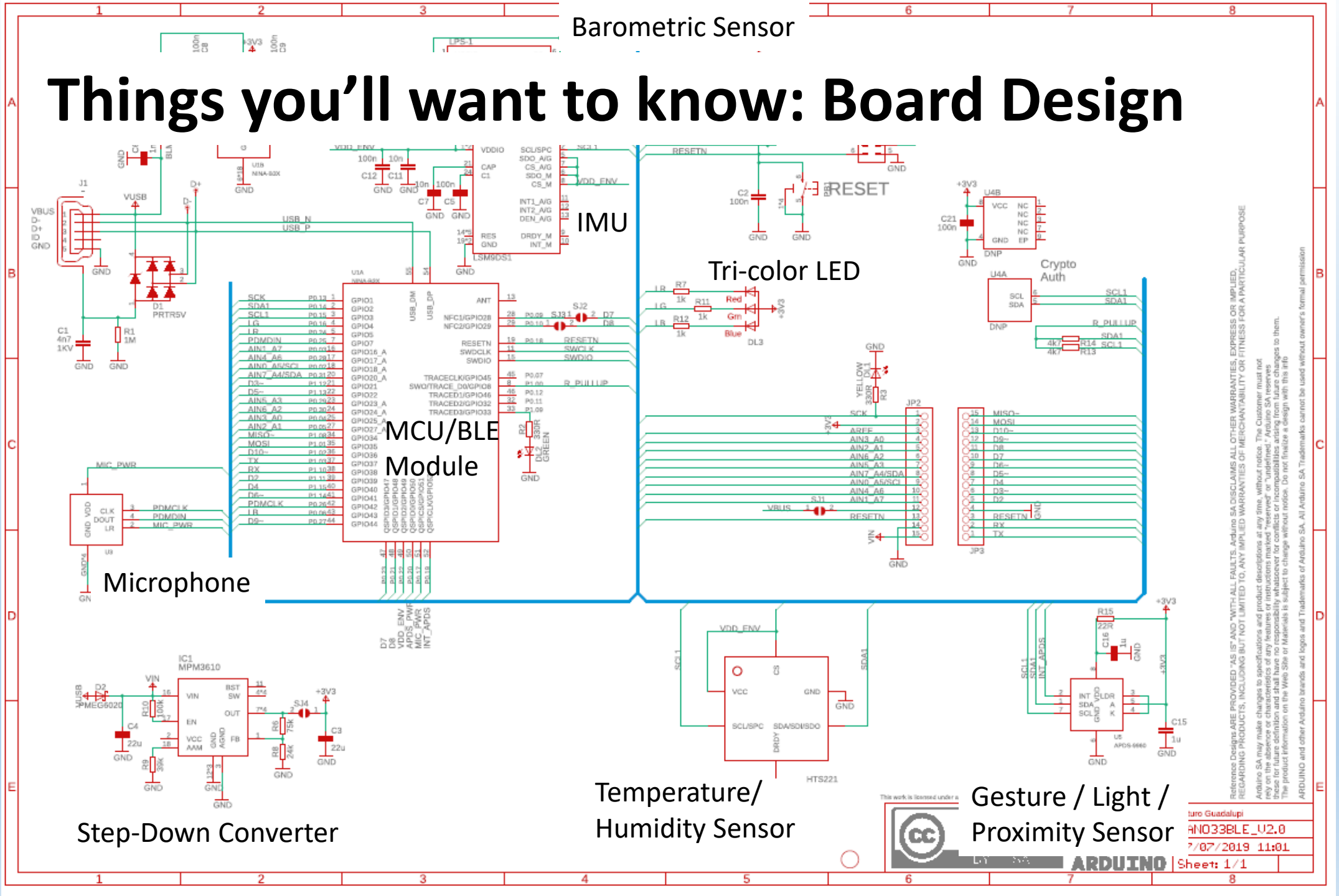
Things you'll want to know: Pinout



Pinout Details from the datasheet

Pin	Funcion	Type	Description
1	D13	Digital	GPIO
2	+3V3	Power Out	Internally generated power output to external devices
3	AREF	Analog	Analog Reference; can be used as GPIO
4	A0/DAC0	Analog	ADC in/DAC out; can be used as GPIO
5	A1	Analog	ADC in; can be used as GPIO
6	A2	Analog	ADC in; can be used as GPIO
7	A3	Analog	ADC in; can be used as GPIO
8	A4/SDA	Analog	ADC in; I2C SDA; Can be used as GPIO (*)
9	A5/SCL	Analog	ADC in; I2C SCL; Can be used as GPIO(*)
10	A6	Analog	ADC in; can be used as GPIO
11	A7	Analog	ADC in; can be used as GPIO
12	V_{USB}	Power In/Out	Normally NC; can be connected to V_{USB} pin of the USB connector by shorting a jumper
13	RST	Digital In	Active low reset input (duplicate of pin 18)
14	GND	Power	Power Ground
15	VIN	Power In	Vin Power input
16	TX	Digital	USART TX; can be used as GPIO
17	RX	Digital	USART RX; can be used as GPIO
18	RST	Digital	Active low reset input (duplicate of pin 13)
19	GND	Power	Power Ground
20	D2	Digital	GPIO
21	D3/PWM	Digital	GPIO; can be used as PWM
22	D4	Digital	GPIO
23	D5/PWM	Digital	GPIO; can be used as PWM
24	D6/PWM	Digital	GPIO; can be used as PWM
25	D7	Digital	GPIO
26	D8	Digital	GPIO
27	D9/PWM	Digital	GPIO; can be used as PWM
28	D10/PWM	Digital	GPIO; can be used as PWM
29	D11/MOSI	Digital	SPI MOSI; can be used as GPIO
30	D12/MISO	Digital	SPI MISO; can be used as GPIO

