Videos

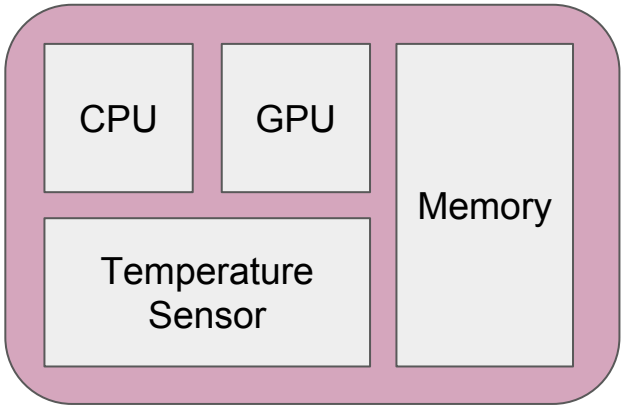
Hardware Platforms and Sensors

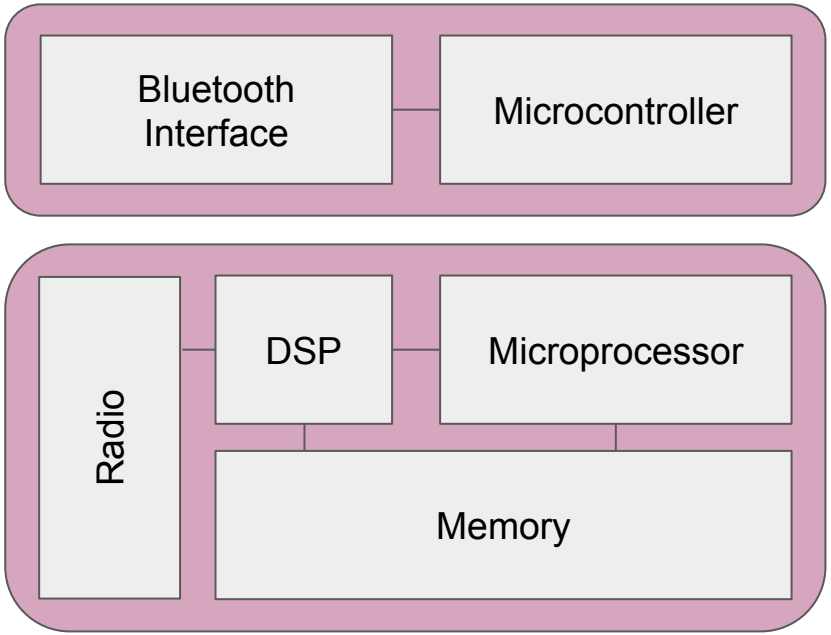
Tom Spink

Including material adapted from Bjoern Franke and Michael O'Boyle

Hardware Platform

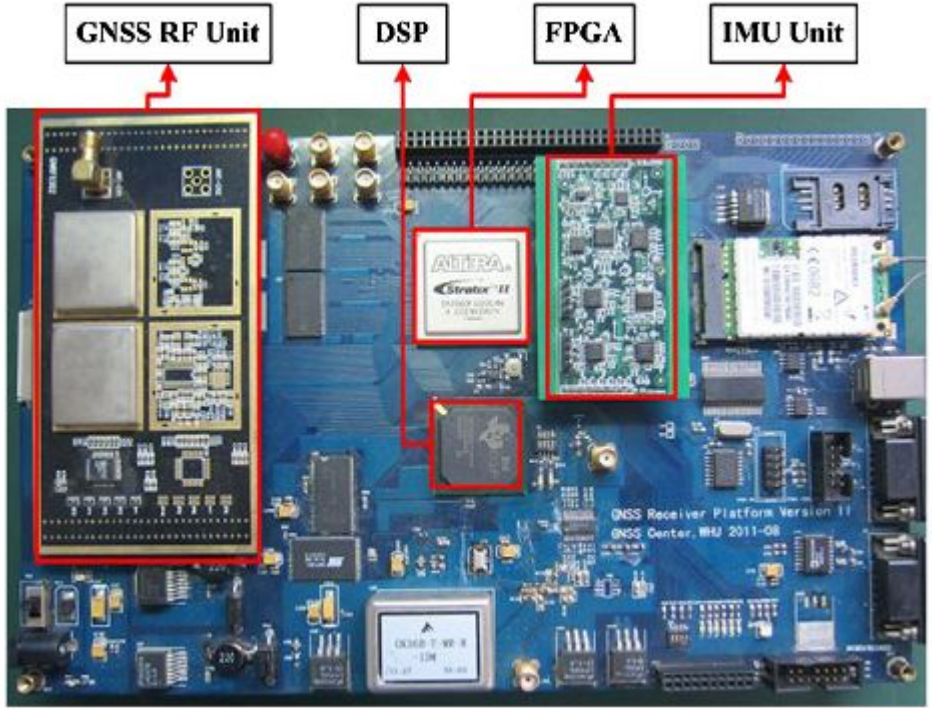
A hardware platform describes the **physical components** that go to make up a particular device.





