INTERNET OF THINGS (IoT)

Nodes

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NEON
Network of Competence on Internet of Things

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UNC Universidad Nacional de Córdoba

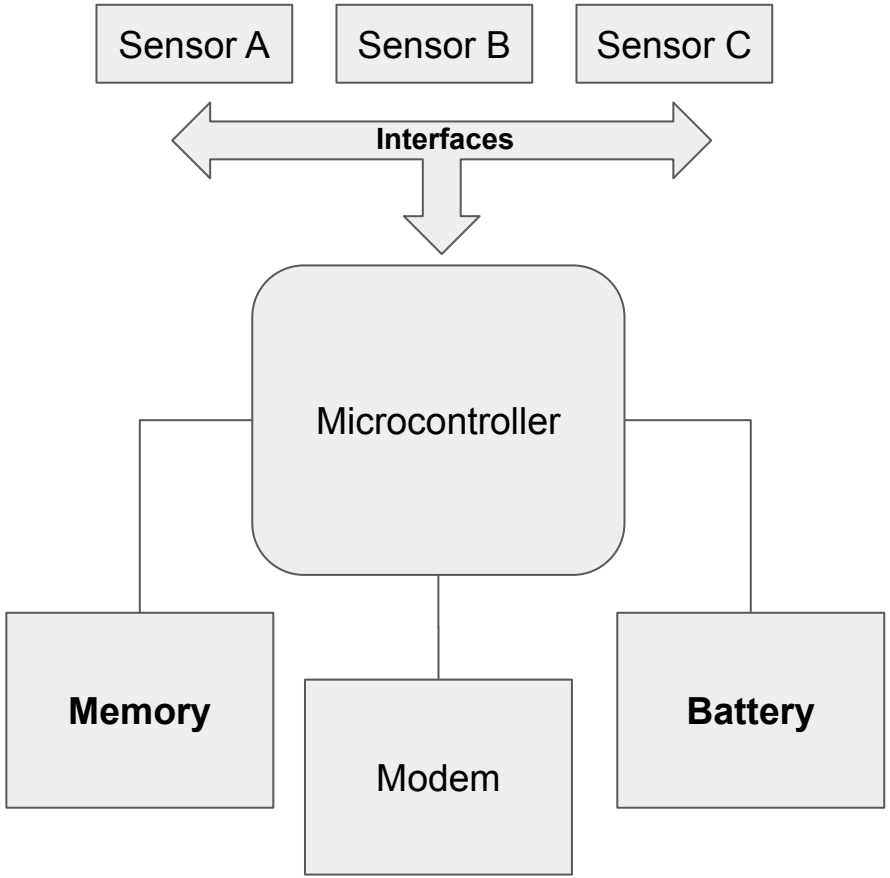
FCEFyN
FACULTAD DE CIENCIAS EXACTAS, FÍSICAS y NATURALES

An IoT node

A typical IoT node is made of microcontroller which is capable of interfacing with sensors and actuators.

This microcontroller needs to temporally store collected data in memory until it is transmitted to a third party

Besides, energy is required to feed all the node's components



Interfaces

Sensor Communication

Analogue sensors require an IoT nodes to be equipped with ADC channels to convert data.

Typically, these ADC have a resolution form 8 to 16 bits and a configurable sampling frequency up to a few KHz

However, most sensors already integrate an ADC and have a digital interface from which data can be retrieved.

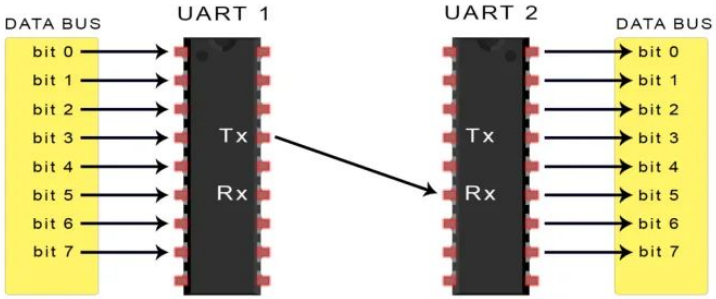
Different digital interfaces are available for this purpose: UART, I2C and SPI

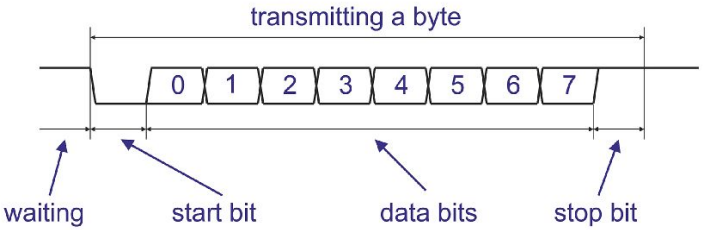
UART Interface

Universal asynchronous receiver-transmitter (UART) provides asynchronous serial communication that allows a host (microcontroller) to communicate with an auxiliary device (sensor).

Only 2 data lines (no clock needed), each device operates at similar baud rates

Low rate (upto a few Mb/s) and each device (sensor) requires a dedicated interface.