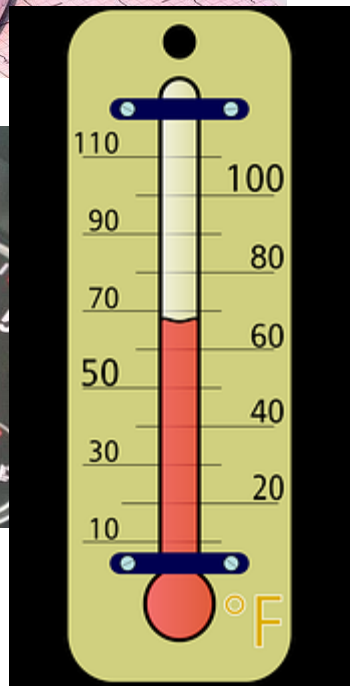
Things you'll want to know: Board Design

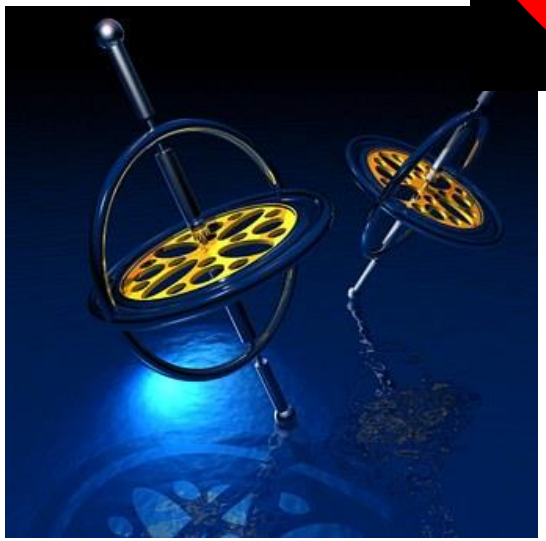


Things you'll want to know: Drivers and their limitations

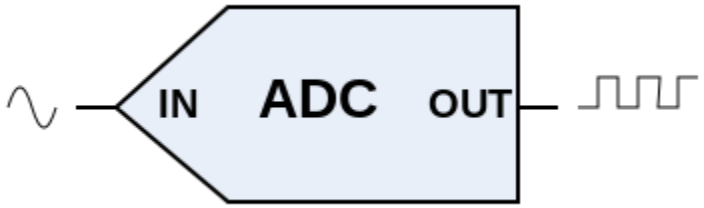
Sensor	Type	Library	Range / Units	Sample Rate
HTS211	Temperature	Arduino_HTS221.h>	-40C to 120 C	one-shot
	Humidity		0 to 100 % rH	one-shot
APDS9600	Proximity	Arduino_APDS9960.h	0 (closest – 255 farthest)	check
	Color & Light Intensity		16 bit integer for R,G,B|,A|	
	Gesture		UP /DOWN /LEFT /RIGHT /NONE	
LSM9DS1	Accelerometer	Arduino_LSM9DS1.h	+/- 4 g	104 Hz
	Magnetometer		+/-400 μT	20 Hz
	Gyroscope		+/-2000 dps	104 Hz
MP34DT05	Microphone	PDM.h		**16 kHz** or 41.667 kHz
LPS22HB	Absolute Pressure	Arduino_LPS22HB.h	260 to 1260 kPa	1 to 75 Hz