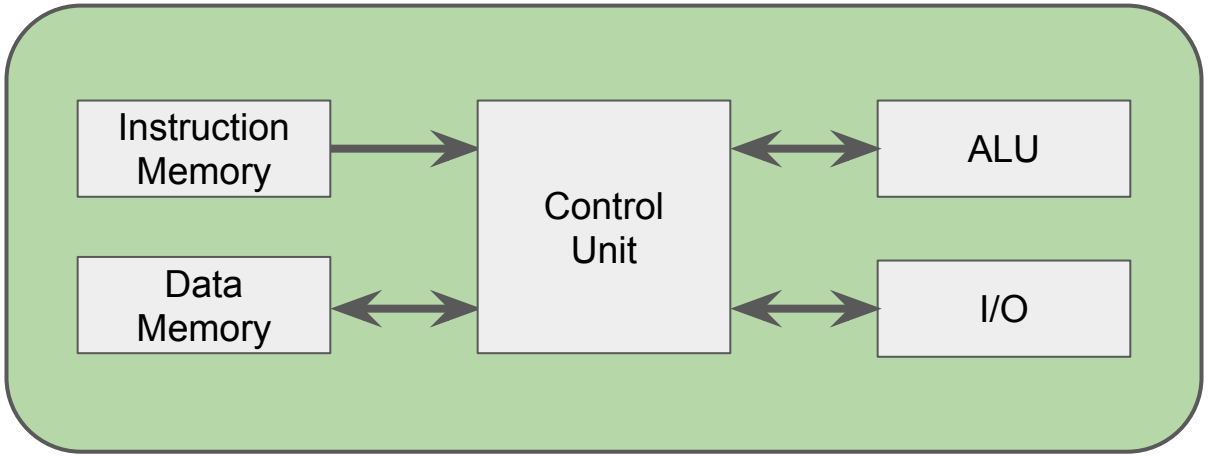
Designing a hardware platform

- Application size/complexity
  - Type of microcontroller
    - Clock speed
  - Additional processors
    - GPUs or DSPs?
- I/O
  - GPIO
  - Serial (I^2C, SPI, etc)
- Connectivity
  - Wired/Wireless
- Power/energy constraints
  - Battery powered
  - Solar powered
  - Grid connected - reliable/unreliable



Microcontrollers

A microcontroller is an **integrated circuit**, containing one or more **processing** units, various **memories**, and a number of **functional** units for **computation** and **I/O**. Typical microcontrollers implement the **Harvard** architecture.



Types of Memory

The embedded memories present in microcontrollers come in different **flavours**, and are used for different **purposes**.

In the **Harvard** architecture, systems have separate **program** and **data** memories, usually backed by different technologies, and with different **capacities**.

Program Memory	Volatile Data Memory	Non-volatile Data Memory	Volatile Data Memory
Flash	**SRAM**	**EEPROM**	**DRAM**

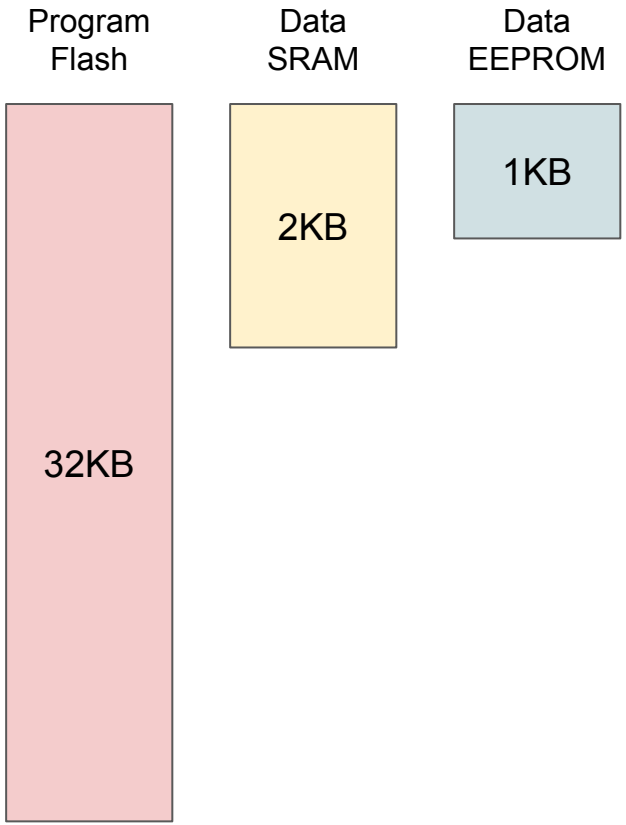
Memory Constraints

Microcontrollers are **memory constrained** devices, e.g. the AVR ATmega328 has:

32k flash, 1k EEPROM and 2k SRAM

Because of small program memory, it is important to try to reduce code size.

