Introduction to Embedded Systems

Unit 1.4: Memory and I/O

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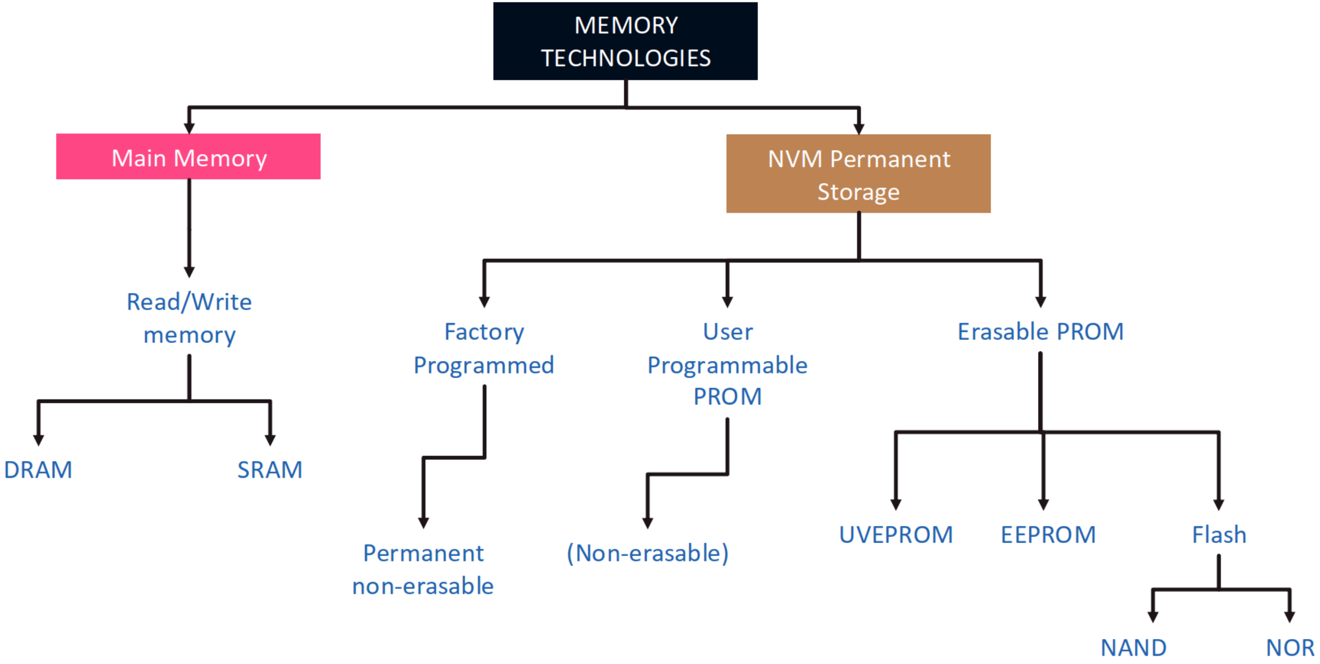
Memory

Memory

- Memory is the embedded system's electronic scratchpad or local store in computer terminology.
- Used for temporary storage of calculations, data, and other work in progress.
- High level categorization:
  - Persistence
    - *Volatile memory* - memory which is temporary
    - *Non-volatile memory* - memory which is permanent
  - Purpose
    - *Program memory* - memory for instructions
    - *Data memory* - memory for variables, operands, and other data

Types of memory

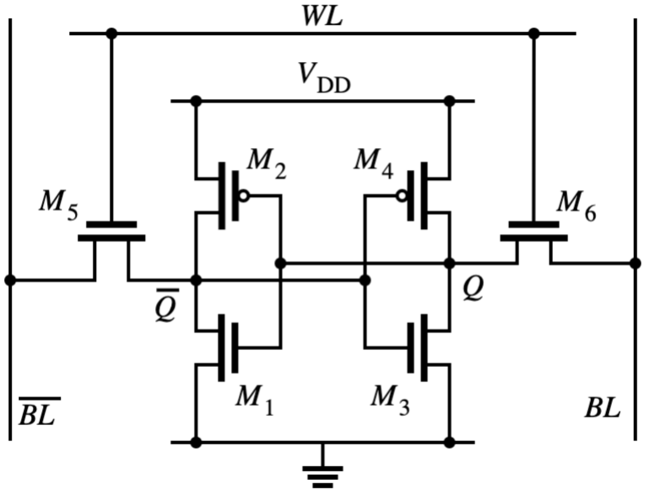


Random access memory (RAM)

- The processor directly stores and retrieves information from it.
- Memory is organized into locations. Each memory location is identified by a unique address. The access time is same for all locations.
- It is volatile: when turned off, everything in RAM disappears

Static random-access memory (SRAM)

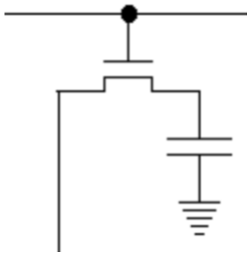
- Single bit is stored in a bi-stable circuit (more specifically, a flip flop)
- Used for:
  - register file within the processor core
  - caches
  - small but fast memories
- More power hungry and less dense than DRAM



One bit of SRAM

Dynamic random-access memory (DRAM)

- Single bit is stored as charge in a capacitor
  - Capacitor loses charge when read, drains over time
  - Needs to be refreshed by an internal timer periodically to retain the data
- Slower than SRAM, depends on access order
- Typically used for main memory



One bit of DRAM

Non-volatile memory (NVM)

- Data stored in NVM cannot be modified, or can be modified only slowly or with difficulty, so it is mainly used to distribute.
- The instructions in NVM are built into the electronic circuits of the chip which is called firmware.
- Read only in nature.

Types of NVM

- Programmable read-only memory (PROM)
  - Can be written to or programmed only once via a special device called a PROM programmer
- Erasable programmable read-only memory (EPROM)
  - Can be (re)programmed via exposure to UV light
- Electrically erasable programmable read-only memory (EEPROM)
  - Can be (re)programmed electrically and erased at the single-byte level
  - Hence do not need to be removed from the embedded system

Flash memory

- Modern type of EEPROM invented in 1984
- Can be erased only in blocks
- Read time is much smaller (tens of nanoseconds) compared write time (tens of microseconds)
- Most common program memory in embedded applications
- Two main technologies:
  - *NOR flash*: uses NOR logic gates, providing faster read speeds and random-access capabilities
  - *NAND flash*: uses NAND logic gates, allowing for high-density memory cells arranged in a grid

Cache memory

- High speed memory kept near to the processor to increase data execution speed
- Major reason for incorporating cache in the system is that the CPU is much faster than the main memory and needs a place to store information that can be accessed quickly
- Cache fetches the frequently used data from the main memory and buffers (stores) it for further processor usage.