Sensors

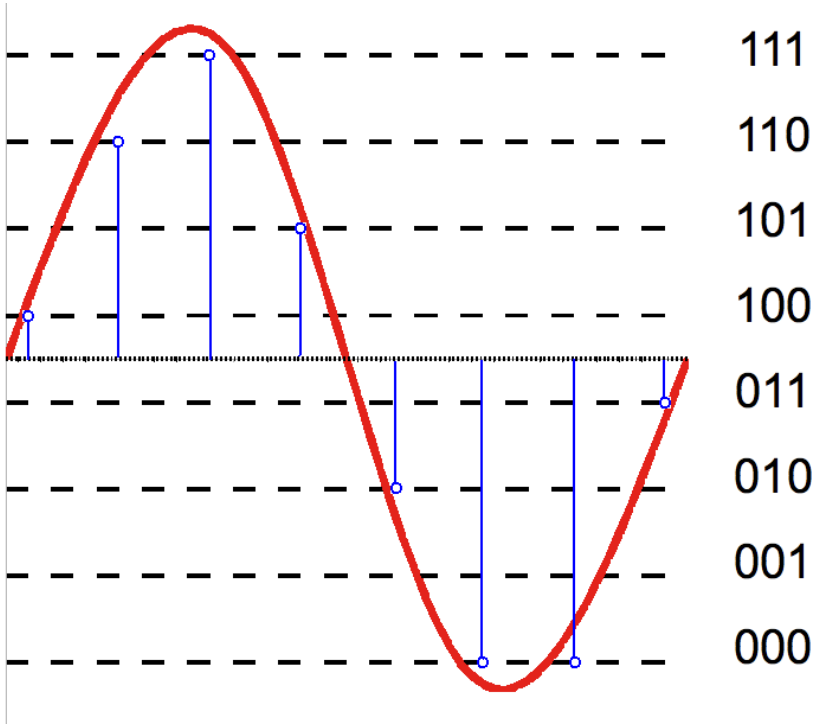




Analog to Digital Converters (ADCs)

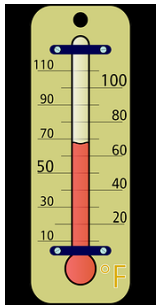


- Analog to digital converters (ADCs) take some continuous, physical quantity and convert it to quantized values at discrete times.
- Many MCU's contain multiple ADC's right on-chip.
- Many sensors include their own ADC(s) and present digital values (in bits) to the MCU.
- Sensor drivers are usually responsible for converting number of bits to a floating point value with correct units.



By Hyacinth - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=30716342

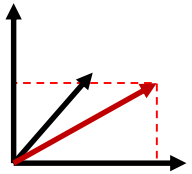
Common Sensors Fall into 3 Categories



Scalars

- Temperature
- Pressure
- Humidity
- Time
- Sound
- Presence
- Gesture

Vector

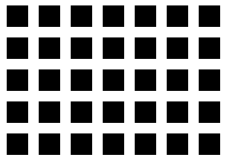


Color (RGB)
Acceleration
Rotation
Magnetic Field

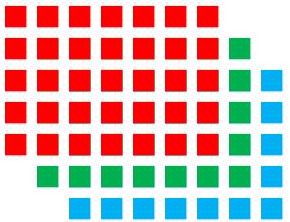
Generally we have direction and vector magnitude =