I²C Interface

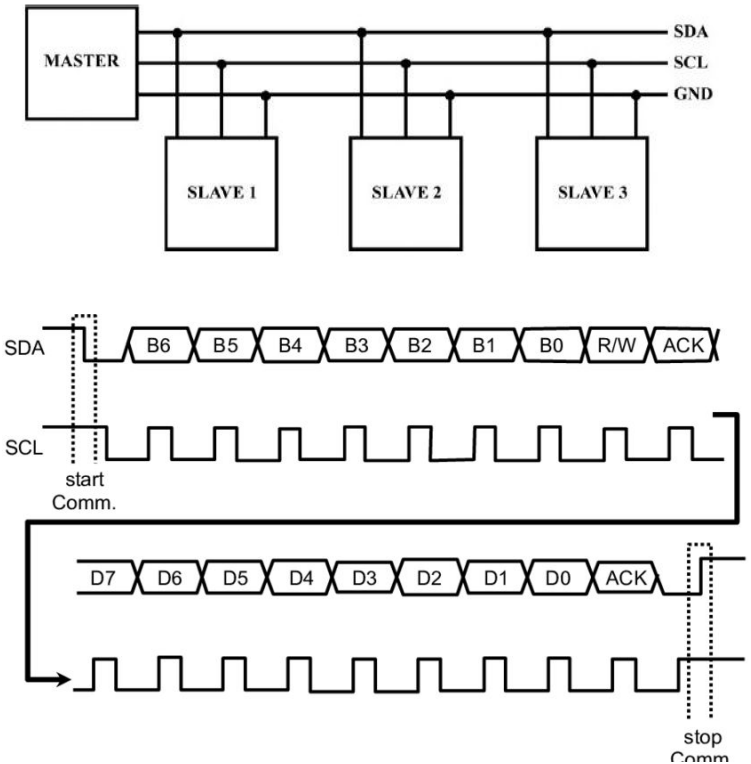
Inter-integrated-circuit (I²C) is a bidirectional two-wire **synchronous** serial **bus**

Requires only 2 wires Serial Data Acceptance (SDA) and Serial Clock line (SCL) to transmit data between **devices** connected to the bus

Both addresses and data sent through the bus

One master and multiple slaves (upto 128)

Very low rates from ~100Kb/s and half-duplex, but supports for multiple devices



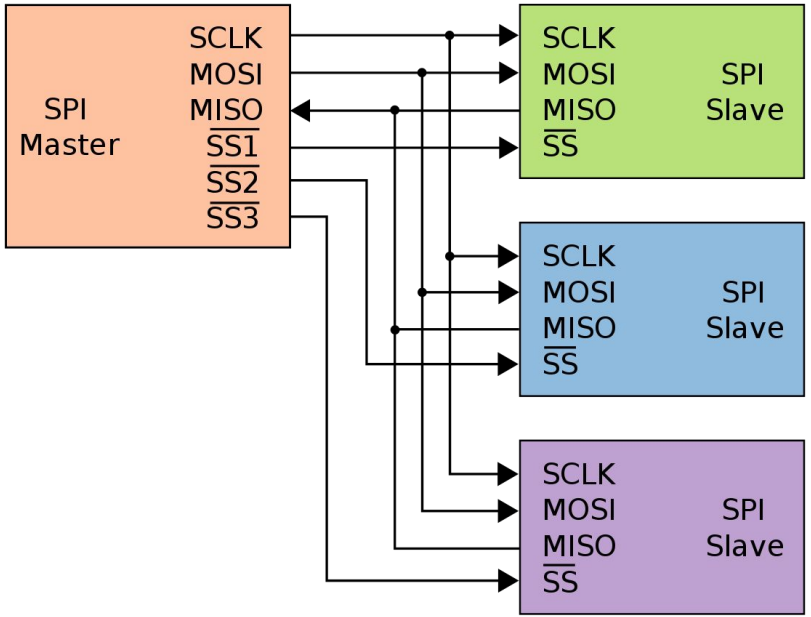
SPI Interface

Serial Peripheral interface (SPI) is similar to I^2C but offer higher rates

Even if data and clock lines are shared between devices, each requires a unique address wire (slave select)

Full-duplex support through directional data lines: MOSI (out) and MISO (in)

Faster than UART and I2C, but since more pins are required, it limits the number of connected devices.



Memory

Data Storage

Memory can be categorized as non-volatile and volatile.

Non-volatile memory (NVM) is capable of retaining data even after power is removed and generally has a lower speed than volatile memory.

Volatile memory, on the other hand, does not retain data after power is removed and has higher per-bit storage costs.

NVM is then used for storing acquired data by sensors

Most popular NVM for IoT is Flash memory because it is inexpensive, reliable, high density and does not consume too much power.

Flash memory

Flash memory falls into two categories: NOR Flash and NAND Flash

NOR Flash is very popular amongst applications requiring code storage, such home gateway and set top boxes, because of its ability to support XIP (execution in place) applications and low standby power consumption,

NAND is more suitable for data storage applications that do not require XIP support.

	NAND Flash	NOR Flash
Cost per bit	Low	High
File storage use	Easy	Hard
Standby power	High	Low
Active power	Low	High
Read speed	Low	High
Write speed	High	Low
Capacity	High	Low
Code execution	Hard	Easy

Storage Sizing

Total amount of data depends on the data resolution (size of each sample) and the acquisition rate, and the transmission frequency

In general, it is assumed that all collected data can be transmitted every time a new transmission opportunity is available.

Typical strategies tend to some collect data before transmitting data

Too expensive (in terms of energy) to transmit data as it is acquired, hence, the acquisition rate is typically faster than the communication one

¿How would you size the memory then?

Power

Power

Amount of energy transferred per unit time, supplied to operate something.

… or amount of energy (Joules) consumed in one second (s).

Usually measured in units of watts (W), where 1 W = 1 Joule / second

Often expressed as a current in units of amperes (A), but assumes a given voltage (V) since W = V x A

Example: 1 A @ 5 V is equivalent to 5 W

In general, electronic devices have voltages between 3-5V and **consume** little current (~mA) when active and almost no current (~uA) when in sleep mode.