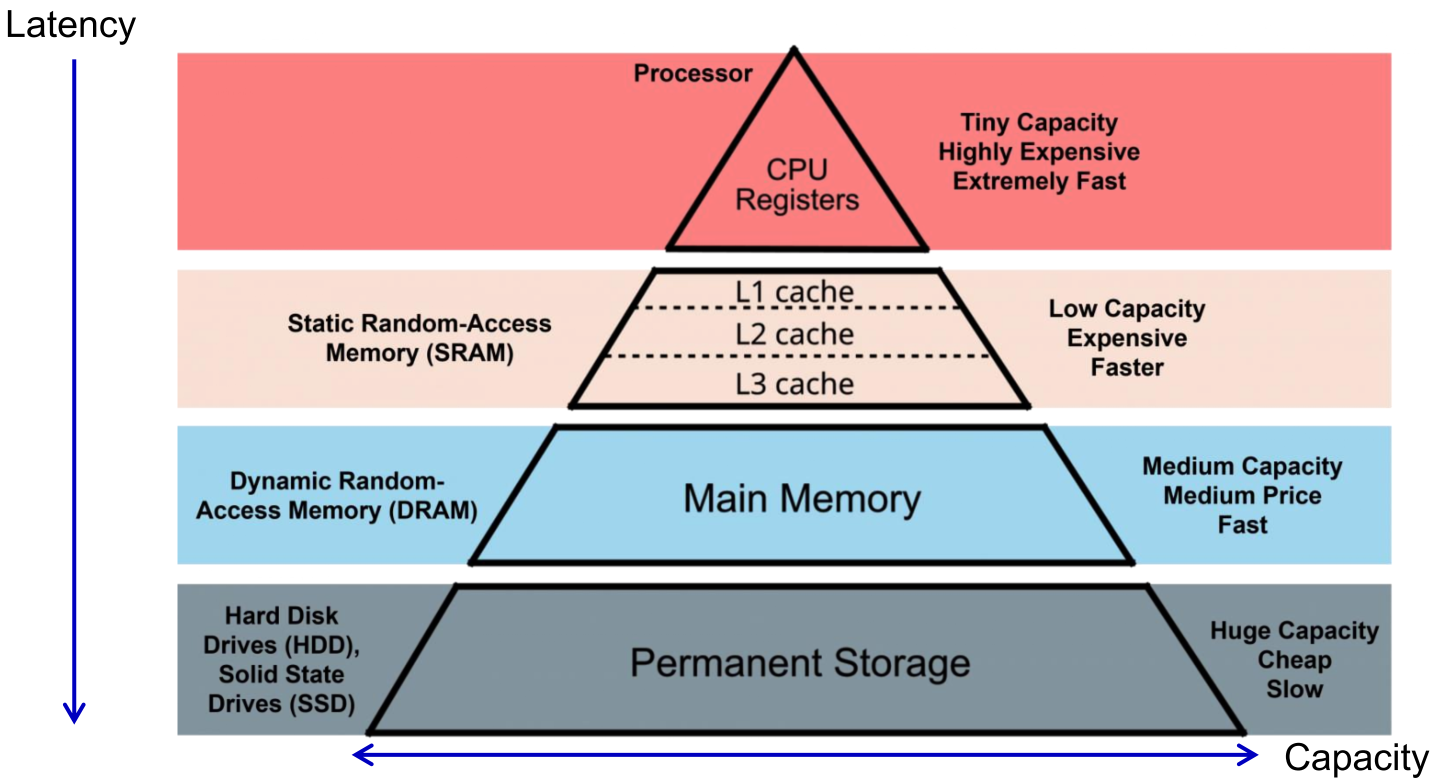
Different levels of cache

- L1 cache
  - The fastest cache
  - Usually comes within the processor chip itself
  - Ranges in size from 8KB to 64KB
- L2 cache
  - Comes between L1 and RAM
  - Bigger than the primary cache
- L3 cache
  - Not found nowadays as its function is replaced by L2 cache
  - Found on the motherboard rather than the processor
  - Comes between RAM and L2 cache

Processor speed

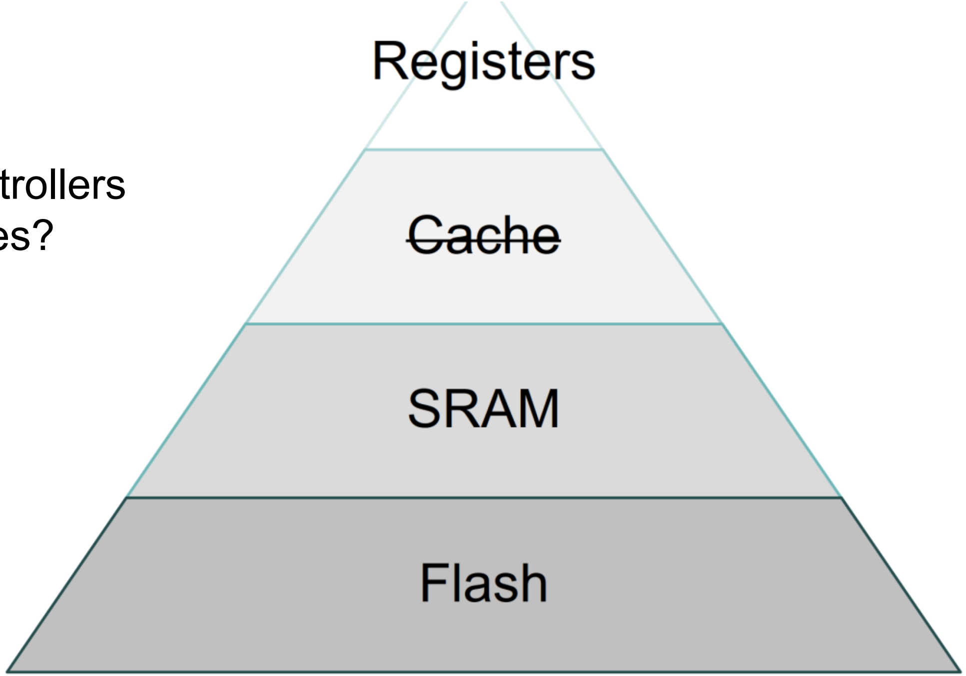
- Speed of a computer system is determined by several factors
  - Clock speed of the processor
  - Speed of the data bus
  - Size of the data bus
- Clock speed is the rate at which the processor processes information and this is measured in millions of cycles per second (Megahertz)
  - The more the number of hertz, the faster is the processing speed
- The larger the bus width and the faster the bus speed, the greater the amount of data can travel on it in each amount of time.

Memory hierarchy for a personal computer



Memory hierarchy for a microcontroller

Why do microcontrollers avoid using caches?



Memory hierarchy for a microcontroller

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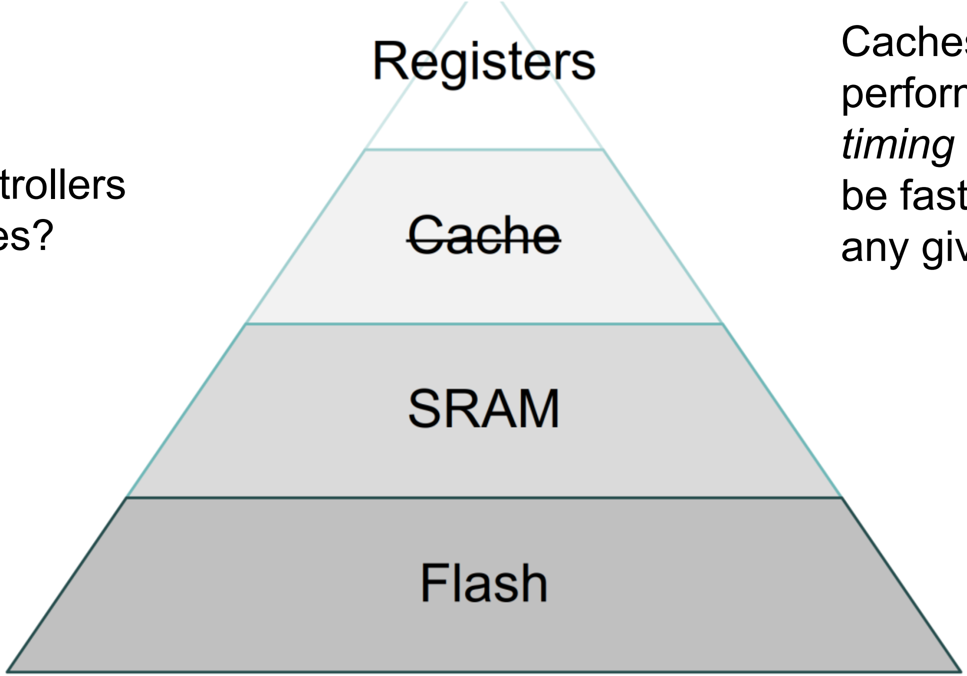


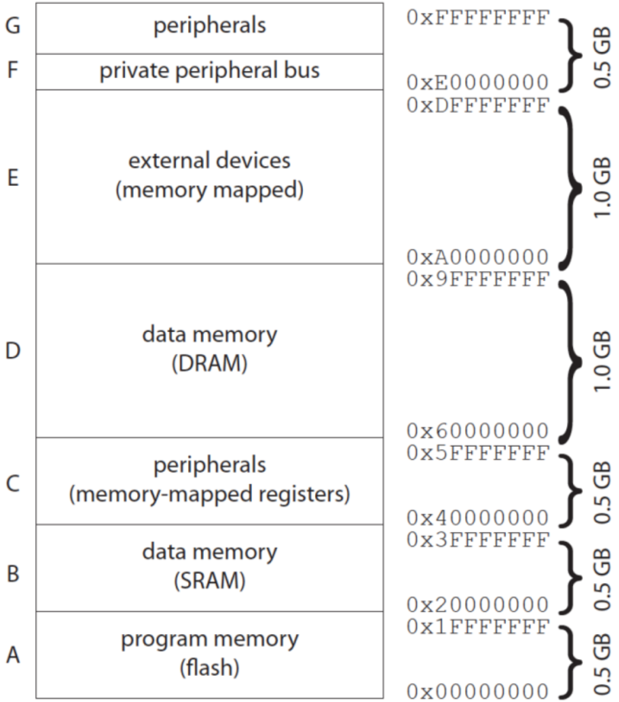
Caches improve performance, but make *timing* unreliable (could be faster or slower in any given case)

Accessing embedded memory

- How do you access:
  - Registers
    - Directly in assembly code
  - SRAM
    - Load/store instructions in assembly code
  - Flash
    - Load instructions in assembly code

Memory map of ARM Cortex-M3 & Cortex-M4

- Defines the mapping of addresses to physical memory
- The address space is partitioned into zones, each one with a dedicated use
    - Memories (readable and/or writeable)
    - Peripheral units
    - Access to debug/trace info