$\sqrt{X^2 + Y^2 + Z^2}$

Matrix or Array



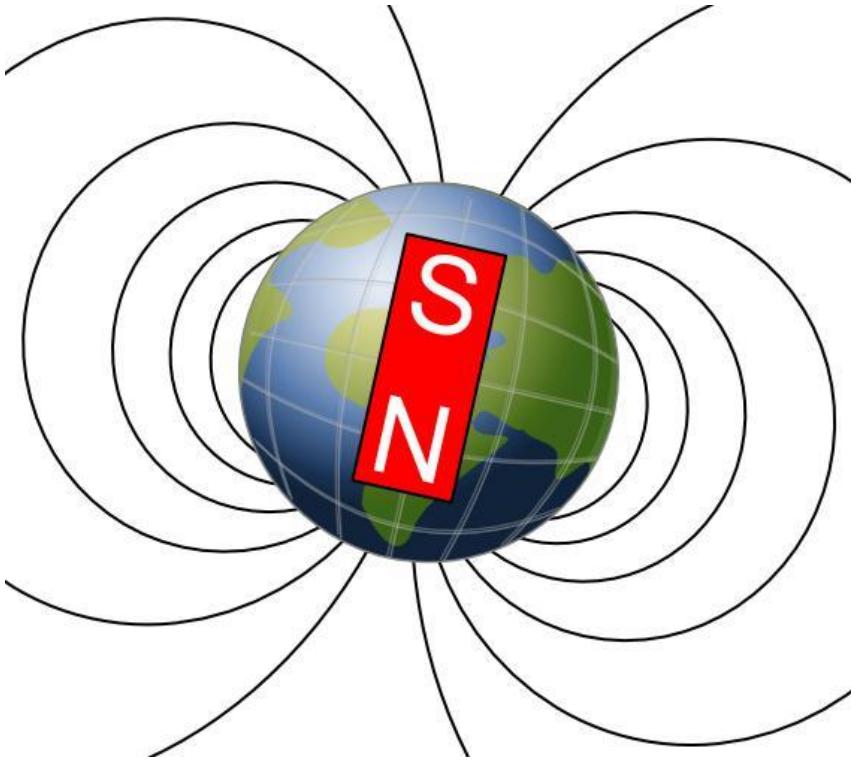
B&W images



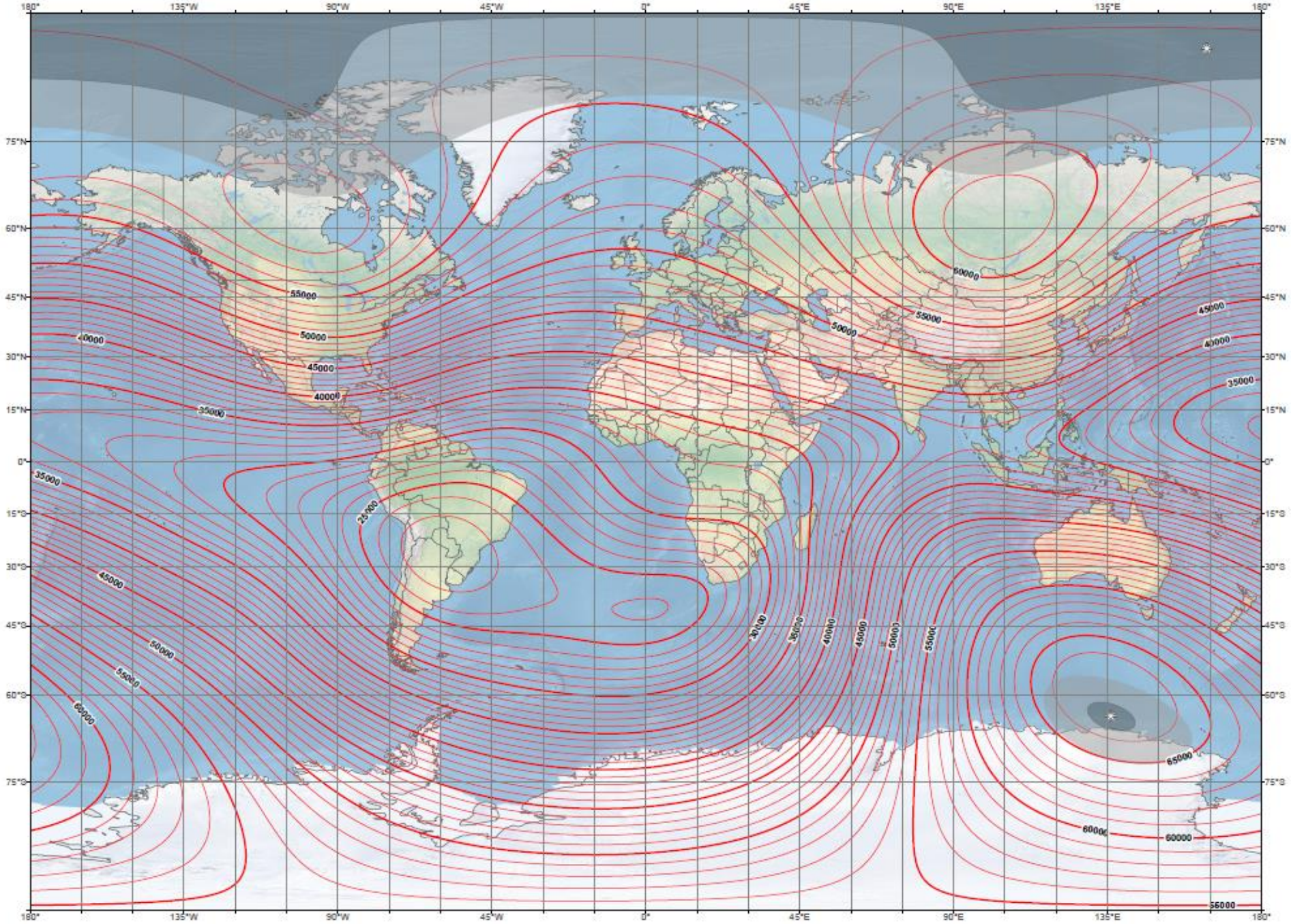
Color images
(RGB components over XY grid)

You might use the vector magnitude as a feature in your ML algorithms to avoid sensor orientation dependencies.

Earth's Magnetic Field



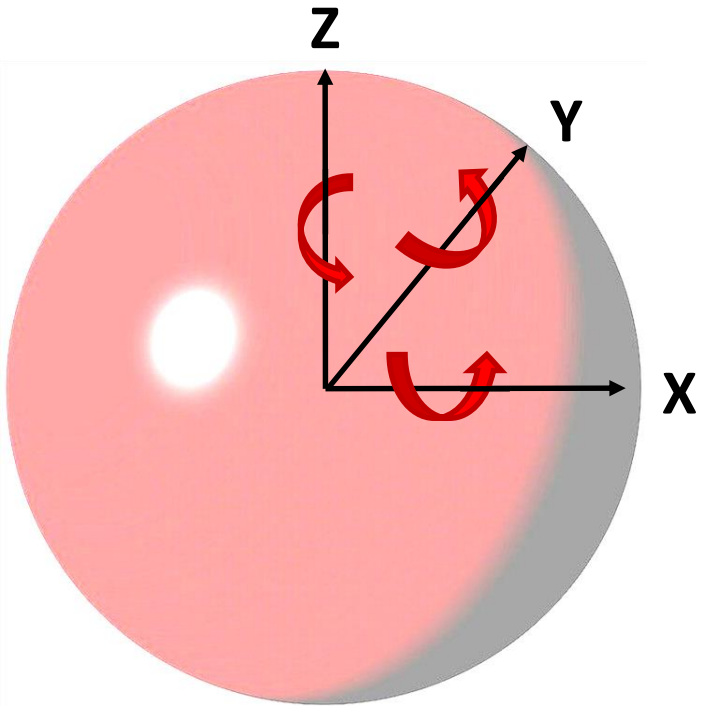
- Varies in both direction and intensity depending upon where you are on the globe
- Changes over time. The 2020 magnetic maps (see next page) are different than the 2015 maps.
- 22 – 63 μT range is easily swamped by other environmental factors and sensor offsets – usually requiring complex magnetic calibration to correct.