Software techniques (and the use of -Os) help, but architectural techniques can also help (e.g. CISC, or "compressed" instruction sets (Thumb))



Power and Energy

Power and energy are first-class issues in embedded systems:

- Battery Life
- Energy Density
- Environment

A processor that uses more power, but takes less time may use less energy:

$$E = \int P(t)dt$$

Important to decide what to optimise for.

Power and Energy

Amps $A = Cs^{-1}$
Volts $V = JC^{-1}$
Watts $W = Js^{-1}$
(Ohms $\Omega = JsC^{-2}$)

$V = I \cdot R$
$P = I \cdot V$

3.5V (nominal) battery with **3Ah** of storage = 3 $Cs^{-1}h$ * 3.5 JC^{-1} = **37.8kJ**

Processor running continually at 1W => 37.8kJ / 1 Js^{-1} = **10.5 hours**

Power Saving Techniques

Dynamic adjustment of Voltage/Frequency: Dynamic Voltage and Frequency Scaling

Usage of sleep modes for microcontroller: Turn off internal functional units when not required.

Power down external peripherals: Turn off radio when not required.

Software optimisation!

Dynamic Voltage and Frequency Scaling

Power Consumption for CMOS circuits

$$P = \alpha C_L {V_{dd}}^2 f$$

- **P:** Power
- **α:** Switching activity
- **C_L:** Load capacitance
- **V_{dd}:** Supply voltage
- **f:** Clock frequency

Delay for CMOS circuits

$$\tau = kC_L \frac{V_{dd}}{(V_{dd} - V_t)^2}$$

- **τ:** Delay time (upper limit of 1/f)
- **V_t:** Threshold voltage (< V_{dd})

Decreasing voltage slows down linearly, but quadratic power saving.

Processors offer valid “pairs” of valid voltage/frequency choices, e.g. Intel Speedstep has 6 choices, ARM big.LITTLE has 18!

Sleep Modes

Microcontrollers may provide a way to manage power by enabling different sleep modes, with different **wake-up sources**, and **quiescent power** usage.

Table 10-1. Active clock domains and wake-up sources in the different sleep modes.

	Active clock domains					Oscillators		Wake-up sources						
Sleep mode	clk_{CPU}	clk_{FLASH}	clk_{IO}	clk_{ADC}	clk_{ASY}	Main clock source enabled	Timer oscillator enabled	INT1, INT0 and pin change	TWI address match	Timer2	SPM/EEPROM ready	ADC	WDT	Other/O
Idle			X	X	X	X	X(2)	X	X	X	X	X	X	X
ADC noise reduction				X	X	X	X(2)	X(3)	X	X(2)	X	X	X	
Power-down								X(3)	X				X	
Power-save					X		X(2)	X(3)	X	X			X	
Standby(1)						X		X(3)	X				X	

Notes:
1. Only recommended with external crystal or resonator selected as clock source.
2. If Timer/Counter2 is running in asynchronous mode.
3. For INT1 and INT0, only level interrupt.

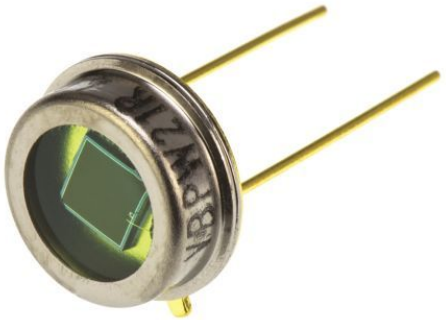
Sensors

A sensor captures a **physical** quantity, and converts it to an **electrical** quantity.