Memory mapped I/O

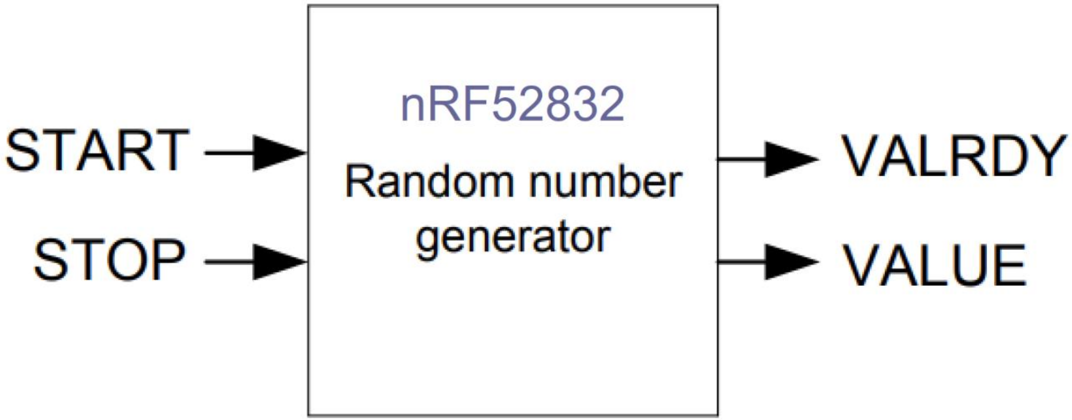
- Microcontrollers have a lot of peripherals
  - System
    - GPIO pins
    - Timers
  - Serial
    - UART controller
    - I^2C controller
    - SPI controller
  - Analog
    - ADC / DAC
  - Motion control
    - PWM generator
    - QEI

- How do they access the peripherals?
  - "Memory-mapped": from CPU perspective
  - Just like reading and writing to any other memory address
  - The various peripheral registers are documented in the user and reference manuals

- Why not create special assembly functions to access them?
  - That would make the processor harder to design

nRF52832 hardware random number generator

Interface:



nRF52832 hardware random number generator

26.3 Registers

Table 45: Instances

Base address	Peripheral	Instance	Description	Configuration
0x4000D000	RNG	RNG	Random Number Generator	

Table 46: Register Overview

Register	Offset	Description
TASKS_START	0x000	Task starting the random number generator
TASKS_STOP	0x004	Task stopping the random number generator
EVENTS_VALRDY	0x100	Event being generated for every new random number written to the VALUE register
SHORTS	0x200	Shortcut register
INTENSET	0x304	Enable interrupt
INTENCLR	0x308	Disable interrupt
CONFIG	0x504	Configuration register
VALUE	0x508	Output random number

nRF52832 hardware random number generator

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CONFIG	0x504
VALUE	0x508

```
#define NRF_RNG_BASE  0x4000D000
```

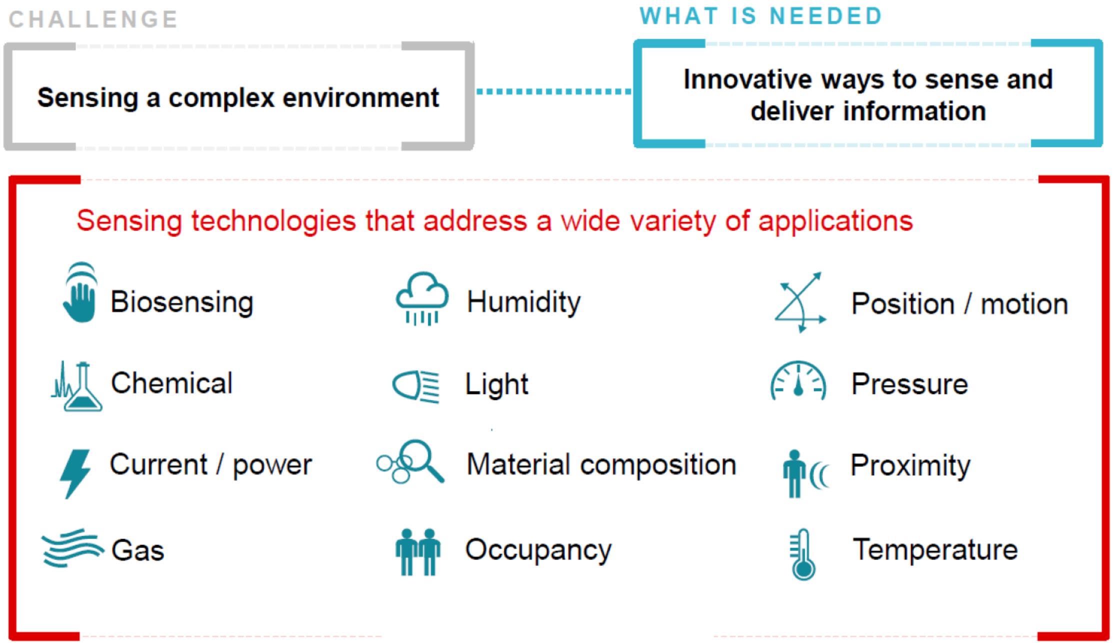
```
/**
  * @brief Random Number Generator (RNG)
  */

typedef struct {
  __O  uint32_t  TASKS_START;
  __O  uint32_t  TASKS_STOP;
  __I  uint32_t  RESERVED0[62];
  __IO uint32_t  EVENTS_VALRDY;

  __I  uint32_t  RESERVED1[63];
  __IO uint32_t  SHORTS;
  __I  uint32_t  RESERVED2[64];
  __IO uint32_t  INTENSET;
  __IO uint32_t  INTENCLR;
  __I  uint32_t  RESERVED3[126];
  __IO uint32_t  CONFIG;
  __I  uint32_t  VALUE;
} NRF_RNG_Type;
```

Sensors & Actuators

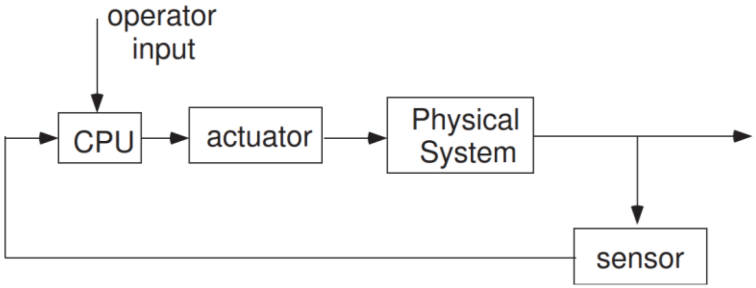
Sensing is a must



Hundreds or thousands of different sensing technologies….

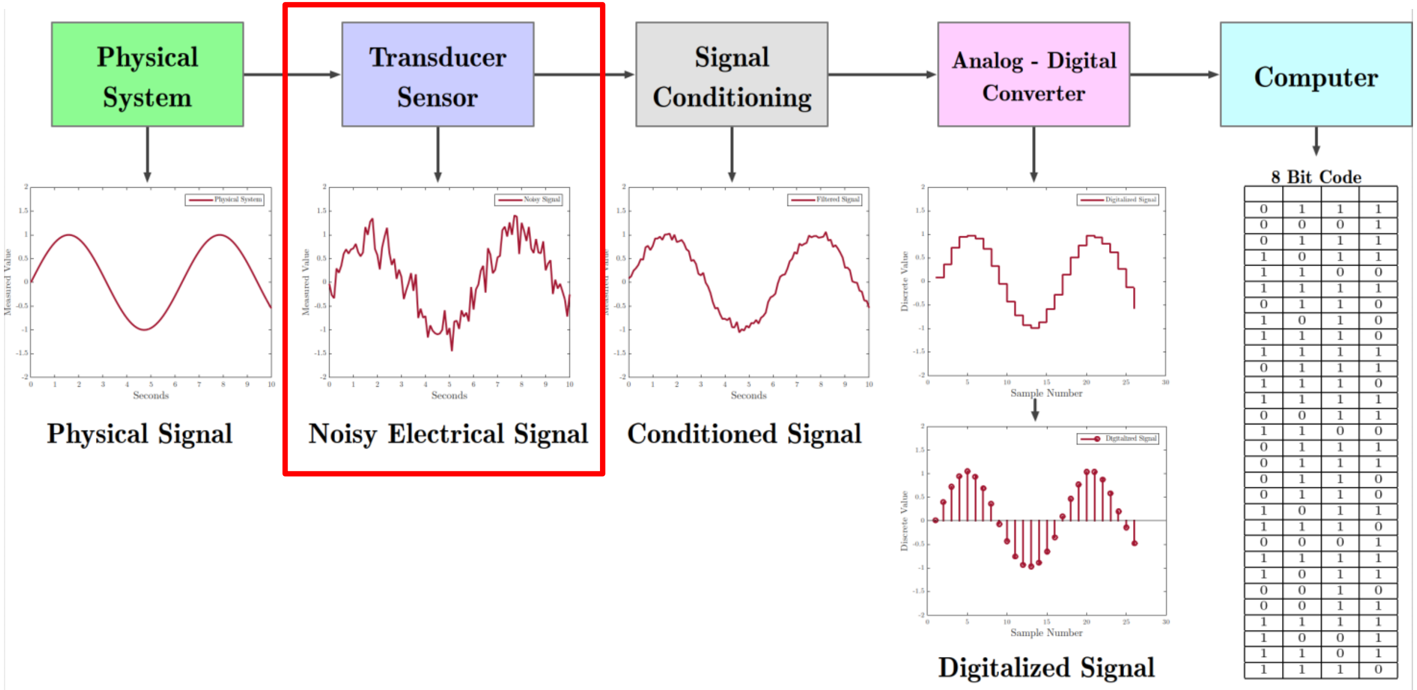
Use of sensors and actuators

- Sensors
  - *"Read from physical world"*
  - Monitor changes and report to operator
  - Record or process data stream
- Actuators
  - *"Write to physical world"*
  - Take action