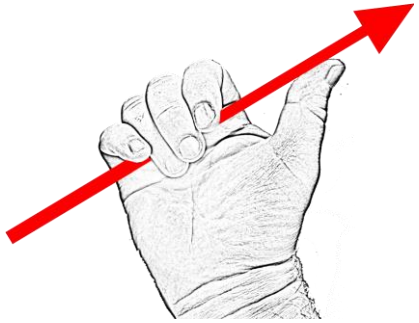
Earth Magnetic Field Intensity (2020)

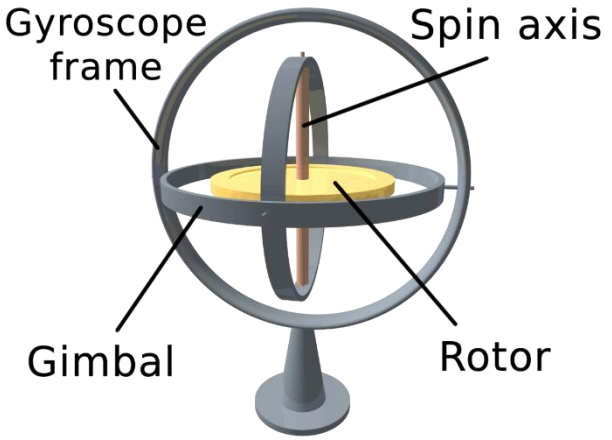
Source: https://www.ngdc.noaa.gov/geomag/WMM/data/WMM2020/WMM2020_F_BoZ_MILL.pdf

Gyroscopes measure rotation

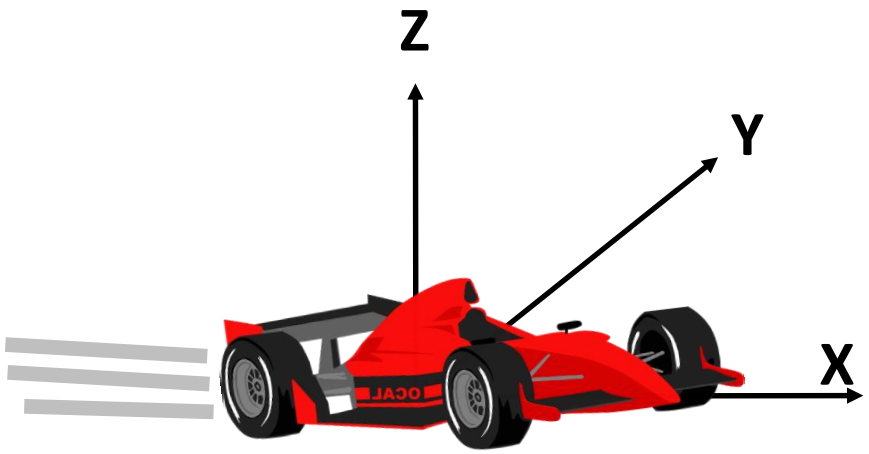


- Just like toy gyroscopes (right), MEMS gyroscopes leverage the Coriolis effect
- They return X, Y and Z components of rotation about the X, Y and Z axes of the sensor (left).
- This is <u>normally</u> according to the Right-Hand-Rule (RHR – but check!)

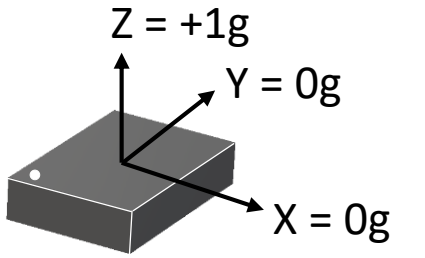




Linear Acceleration



- Accelerometers measure gravity plus linear acceleration X, Y & Z components relative to the sensor
- It is common practice to align the axes of accelerometer, magnetometer and gyroscope - but check!
- These three sensors are sometimes co-packaged as an inertial module.



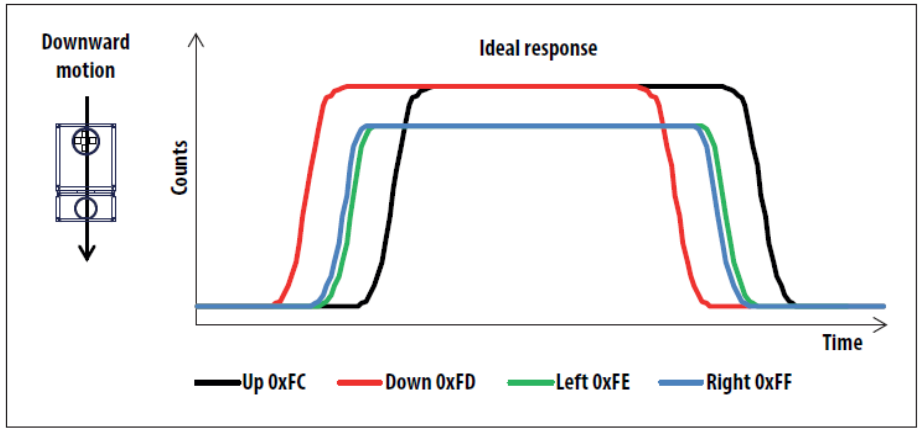
Readings at rest for a RHR accelerometer lying flat