Many physical effects are used for constructing sensors:

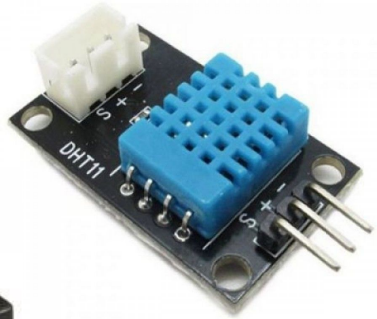
- Law of induction (generation of voltages in a magnetic field)
- Mechanical properties leading to varying electrical resistances
- Photo-electric effects

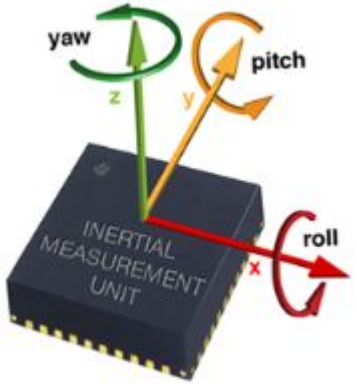
$$\Phi_b = \iint_{\sum(t)} B(r,t) \cdot dA$$

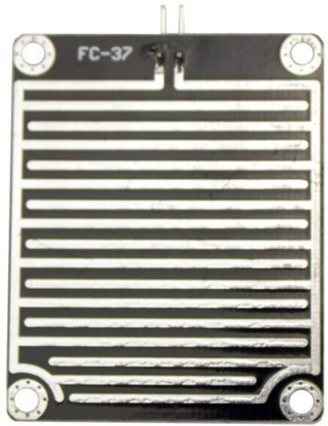


Types of sensors

- Push-button/switch
- Acceleration
- Gyroscope
- Magnetometer
- Temperature
- Pressure
- Image/Optical
- Rain
- Proximity
- Hall-effect





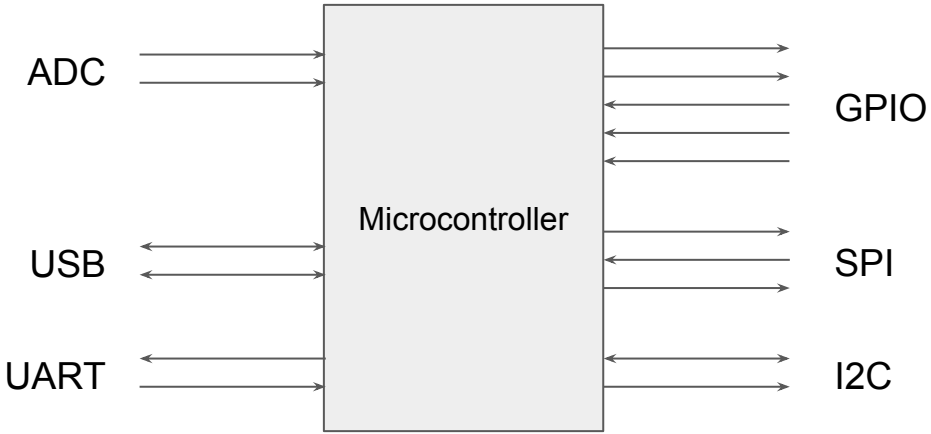


All deliver an electrical representation of a physical quantity

Input/Output

I/O is how the device **interacts with**, and **senses**, the real world. I/O can be as simple as an on/off electrical signal (GPIO), or a more complicated signalling protocol for data transfer, such as I^2C, SPI or CAN.

I/O is **required** for interfacing with sensors.



General Purpose Input/Output (GPIO)

GPIO are simple **on/off** voltage signals, that can drive outputs, or signal inputs to the microcontroller. They appear as physical pins on the microcontroller.

Microcontrollers generally have current **sinking** and **sourcing** limitations (e.g. in the range of 50mA), meaning that GPIOs are limited to low-current applications. They can be used to drive higher current loads through transistors and relays.

Input pins can be configured to signal **interrupts** - important for waking up from sleep modes, and real-time applications.

Pulse-width Modulation

If you switch a GPIO on and off fast enough, you can generate a **pulse-width modulation** (PWM) signal, to **approximate** varying output voltages. Microcontrollers typically have dedicated configurable PWM drivers.

Commonly used technique for varying power to **inertial** loads. The choice of switching frequency varies depending on the target load.

The greater the duty cycle, the more power is transferred to the load.

Made practical by modern electrically controlled (solid-state) power switches, e.g. MOSFETs. Very efficient power transfer, as typically zero current flows when the switch is open, and very little voltage drop ($R_{DS,ON}$ is low) when switch is closed.