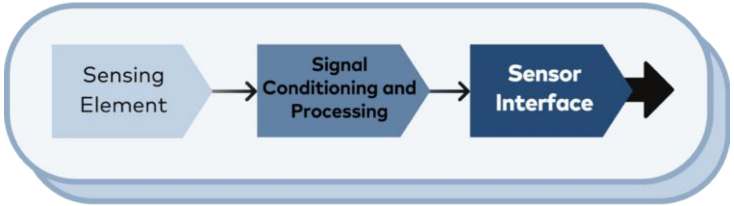
Example of closed loop feedback system

Sensors within data acquisition systems

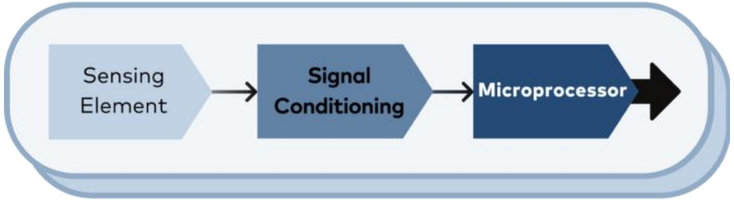


Sensor architectures

- Conventional integrated sensors:



- Smart sensors:



Selecting the right sensor

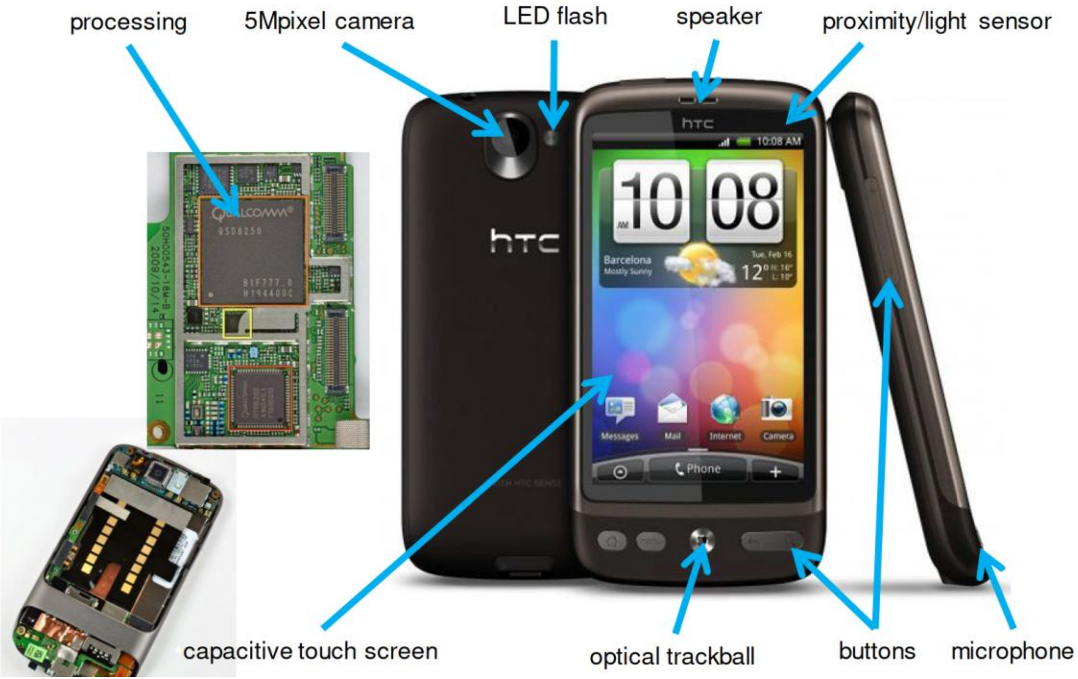
- What variable does the sensor measure?
- What physical principle is used to obtain a measurement?
- Is the sensor analog or digital?
    - Some sensors generate analog signals (voltage, current)
    - Others generate a digital signal directly
- What signal conditioning is required?
- What type of interface electronics are needed?
- What are potential error sources?
- How rapidly must the sensor be read?
- Etc.

Many sensors

- Accelerometers
- Gyroscopes
- Magnetometers
- Cameras
- Microphones
- Radar
- Lidar

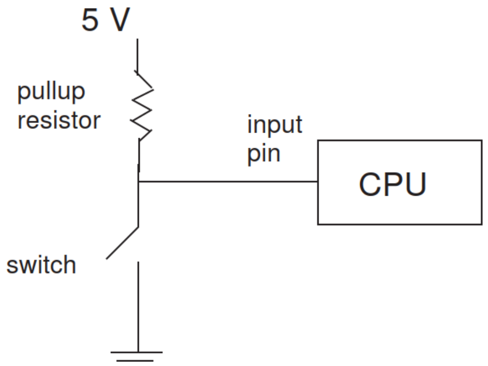
- Chemical sensors
- Pressure sensors
- Strain gauges
- Position encoder
- Photodiodes
- Switches/buttons
- Potentiometers

Example: sensors in a smartphone



Switches / buttons

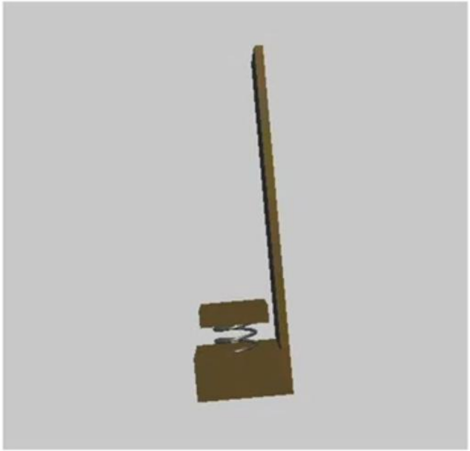
- Small switches or pushbuttons are used to generate an “on” or “off” signal
- When switch is closed, it may “bounce” several times before settling
- The duration of bouncing is short (≈20msec), and is not detectable to a human.
    - However, a microprocessor may respond to these fluctuations and generate erroneous signals.
- Debouncing can be hardware-based, e.g. with a capacitor, or software-based, e.g. with a timeout



Accelerometers

- Measures acceleration
  - F = ma
  - Earth's gravitational force is balanced by the restoring force of the spring
- Uses:
  - Navigation
  - Orientation
  - Drop detection
  - Image stabilization
  - Airbag systems

Spring-Mass-Damper model



Gyroscope

- Measures change in orientation / angular velocity
- Uses:
    - Step counting
    - Game controller
    - VR head tracking

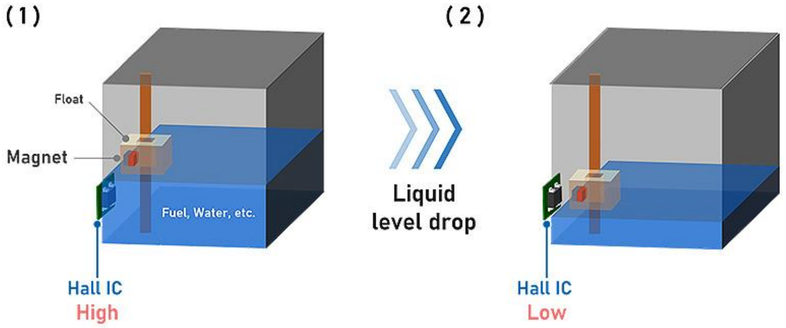
Magnetometer

- Measures magnetic field
  - Hall effect

- Uses:
  - Compass
  - Proximity sensor
  - Wheel speed sensor
  - Camshaft position sensor

Fluid level sensor

- Magnet in float moves with level
- Hall IC senses magnetic field and outputs a digital on/off or analog voltage proportional to level
- No mechanical contact with fluid
- Bounce-free
- Sensitive to magnetic interference