Energy

Refers to an amount of energy (Joules) or delivered power considering a reference time duration (hour)

Usually measured in units of watts-hour (Wh), where 1 Wh = 3600 Joules

Often expressed as a current in units of amperes (Ah), but assumes a given voltage (V) since Wh = V x Ah

Example: 1 Ah @ 5 V is equivalent to 5 Wh

In general, electronic devices have voltages between 3-5V and **store** little energy (~mAh) in batteries which is mainly consumed when active (awake).

Batteries

Energy can be stored in batteries: its capacity is expressed in Wh in general or in Ah for electronic devices, typically.

Batteries can be split in two families: primary batteries which can not be recharged, and secondary ones which are rechargeable.

Nominal voltage *U* is the potential difference observed at battery terminals

However, as explained thereafter, the available supply voltage is lower, and depends on the required current and the internal resistor of the battery.

Cell

Batteries are generally composed of one or several cells, thus nominal voltage U is sometimes given per cell.

Several cells in series yield a higher voltage (a multiple of the base nominal voltage), while several cells in parallel provide a greater current capability.

To describe those associations, the *xSyP* notation is used, where *x* is the number cells in series and *y* the number of cells in parallel.

Each chemical technology yields a specific nominal voltage per elementary cell.

Cell Technologies

Battery family	Technology	Chemical composition	U_{nom} (V)
Primary	Alkaline	Zn-MnO2	1.5
	Lithium-Manganese-Dioxyde	Li-MnO2	3.0
	Lithium-Thionyl-Chloride	Li-SOCl2	3.6
Secondary	Nickel-Metal-Hybrid	Ni-MH	1.2
	Lead-Acid	Pb-SO4	2.1
	Lithium-Ion Cobalt-Oxide	Li-CoO2	3.7
	Lithium-Ion Iron-Phosphate	Li-FePO4	3.2
	Lithium-Ion Manganese-Oxide	Li-MnO2	3.9
	Lithium-Ion Sulfur	Li2S8	2.1
	Nickel-Cadmium	Ni-Cd	1.2
	Lithium-Polymer	Li-Po	3.7

Capacity

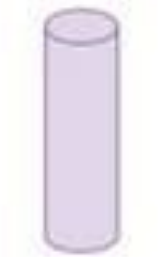
Represents the quantity of energy contained in the battery, and allows the designer to estimate its operating time depending on the required power.

Capacity is expressed in Ah or mAh (1Ah = 1000 mAh), where 1Ah means providing a 1A continuous current for an hour at a specific voltage.

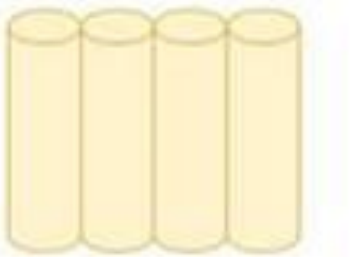
An accumulator with a capacity C, which provides a continuous current *I* will operate for a time *t* equal to *C/I* (since $C = I \times t$)

Activity: What technology is your phone battery? Voltage? Cells? Capacity? How much does your phone consume on average?

Voltage & Capacity



1s1p
Single Cell
3.7V - 1500mAh



1s4p
Four Cells in Parallel
3.7V - 6000mAh

2s1p
Two Cells in Series
7.4V - 1500mAh

Mass density

Ratio between the energy a battery provides and its **weight**, expressed in Wh/kg. The higher the mass density, the lighter the battery.

Battery family	Technology	Mass density ($W.h.kg^{-1}$)
Primary	Alkaline	85 — 190
	Lithium-Manganese-Dioxyde	150 — 330
	Lithium-Thionyl-Chloride	700
Secondary	Nickel-Metal-Hybrid	30 — 80
	Lead-Acid	30 — 40
	Lithium-Ion Cobalt-Oxide	90 — 140
	Lithium-Ion Iron-Phosphate	90 — 130
	Lithium-Ion Manganese-Oxide	160
	Lithium-Ion Sulfur	300
	Nickel-Cadmium	40 — 60
	Lithium-Polymer	100 — 265

Energy density

Ratio between energy capability and the **volume** of the battery, expressed in Wh/L
The higher the energy density, the smaller the battery.

Battery family	Technology	Energy density ($W.h.L^{-1}$)
Primary	Alkaline	250 — 430
	Lithium-Manganese-Dioxyde	300 — 710
	Lithium-Thionyl-Chloride	1200
Secondary	Nickel-Metal-Hybrid	140 — 300
	Lead-Acid	60 — 75
	Lithium-Ion Cobalt-Oxide	220 — 350
	Lithium-Ion Iron-Phosphate	350
	Lithium-Ion Manganese-Oxide	270
	Lithium-Ion Sulfur	400
	Nickel-Cadmium	50 — 150
	Lithium-Polymer	185 — 220