Pulse-width Modulation

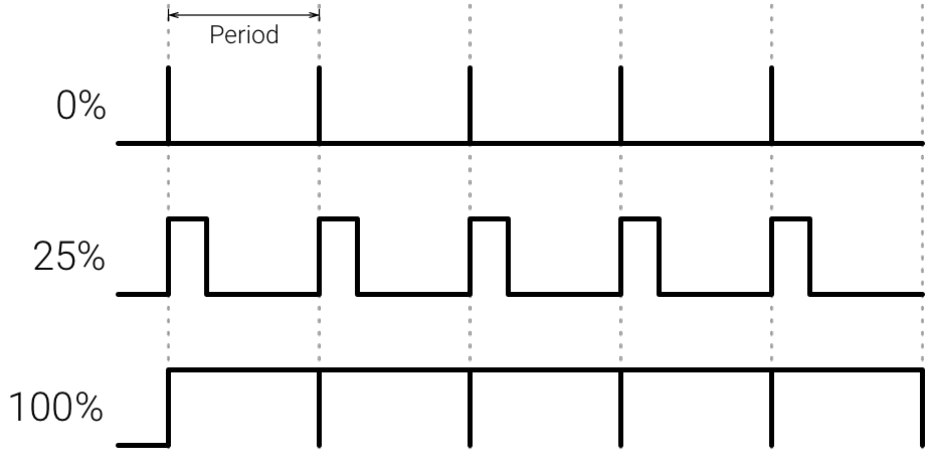
Duty Cycle (%): Percentage of time on during a period

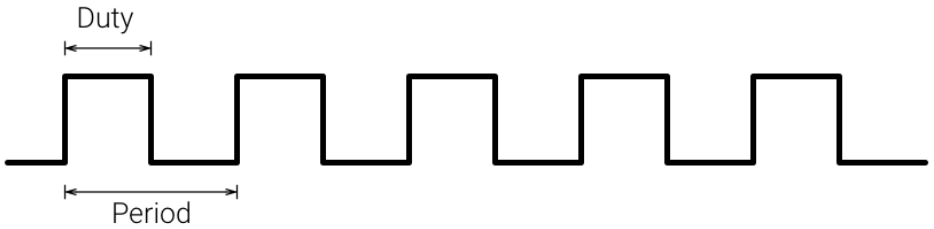
Frequency (Hz): Rate of periods

Period (s): 1/f

Amplitude (v): Output voltage

$$V_{avg} = V_{amp} \cdot (\frac{DutyCycle}{100})$$





Analogue-to-Digital

Another form of simple I/O are **analogue-to-digital inputs**. These inputs read a voltage level (usually between ground and some reference voltage), and report back a **discrete number** indicating the level of this voltage.

Digital computers require a discrete mapping from the **time domain**, to the **value domain**. Taking a reading at a particular point in time is called **sampling**.

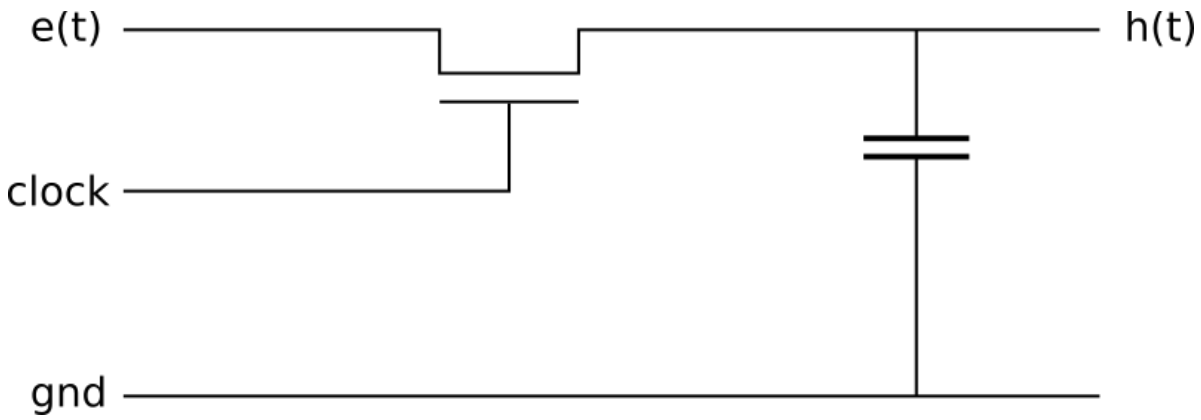
$$s : D_t \rightarrow D_v$$

The **sampling rate** relates to how fast the input can read a (stable) voltage level.

Regular sampling allows recording incoming waveforms.