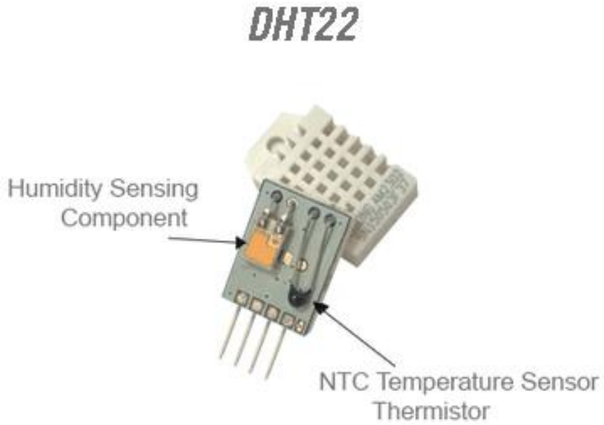


Inertial measurement unit (IMU)

- Combined accelerometer + gyroscope (+ magnetometer)
- Uses:
  - UAV / MASS
  - Satellite

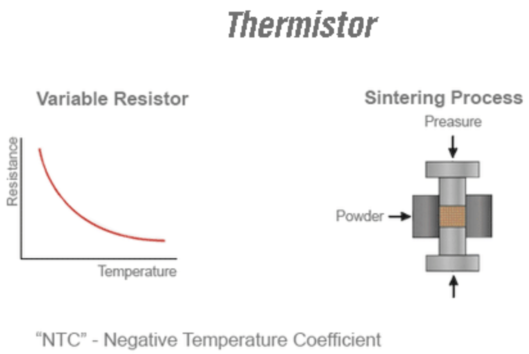
Digital humidity and temperature (DHT) sensor

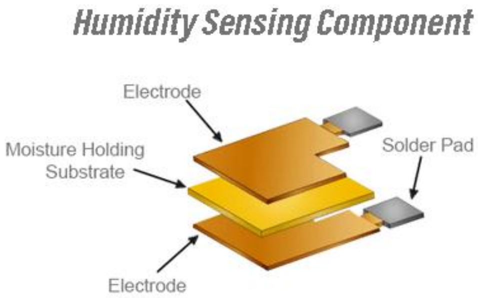
- Measures both temperature and humidity
- Uses:
  - Thermostats
  - Incubators



DHT22

- Negative Temperature Coefficient (NTC) thermistor
  - Resistance is negatively proportional to temperature
  - Temperature range: -40 - 80°C
- Humidity sensing component
  - Is a moisture-sensitive capacitor
  - Capacitance is converted to relative humidity value
  - Humidity range: 0 – 100%





Ultrasonic sensors

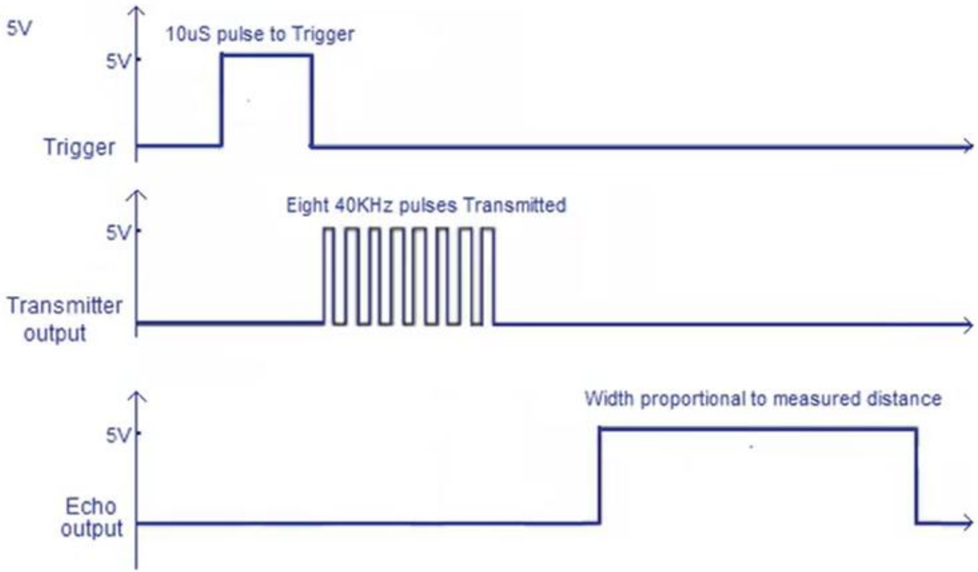
- Use sound waves to detect objects
- Short range
- Use cases:
  - Distance measurement
  - Water level indicator
  - Obstacle avoiding robot
  - Car parking
  - Dimensions of object

HC-SR 04

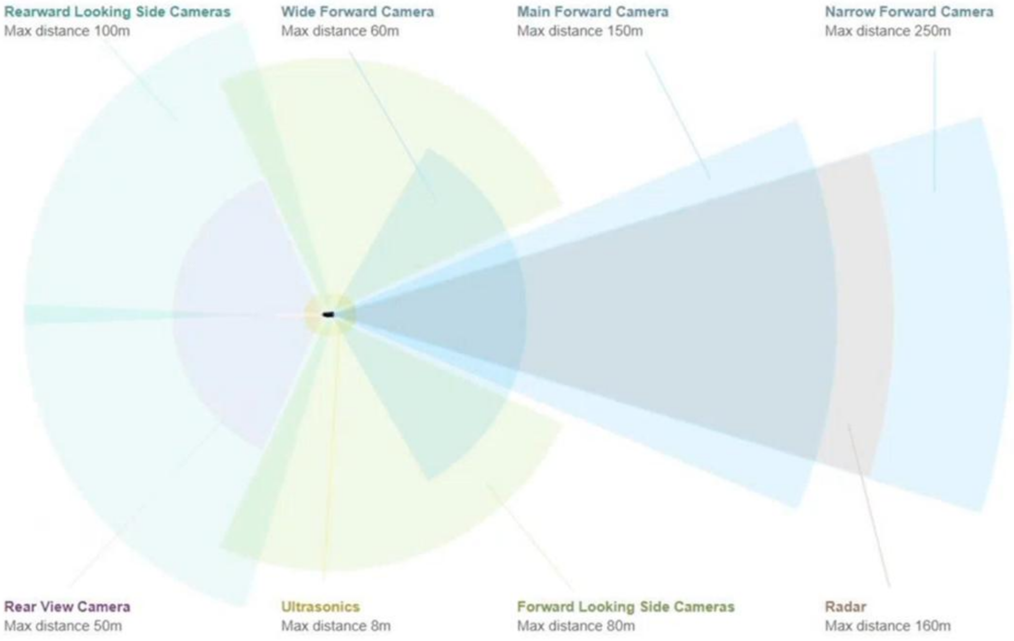
- Operating voltage: 5V DC
- Operating current: 15mA
- Measure angle: 150 degrees
- Ranging distance: 2cm - 4m

Output signal

- Trig -> 10 us pulse
- Echo -> HIGH
- Read echo pulse duration



Sensor technology comparison for self-driving cars (Tesla)



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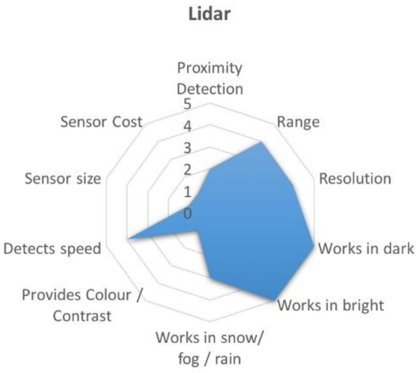
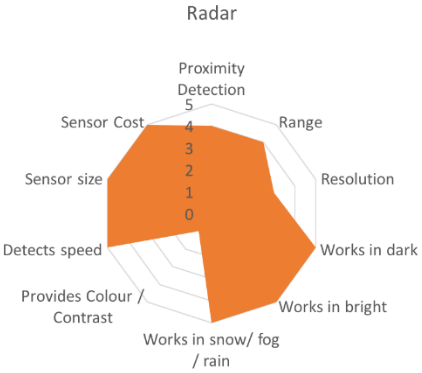
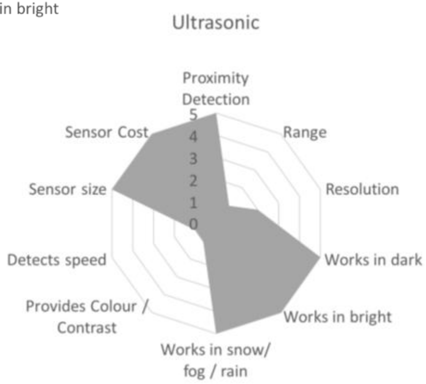
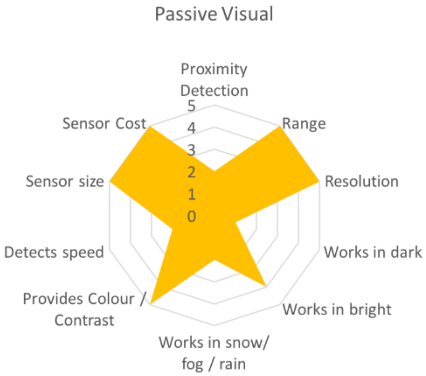