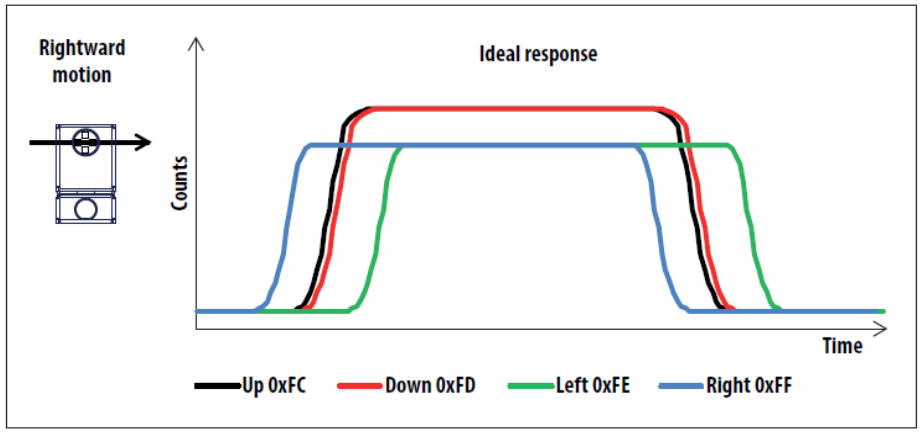
Light Sensor APDS-9960

Source: mouser.com

Clever state machines coupled with on-chip LED and light sensitive diodes enable one device to provide sensor readings for:

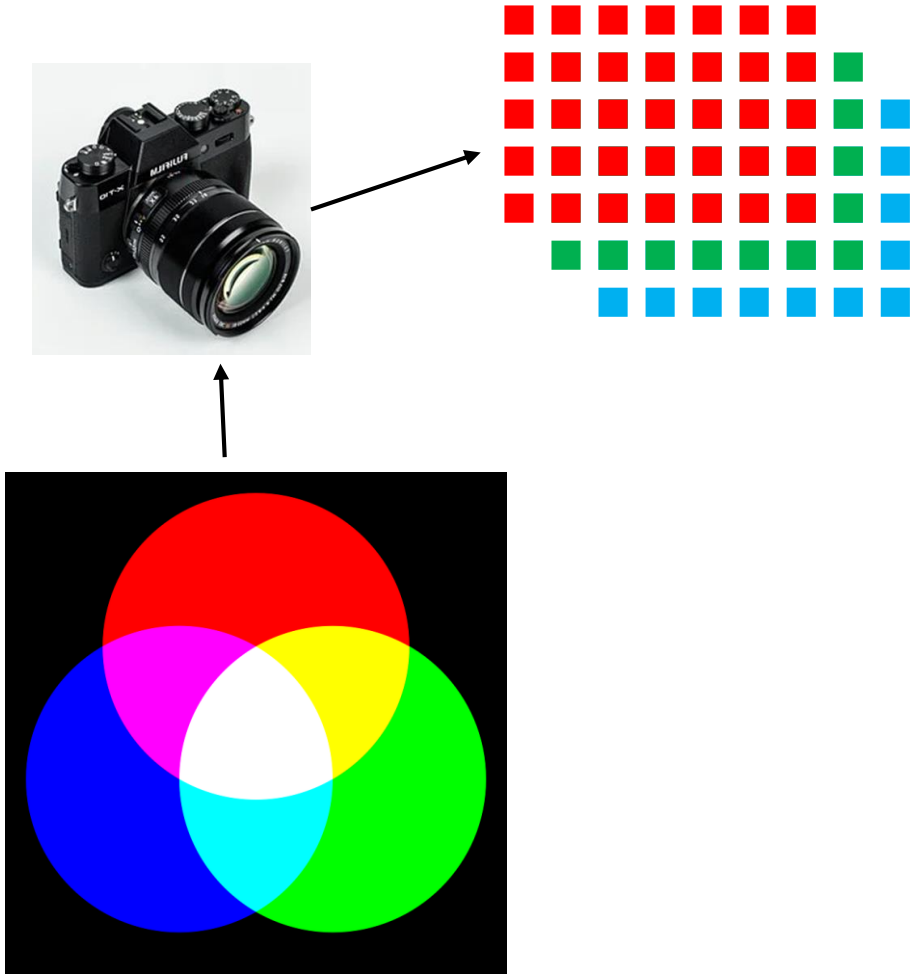
- Proximity (distance)
- Ambient light
- RGB color mix
- Gesture detection