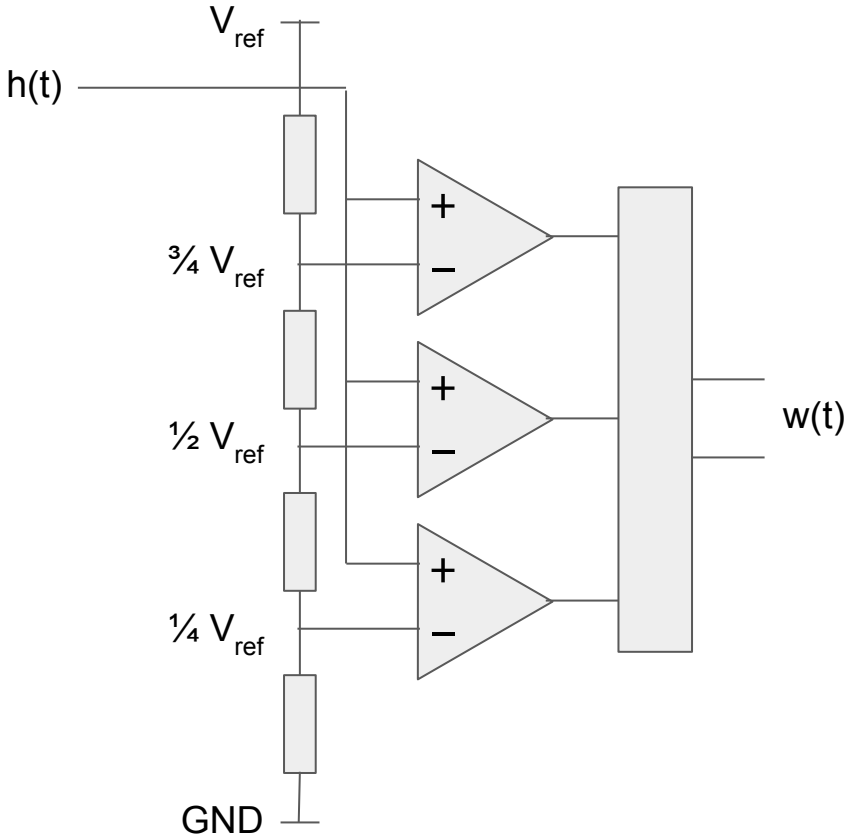
Analogue-to-Digital (Sampling)

Sample-and-hold: clocked transistor and capacitor; the capacitor holds the sequence values