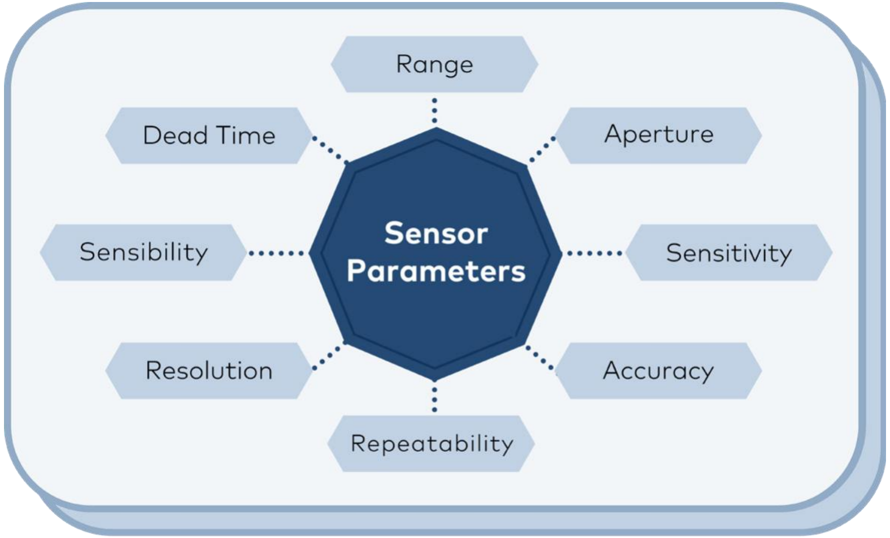






Reference:
https://web.archive.org/web/20190509135018/https://cleantechnica.com/2016/07/29/tesla-google-disagree-lidar-right/

Sensor parameters



Sensor limitations

- Calibration
- Non-linearity
- Sampling
- Noise
- Failure

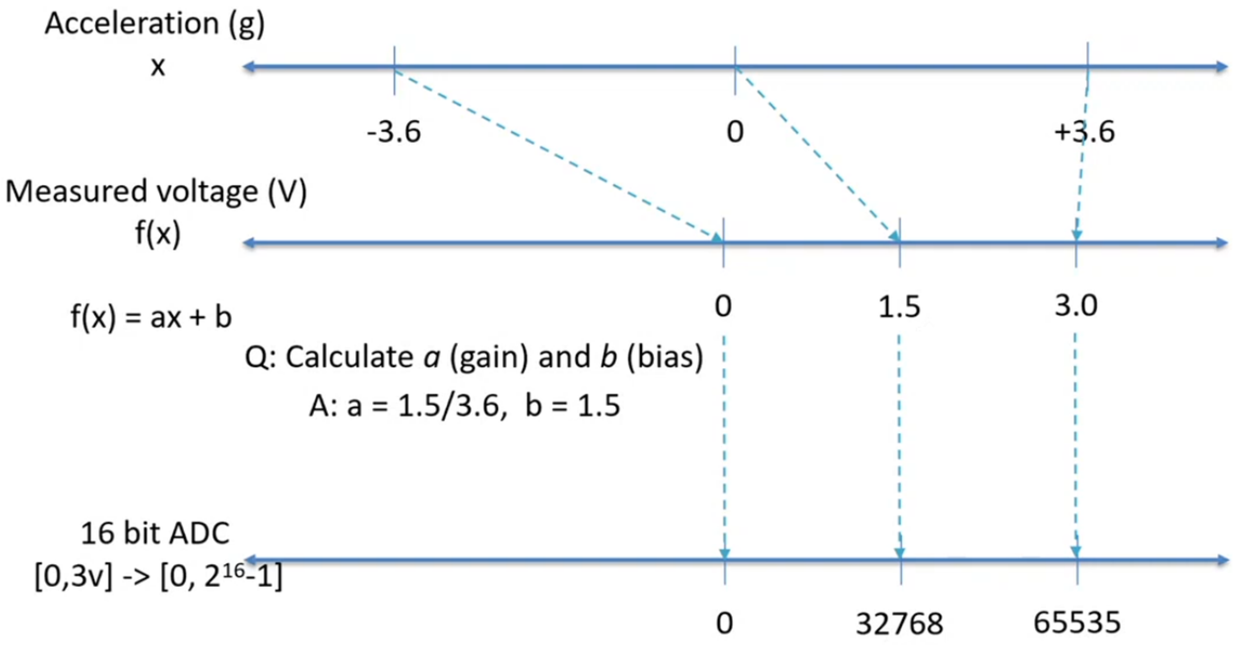
Calibration

- A sensor measures a physical quantity *x* and reports it to be *f(x)*
- Can approximate *f(x)* with linear and affine model

$$f(x(t)) = \begin{cases} ax(t) + b & \text{if } L \leq x(t) \leq H \\ aH + b & \text{if } x(t) > H \\ aL + b & \text{if } x(t) < L, \end{cases}$$

  - Where *a* is the sensitivity (gain) and *b* is the bias
  - Saturated if outside range [L, H]
- Calibration: Determine a and b

Calibration



Example accelerometer range and sensitivity in datasheet

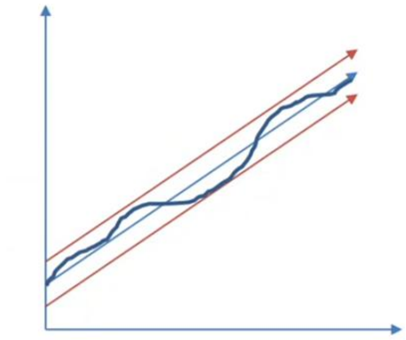
9.1 Accelerometer mechanical characteristics

Table 3. Accelerometer mechanical characteristics @ VDD = 2.5 V, VDDIO = 1.8 V T = 25 °C unless otherwise noted.

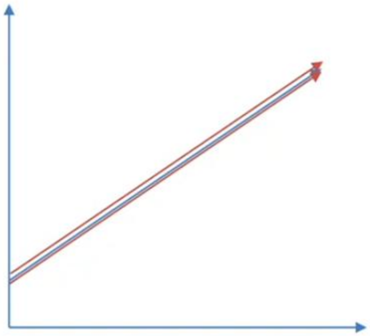
Symbol	Parameter	Conditions		Min	Typ	Max	Unit
FS_{ACC}	Measurement range	±2 *g* mode	[1]	-	±2	-	g
		±4 *g* mode		-	±4	-	
		±8 *g* mode		-	±8	-	
SEN_{ACC}	Sensitivity	±2 *g* mode		-	4096	-	LSB/*g*
				-	0.244	-	mg/LSB
		±4 *g* mode		-	2048	-	LSB/*g*
				-	0.488	-	mg/LSB
		±8 *g* mode		-	1024	-	LSB/*g*
				-	0.976	-	mg/LSB
TCS_{ACC}	Sensitivity change with temperature	±2 *g*, ±4 *g*, ±8 *g* modes	[1]	-	±0.01	-	%/°C
$SEN\text{-}TOL_{ACC}$	Sensitivity accuracy			-	±2.5	-	$\%SEN_{ACC}$
OFF_{ACC}	Zero-*g* level offset accuracy	±2 *g*, ±4 *g*, ±8 *g* modes	[2]	-	±20	-	mg
$OFF_{ACC\text{-}PBM}$	Zero-*g* level offset accuracy post-board mount	±2 *g*, ±4 *g*, ±8 *g* modes	[4]	-	±30	-	mg
TCO_{ACC}	Zero-*g* level change versus temperature	–40 °C to 85 °C	[1]	-	±0.2	-	mg/°C
NL_{ACC}	Nonlinearity (deviation from straight line)	Over ±1 *g* range normal mode	[5][6]	-	±0.5	-	$\%FS_{ACC}$
$STOC_{ACC}$	Self-test output change		[7]				LSB
		±2 *g* mode, X-axis		+192	-	-	
		±2 *g* mode, Y-axis		+270	-	-	
		±2 *g* mode, Z-axis		+1275	-	-	

Non-linearity

- Measurements may not be proportional to physical phenomenon
- Correction may be required
- Feedback can be used to keep operating point in the linear region