Mass vs Energy Density

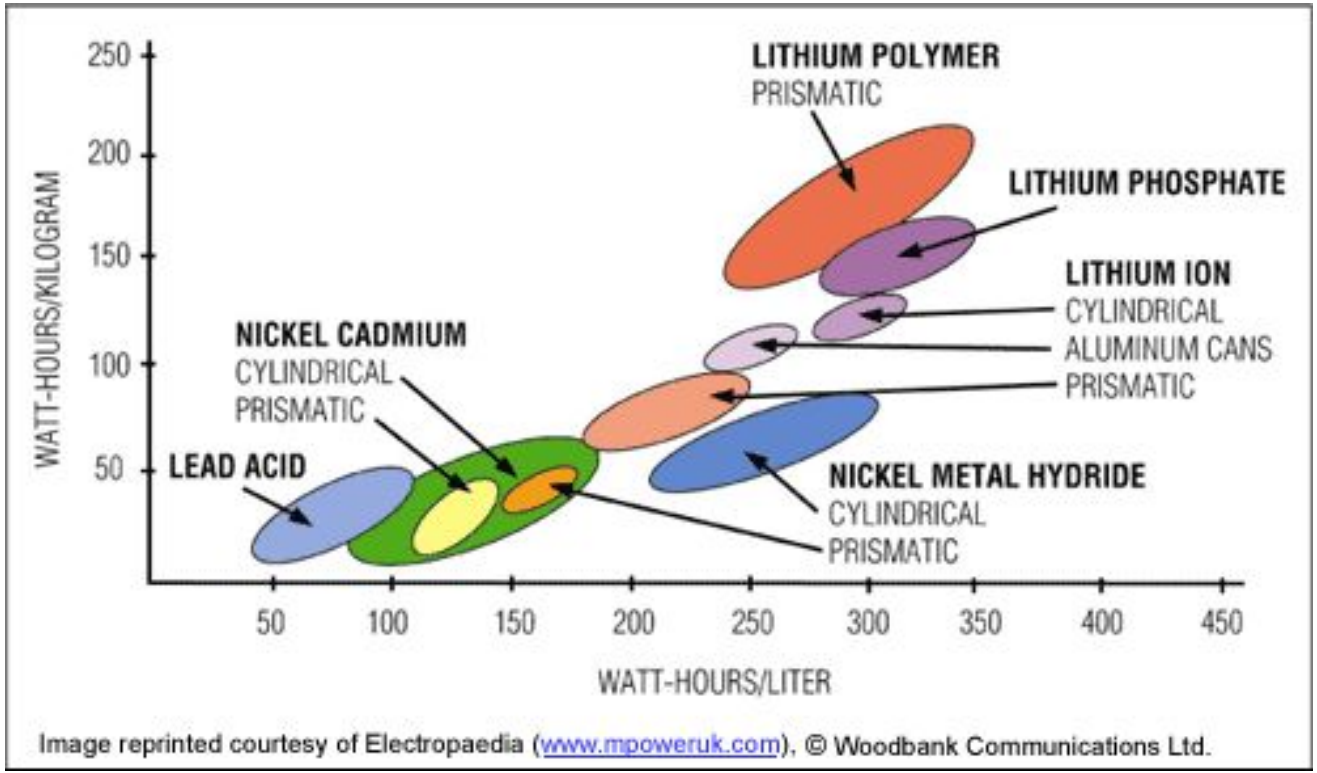


Image reprinted courtesy of Electropaedia (www.mpoweruk.com), © Woodbank Communications Ltd.

Ageing

Capacity of rechargeable cells decreases with time: every time the accumulator is charged and discharged, its capacity decreases. Designed for a specific number of charge and discharges cycles.

Battery family	Technology	Cycles
Secondary	Nickel-Metal-Hybrid	1500
	Lead-Acid	500 — 800
	Lithium-Ion Cobalt-Oxide	1200
	Lithium-Ion Iron-Phosphate	1000 — 2000
	Lithium-Ion Manganese-Oxide	1200
	Lithium-Ion Sulfur	disputed
	Nickel-Cadmium	2000
	Lithium-Polymer	500

Memory effect!

Battery Lifespan

Takes into to account IoT node states: *sleep, acquisition and communication*

On each state, different current values are present

- Sleep (S): typically in the order of nA
- Acquisition (A): a few uA (depends on sensors)
- Communication (C): a few mA

In general, battery span can be approximated assuming only acquisition and communications currents, since sleep currents are very low.

Acquisition Energy

Assume N_a acquisitions are required per day, each lasting T_a with a power consumption of P_a

Hence, a typical day consumes $N_a * T_a * P_a$ form the battery

For example, for N_a = 24*60, T_a = 100 ms, P_a = 5 uA, then 0.72 mAh per day

Hence, we expect to spend over a year only 262.8 mAh for acquisition

A 1000 mAh battery will last then about 3.8 years

Communication Energy

Assume N_c communications messages are required per day, each lasting T_c with a power consumption of P_c

Hence, a typical day consumes $N_c * T_c * P_c$ form the battery

For example, for N_a = 1, T_a = 1 s, P_a = 3 mA, then 3 mAh

Hence, we expect to spend over a year only 1095 mAh for communication

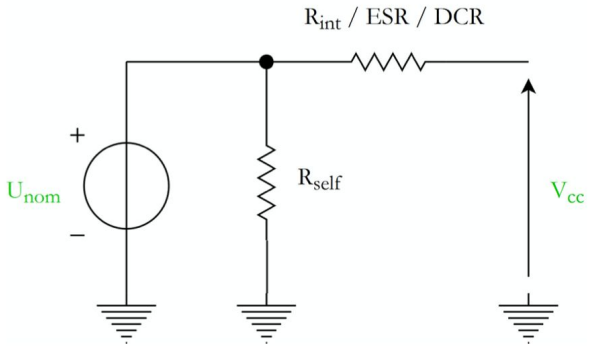
A 1000 mAh battery will NOT last a full year then.

Battery model

Actual delivered voltage *V* depends on the internal resistor (R_{int}) and the maximum current *Imax* required by the device: $V = U - I_{max} \times R_{int}$

A parallel resistor R_{self} causes self-discharge of the battery: a small current is continuously drained from the battery even if it remains in open-circuit. The smaller R_{self}, the higher the parasitic current I_{self} and the faster the self-discharge.