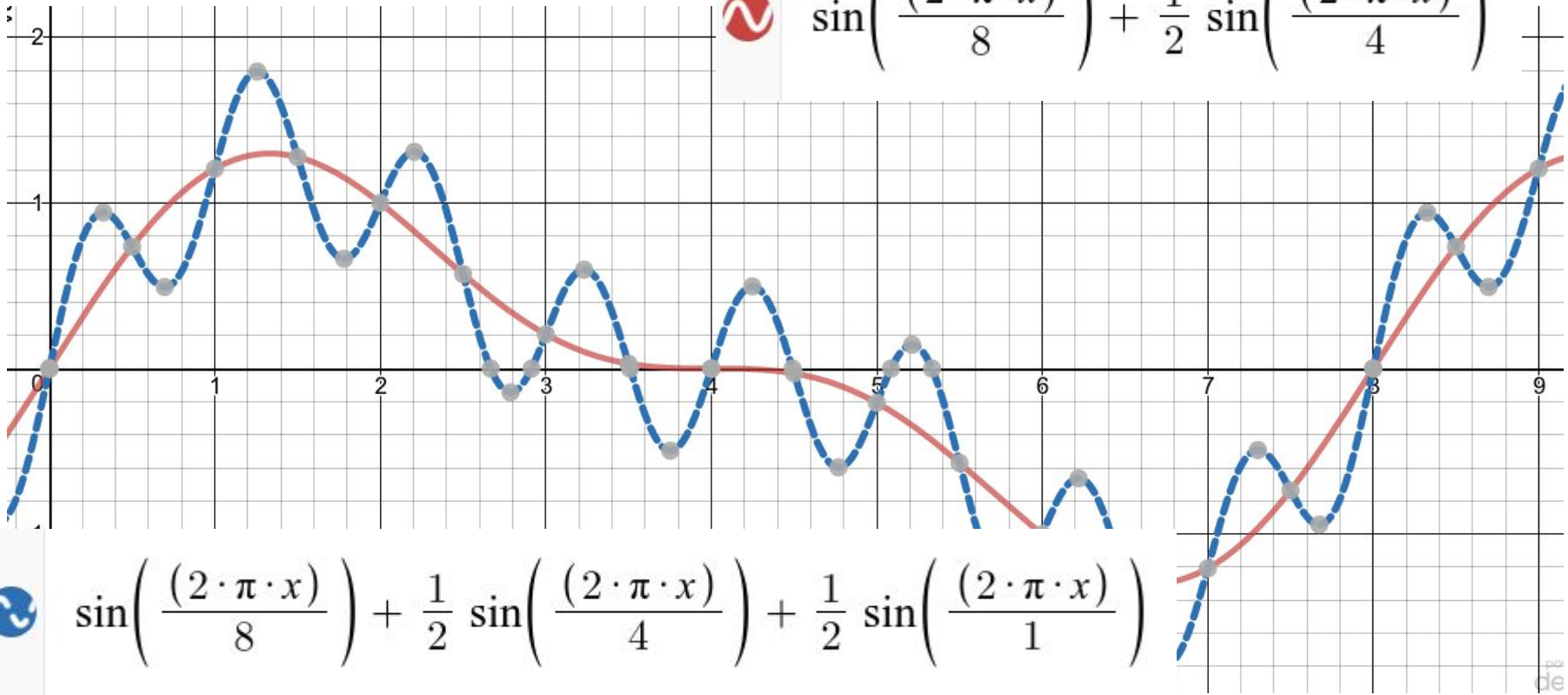


$$e(t) : \mathbb{R} \rightarrow \mathbb{R}, h(t) : \mathbb{Z} \rightarrow \mathbb{R}$$

Analogue-to-Digital (Sampling)



Aliasing


1
$\sin\left(\frac{(2\cdot\pi\cdot x)}{8}\right)+\frac{1}{2}\sin\left(\frac{(2\cdot\pi\cdot x)}{4}\right)$
2
$\sin\left(\frac{(2\cdot\pi\cdot x)}{8}\right)+\frac{1}{2}\sin\left(\frac{(2\cdot\pi\cdot x)}{4}\right)+\frac{1}{2}\sin\left(\frac{(2\cdot\pi\cdot x)}{1}\right)$

Sampling Theorem

Reconstruction is **impossible**, if not sampling frequently enough

How frequently do we have to sample?

Nyquist criterion (sampling theory):

Aliasing can be avoided if we restrict the frequencies of the incoming signal to less than half of the sampling rate.

$\mathbf{p_s < ½\ p_n}$: where $\mathbf{p_n}$ is the period of the "fastest" sine wave
$\mathbf{f_s > 2\ f_n}$: where $\mathbf{f_n}$ is the frequency of the "fastest" sine wave

f_n is the Nyquist Frequency, f_s is the sample rate.

Analogue-to-Digital (Resolution)

The **resolution** determines how precise the reading can be for a given voltage range. The resolution of an ADC converter is typically stated in **bits**.

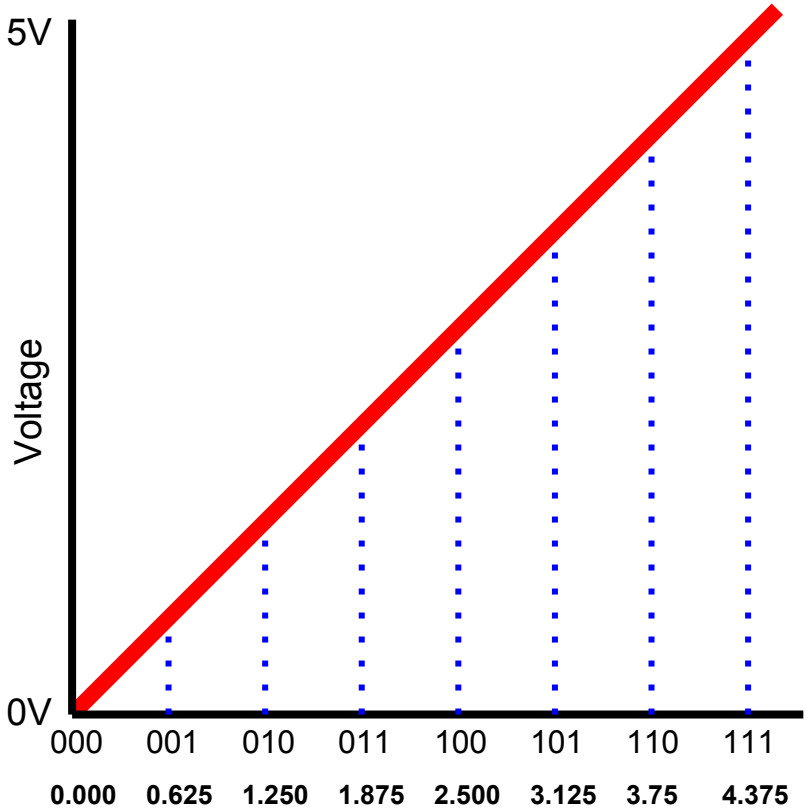
Q = resolution in volts-per-step

$\mathbf{V_{FSR}}$ = difference between largest and smallest voltage

n = number of voltage intervals

For example, **10-bit resolution** means $\mathbf{2^{10} = 1024}$ discrete voltage levels.
With a voltage range of 0-5V, this means **Q = 5/1024 = 0.0049V per step**