Non-linearity=+-5%

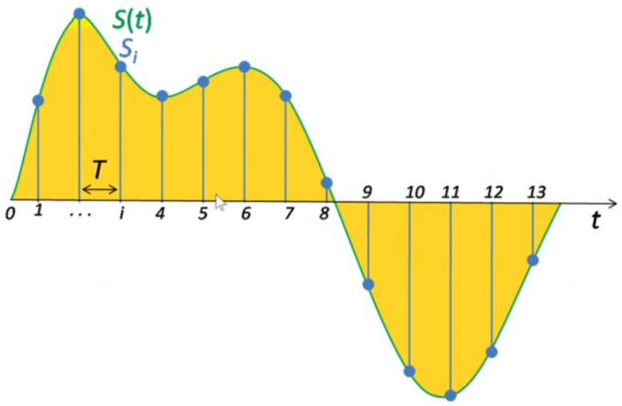


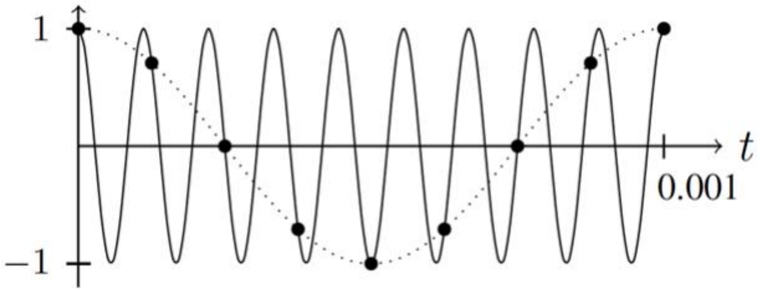
Non-linearity=+-0.5%

Sampling

- Aliasing
  - High frequency components masquerade as low frequency components.
- Missed events

- E.g. For IMU
  - 14-bit ADC resolution for acceleration measurements
  - 16-bit ADC resolution for magnetic measurements





Noise

- All sensors are noisy (at varying degrees)
- Filtering improve robustness
- Low/high pass filters (cut off low or high values of certain thresholds)
- Exponential weighted moving average (EWMA) filter: S(t) = a * Y(t) + (I-a) * S(t-I)

Noise

2. Features and benefits

- Complete 6-axis, e-compass hardware solution
- 1.95 V to 3.6 V VDD supply voltage, 1.62 V to 3.6 V VDDIO voltage
- ±2 *g*/±4 *g*/±8 *g* dynamically selectable acceleration full-scale range
- ±1200 μT magnetic sensor full-scale range
- Output data rates (ODR) from 1.563 Hz to 800 Hz for each sensor, and up to 400 Hz when operated in hybrid mode with both sensors active
- Low noise: < 126 μg/√Hz acceleration noise density at 200-Hz bandwidth, < 100 nT/√Hz magnetic noise density at 100-Hz bandwidth
- 14-bit ADC resolution for acceleration measurements
- 16-bit ADC resolution for magnetic measurements
- Low power: 240 μA current consumption at 100 Hz, and 80 μA at 25 Hz with both sensors active

Failure

- Sensors are physical devices; like all physical devices, they suffer wear and tear, and can have manufacturing defects
- Some are more prone than others
- Common causes:
    - Physical damage
    - Obstruction (e.g., dust)
    - Bad weather
- You cannot assume all sensors of a system will work all the times.

Attacks

Hackers may deliberately affect sensor performance!

To be discussed in Module 3…

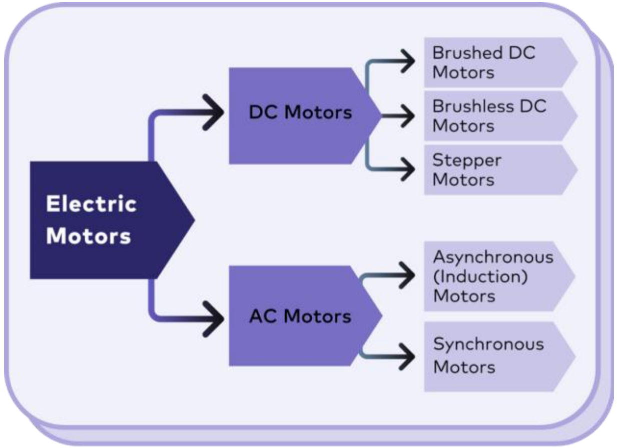
Many actuators

- The other side of the coin from sensors...

- Motors
- Solenoids
- LEDs, lasers
- LCD and plasma displays
- Speakers, buzzer
- Switches
- Valves
- Transistor, relay, optocoupler

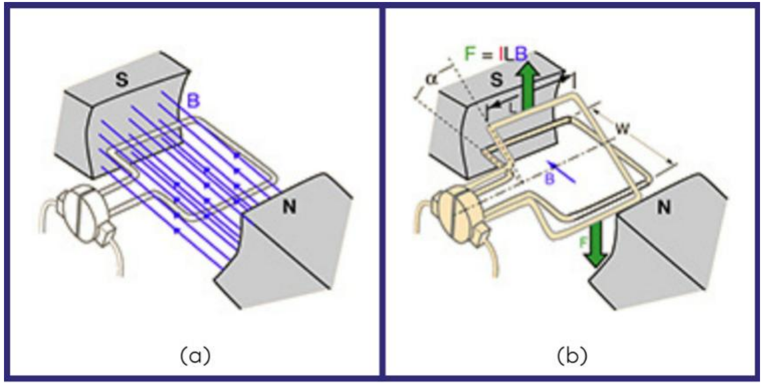
Motors

- Used to transform electrical into mechanical energy using principles of electromagnetics
- Several types, all of which use electrical energy to turn a shaft
- Two main types: time-invariant direct current (DC) and time-varying current (AC)



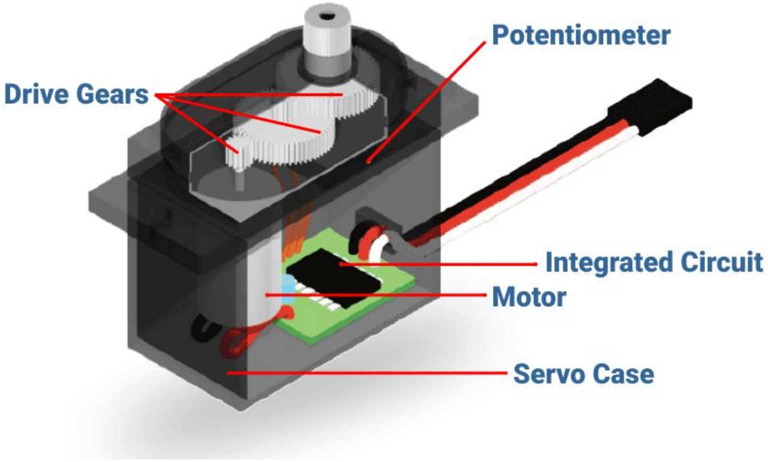
Motors

- When voltage is applied to the ends of the metal frame (loop of wire), a current flows through the frame
- The magnetic field created by the magnet poles coincides with the current, causing a force to be exerted on the frame
- The frame begins to revolve around its own axis
- This process is repeated as electricity is applied to the frame
- Use this force to do some mechanical work



Servo motors

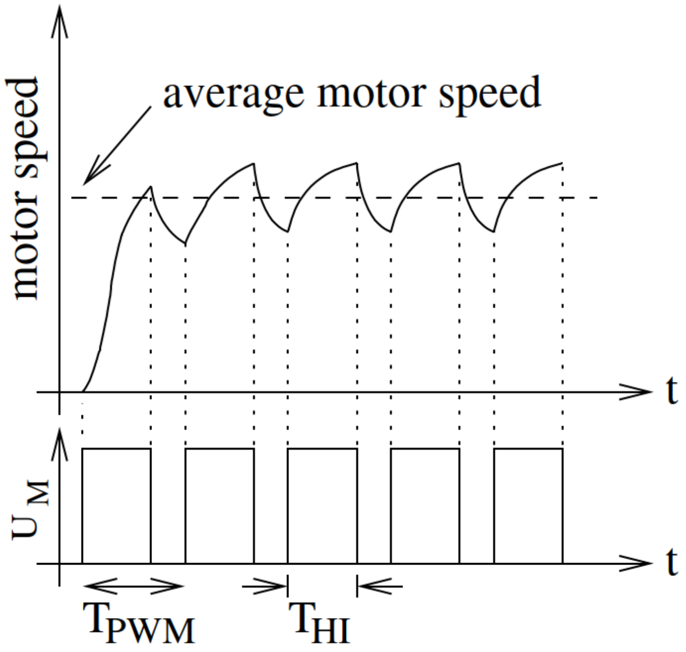
- Allows for precise control of angular or linear position, velocity and acceleration
- Main components:
    - DC motor
    - Potentiometer
    - Drive gears
    - Integrated circuit
- Uses closed-loop control feedback to reduce steady-state error and improve dynamic response