Self-discharge is expressed as a percentage *a* of the initial capacity *C* lost per year



$$\frac{a}{100} \times C = I_{self} \times 365 \times 24 \quad \Rightarrow \quad I_{self} = \frac{a \times C}{876000}$$

Charge (Discharge) Rates

Charge and discharge rates are often given as C_{rate}, which is a measure of the rate at which a battery is charged or discharged relative to its capacity.

The C_{rate} is defined as the charge or discharge current divided by the battery's capacity C to store an electrical charge. It is expressed in units of 1/h (per hour)

Never negative: so whether a charging or discharging depends on the context.

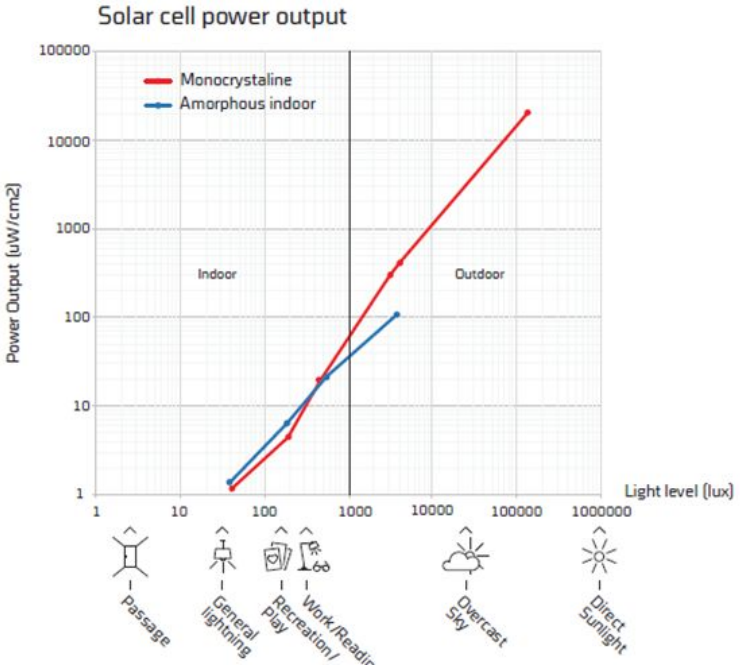
For a 500 mAh battery, a discharge current of 50 mA corresponds to a C_{rate} of 10 (per hour), meaning that such a current can discharge such batteries in 10 hours. Likewise, a charge current of 250 mA corresponds to a C_{rate} of 1/2 (per hour), meaning that it will increase its charge by 50% in one hour.

Energy Harvesting

Typically, solar panels can be used for energy harvesting in IoT

Converts the electromagnetic energy of the sun into electrical energy. The total amount of solar energy over a given area per unit of time is known as *irradiance* and it is measured in watts per square meter (W/m^2).

This energy is normally averaged over a period of time, so it is common to talk about total irradiance per hour,day or month.



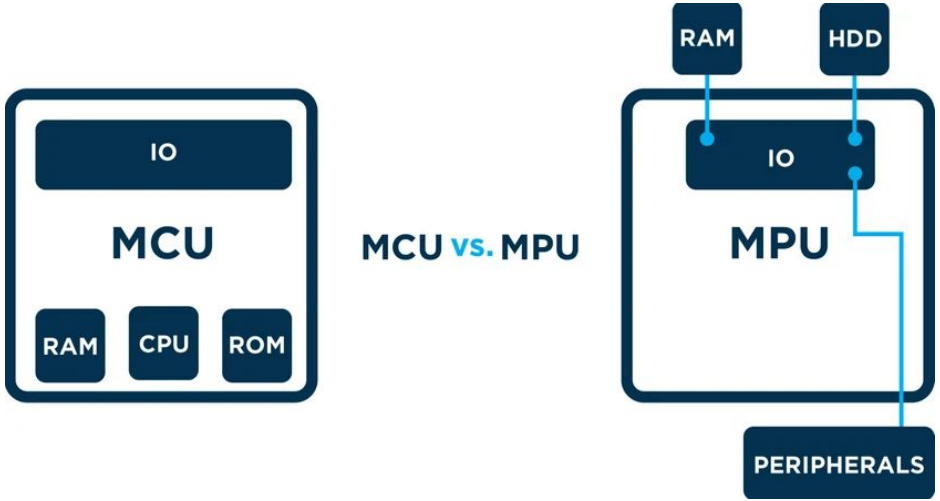
Control

Microprocessors vs. Microcontrollers

Microprocessors (MPU) are different than microcontrollers (MCU) in their design.

Microprocessors have only CPU inside and no in-memory support.

Microcontrollers have CPU, RAM, ROM and other peripherals which are all embedded on the same chip.



IoT devices tend to use microcontrollers or *System on Chip (SoC)* which also integrated ADC and radio communications capabilities

IoT Microcontroller Key Features

- **Bits**: supported number of bits. Impacts the speed at which they are able to perform non-trivial computations. Typically either 8-bit or 32-bit
- **RAM**: fast-access volatile memory, which allows your MCU to quickly perform various actions. The more you have, the better, but increases the cost. From a up to fea KB (8-bit MCU) to a few MB (32-bit MCU)
- **ROM**: stores the application program in the microcontroller. Bigger the size, the more complex it becomes. Typically emulated using a Flash memory
- **Input / Output Ports**: interfaces and GPIO pins that you will use for connecting your sensors and actuators. Ranges from a few to hundreds.
- **Operating System**: from no operating system (bare metal) to Linux-based ones, which are much easier to program.