Resolution Example (3-bit)



$5V / 2^3$ steps
$= 0.625\ Vstep^{-1}$

Signal-to-noise Ratio

Typically expressed in dB

$$SNR = 20log_{10}(\frac{V_{signal}}{V_{noise}})$$

e.g. $SNR = 20log_{10}(\frac{5}{0.5}) = 20dB$

SNR for ideal n-bit converter is:

$$n \cdot 6.02 + 1.76$$

e.g. 10-bit converter:

$$10 \cdot 6.02 + 1.76 = 61.96dB$$

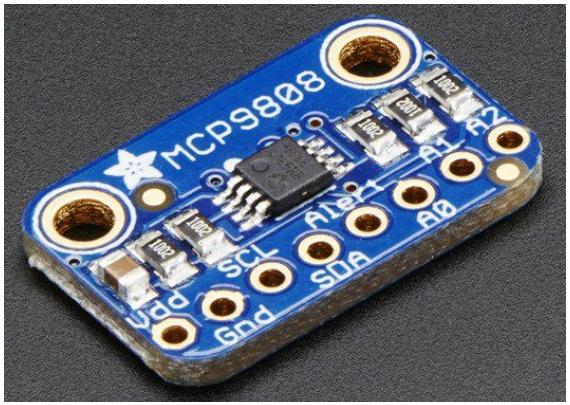
Digital-to-analogue

The reverse of analogue-to-digital is **digital-to-analogue**. In this case, you tell the driver what voltage to produce, and it will generate the requested voltage, or even a (possibly complex) **waveform**.

Some applications for digital-to-analogue conversion can be approximated with PWM, e.g. dimming an LED.

Quality of DAC (frequency, resolution) important for application, e.g. audio.

Interfacing with other sensors



Non-trivial sensors may have a **dedicated communications interface**, or it may simply be convenient to use a **communications bus** if using many sensors.

Retrieving a value from the sensor requires interrogating the sensor's **internal registers**, by using communication channels such as: I^2C, SPI, One-wire-bus, 4-20ma+HART, CAN, UART.

Example: MCP9808 I^2C Temperature Sensor: send a command to retrieve current temperature reading.

Benefit: Sensor does all the heavy-lifting for A-to-D conversion (+ ability to easily multiplex sensors)

Actuators

Actuators turn a digital signal into a physical effect.

- Indicators (LEDs, bulbs, LCDs)
- Motors
- Relays
- Speakers/Buzzers
- Heaters

Embedded systems typically can’t drive high-power loads directly, so must use power switches (MOSFETs, IGBTs, relays, contactors, etc) to operate them.

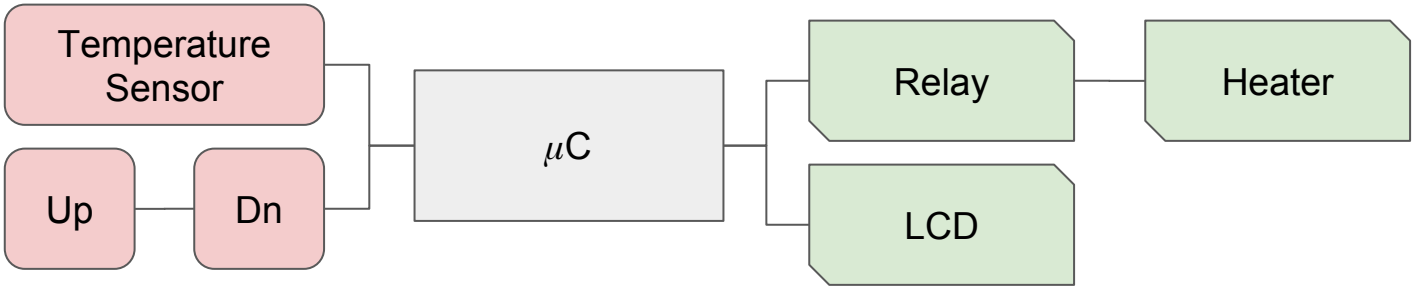
Application: Heating System

Sensors: Temperature, Up/Down Buttons

Actuators: Heating Element (via relay), LCD

Microcontroller: 1 analogue input, 2 digital inputs, 1 digital output, SPI interface for LCD

Implementation: PID control loop



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