Source: APDS-9960 Datasheet

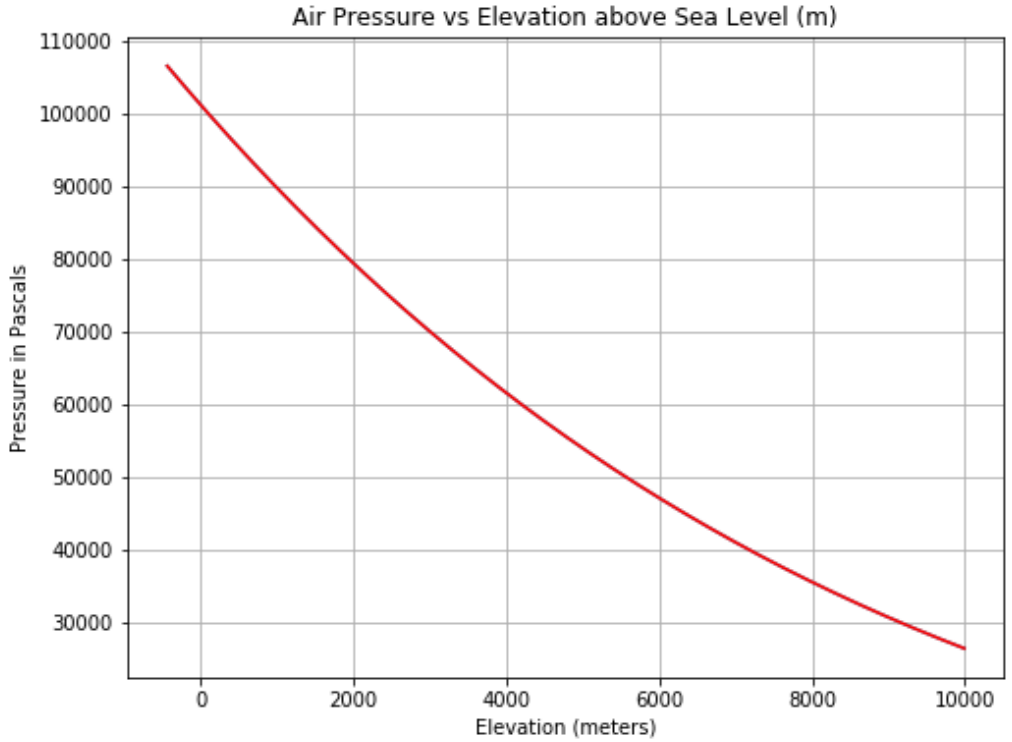
Imaging



- Convolutional neural networks were designed to take advantage of the regular structure inherent in camera data.
- Using the additional time variable, it is possible to recast other sensor data types into similar structures so that CNNs can be used to detect events in time.
- Because the number of bits in an image is huge, there is a lot of work underway to develop smart cameras which embed machine learning right in the camera sensor itself. Goals include:
  - Transmitting “context” instead of raw bits to preserve bandwidth
  - Protecting privacy

Absolute Air Pressure and Elevation

- Mount Everest tops out at 8,950 meters (29,035 feet) above sea level
- The surface of the Dead Sea is 430.5 meters (1,412 feet) below sea level
- The LPS22HB pressure sensor on the Arduino Nano 33 BLE Sense
  - has an output range of 26 kPa to 126 kPa
    Has a resolution of 1pA = 40.96 LSBs



If hardware drivers are not available…

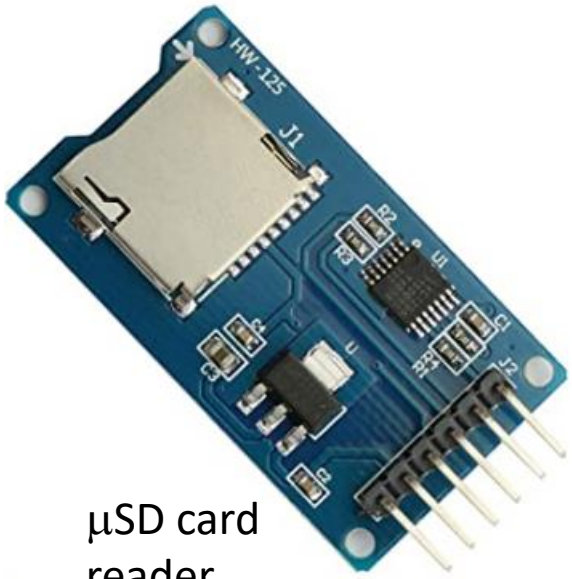
- Get someone on your team who is comfortable with embedded software development
- Sensors typically interface with your MCU in one of several ways:
  - I^2C bus
  - SPI bus
  - Via the MCU memory bus
  - Specialized camera interface (CSI, MIPI, ...)
- High speed interfaces may offer optional Direct Memory Access (DMA) support
- The point here is that the driver developer must be familiar with BOTH the MCU interface and sensor hardware.