Servo motor speed control

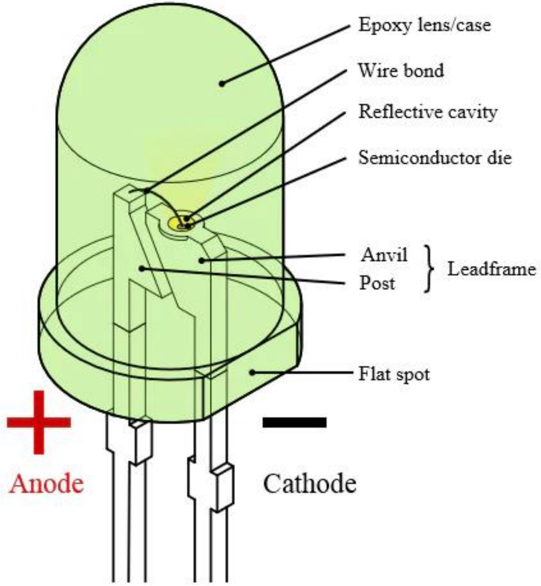
- Use inertia of servo motor to obtain relatively constant speed
- Achieved via a digital *pulse width modulation* (PWM) signal which rapidly switch turns servo motor on and off
- Creates perception of analog output
- Increasing/decreasing *duty cycle* increases/ decreases perception of power output level
- The shorter the *period*, the smoother the motor rotation will become

$$v_M \propto T_{HI}/T_{PWM}.$$



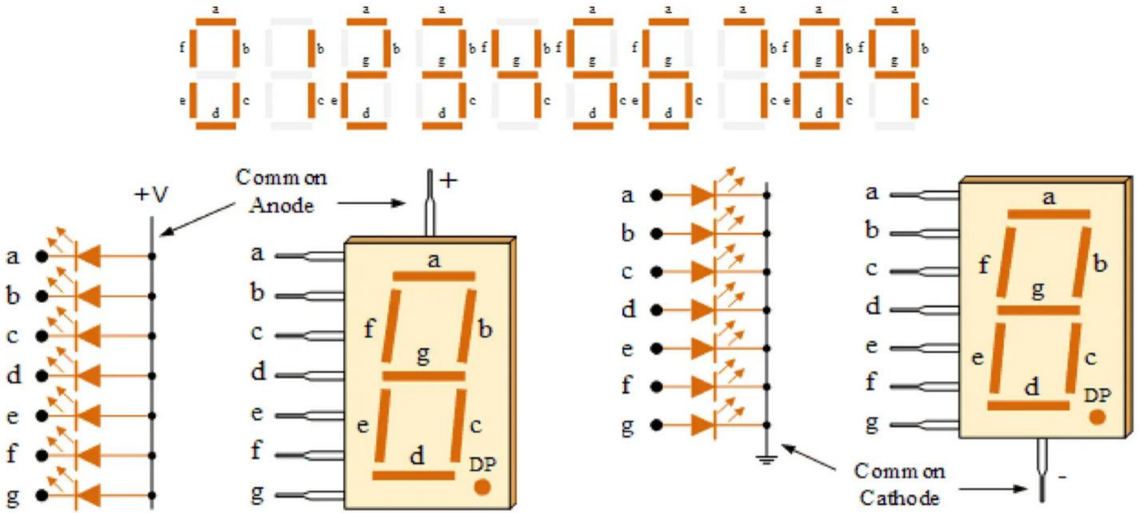
Light emitting diode (LED)

- Provide visual feedback or an indication of the status of a system
- Two-terminal polarized device
- When the cathode terminal is connected to ground and the anode terminal is connected to a positive voltage, the LED will turn on
- Current must be limited to value below maximum current that it can conduct



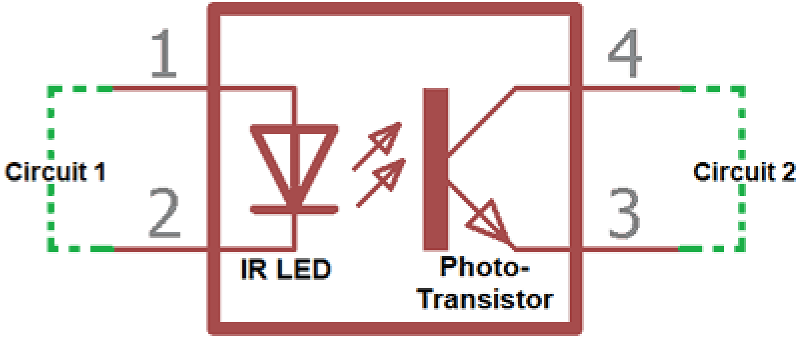
Alphanumeric display

- Displays alphanumeric characters
- Contains 8 LED segments, including a dot point (DP)



Optocoupler

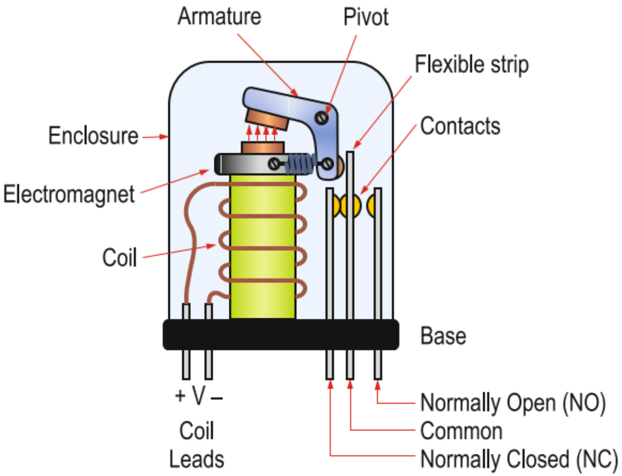
- Allows an electrical signal to be transmitted between two isolated circuits
- Combines LED and phototransistor in a single housing (package)
- Input circuit uses the signal to turn on the LED
- Output circuit detects the light outputs and produces a current



Opto-coupler

Electromechanical relay

- Electrically controlled switch
- No connection between the coil and contacts
- When voltage is applied to the relay coil, current flows and induces a magnetic field
- The field attracts the armature, which is normally held in the open position by a spring
- The normally open contacts close while the normally closed contacts open
- Relay remains in this state until the coil is de-energized.



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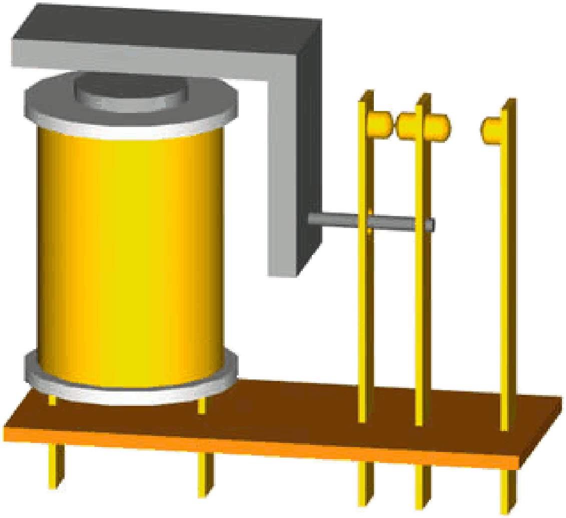
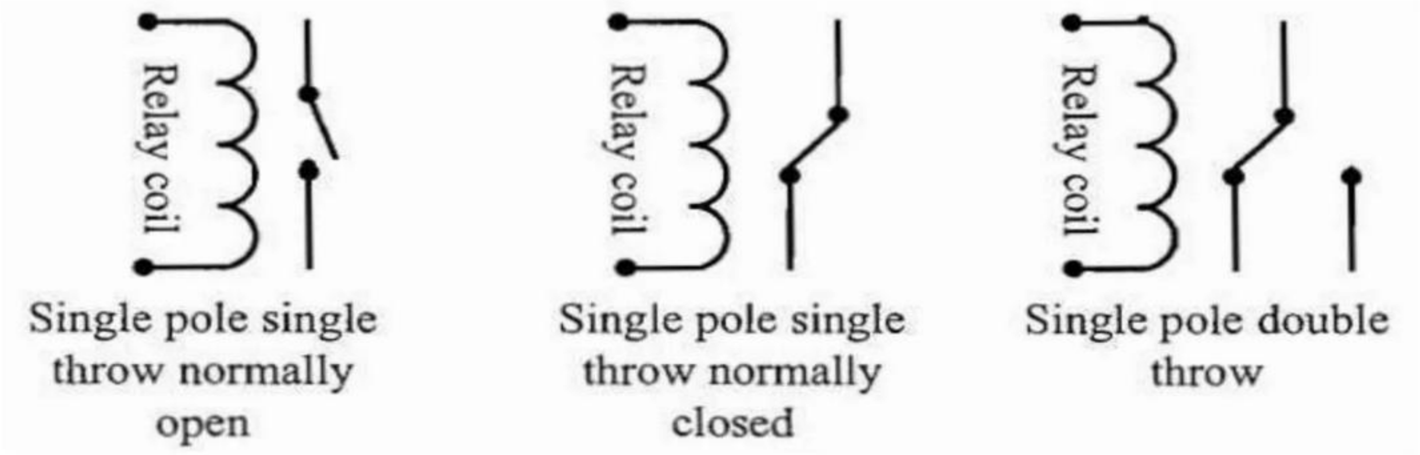


Relay configurations



Piezo buzzer

- Generates audio signals
- Contains a piezoelectric diaphragm which produces audible sound in response to voltage applied to it
    - Piezoelectric = the ability certain materials have to generate electric voltage when subjected to a mechanical stress (and vice versa)
- Two types:
    - Self-driving: supports one tone
    - External driving: supports multiple tones