IoT Microcontrollers: # Bits

Primary distinction between different MCUs:

- **8-bit**: mostly used in a very cost constrained. Mostly with a simple control loop, but sometimes running an RTOS. Example: Arduino
- 16-bit: not very common in IoT, typically switch between 8 and 32-bit.
- **32-bit**: normal entry point unless the application can fit on 8-bit architecture and has cost constraints. Example: Raspberry Pi
- 64-bit: reserved for high-end systems, normally Linux or other OS. Normally you need a specific (compute intensity) reason to jump from 32-bit to 64-bit.

Besides #bits, the frequency (MHz) is also important. The larger, the faster but also more power consuming. Typically, frequencies range from 20MHz to 100MHz

IoT Microcontrollers: OS

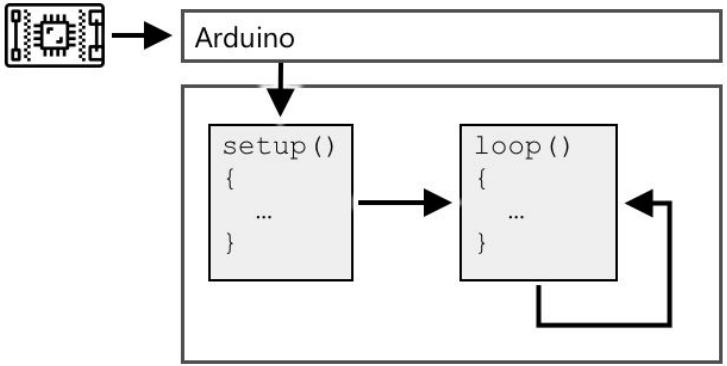
Bare Metal	RTOS (Real-Time Operating System)	Linux-based
Original and simplest approach	Provides guarantees for the timing of processing with input/output events	Popular open-source operating system based on UNIX, originally for personal computers
No operating system	Program runs within the operating system	Significantly more accessible and easier to program
Code talks directly to the computing components	Have the ability to suspend a task and have a high-priority task execute	Robust community of people who can help with support
Limited programming support	Quick to set up but time-consuming to debug	More difficult to get real-time performance

Arduino Microcontroller

Arduino is probably the most popular microcontroller framework, especially among students, hobbyists and makers.

Open source electronics platform combining software and hardware.

Arduino boards are coded in C or C++ which allows to be compiled very small and run fast, something needed on a constrained device such as a microcontroller



Single Board Computers (SBC)

A single-board computer is a small computing device that has all the elements of a complete computer contained on a single small board.

Have specifications close to a desktop or laptop PC or Mac, run a full operating system, but are small, use less power, and are substantially cheaper.

The Raspberry Pi is one of the most popular single-board computers.

Single-board computers are fully-featured computers, so can be programmed in any language. IoT devices are typically programmed in Python.

Commercial Microcontrollers (SoC)

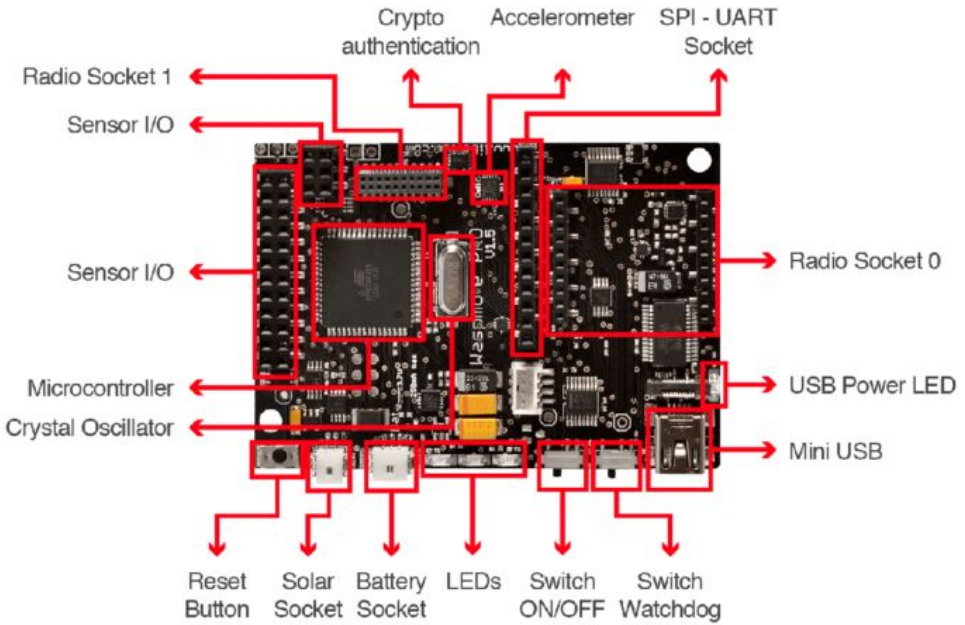
Brand	Models	CPU	RAM	+	Price	Type	Connectivity
Arduino	20+ and many clones (Spark, Intel, and so on)	ATmega, 8–64 MHz, Intel Curie, Linino	16 KB–64 MB	Largest community	~30 USD	RTOS, Linux, hobbyists	Pluggable extension boards (Wi-Fi, GPRS, BLE, Zigbee, and so on)
Raspberry Pi	A, A+, B, B+, 2, 3, Zero	ARMv6 or v7, 700 MHz -1.2 GHz	256–1 GB	Full Linux, GPU, large community	~5-35 USD	Linux, hobbyists	Ethernet, extension through USB, BLE (Pi3)
Intel	Edison	Intel Atom 500 MHz	1 GB	X86, full Linux	~50 USD	Linux, hobbyist to industrial	Wi-Fi, BLE
BeagleBoard	BeagleBone Black, X15, and so on	AM335x 1 GHz ARMv7	512 MB–2 GB	Stability, full Linux, SDK	~50 USD	Linux, hobbyist to industrial	Ethernet, extension through USB and shields
Texas Instruments	CC3200, SoC IoT, and so on	ARM 80 MHz, etc.	from 256 KB	Cost, Wi-Fi	<10 USD	RTOS, industrial	Wi-Fi, BLE, Zigbee
Marvell	88MC200, SoC IoT, and so on	ARM 200 MHz, etc.	from 256 KB	Cost, Wi-Fi, SDK	<10 USD	RTOS, industrial	Wi-Fi, BLE, Zigbee
Broadcom	WICED, and so on (also at the heart of the Raspberry PIs)	ARM 120 MHz, and so on	from 256 KB	Cost, Wi-Fi, SDK	<10 USD	RTOS, industrial	Wi-Fi, BLE, Zigbee, Thread