Easy Hardware Expansion

- The Arduino Nano 33 BLE Sense has external analog inputs, GPIO, SPI and I²C. This makes it easy to attach other devices. This is true of most MCUs.

two for $8

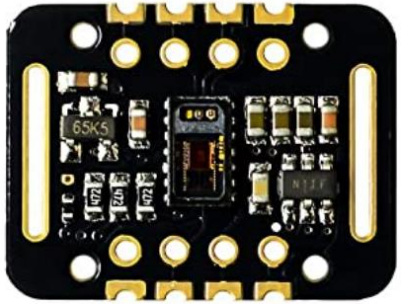
potentiometers
20 for $7



µSD card
reader
two for $5

PIR Sensors
3 for $8.5

Heart rate &
Blood Oxygen Concentration Sensor
two for $12



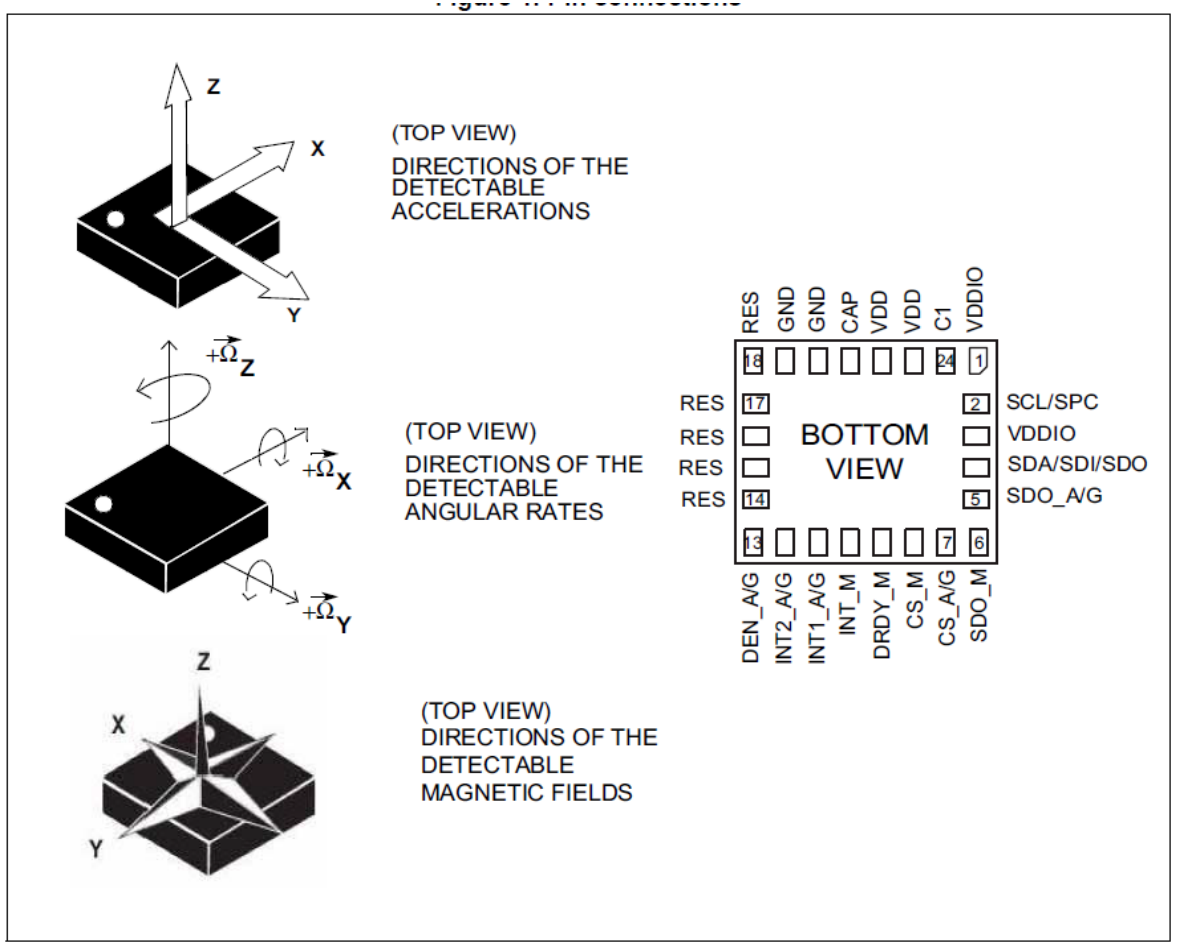
Pictures & prices from Amazon.com 6 June 2021

Summary / Wrapup

- This lecture has focused on hardware fundamentals for embedded programming.
- We've reviewed
  - the differences between computing platforms
  - various types of hardware interfaces
  - a number of sensor types
  - things to consider when picking a hardware platform

Next time: Embedded Code Development. We'll also discuss hardware interfaces for the IDE.

Inertial Measurement Unit



Source: LSM9DS1 Datasheet

WARNING!

- The ST Microelectronics LSM9DS1 iNemo inertial module on the Arduino Nano 33 BLE Sense board does NOT consistently follow the right hand rule.
- This is must be corrected mathematically in the hardware abstraction layer (HAL) for sensor fusion applications, but may not matter for sensor-based machine learning applications.