Source: Building the Web of Things: book.webofthings.io

- Arduino
- Raspberry
  - BCM

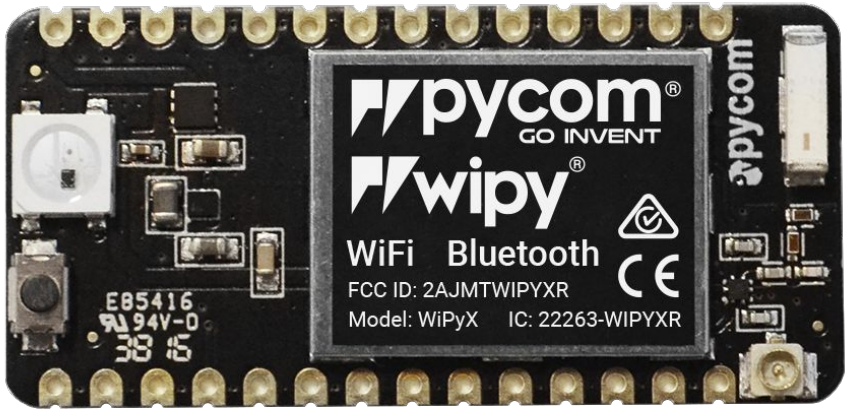
Libelium Waspmote

- Microcontroller: ATmega1281
- Frequency: 14.74 MHz
- SRAM: 8 kB
- EEPROM: 4 kB
- FLASH: 128 kB
- SD card: 16 GB
- Weight: 20 g

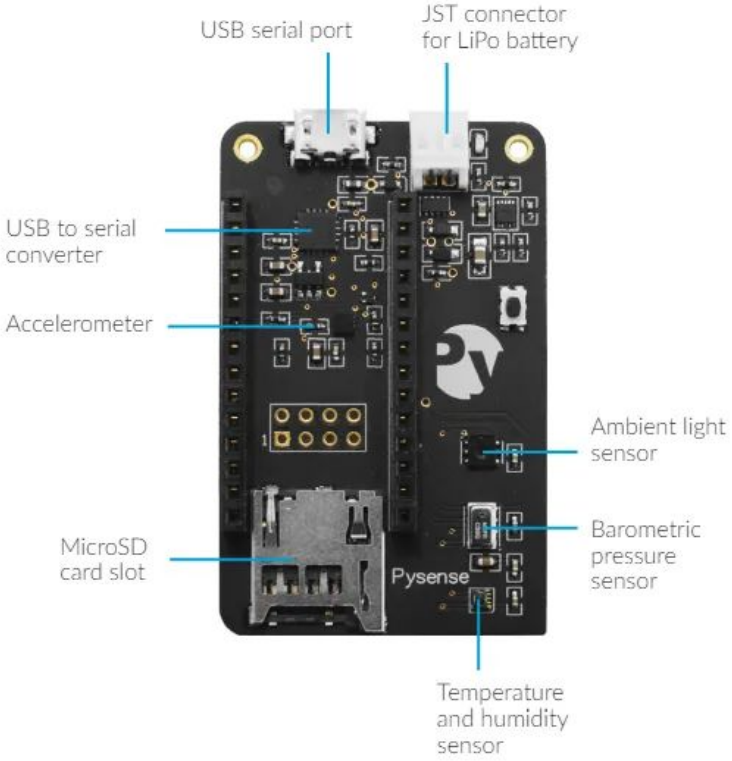


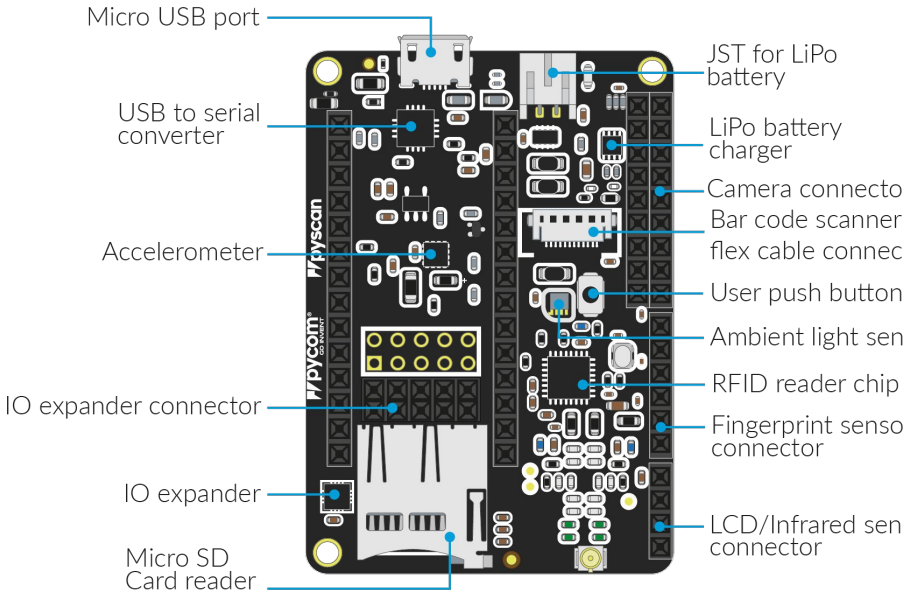
Pycom

- Espressif ESP32 chipset
- 2 x UART
- 2 x SPI
- I2C
- Micro SD card
- Analog channels: 8_12 bit ADCs
- GPIO: Up to 24



Pysense & Pyscan Modules





Protection

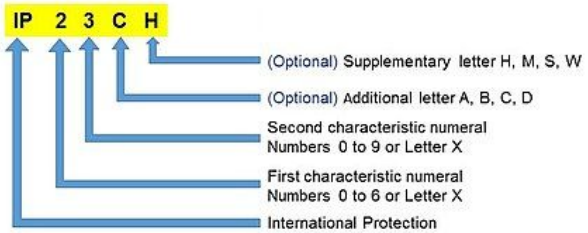
Indoor vs. Outdoor

An IoT node typically needs to be protected by a case from its surrounding environment and conditions.

Main scenarios are either indoor or outdoor conditions.

Cases are classified by a specific code known as the IP cod (Ingress Protection Code) that rates the degree of protection provided by mechanical casings and electrical enclosures against intrusion, dust, accidental contact, and water.

Outdoor cases for IoT often provide IP67 protection



IP Code

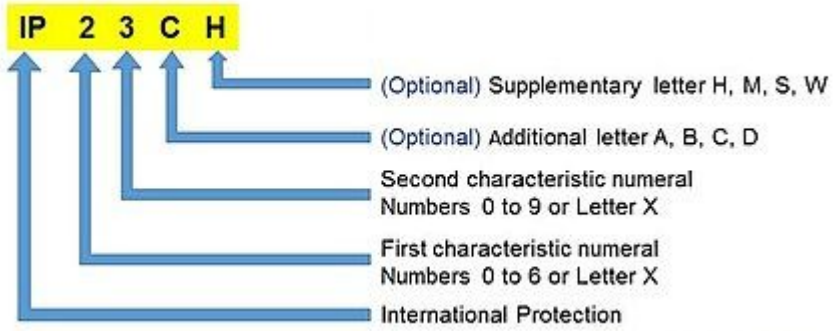
IP followed by a 4-digit code

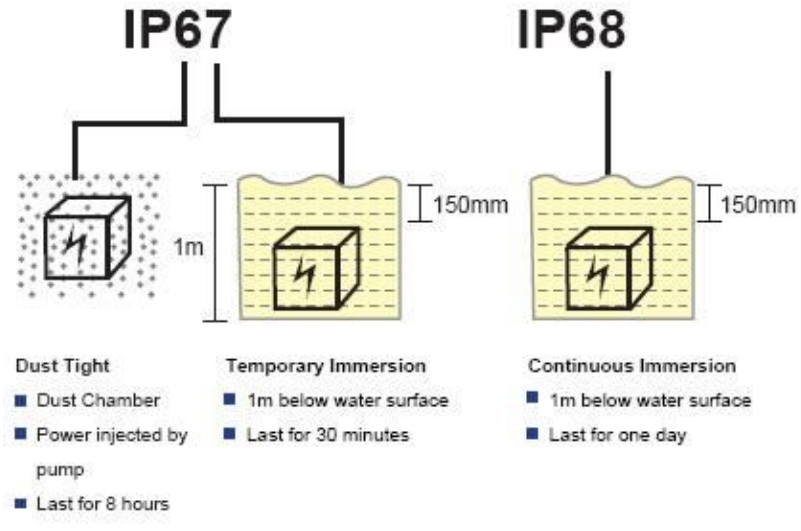
First characteristic numeral: Solid particle protection

Second digit: Liquid ingress protection

Additional letter: Other protections

Supplementary letter: Other protections





IP Code Table

Solids

1	2	3	4	5	6
					
Solid objects greater than 50 mm, such as the back of a hand.	Solid objects greater than 12.5 mm, such as a finger.	Solid objects greater than 2.5 mm, such as a screwdriver.	Solid objects greater than 1 mm, such as a wire.	Limited ingress of dust. It must not interfere with the actuator operation.	No ingress of dust.

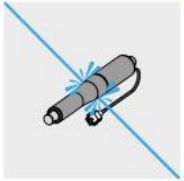
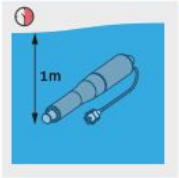
Codification example

Ingress Protection

Solids

Liquids

Liquids

1	2	3	4	5	6	7	8
							
Vertically falling drops.	Vertically falling drops over an actuator tilted 15°.	Sprays of water at any angle up to 60° from the vertical.	Sprays of water at any angle.	Water jets.	Powerful water jets.	15cm-100 cm immersion during 30 min.	Immersion under harder conditions than in IPX7.